ECOSYSTEM SERVICES ANALYSIS FOR THE DESIGN OF
REGENERATIVE URBAN BUILT ENVIRONMENTS

BY

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ABSTRACT:

Humans will need to mitigate the causes of, and adapt to climate change and the loss of biodiversity, as the now inevitable impacts of these changes become more apparent and demand urgent responses. The built environment cannot solve these issues alone. Because it contributes significantly to these problems however, and because it is the main site of cultural and economic activities, it could potentially make a contribution to addressing these problems.

Typical built environment focused responses to climate change and biodiversity issues are inadequate given the urgency and scale of the predicted impacts. They tend not to take advantage of the interconnected nature of the causes and effects of climate change and biodiversity loss. Aiming for 'neutral' environmental impact buildings in terms of energy, carbon, waste or water sets worthwhile and difficult targets. It is becoming clear however, that built environments may need to go beyond having little negative environmental impact in the future, to having positive environmental benefits. Regenerative design could be useful in this regard because it works to mitigate the causes of climate change and ecosystem degradation (and therefore biodiversity loss). Regenerative design ideally increases the health of ecosystems and resilience to change by utilising the mutually reinforcing aspects of mitigation, adaptation and restoration strategies. The goal of the research is to identify whether regenerative design is possible in urban settings, and to determine where key leverage points for system change may be within the built environment.

Regenerative design is in need of further definition and exploration, and lacks quantitative evidence of its potential either by monitoring of built examples, or basic theoretical measurements. Regenerative design literature suggests that mimicking organisms or ecosystems could be an important part of such an approach to design. This is often termed 'biomimicry'. The concept and practice of biomimicry is also in need of critical investigation for its potential contribution to increased sustainability outcomes. Different kinds of biomimicry exist in terms of type, underlying motivation, and environmental performance outcomes. The thesis examines current

understandings of ecological systems in relation to the built environment, and aims to define an ecosystem biomimetic theory for the practical application of regenerative design in urban environments. In order to do this, ecosystem services are examined and potential key ecosystem services that are applicable to a built environment context are identified. The research primarily investigates one area of human knowledge (ecology and biology) for its transferable applicability to another (the urban built environment). Finally, the research determines how such theory could be practically applied to urban and architectural design and tests this through conducting a case study of an existing urban environment.

It is posited that the incorporation of an understanding of the living world into architectural and urban design may be a step towards the creation of a built environment that is more sustainable or potentially regenerative, and one where the potential for restoration of natural carbon cycles is increased. Practical examples of this are given in chapter five. The outcome of such an endeavour depends on the wider context that the built environment is situated in, including the time left for action to be taken before the impacts of climate change and biodiversity loss become extreme, and the inability of the dominant global financial system to allow rapid and widespread action to occur that effectively addresses these issues.

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1.0 CHAPTER ONE: INTRODUCTION

This introductory chapter describes the objectives, aims and scope of the research undertaken. It examines the challenge of climate change and the decline of biodiversity health in relation to the built environment, and presents the strategy examined for its potential to address these dual issues. The chapter will define the fields of knowledge the thesis draws from and to which it contributes. It will conclude with an explanation of the research methodology used in the thesis.

1.1 THE STATE OF THE PLANET: CLIMATE AND ECOSYSTEMS

There is ample evidence to suggest that the narrow band of climatic conditions that supports the on-going survival of the human species is changing (IPCC, 2007d)¹. This affects not only humans but also many, if not most of the other species that inhabit the planet as well as the complex web of relationships between them (Parmesan, 2006, MEA, 2005b)². These relationship networks make up ecosystems. The negative impact of climate change, combined with human caused drivers of environmental change means most ecosystems are in crisis or decline (Walther et al., 2002). The Millennium Ecosystem Assessment (2005b) estimates for example that 60% of global ecosystem services³ are degraded or are being managed unsustainably.

Human caused drivers of negative environmental changes include: the pollution of waterways, oceans, soil, and atmosphere caused by the industrial, agricultural,

¹ The Intergovernmental Panel on Climate Change (IPCC) is a scientific body that was formed by the United Nations Environment Programme (UNEP) and World Meteorological Organization (WMO) in 1988. In 2012 194 countries were members of the IPCC. Thousands of scientists from numerous countries contribute to the substantial IPCC reports about climate change on a voluntary basis (Lord May of Oxford, 2005). For a list of IPCC publications see: <http://www.ipcc.ch/index.html>.

² The Millennium Ecosystem Assessment (MEA) was undertaken by the United Nations beginning in 2001 to 'assess the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being'. The study involved more than 1360 international, multi-disciplinary scientists, was conducted over several years, and culminated in the publication of several state of the art documents in 2005 (Haines-Young and Potschin, 2008). For a list of MEA publications see: <http://www.maweb.org/en/index.aspx>.

³ Ecosystem services are the benefits that humans derive, either directly or indirectly from the functions of ecosystems (Costanza et al., 1997). These are discussed in detail in chapter four.

commercial and transportation activities of people along with the creation of huge amounts of waste (IPCC, 2007c); removal of non-human dominated ecosystems to provide land for urban centres, agriculture and energy generation (such as crop land for biofuels) (Rands et al., 2010); industrial fixation of nitrogen for agricultural purposes (Rockstrom et al., 2009, Chapin et al., 2000); and rapid and escalating consumption of finite fossil fuels, minerals, metals, and over-exploitation of timber, fresh water, and animal and plant life (McGranahan et al., 2005, page 818). These issues are compounded by a rapidly increasing global human population that demands an increasing per capita use of resources and energy (Moran et al., 2008, Rands et al., 2010). Each of these drivers of change is significant in its own right and if not addressed will continue to contribute to significant negative impacts on human individual and societal physical, psychological, cultural and economic wellbeing. It is the convergence and synergistic⁴ effects of these factors however that presents a scenario of grave importance that must be responded to urgently and on a large scale (Brook et al., 2008, Gitay et al., 2002).

The on-going existence of human civilisation in its current form is potentially in danger not only due to climate change but also because of ecosystem degradation and the loss of biodiversity (MEA, 2005a, Rands et al., 2010). Because these two problems are caused mostly by humans, it is apparent that the way many humans currently live, particularly in industrialised countries is not conducive to the long term continuation of human civilisation (Turner, 2008, Atkinson, 2007a). Figure 1 clarifies this. It illustrates that humans exist within ecosystems, rather than as separate from them. Ecosystems in turn exist within and influence the greater global climatic system. Humans impacts on climate change and biodiversity are represented by the red arrows in figure 1. The importance of climate change and the on-going decline in the health of global biodiversity is discussed in the following sections.

⁴ 'Synergistic' here refers to the simultaneous action of separate processes that when combined have a greater total effect due to amplifying feedbacks than they would as single drivers of change (Brook et al., 2008).

Human activities and behaviours have impacted negatively on the climate and on ecosystems (represented by the red arrows). Changes in climate are known to be largely anthropogenic in origin, and stem from many different kinds of human activities (Walther et al., 2005, IPCC, 2007d). This means direct and indirect impacts of climate change on human societies are occurring (represented by blue arrow 4). The degradation of ecosystems and loss of biodiversity are also caused by numerous human activities (Wood et al., 2000). This results in the loss of ecosystem services, in terms of both quality and quantity (Díaz et al., 2006) (represented by blue arrow 3). The importance of these two interconnected sets of impacts is discussed in sections 1.4.1 and 1.5.1. The feedback caused by human induced drivers of change between the climate and ecosystems amplifies in many instances the speed and scale of both climate change and biodiversity loss (illustrated by blue arrows 5 and 6) creating a self-reinforcing feedback loop (Bazzaz, 1990, Dembowski, 2010, Rockstrom et al., 2009, Chapin et al., 2000, Lashof and DeAngelo, 1997, Gitay et al., 2002).

FIGURE 1 DRIVERS AND RESULTS OF CHANGE.

1.1.1 THE CHALLENGE OF CLIMATE CHANGE

Controversy still exists about climate change. The nature of the controversy has changed from debating the existence of climatic changes and the causes of them, to the effects they will have and what humans should do about them in a local and international context (Walther et al., 2005, Gluckman and Boyle, 2003, Chapman et al., 2006). Evidence from established and reputable sources suggesting that the causes of observed global climatic changes are anthropogenic in nature is overwhelming (Hamin and Gurran, 2009, Walther et al., 2005). The fact that current climate change is anthropogenic in nature is represented in figure 1 by the red arrow (2) that connects the behaviour and activities of humans to the climate, and results in the negative impact of climate change.

The combustion of fossil fuels along with deforestation and changing land uses has resulted in a 30% increase in carbon dioxide (CO₂) levels in terms of atmospheric concentrations and a 50% increase in methane concentrations relative to levels three hundred years ago. At least half of these increases have occurred since 1960 (Chapin et al., 2000). Humans add approximately 7 billion tonnes of carbon to the atmosphere annually while oceans and forests have an absorption capacity (that is decreasing) of 3 to 3.5 billion tonnes per year (Gebeschuber et al., 2009). As a result average global temperatures are predicted to rise by between 1.1 and 6.4°C by the year 2100 (relative to 1990 temperatures). The 'best estimate' of temperature increases is between 1.8 and 4.0°C for the same period (IPCC, 2007d, page 13). The mean global temperature has already increased by 0.4°C in the period from 1992 to 2010 (UNEP, 2011).

The impacts of these temperature increases are of huge consequence. For example, with temperature increases of between 1 and 4°C the Greenland Ice Sheet will experience a partial deglaciation leading to a possible sea level rise of between 4 and 6 metres (over an estimated time frame of several hundred years). When temperatures increase by 2 to 3°C coastal flooding could displace between 70 and 250 million people, and if temperatures increase by 3°C, 15 to 37% of the earth's species would face pressures that would be likely to lead to their extinction

(Ewing and Rong, 2008, Thomas et al., 2004)⁵. This final point is illustrated in figure 1 as the blue arrow (6) that shows that climate change leads to further biodiversity loss. Recent research indicates that predictions given by the IPCC (IPCC, 2007b, page 662) of when the Arctic Ocean will be ice free during summer may be underestimates (Stroeve et al., 2012). The Arctic may be predominantly ice free over the sea during summer in less than ten years and completely ice free by 2030 (Wadhams, 2012, Stroeve et al., 2012). This would lead to increased melting of permafrost resulting in methane emissions and increased climate change. Increased precipitation will also result and cause increased melt rates of terrestrial ice cover including that in Greenland (Wadhams, 2012). This demonstrates the increasing urgency for humans to address anthropogenic causes of climate change. For a summary of likely climate changes specific to New Zealand see appendix one.

1.1.2 THE CHALLENGE OF ECOSYSTEM DEGRADATION AND BIODIVERSITY LOSS

A broad definition⁶ of biodiversity is:

‘...the number, abundance, composition, spatial distribution, and interactions of genotypes, populations, species, functional types and traits, and landscape units in a given system’ (Díaz et al., 2006).

The causes of observed global biodiversity loss are undoubtedly anthropogenic in nature (Díaz et al., 2006) (represented in figure 1 by the red arrow 1) and are exacerbated by on-going climate change (Gitay et al., 2002), particularly because climate change accelerates habitat destruction, overexploitation and the prevalence of invasive species (Brook et al., 2008).

⁵ Even using climate change scenarios with minimal warming predictions, extinction rates will reach at least 9% (Thomas et al., 2004).

⁶ It is acknowledged that the very definition of biodiversity can be controversial and that the term means different things to different people (Hanski, 2005).

Changes in biodiversity are of a large and accelerating magnitude despite increases in worldwide conservation efforts, and recognition that the benefits derived by humans from diverse and healthy ecosystems are thought to exceed the costs of maintaining or protecting them by 10 to 100 times (Rands et al., 2010, Sala et al., 2000). Rates of species extinctions are currently 100 to 1000 times greater than natural background rates⁷ (Chapin et al., 2000, Rockstrom et al., 2009) while populations of wild species are declining at a rate of 0.5 to 1% per annum on average. Declines are particularly high in the developing world (Turner and Daily, 2008). Estimates from the Living Planet Index are that there has been a 30% loss of health in the planet's species since 1970⁸ (World Wide Fund for Nature (WWF), 2010). 12% of this decline has occurred since 1992 (UNEP, 2011).

Changes in biodiversity and the on-going degradation of ecosystems will probably have severe, and difficult to predict impacts on human society in terms of physical, psychological, and economic wellbeing (Rockstrom et al., 2009, Chapin et al., 2000, MEA, 2005a, The Economics of Ecosystems and Biodiversity (TEEB)⁹, 2011a). The behaviour and activities of humans impact on biodiversity within ecosystems and result typically in the loss of ecosystem services (Chapin et al., 2000) (represented in figure 1 by the blue arrow 3). These changes, and related impacts on the built environment, are expected to increase in intensity in the future, particularly as the climate continues to change (Gitay et al., 2002).

The first reason why addressing global biodiversity loss is as urgent and important as climate change is that the very survival of humans is dependent on the diverse

⁷ 5 to 20% of the species in most organism groupings have already become extinct probably due to human caused environmental changes, with similar numbers of species being classified as threatened by extinction (Chapin et al., 2000). Mammals are particularly vulnerable with 24% now extinct or endangered (Hanski, 2005). There are a small number of organism types that are 'winners' as a result of global change (Díaz et al., 2006, WWF, 2010).

⁸ This is based on evidence gathered from 7,953 populations of 2,544 mammal, bird, reptile, amphibian, and fish species. There are large differences between tropical and temperate regions in terms of biodiversity changes. A loss of 66% in the Living Planet Index has occurred in the Indo-Pacific region (including New Zealand) since 1970 (WWF, 2010).

⁹ The Economics of Ecosystems and Biodiversity (TEEB) study is an international initiative to draw attention to the global economic benefits of biodiversity and to highlight the growing costs of biodiversity loss and ecosystem degradation. It is hosted by the United Nations Environment Programme (UNEP) with financial support from the European Commission, Germany, the United Kingdom, Netherlands, Norway, Sweden and Japan. Work on TEEB began in 2007 as part of the Potsdam Initiative for biodiversity. Highly regarded scientists, economists and researchers from around the world contribute to TEEB. For a list of TEEB publications see: <http://www.teebweb.org/>.

range of organisms inhabiting the planet because they affect ecosystem processes and therefore ecosystem services (Díaz et al., 2006). Ecological processes that are disrupted by biodiversity loss could lead to cascading co-extinctions termed 'chains of extinction' (Brook et al., 2008). Levin (1999, page 26) points out that:

'Maintaining biodiversity, from the human perspective, is analogous to employing a conservative investment strategy: it increases the chance that we will not lose our entire portfolio.'

FIGURE 2 THE ROLE OF BIODIVERSITY IN GLOBAL CHANGE (SOURCE: CHAPIN ET AL., 2000).

The drivers and feedback mechanisms between biodiversity, ecosystem processes and ecosystem services are complex, non-linear and can be synergistic. They can

relate to diversity at all organisational levels, from the genetic diversity found within populations to the diversity of ecosystems within continuous landscapes (Brook et al., 2008). The exact mechanisms of these interactions can be controversial (Loreau et al., 2001, Rands et al., 2010), but Chapin et al. (2000) provide a summary and examples of how species diversity can specifically effect ecosystem processes and services (see also figure 2).

FIGURE 3 CHANGES IN THE ECOLOGICAL FOOTPRINT AND GLOBAL BIOCAPACITY AVAILABLE PER PERSON (SOURCE: WWF, 2010).

As biodiversity is lost and ecosystems are degraded, the bio-capacity of the planet to support living organisms reduces. As bio-capacity decreases there are diminishing resources available to support a growing human population and increasing collective ecological footprint¹⁰. This is the second reason why decline

¹⁰ 'Ecological Footprint' methodologies measure the amount of biologically productive land and water area required to produce the resources an individual, population or activity consumes and to absorb the waste it generates, given prevailing technology and resource management. This area is expressed in global hectares (hectares with world-average biological productivity)' (WWF, 2010). Ecological Footprint analysis is discussed in more detail in section 5.1.2.3.

in biodiversity health is an urgent issue for humans to address. As illustrated in figure 3, the number of available global hectares per person (bio-capacity) has dropped from approximately 3.7 to 1.8 since the 1960s (WWF, 2010)¹¹.

FIGURE 4 SYNERGISTIC EFFECTS OF HABITAT LOSS AND CLIMATE CHANGE (SOURCE: BROOK ET AL., 2008).

Ecosystems and the biodiversity within them can affect climate through interacting terrestrial feedback mechanisms such as CO₂ fertilization, carbon storage in vegetation and soils, vegetation albedo¹², evapotranspiration, structural change in

¹¹ It is possible for the human population currently to use more land than is available according to ecological footprint analysis because accounting for overshoots (growth beyond an area's biological carrying capacity) is a dynamic concept, involving time delays and cumulative effects so should be considered as a measure over time rather than at a particular given moment (Wackernagel et al., 2004). Factors that contribute to humans being able to continue to function although consumption exceeds global carrying capacity include: global trade (meaning that resources can be transported to places of high resource use such as cities); human management of land (this has led to large increases in the bio-productivity of some areas. Intensive modern agriculture is an example of this); and the ability of humans to adapt (humans are able to adapt in the short term to shortages of specific materials or ecological capacity to process wastes in some cases through the use of technology, substitution of materials or land, or increased resource efficiency if alternative sources are available) (Wackernagel et al., 2004). The mining or utilisation of non-renewable minerals and fuels also means humans currently use resources that will not be available in the future and can for a time, continue during a period of ecological overshoot.

¹² For example at high latitudes the replacement of snow covered tundra with a darker coloured conifer canopy, driven by human demand or a change in climate that enables conifers to exist at different latitudes, can increase the local absorption of solar energy to such a degree that a powerful positive feedback loop is created resulting in more regional warming (Chapin et al., 2000).

biological communities, and peat-land methane emissions (Gitay et al. 2002). Lashof and DeAngelo (1997) state:

‘While the processes involved are complex, not readily quantifiable, and demonstrate both positive and negative feedback potential, we conclude that the combined effect of the feedback mechanisms... will likely amplify climate change relative to current projections...’

This is illustrated in figure 1 as the blue arrow (5) that shows that biodiversity loss can lead to further climate change (Chapin et al., 2000, Lashof and DeAngelo 1997). This positive feedback loop between continued climate change and ongoing loss of biodiversity is the third reason why biodiversity issues should be considered to be as important as climate change issues and why the two must be considered in tandem. Because there is a relationship between climate and biodiversity it may be possible to harness this to both reduce the causes of climate change and to reduce the loss of biodiversity. This concept is discussed further in section 1.6.

1.2 THE BUILT ENVIRONMENT AS A MEDIUM OF CHANGE

The research presented in this thesis cannot attempt to address all of the drivers of environmental change, but will focus on the dual challenge posed by human induced climate change and degradation of ecosystems leading to biodiversity loss. Addressing such large problems in terms of both scale and scope needs many solutions to fit the vast variety of political, economic, cultural, climatic, and ecological conditions within which humans dwell. Strategies that employ the medium of the built environment to effect change in human behaviour could be one such set of solutions. If the dominant economic philosophies and structures of human society and their resulting behaviours do not or cannot change in the short to medium term, it is doubtful that new or existing forms of design thinking and practice will alone be able to create significant change, before humanity is threatened or severely affected by the degradation of ecosystems and changes in climate (Turner, 2008, Mitchell, 2012, Atkinson, 2007a).

Activities and behaviours that cause climate change and biodiversity loss are numerous, complex and interconnected, and stem largely from the way humans live in, understand and relate to the world around them. This means that although the built environment cannot alone be tasked with solving all of the identified issues, the way people inhabit the built environment does make a large contribution to the causes of both climate change (as discussed in section 1.3) and biodiversity loss (as discussed in section 1.4). It can also therefore potentially be a medium where these problems can be addressed (McGranahan et al., 2005, page 821).

The IPCC (2007a, page 59) states for example that buildings offer more opportunities for cost-effective greenhouse gas (GHG) mitigation than any other sector, although significant changes in current practice are required to achieve such an aim. Many technologies and established design techniques already exist that are able to mitigate or adapt to climate change mitigation, and work towards restoring the healthy functioning of ecosystems. Regarding just climate change, Lowe (2000) estimates for example, that reductions of 80% in carbon emissions associated with the built environment are possible using current technologies. The potential of well-known design techniques to reduce dependence on fossil fuel derived energy is also well understood and documented (see for example: Mazria, 1979, Wright, 1984, Santamouris, 2001, Roaf et al., 2005, Omer, 2008, Bainbridge and Haggard, 2011, Morrissey et al., 2011, La Roche, 2012).

Estimates of how high the contribution to global GHG emissions is from cities vary from 30% to as high as 80% (Spiegelhalter and Arch, 2010). In the United States almost half of all GHG emissions can be attributed to the built environment (Architecture 2030, 2008). Satterthwaite (2008) and Dodman (2009) discuss the difficulties of measuring or understanding the contribution of cities to GHG emissions in depth. Dodman (2009) points out that per capita carbon emissions are actually typically lower for people living within cities than their rural counterparts within the same country and state that:

‘Attempts to blame cities for climate change serve only to divert attention from the main drivers of GHG emissions – namely unsustainable consumption, especially in the world’s more affluent countries’.

Although 33% of urban residents live in slums worldwide (14% of the total human population)¹³, urban populations tend to be more wealthy and consume more in some instances (Bloom et al., 2008, UNEP, 2011), and cities may offer unique opportunities for policy and governance changes leading to more tangible and immediate action to mitigate climate change (Hunt and Watkiss, 2011). Rosenzweig et al. (2010) point out that it is at the city level that most actions to either mitigate the causes of climate change or adapt to them are occurring globally. Local authorities have more direct control in many instances over emissions from cities through planning and land use policies, energy supply management, waste management, enforcement of industrial regulations, and transport planning than central government (Bulkeley and Betsill, 2005, Dodman, 2009), although regulations for individual buildings are determined by national building codes in most places.

TEEB (2011b) also note that the trend to decentralise government is increasing globally, meaning that local authorities are responsible for an increasing proportion of local environmental management and that the medium of urban built environments could therefore be a place where rapid change can occur. Urban environments in some instances achieve an economy of scale meaning that access to capital exists, methods or technologies to mitigate climate change could potentially be more easily deployed, and that cities may be able to act as centres of innovation and as catalysts for social learning (Dixon, 2011).

Many European Organisation for Economic Co-operation and Development (OECD) countries, most former Soviet Union countries, and a small handful of

¹³ ‘A slum household is defined as a group of individuals living under the same roof lacking one or more of these conditions: access to improved water; access to improved sanitation; sufficient-living area; durability of housing; security of tenure’ (UNEP, 2011).

other nations¹⁴ have recorded reductions in national CO₂ emissions due to fuel combustion between 1990 and 2009 (International Energy Agency (IEA), 2011, page 48)¹⁵. It is likely that reductions due to climate change mitigation policies rather than economic or political factors, or demographic changes only account for those in the more wealthy European countries. Moreover, Baiocchi and Minx (2010) point out in regard to the United Kingdom's recorded reduction in emissions, that some of these reductions are not due to increased efficiencies, or changes in consumption behaviour, but can instead be attributed to production rather than consumption based emission accounting models that do not reflect changes in the global division of labour in the production of goods and services (see also: Hoornweg et al., 2011). Several cities, including San Francisco, Portland, Philadelphia and Vancouver, that are located within countries that have recorded increases in GHG emissions in the same period, claim to have actually reduced their emissions¹⁶, indicating that urban areas are capable of contributing to climate change mitigation even if located within a country that is unable or unwilling to engage in this.

Although the urban built environment occupies only 2.8% of global land area (Ruth and Coelho, 2007), it should also be remembered that it is the main site of human economic, social and cultural life in terms of both magnitude and significance. More than half of all humans now live in urban built environments¹⁷, a figure predicted to

¹⁴ European OECD countries recording reductions in CO₂ emissions between 1990 and 2009 were: Belgium, Czech Republic, Denmark, Finland, Germany, Hungary, Italy, Luxembourg, Poland, Slovak Republic, Sweden and the United Kingdom. Former Soviet Union countries recording reductions in CO₂ emissions between 1990 and 2009 were: Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Ukraine and Uzbekistan. Other countries recording reductions in CO₂ emissions between 1990 and 2009 were: Albania, Bosnia, Bulgaria, Croatia, Cuba, DPR Korea, Macedonia, Mongolia, Romania, Serbia, Zambia, and Zimbabwe (IEA, 2011).

¹⁵ These results refer to national rather than per capita emissions. There are several issues with comparing results for different countries over time such as differences and changes in accounting methods, different base line years, discrepancies in record keeping, and changes in political boundaries. IEA (2011) highlights these issues as they occur throughout the publication.

¹⁶ No authoritative source could be located and cited here that provided conclusive research to verify the assertions of these North American cities. Claims have been made by the city authorities themselves in most cases through various forums including council websites and other online sources. Mexico City (Mexico), Barcelona (Spain), and Bristol (United Kingdom) also make similar unverifiable claims. Dixon (2011) provides credible details of cities in the United Kingdom including Greater London, Birmingham, Leeds, Glasgow, Sheffield, Edinburgh, Manchester, Bradford, Liverpool, and Cardiff that have successfully reduced their GHG emissions between 2005 and 2009.

¹⁷ 220 million people lived in urban areas (13%) in 1900. 3.2 billion (49%) lived in urban areas in 2005. By 2030 the number could be 4.9 billion (Eigenbrod et al., 2011). In New Zealand 85% of people live in cities and

Footnote continued on next page...

rise to 60% by 2030 (Eigenbrod et al., 2011), and people spend approximately 75% of their time indoors (Grimm et al., 2008, Chan and Cheng, 2006). It is also where nations invest large amounts of money and resources in terms of energy and materials. Even just considering the domestic arena in New Zealand, where homes are collectively valued at US\$280 billion (NZ\$337 billion), this is approximately three times as much as national annual gross domestic product (GDP) (IPCC, 2007b, page 521). It is important then that the built environment remains a habitable place for humans.

Because of the built environment's dual role as driver of many of the causes of negative climate and biodiversity changes, because it is the primary habitat for humans, and because a focus on the built environment presents potential opportunities for change, this thesis focuses on the built environment as a medium for mitigating the causes of climate change. It also looks at how the built environment can adapt to climate change impacts while concurrently responding to the degradation of ecosystems and the loss of biodiversity.

1.3 CLIMATE CHANGE AND THE BUILT ENVIRONMENT

The aim of this section is to establish a broad overview of the contribution the built environment makes to causing climate change and the major impacts predicted for the built environment due to climate change. The results of a literature review will be described followed by a discussion of the difference between direct and indirect impacts.

Globally, at least 30% of global anthropogenic GHG emissions come from building construction and operation¹⁸ (de la Rue du Can and Price, 2008, UNEP, 2007, Satterthwaite, 2008). In New Zealand the figures are slightly different with the built environment being responsible for 45% of national electricity use (22% commercial

towns (Howden-Chapman et al., 2010). International figures are based on widely varying definitions of what constitutes 'urban' areas in each country, so exact percentages are at best difficult to calculate and should be accepted with caution. The crucial point being made however is that a large proportion of people live in cities or towns.

¹⁸ This is due to their high energy consumption, large production of waste (Bulkeley and Betsill, 2005) and links with transport (Ewing et al., 2008).

and 23% residential), 50% of total waste sent to landfill or cleanfill, and 17% of total national GHG emissions (Sinclair Knight Merz, 2008, Storey et al., 2003). This is made up of 8% from commercial buildings and 9% from residential buildings. This figure may be lower than international sources due to differences in measuring methods and also because of the significant contribution agriculture makes to New Zealand's total GHG emissions. It is the emission of such gases (including carbon dioxide, methane, nitrous oxide, tropospheric ozone and chlorofluorocarbons) and their effect on the atmosphere that is the leading cause of climate change (Walther et al., 2005). Up to 40% of all energy and material resources are used to construct and operate buildings and up to 40% of total solid waste results from construction and demolition activities¹⁹. UNEP (2011) states that:

'The global use of natural resource materials increased by over 40% between 1992 and 2005, from about 42 to nearly 60 thousand million tonnes. On a per capita basis, the increase was 27%... There has been a major increase in extraction of construction minerals of almost 80%.'

1.3.1 THE IMPACTS OF CLIMATE CHANGE ON THE BUILT ENVIRONMENT

Climate change will have many important and probably severe impacts on human society (Alley et al., 2003, Stern, 2006, Walther et al., 2002, Robertson, 2006, Schneider and Lane, 2006). Because these are numerous in scope, are both spatial and temporal in scale (Kenny et al., 1995, Hunt and Watkiss, 2011), and a thorough examination of all of them is beyond the scope of this thesis, this section will explore in depth only those climate change impacts that will affect the built environment. These are many and varied, and although they require further research and are difficult to quantify in some cases (IPCC, 2007b, pages 357-385), they have been explored by several researchers (Wilby, 2007, Koepfel and Ürge-Vorsatz, 2007, Hunt and Watkiss, 2011). These changes, and therefore related impacts on the built environment (table 1), are expected to increase in intensity in

¹⁹ Construction and demolition waste can contribute to climate change either through the emission of GHGs as materials decompose (particularly gypsum board products which release hydrogen sulphide if disposed of in certain landfill conditions) or due to the release over time of high global-warming potential fluorinated gases from certain construction and demolition related wastes such as chlorofluorocarbon (CFC) or hydrofluorocarbon (HCFC) containing rigid foam insulation (Bogner et al., 2008).

the future, suggesting that a re-evaluation of the current and future built environment is necessary (IPCC, 2007c, pages 391-393).

The impacts that climate change will have on the built environment are both direct and indirect. Direct impacts will affect the actual physical fabric of the built environment, while indirect impacts will affect the economic, social and environmental context in which the built environment operates (O'Connell and Hargreaves, 2004).

1.3.1.1 DIRECT IMPACTS

Impacts will vary greatly depending on the location and local quality of the existing built environment; however those changes in climate that will be most significant in terms of impacts on the built environment in an international context have been identified by Hunt and Watkiss (2011) as follows:

- Sea level rise and storm surges²⁰.
- Increased extreme weather events including high winds, floods and heat extremes.
- Changes in water availability.

The results of a review of research examining the main direct impacts of climate change on the built environment have been summarised in table 1. A brief summary of each direct impact follows. Although the impacts listed relate to the built environment in general, there is a focus on New Zealand examples and conditions in the explanation of the impacts. Because climate change will affect various locations in different ways, making the discussion location specific enables the summary to be more detailed and focused.

Camilleri et al. (2001) and O'Connell and Hargreaves (2004) identify increased inland flooding, increased temperatures, and increased damage resulting from a possible rise in the number and intensity of tropical cyclones as three significant

²⁰ 65% of cities with a population exceeding 5 million and more than 50% of the global human population are coastal or low lying (Hunt and Watkiss, 2011).

TABLE 1 DIRECT CLIMATE CHANGE IMPACTS ON THE NEW ZEALAND BUILT ENVIRONMENT

Potential Direct Climate Change Impacts:	Consequences for the built environment:	Possible scale of the negative impact.	Sources:
Changes in temperatures (Likely to increase in most areas)	Increased overheating and air conditioning load	High	BRANZ (2001), Camilleri et al. (2001), Gluckman and Boyle (2003), Honey and Buchanan (1992), Mullan et al. (2008), O'Connell and Hargreaves (2004).
	Intensified urban heat island effect	High	
	Decreased winter space heating	Low (potentially positive)	
	Decreased water heating energy	Low (potentially positive)	
Increased intense weather events	Damage to buildings and infrastructure	High	BRANZ (2001), Camilleri et al. (2001), Gluckman and Boyle (2003), Honey and Buchanan (1992), Mullan et al. (2008), O'Connell and Hargreaves (2004).
Changes in precipitation patterns	Increased inland flooding	High	BRANZ (2001), Camilleri et al. (2001), Gluckman and Boyle (2003), Honey and Buchanan (1992), Mullan et al. (2008), New Zealand Climate Change Programme (2001), O'Connell and Hargreaves (2004), Woodward et al. (1998).
	Increased erosion, landslips, rock falls	High	
	Changes in aquifers and urban water supply and quality	High	
	Heavier snow or ice loads	Medium	
	Increased fire risk associated with more frequent droughts	Medium	
	Damage to foundations, underground pipes / cables etc.	Medium	
	Increased subsidence (clay soils)	Medium	
	Increased pressure on urban drainage systems	Medium	
	Increased storm water run-off and leaching of pollutants into water ways or aquifers	Low	

	Damage to facades and internal structure due to rain penetration	Low	
Thermal expansion of oceans and changes in the cryosphere (ice systems) such as retreating snow lines and ice packs, and melting glaciers	Increased coastal flooding	High	BRANZ (2001), Camilleri et al. (2001), Gluckman and Boyle (2003), Honey and Buchanan (1992), Mullan et al. (2008), New Zealand Climate Change Programme (2001), O'Connell and Hargreaves (2004), Woodward et al. (1998).
	Increased erosion and loss of land	High	
	Relocation or displacement from coastal areas	High	
	Changes in water tables and possible increased salinity of aquifers and estuaries.	High	
	Loss of inter tidal areas acting as buffer zones	High	
	Impeded drainage	Medium	
Changes in wind patterns and intensities	Changes in wind loading on buildings	Medium	BRANZ (2001), Camilleri et al. (2001), Gluckman and Boyle (2003), Mullan et al. (2008), New Zealand Climate Change Programme (2001).
Increased air pollution	Impacts on interior air quality management	Medium	BRANZ (2001), Mullan et al. (2008).
	Damage to building facades	Low	
Impacts on urban biodiversity	Changes in cooling, shading and evapotranspiration benefits from urban biodiversity	Medium	O'Connell and Hargreaves (2004), Woodward et al. (1998).
	Changes to storm water management	Low	

negative direct impacts of climate change that are likely to affect the New Zealand built environment. These issues are highlighted by a number of additional sources (Woodward et al., 1998, Gluckman and Boyle, 2003, BRANZ, 2001, New Zealand Climate Change Programme, 2001, Honey and Buchanan, 1992, Mullan et al., 2008)²¹. The main problems associated with tropical cyclones are the effects of extreme winds and driving rain (O'Connell and Hargreaves, 2004). BRANZ (2001) identifies the possibility of combinations of one or more extreme climatic events as a potential threat to the built environment.

The most significant potentially positive direct impacts of climatic changes on the built environment are decreased need for winter space heating, and to a lesser degree decreased water heating needs due to rising temperatures (Honey and Buchanan, 1992, Camilleri et al., 2001, BRANZ, 2001). Because of the moderating effect of the ocean surrounding New Zealand, it is thought that New Zealand will only become warmer by two thirds of the global average (Gluckman and Boyle, 2003, O'Connell and Hargreaves, 2004). New Zealand temperatures will increase by approximately 1°C by 2040 (the range of predictions is from 0.2 to 2.0°C) relative to 1990 levels and by 2°C by 2090 (the range of predictions is 0.7 to 5.1°C). The range is wide due to different IPCC emissions scenarios being used in conjunction with different climate models (Mullan et al., 2008).

Precipitation patterns are predicted to change (Woodward et al., 1998) (figure 5). The increase in precipitation in some areas, drought in others and changes in intensity of rainfall will affect the built environment (Woodward et al., 1998, BRANZ, 2001, Honey and Buchanan, 1992, Gluckman and Boyle, 2003, O'Connell and Hargreaves, 2004, Reisinger et al., 2010). Possible impacts of these changes in precipitation patterns may be damage to foundations caused by changes in groundwater pressure and damage to facades and internal structures caused by increased rain penetration. Additional impacts identified were increased subsidence, increased erosion and landslips, changes in aquifers and urban water

²¹ Most sources referred to in this section use IPCC scenarios with a 1990 baseline and time frame of up to 2040 or 2090. See: Mullan et al. (2008) for example.

supply and quality, and increased pressure on drainage systems (Gluckman and Boyle, 2003, O'Connell and Hargreaves, 2004).

FIGURE 5 PROJECTED ANNUAL MEAN PRECIPITATION CHANGE BETWEEN 1980 AND 2099 IN NEW ZEALAND (SOURCE: MULLAN ET AL., 2008).

Mullan et al. (2008) calculate a rise in sea levels for New Zealand of at least 18 to 59cm between 1990 and 2100. The impacts of this relevant to the built environment include: increased coastal flooding and erosion; changes in sedimentation patterns, water tables, run off rates, and infiltration of aquifers in some areas (of salt or other pollutants); retreat and relocation from coastal regions and slowing or prevention of building in such areas; increased shoreline retreat resulting in 'coastal squeeze'²² (Gluckman and Boyle, 2003); and loss of the inter-tidal areas and the buffering nature of these areas in storms and high tide events.

²² If the shoreline retreats it may become closer to where the built environment begins, resulting in a narrower shore / beach / tidal area.

Despite predictions of up to a 10% increase in strong winds, particularly westerlies (Mullan et al., 2008), the significance of changes in wind loading on buildings is not well understood in a New Zealand context.

Camilleri et al. (2001), the New Zealand Climate Change Programme (2001), Honey and Buchannan (1992) and BRANZ (2001) discuss the inter-relationship of the depleted ozone layer with climate change impacts. There may be some minor impacts on the durability of polymers caused by this (Camilleri et al., 2001). It is acknowledged by the New Zealand Climate Change Programme (2001) that there may be a slowing of the recovery of the ozone layer in combination with climate change.

Most of the research cited in this section takes the approach of investigating the impacts of climate change on the fabric of the physical built environment in isolation from the wider context in which the built environment exists including society and ecosystems. It also ignores converging issues that will have significant impacts on the built environment, including increased scarcity of global food, water and energy resources, and a general decline in the ability of ecosystems to provide ecosystem services to people (Mooney et al., 2009), all of which are exacerbated by climate change. Population increase, changes in demographics, and increased urbanisation will also be significant issues for the built environment of the future. Because of this narrow scope of research, the results discussed here may give the impression that the most serious impact of climate change on the built environment might be some water, wind, or storm damage or some occasional overheating.

Indirect impacts such as food shortages, increased disease risk, financial or political instability, or even the inability to use private vehicles might have more of an impact on the viability of the current built environment in the future. This illustrates that it is important to consider the impacts of climate change in the context of urban environments alongside related issues, or to take a whole-systems approach to such research (O'Connell and Hargreaves, 2004). As Reisinger et al. (2010) point out:

‘...Understanding of climate change impacts and adaptation options... requires an appreciation of the global socio-economic and biophysical changes associated with those scenarios. Such global changes could have significant flow-on effects on New Zealand through alternative global and regional socio-economic and policy developments, as well as global climate change impacts and global-scale responses to those impacts’.

1.3.1.2 INDIRECT IMPACTS

Indirect impacts will vary greatly depending on location. The most significant impacts internationally have been identified by Hunt and Watkiss (2011) as follows:

- Health effects relating to food and water borne disease and extremes of heat and cold and flooding.
- Increases in demand for energy in the built environment, exacerbated by the urban heat island effect particularly for cooling in warmer cities.

The substantial current and anticipated economic, environmental and social impacts of climate change are well documented (Chapman et al., 2006, IPCC, 2001, Stern, 2006). This section will discuss some of the major indirect impacts of climate change that could affect the built environment in a New Zealand context. Indirect impacts of climate change on the built environment are listed in table 2.

The New Zealand built environment accounts for 45% of the nation’s total electricity usage (Sinclair Knight Merz, 2008). 72% of electricity was generated from renewable sources in the September quarter of 2011 (Ministry of Economic Development, 2011). Renwick et al. (2010) point out that:

‘New Zealand’s energy sector is especially sensitive to climate influences, since a large fraction of the country’s electricity is generated from climate sensitive renewable fuel sources, and since the climate of New Zealand varies widely on all time scales.’

TABLE 2 INDIRECT CLIMATE CHANGE IMPACTS ON THE NEW ZEALAND BUILT ENVIRONMENT

Potential Indirect Climate Change Impacts:	Consequences for the built environment:	Possible scale of the negative impact.	Sources:
Changes in food growing areas, agricultural production and reliability and timing of crops.	The built environment may be expected to allow for increased food growing.	High (potentially positive)	Dynes et al. (2010), New Zealand Climate Change Programme (2001), O'Connell and Hargreaves (2004), Woodward et al. (1998).
Decreased biodiversity.	See table 3.	High	See table 3.
Changes in transportation patterns	Changes in population and activity patterns will affect expectations of and viability of some parts of the built environment.	High	Hamin and Gurran (2009), Steemers (2003a).
Changes in global and regional economies.	Shifts in money and resources available for construction.	High	Dynes et al. (2010), Seo (2011), Stern (2006).
Negative impacts on animal and human health (air, water, and food quality. Food and water availability. Temperature changes).	Capabilities in design, construction and maintenance may be affected.	High	Gluckman and Boyle (2003), Howden-Chapman et al. (2010), Hunt and Watkiss (2011), Mullan et al. (2008), New Zealand Climate Change Programme (2001), O'Connell and Hargreaves (2004), Robertson (2006), Woodward et al. (1998).
	User capabilities and expectations of the built environment may change.	Medium	
Increased disease and pest risk	Human work force and inhabitants may be negatively affected.	High	Dynes et al. (2010), Howden-Chapman et al. (2010), Mullan et al. (2008), New Zealand Climate Change Programme (2001), O'Connell and Hargreaves (2004), Robertson (2006), Woodward et al. (1998).
	Building materials such as timber may be affected.	Medium	
Increased local and international emigration and immigration (likely to be immigration into New Zealand).	Changes in expectations of the built environment to accommodate different and possibly increased numbers of users.	Medium	Honey and Buchanan (1992), Howden-Chapman et al. (2010), IPCC (2001), Woodward et al. (1998).

Social dislocation that may particularly affect indigenous, poor and marginalised communities.	Changes in expectations of the built environment to accommodate different and possibly increased numbers of users.	Medium	Gluckman and Boyle (2003), Howden-Chapman et al. (2010), King et al. (2010), Woodward et al. (1998).
	Poorer quality of building stock.	Medium	
Changes in insurance costs and coverage.	Changes in areas suitable for human habitation.	Medium	BRANZ (2001), Camilleri et al. (2001), O'Connell and Hargreaves (2004).
Increased cost of disaster relief and emergency management.	Shifts in money and resources available for construction.	Medium	Gluckman and Boyle (2003).
Changes in plant growth patterns and soil quality.	Changes in growth rates and quality of plantation grown timbers and other grown resources.	Medium	Camilleri et al. (2001), Dynes et al. (2010), Gluckman and Boyle (2003), Honey and Buchanan (1992), New Zealand Climate Change Programme (2001), Rutledge et al. (2010).
Changes in energy types available and costs (including electricity).	Changes in costs to run and build the built environment will affect its design and expectations.	Medium	BRANZ (2001), Camilleri et al. (2001), Gluckman and Boyle (2003), Honey and Buchanan (1992), Hunt and Watkiss (2011), Renwick et al. (2010b).
	Increase in passive design (potentially).	Potentially positive	
	Increase in renewable energy use on buildings (potentially).	Potentially positive	
Changes in regulations to prepare for adaptation.	Changes in flood zones, development zones and defined hazards.	Medium (potentially positive)	BRANZ (2001), Camilleri et al. (2001), O'Connell and Hargreaves (2004), Woodward et al. (1998).
	Changes in materials available, suitable, and desirable for construction.	Low (potentially positive)	
	Changes in construction methods.	Low (potentially positive)	
	Changes in building standards, codes and regulations.	Potentially positive	
Changes in regulations to mitigate GHG emissions, following international treaties.	Increased regulatory / compliance requirements & costs.	Low	BRANZ (2001), Camilleri et al. (2001), Gluckman and Boyle (2003), O'Connell and Hargreaves (2004).

Changes in regulations to mitigate GHG emissions, following international treaties.	Increased regulatory / compliance requirements & costs.	Low	BRANZ (2001), Camilleri et al. (2001), Gluckman and Boyle (2003), O'Connell and Hargreaves (2004).
	Changes in construction methods	Low (potentially positive)	
	Changes in building standards, codes and regulations.	Potentially positive	
	Increased pressure / need to design for mitigation of GHG emissions & adaptation to climate change.	Potentially positive	
Decline in human mental health.	Changes to workforce available to build and maintain the built environment.	Low	Howden-Chapman et al. (2010).
Increased demand for energy efficient, zero carbon emission design as well as design able to adapt to climate changes.	Greater skill and knowledge required to design.	Low (potentially positive)	BRANZ (2001), Gluckman and Boyle (2003), Mullan et al. (2008).
	Increased multidisciplinary collaboration.	Potentially positive	
	Increased use of the precautionary principle.	Potentially positive	

The majority (53%) of electricity is generated by hydro power in New Zealand (Ministry of Economic Development, 2011). Changes in hydro generation will be brought about by changes in precipitation patterns, and by retreating snow lines and glaciers²³. In some areas, particularly the South Island, hydro generation may be enhanced in spring and winter (Gluckman and Boyle, 2003, Honey and Buchanan, 1992). It is likely that demand will also increase, particularly in summer (Renwick et al., 2010).

In the September quarter of 2011 28% of electricity was produced by coal and natural gas in New Zealand (Ministry of Economic Development, 2011). This proportion of the New Zealand electricity supply will be affected by the need to mitigate carbon emissions and to a lesser extent by the local and global decline of cheap oil and gas. These factors will result in changes in energy costs (BRANZ, 2001, Camilleri et al., 2001). Changes in the availability of energy sources and fuels that are socially and legally acceptable to use may also occur²⁴. Reduction in the availability of cheap fossil fuels will also have significant impacts on transportation.

Camilleri et al. (2001), Gluckman and Boyle (2003), and BRANZ (2001) discuss the economic implications for the built environment of predicted increased costs due to future carbon or GHG emission charges. It is likely that some form of carbon trading or taxing will become standard (Chapman et al., 2006). This will likely impact on the built environment's operating costs and also affect design, materials used and construction methods employed.

²³ 1% of the world's glaciers are found in New Zealand. In the 20th Century in New Zealand glaciers retreated by an average of 38% (Chinn, 2001). Many of New Zealand's South Island hydropower generating schemes are affected by these changes in glaciers. For example, 39% of New Zealand's glacier ice is found in glaciers that drain into Lake Pūkaki and the Waitaki River system, where eight hydropower stations are located (McSaveney, 2009). The interaction between glaciers and climate change is complex in New Zealand due to varying feedback mechanisms and time delays between causes of change and effects (Chinn, 2001). Retreating glaciers would in some cases increase base flows for a time in rivers in New Zealand due to increased meltwater (Chinn, 2001), but this may only be for a few years or decades and flows are likely to recede over time (Orlove, 2009).

²⁴ Legislation governing the domestic burning of coal and wood is increasing in New Zealand (Baines et al., 2003), while the social acceptability of using land to grow biofuels rather than food crops, or of using biofuel derived from crops that would have otherwise been used as a food source is decreasing internationally (Rosegrant, 2008).

Temperature increases and precipitation decreases in line with IPCC predictions could cause declines of an estimated 34% in gross cell product (GCP)²⁵ in the Oceania region over the long term (Seo, 2011). This could affect employment prospects and the cost of living for people and result in changes in the ability to construct, alter, and maintain the urban environment.

More frequent extreme weather events and the loss of coastal property will have large economic and social impacts (Wilby, 2007, O'Connell and Hargreaves, 2004, Robertson, 2006). Considering that before the devastating earthquakes in Canterbury in 2011²⁶, approximately 75% of insurance pay-outs for damages caused by natural hazards in New Zealand over the past 40 years were for weather related hazards (NIWA et al., 2011a), an increase in these costs due to more frequent climate change induced weather events may lead to price rises or difficulty in securing insurance. This could result in changes in the ability to build, alter or maintain the built environment (Camilleri et al., 2001, O'Connell and Hargreaves, 2004, BRANZ, 2001). The loss of human life, economic damages from natural disasters and reported numbers of natural disasters themselves have increased globally since 1992 (UNEP, 2011). Large reinsurance companies have estimated that by 2016 annual global economic losses caused by climate change could be as high as \$US300 billion per year (Gebeschuber et al., 2009). Money spent on disaster relief and emergency management is expected to increase along with the amount of resources allocated to monitoring and early warning systems of natural hazards (O'Connell and Hargreaves, 2004, Gluckman and Boyle, 2003).

With increasingly unpredictable climatic patterns, an increase in the use of the precautionary principle in relation to approaching climate change impacts may occur (Gluckman and Boyle, 2003). There may be attempts to overdesign network capabilities to accommodate unexpected events and designers may be expected

²⁵ Gross cell product (GCP) is defined by Seo (2011) as: '*...the same as... Gross Domestic Product and Gross Regional Product... [but] the main difference between GCP and GDP is that the former is defined by a geographic unit of 1° latitude by 1° longitude grid cell, whereas the latter is defined by political boundaries such as countries or provinces*'. Seo (2011) also describes in some depth why GCP is more appropriate to use in relation to quantifying climate change impacts than GDP.

²⁶ On February the 22nd 2011 Christchurch, a city in the South Island of New Zealand, experienced a large earthquake that caused significant loss of life and destroyed many buildings and large amounts of urban infrastructure.

to have greater insight into possible future conditions. Predictions of future weather events based on historical climatic data may be less reliable and projections may become increasingly uncertain (O'Connell and Hargreaves, 2004, Gluckman and Boyle, 2003).

Poorer people of the Asia Pacific region and indeed the world will be affected more by climate change than wealthier people (King et al., 2010, Woodward et al., 1998, Hunt and Watkiss, 2011). Because of the particular vulnerability of some low lying Pacific Islands to sea level rise and the relationships with and proximity to New Zealand, there may be increased populations of 'environmental refugees' from these areas wanting to reside in New Zealand (IPCC, 2001, Woodward et al., 1998). This could have impacts on expected performance and capability of the built environment as migration and possibly social dislocation and poverty increase.

Significant potential impacts for Tangata Whenua (the indigenous people of New Zealand) have been identified (New Zealand Climate Change Programme, 2001, King et al., 2010, NIWA et al., 2011a, Hennessy et al., 2007) including adverse effects on fisheries, food gathering areas, Wāhi Tapu (sacred) sites, and culturally significant flora, fauna and landscapes, particularly in coastal environments (Gluckman and Boyle, 2003, Hennessy et al., 2007).

A number of sources highlight major impacts that will be caused by climate change on plant and animal (including human) health (Robertson, 2006, Woodward et al., 1998, National Academy of Sciences et al., 1996, Hunt and Watkiss, 2011, Howden-Chapman et al., 2010). Any generalised negative impacts on human health will affect the built environment in terms of user capabilities and expectations, and construction, maintenance and design options. Some potential impacts on health that have been identified include increased infectious disease rates, decreased air quality, changes to food growing areas and crop yields, poorer nutrition (due to changes in vegetation), and decreased quantity and quality of water supplies (Woodward et al., 1998, Robertson, 2006, Gluckman and Boyle, 2003, O'Connell and Hargreaves, 2004, New Zealand Climate Change Programme, 2001, Howden-Chapman et al., 2010). This is in addition to direct human health impacts from climate change such as increased heat waves and

increasing intensity and frequency of storms (Woodward et al., 1998, Howden-Chapman et al., 2010).

In terms of the health of timber plantations, there may be changes in timber properties and growth speeds (Honey and Buchanan, 1992), the establishment of new diseases or pest threats (O'Connell and Hargreaves, 2004), and new ecological niches may be created, changing areas suitable for the growing of both timber and perhaps more importantly food (Woodward et al., 1998). This could impact on the availability of certain timber products for construction purposes.

Building standards, codes and regulations will continue to be changed to address climate change impacts for example (O'Connell and Hargreaves, 2004). New Zealand's Resource Management Act (RMA) was amended in 2004 requiring that particular regard be given to climate change (Schofield and Lyons, 2012), and the New Zealand Building Code was amended in 2007, reflecting an increased awareness of climate change in several areas (Department of Building and Housing, 2007). Summaries and discussion of current New Zealand legislation that relates to preparing and planning for climate change can be found in Mullan et al. (2008), Allan (2011) and Reisinger et al. (2011). In New Zealand reassessment of flood zones, development zones, and identification of hazards may also occur (Gluckman and Boyle, 2003).

The research discussing indirect impacts presented in this section tends to take a conservative approach to predicted major impacts of climate change. More alarming research, published in reputable sources, predicting for example that wars, famines, epidemics, financial collapse, the collapse of governments, wide spread extinctions, and declines in human population could occur as a result of future climate change does exist. This may provide further background to possible extreme changes that may occur in society, leading to significant impacts on the physical built environment (Gills, 2010, George, 2010, Hamilton, 2009, Atkinson, 2007a, Robertson, 2006, Mitchell, 2012, Nordås and Gleditsch, 2007, Mooney et al., 2009, and Turner, 2008). Many of these impacts are compounded by, or interact negatively with, other worldwide trends such as population growth, urbanisation, loss of biodiversity, and importantly, the decline of sources of cheap

oil and other fossil fuel based energy sources (Holdren, 2006, North, 2010, Newman et al., 2009, Hunt and Watkiss, 2011). The combination of climate change mitigation strategies and peak oil will also have profound effects on transportation, which is intimately linked to the built environment (Ewing et al., 2008). The interactions of these various drivers, although recognised in literature as being important to understand, are not usually analysed in depth (Ruth and Coelho, 2007). These drivers will cause serious changes, and as such any action to mitigate the causes of climate change or adapt to it must be considered in the context of complex and unique site specific situations.

1.3.2. INTERNATIONAL RESPONSES TO CLIMATE CHANGE IN THE BUILT ENVIRONMENT

Established and common responses to climate change in the built environment broadly fall into two categories:

1. Mitigating the causes of climate change including reducing GHG emissions.
2. Adapting the existing and future built environment to known and predicted climate change impacts.

An examination of responses to climate change impacts leads to further investigation, related specifically to mimicking the natural world, in chapter two.

1.3.2.1 MITIGATION

As the impacts of climate change increase, policies and actions to mitigate GHG emissions must expand rapidly. Mitigation strategies or techniques aim to reduce current or future GHG emissions. In the urban built environment this includes construction, operation, maintenance and demolition activities. Actions related to the red arrow (2) in figure 1 can be understood as being strategies that mitigate the causes of climate change.

Typical current mitigation strategies according to Hamin and Gurrán (2009) include:

- Design for energy conservation.
- Creating or maintaining urban forests and green space where possible (to both sequester carbon and provide shading).
- Carbon storage or sequestration.
- Provision of renewable energy sources.
- Increasing the density²⁷ and limiting sprawl of urban form to reduce building energy use²⁸ and to reduce emissions from vehicles.

Advocating that simply increasing density in urban environments will mitigate the causes of climate change is controversial (Tratalos et al., 2007). Preventing unbounded urban sprawl is up to three times more beneficial in terms of limiting the loss of stored carbon²⁹ (as well as preventing conversion of agriculturally productive land) (Eigenbrod et al., 2011), and may in some cases reduce transport related GHG emissions (Steemers, 2003a). Densification may however also increase stormwater flows and run-off caused by increased imperviousness (Loram et al., 2007, Tratalos et al., 2007); significantly increase the number of people living in potential flood zones (Eigenbrod et al., 2011); increase air pollution and urban noise (Steemers, 2003a); reduce options for building integrated renewable energy generation and increase energy demand of individual buildings through increased thermal and lighting loads (Steemers, 2003a); increase maximum urban temperatures (Tratalos et al., 2007); result potentially (but not in all cases) in conversion of urban green and garden space resulting in loss of biodiversity, carbon sequestration potential, ecosystem service provision³⁰, and urban food

²⁷ This kind of development has various terms such as 'walkable cities', 'new urbanism', 'brownfield development', 'infill', 'transit oriented developments', 'compact cities', 'smart growth' (Ewing et al., 2008), 'eco-localisation' (North, 2010), 'mixed use developments', and 'new localism' (Bulkeley and Betsill, 2005).

²⁸ This is based on the assumption that detached or low density housing requires more energy to heat or cool it and that more energy is used in such dwellings to create and maintain energy distribution networks (Hamin and Gurran, 2009). This is not a proven assumption however and some researchers disagree. This is discussed further below.

²⁹ This refers to carbon stored in vegetation and soil. When vegetation and topsoil are removed, as is often the case during the construction of buildings, the carbon is no longer stored. Eigenbrod et al. (2011) provide further details of typical carbon storage in urban areas and how this is altered under different models of urbanisation.

³⁰ *'As ecosystem services such as carbon sequestration, storm-water inception, climate regulation and biodiversity potential are influenced by the amount and type of vegetated ground cover, increased densification, if it brings with it a reduction in the proportion of such cover and changes in its spatial configuration, may have undesirable effects on these services... Additional ecosystem services [that are]*
Footnote continued on next page...

growing potential (Loram et al., 2007, Tratalos et al., 2007); and compete in some cases with ecosystem conservation efforts (Niemelä, 1999). This suggests that it should not be assumed, as is often the case (Tratalos et al., 2007), that a policy of increasing density of urban environments is necessarily the best way forward, particularly if densification will exacerbate other environmental issues (Steemers, 2003a). Tratalos et al. (2007) point out that:

‘The net ecological effect of moving towards high-density urban forms clearly depends on the balance of the benefits of reduced land take against the changes in ecosystem function of the higher density urban areas... We have shown that high-density urban developments were generally associated with poor environmental performance...[and] that ecosystem quality tends to decline continuously as urban density increases, although... for any given urban density, and with appropriate consideration given to the proportion and configuration of green space and tree cover, there is substantial scope for maximising ecological performance ’.

This ‘density conundrum’ (Hamin and Gurran, 2009) is discussed further in section 1.3.2.3.

Because of the strong link between buildings and transportation in an urban context, and because the effect of urban form on transportation emissions has been studied more extensively, reducing emissions from vehicles is often part of built environment mitigation strategies (Hamin and Gurran, 2009, Reisinger et al., 2011, Ewing and Rong, 2008). The urban development variables that can contribute to reducing vehicle emissions as described by Reisinger et al., (2011) are:

- Density: Increasing the amount of people, jobs and/or dwellings per unit of area (but see the discussion above).

associated with tree cover [are]... temperature, noise buffering, air quality improvement and aesthetic value.’ (Tratalos et al., 2007).

- Diversity: Providing a mixture and balance of land uses such as residential, retail, commercial etc.
- Design: Carefully considering block sizes, street widths and shapes, footpaths and building setbacks, urban landscaping etc.
- Destination accessibility: Ensuring a high number of attractions are reachable within a given time frame and area.
- Distance to transit: Ensuring distances between home and work (or a public transport station) are short.

There are other actions that could be taken that would likely have a positive and rapid effect on reducing transport related GHG emissions without relying on slower and perhaps more costly changes to the built environment. For example, banning the sale of private cars, placing a limit on vehicle engine size, or determining petrol rations on a per capita basis are not typically included in lists such as those given above. This may be because these actions seem to be politically unrealistic or unacceptable at present. It is possible the perception of what is an acceptable response to the urgency of the climate change will change in the future. For example, seemingly radical actions have been taken in the past in response to other perceived crises. From the 31st of July 1979 to the 12th of May 1980 the New Zealand Government initiated mandatory 'carless days' and a ban on weekend petrol sales in an effort to reduce petrol consumption in response to the second global 'oil shock'. Each car owner chose one day of the week when their car was not to be used³¹.

1.3.2.2 ADAPTATION

Climate change is not an event that will take place in a distant future (Gill et al., 2007). Shifts (both temporal and spatial) in weather patterns and temperatures, attributed to climate change in many places in the world, have already produced changes in precipitation patterns, greater cyclone intensities, more frequent

³¹ Ultimately petrol consumption did not go down significantly during this period due to people delaying rather than cancelling trips, using other vehicles to make journeys (Johnston et al., 1983), and widespread use of exemptions (Walker, 1984). A decrease in pedestrian deaths was noted during the period and was partly attributed to the carless days scheme however (Roberts et al., 1992).

wildfires, and more extreme rain or snow storms (Ewing and Rong, 2008). Changes in phenology (timing) and distribution patterns have also been observed in a wide range of species types and in whole terrestrial, fresh water and marine ecosystems on all continents and in all oceans (Parmesan, 2006, see: Lundquist et al., 2011 for a summary of climate change impacts on New Zealand biodiversity). Changes in species distribution, morphology, physiology and behaviour, and community compositions, have also been associated with climate change (Gitay et al. 2002). These shifts are linked to anthropogenic induced climate change and are documented in numerous scientific journals (Schofield and Lyons, 2012, Walther et al., 2002). As Parmesan (2006) points out:

‘...Independent syntheses of studies worldwide have provided a clear, globally coherent conclusion: Twentieth-century anthropogenic global warming has already affected Earth’s biota.’

Even if all GHG emissions were immediately halted, climate change caused by past emissions would still be experienced due to the slow response of the planet’s atmosphere, oceans and other carbon sinks (IPCC, 2007d, page 12)³². Despite international climate change initiatives, global GHG emissions are still increasing (IPCC, 2007c, page 97). Building sector carbon emissions including those from energy generation used to power buildings have increased annually by 2% since 1970, while emissions from commercial buildings have increased by 3% annually since 2002 (Levine et al., 2007, page 391). This is a higher growth rate than that of global human population, which has varied from approximately 1.8% per annum in 1970 to slightly more than 1% in 2011 (Population Reference Bureau, 2006). This suggests that buildings have become higher energy consumers or that building floor area is increasing.

Because the urban built environment is now the principal habitat of humans (section 1.2), it is important that built environment professionals not only work towards mitigating the causes of climate change, but also devise strategies to

³² Even if emissions had stabilised at 2000 levels, a rise of 0.1 degree per decade would still occur for a considerable period (IPCC, 2007d, page 12). Much of the changes in climate that will be experienced over the next forty years at least have already been determined by historic emissions (Gill et al., 2007).

adapt to the inevitable impacts within an urban context. The IPCC (2007b, page 375) estimates potential significant and more frequent risks for buildings, transport, communication and power infrastructure by 2030³³. Significant adaptation measures are required to maintain safe, healthy, productive, and comfortable living conditions for humans (Gluckman and Boyle, 2003, Altomonte, 2008b, Camilleri et al., 2001, O'Connell and Hargreaves, 2004, Takahiko, 2004). Adaptation strategies aim to make changes to the built environment and its social and economic context, so that the negative effects of climate change are avoided or minimised.

Actions related to the blue arrow (4) in figure 1 are adaptation strategies that respond to existing or anticipated direct and indirect impacts of climate change. There is not a large body of work that discusses how to strategically adapt new or existing buildings to climate change, beyond discussion about how to make buildings more adaptable in general through design techniques such as design for deconstruction, materials recycling and reuse, and making lightly-treading foundations (Fernandez, 2004, Steemers, 2003b, IPCC, 2007b, page 379). Strategies that have been employed or suggested for climate change adaption in the built environment include:

- Provision of open land and urban green space / roof tops / vegetation for stormwater management and provision of cooling microclimates (Gill et al., 2007).
- Provision of wild life corridors (to allow for the changing ranges of species and thus the preservation of urban biodiversity and the ecosystem services it provides) (Hamin and Gurran, 2009).
- Protection of wetlands to mitigate the effects of severe storms in some instances (Hamin and Gurran, 2009).
- Restricting heights and density of buildings to allow for increased ventilation (Hamin and Gurran, 2009).
- Expansion of areas of restricted development in flood plains and coastal areas vulnerable to sea level rise (Kirshen et al., 2008).

³³ This is under the 'fossil intensive' A1FI emissions scenario (Nakicenovic et al., 2000).

- Implementation of policies or technologies to prepare for climate change impacts. For example changing building codes to reflect increased extreme weather events and different heating and cooling needs in the future, or increasing urban vegetation or high albedo roofs (Kirshen et al., 2008).
- Building or changing structures such as sea walls or levees (to address sea level rise and flooding) or increasing structural strength of buildings (to address increased storms) (Hamin and Gurran, 2009, Kirshen et al., 2008).
- Increased use and provision of renewable energy and increasing building energy efficiency (Newman et al., 2009, pages 59 and 64).
- Increased provision for pedestrians, bicyclists and public transport in urban areas (Newman et al., 2009, page 100).

These strategies are still seen as inadequate for the task of preparing cities for the impacts of climate change (Dodman, 2009). While research and policy targeting adaptation strategies for the built environment is not as advanced as that for mitigation strategies, important links to the established area of planning for natural disasters can be made and drawn upon (Hamin and Gurran, 2009).

1.3.2.3 THE RELATIONSHIP BETWEEN ADAPTATION AND MITIGATION STRATEGIES

Working towards mitigating the causes of climate change is a response to the predicted effects of climate change that is both optimistic and responsible. It is important that humans do all that is in their power to halt and reverse if possible the damage that is being done to the climate, if other species on the planet, and indeed future generations of humans, are deemed to be important. Mitigation strategies assume that because humans have caused climate change through certain behaviours and cultural norms it is also possible to limit, stop, or reverse this through similar means. This is uncertain and difficult however (Hamilton, 2009). The difficulty of focusing all efforts on mitigating the causes of climate change is that this ignores the fact that the climate is already changing (O'Connell and Hargreaves, 2004).

Adaptation can be seen to be supporting a 'business as usual' approach to climate change because it stems from an understanding that the climate is damaged, it may not be possible to change this, and humans must learn to live with this damage. The danger of promoting adaptation strategies without mitigation alongside is that the assumption can be made that if humans can adapt to climate change, why work to stop the changes? Mitigation and adaptation strategies relating to climate change impacts must be considered in tandem in the built environment. The IPCC (2007a, page 65) point out that:

'...Neither adaptation nor mitigation alone can avoid all climate change impacts... Adaptation is necessary both in the short term and longer term to address impacts resulting from the warming that would occur even for the lowest stabilisation scenarios... Reliance on adaptation alone could eventually lead to a magnitude of climate change to which effective adaptation is not possible, or will only be available at very high social, environmental and economic costs.'

Effective programmes to both mitigate and adapt to climate change can exist while taking account of possible synergies and avoiding conflicts between the two (O'Connell and Hargreaves, 2004, Kirshen et al., 2008). For example, in the event of increased temperatures, one strategy would be to increase air conditioning. This would potentially be an effective adaptation strategy but would be in conflict with the need to mitigate emissions if the air conditioners are powered by electricity generated through the burning of fossil fuels. Another strategy would be to utilise passive techniques to create more comfortable internal temperatures. This is in line with the need to both adapt to climate change impacts and mitigate GHG emissions and therefore has 'positive synergy' (O'Connell and Hargreaves, 2004). It is acknowledged that passive architectural techniques are likely to be more effective when considered at the design stage of a building rather than retrofitted into existing buildings.

Hamin and Gurran (2009) present research analysing conflicts between mitigation and adaptation goals in a built environment context at the level of local government policy. They conclude that almost half of actions that have been taken to adapt to

climate change or mitigate the causes of it actually conflict. Mostly this is due to the assumption that densification of the urban environment is desirable under a mitigation regime (section 1.3.2.1) and that maintaining medium density with fingers of green infrastructure running through an urban environment is better in an adaptation context.

Actions that have been identified by Hamin and Gurran (2009) that adapt to climate change and mitigate the causes of it at the same time are:

- Decentralising energy, water and waste systems.
- Prioritising new infrastructure that delivers multiple environmental services.
- Encouragement of 'self-providing' development in terms of water and energy.
- Maximising viability of public transport through urban built form.
- Prioritising and fostering local food production.
- Designing buildings that respond appropriately and passively to local climatic conditions.
- Utilisation of urban shading strategies.
- 'Weatherisation' programmes to reduce home energy use and improve resilience to storm events.
- Establishing effective participatory processes for the public to be part of determining climate change responses.

This list and those given in previous sections are not exhaustive but do indicate that it may be possible to mitigate the causes of climate change while adapting to its impacts. Many typical mitigation and adaptation strategies do not address the degradation of ecosystems or the loss of biodiversity and so an opportunity is lost to use the strengthening of ecosystem health as a means to increase carbon sequestration, and thus aid climate change mitigation, and to increase overall ecosystem resilience, and therefore adaptation to climate change impacts.

1.4 ECOSYSTEM DEGRADATION, BIODIVERSITY LOSS AND THE BUILT ENVIRONMENT

The aim of this section is to establish a broad overview of the impact urban areas have on biodiversity and to determine the predicted major impacts of biodiversity loss and ecosystem degradation for the built environment. Responses to these impacts relevant to a built environment context will also be examined. The results of a literature review will be described.

Key drivers of biodiversity change are land-use or land cover change³⁴ (Lambin et al., 2001), climate change (including increased concentration of CO₂ in the atmosphere) (Gitay et al., 2002), nitrogen deposition and acid rain, and the introduction of invasive species to ecosystems (termed 'biotic' exchange) (Chapin et al., 2000, Sala et al., 2000). The built environment contributes to each of these drivers.

The relationship of the built environment to climate change and GHG emissions has been established in section 1.3. In terms of land-use change, cities occupy less than 3% of global available land (McGranahan et al., 2005, page 797), but urbanisation does impact on land-use change through important urban-rural linkages and cannot be ignored (Lambin et al., 2001, Pickett et al., 2008, pages 113-114, McGranahan et al. 2005, page 820). Demand for building materials, particularly timber³⁵, is a driver of change (Pollock, 2009, Rands et al., 2010). Demand for increased food for growing urban populations also results in land beyond city limits being converted to agricultural production³⁶, particularly the conversion of land into pasture (Lambin et al., 2001). The expansion of urban

³⁴ The globally pervasive change in land cover since the mid-1800s has contributed significantly to climate change, soil degradation and loss of ecosystem services as well as loss of biodiversity (Lambin et al., 2001). It is the largest driver of biodiversity change due to loss of available habitat and resulting extinctions (Sala et al., 2000).

³⁵ Rands et al. (2010) state that: *'Much of the global timber trade is based on unsustainable or illegal logging that destroys biodiversity-rich habitat, as shown across five major timber-producing countries in 2009 where, on average, only 14% of licensed logging area was sustainability-certified, while up to half of all harvesting was illegal'*.

³⁶ The global expansion of croplands since 1850 has converted approximately 6 million km² of forests and woodlands and 4.7 million km² of savannahs, grasslands and steppes (Lambin et al., 2001).

areas and their satellite settlements along with the construction of supporting infrastructure can result in fragmentation and therefore degradation of ecosystems (Krauss et al., 2010, Hanski, 2005, Brook et al., 2008)³⁷. Urbanisation also converts large areas of land, destroys habitat, and is usually irreversible (Lambin et al., 2001). The conversion of wild land or agricultural land to urban or suburban use is expanding at a rate faster than urban population increase (Pickett et al., 2008, page 100). Places that experience the most human development are often places of the highest biological diversity such as riparian corridors and coastal land margins. This leads to significant biodiversity loss (Sala et al., 2000).

Nitrogen deposition is mostly related to industrial fixation of nitrogen for fertilizer. This has resulted in a doubling of the processes that make nitrogen biologically available (Rockstrom et al., 2009). Through run off of these nutrients from agricultural and urban areas, major ecological changes in river basins, estuaries and coastal zones have occurred (Chapin et al., 2000). The current form of urban environments being made up of mostly impervious surfaces (such as roads, footpaths and buildings) contributes to this. Nitrous oxides also directly contribute to global warming. Acid rain is caused by certain gases dissolving in atmospheric water to form acids, which falling as rain, can cause defoliation in land ecosystems and severe negative changes in aquatic systems. Although the cause of acid rain can be natural, for example from volcanic eruptions, it is mostly caused by human emissions of oxides of carbon, sulphur and nitrogen. These emissions are caused by industrial processes, the generation of power by fossil fuels (coal in particular) and use of petrol and diesel burning vehicles (Mehta, 2010). The built environment, therefore, is strongly implicated.

Finally, the nature of urban environments and the movement of humans between them increases the prevalence of species exotic to a particular place and therefore

³⁷ Fragmentation can result in an 'extinction debt' meaning that it can take up to 50 years for the results of the impacts on biodiversity to occur. This means conventional management strategies of fragmented ecosystems are insufficient to prevent future loss of biodiversity (Krauss et al., 2010). The impact of climate change on biodiversity is likely to be worse in fragmented landscapes (Hanski, 2005), and penetration of predators, invasive species, wind damage, and fire risk is increased. Tree mortality and damage can be three times higher within 60m of the forest edge compared with the forest interior for example (Brook et al., 2008). Fragmentation also prevents species migrating in response to introduced threats or climate change. This is because habitat patches become isolated in a matrix of built up impervious areas and roads (Niemelä, 1999).

the existence of invasive species in native ecosystems³⁸ (Niemelä, 1999, Gaston, 2005). Along an urban-rural gradient³⁹, for many taxa of organisms the number of non-native species increases towards an urban core while the number of native species decreases, though this is not a linear change (McKinney, 2002, Niemelä, 1999). New Zealand ecosystems are particularly vulnerable to invasive species because they evolved over millions of years in isolation. This threat will increase with climate change (Gitay et al. 2002).

1.4.1 THE IMPACTS OF ECOSYSTEM DEGRADATION AND LOSS OF BIODIVERSITY ON THE BUILT ENVIRONMENT

Because the impacts of ecosystem degradation are numerous in scope at both spatial and temporal scales and relate to specific places, this section will only detail broad trends. Unlike the impacts of climate change, changes in biodiversity tend not to affect the physical fabric of the built environment directly and are therefore indirect in nature. The results of a review of international research examining the main impacts of changes in biodiversity related to the built environment have been summarised in table 3. Rapid or non-linear changes caused when ecosystem or biodiversity thresholds are reached will vary greatly from region to region (Chapin et al., 2000). It is important, therefore, to understand the nature and timing of these changes from a local perspective when designing for a specific site.

While some of the impacts listed in table 3 may appear to be less severe than climate change impacts because they are less direct in nature, the overall outcome of continued loss of biodiversity results in a threat to the continuation of human society and to humans as a species (Chapin et al., 2000). This is because humans not only negatively affect biodiversity, but are also affected by the health of

³⁸ Humans import species into urban places. The planting of exotic plant species in residential gardens contributes to the release of invasive species into fragmented native ecosystems and often results in their degradation. Areas disturbed by humans, provide opportunities for non-native 'weedy' species to colonise these areas. The amount of energy and matter available for species also increases towards a city core (due to rubbish and the heating of buildings) and some 'urban exploiter' species such as pigeons, sparrows, starlings, mice, rats and cockroaches thrive in these conditions and compete with native species (McKinney, 2002). Urban areas tend to be warmer though the heat island effect and so become climatically unsuitable for some native species (Niemelä, 1999).

³⁹ Urban to rural gradient studies examine changes in species along a line from inner city cores to surrounding, more natural ecosystems to understand effects of urbanisation and sprawl on organisms and ecosystems (McKinney, 2002).

TABLE 3 IMPACTS OF CHANGING BIODIVERSITY ON THE BUILT ENVIRONMENT

Potential Indirect biodiversity loss/alteration Impacts:	Potential consequences for the built environment:	Possible scale of the negative impact.	Source:
More rapid climate change due to biophysical feedbacks of ecosystems and loss of carbon sequestration.	See tables 1 and 2.	High	Brook et al. (2008), Gitay et al. (2002), Lashof and DeAngelo (1997). See also tables 1 and 2.
Reduction in resilience of ecosystems to environmental change.	Increased damage to buildings and infrastructure from storm events, floods, landslides and wildfire.	High	Brook et al. (2008), Chapin et al. (2000), Diaz et al. (2006), MEA (2005a).
	Increased cost of disaster relief and emergency management.	Medium	
	Increased repair/maintenance/insurance costs.	Medium	
Increased disease/pest risk to crops, animals and humans. Changes in reliability/productivity /timing of crops. Potential loss of harvestable species. More risk of crop failures. Loss of available protein and vitamins from food sources. Loss of soil nitrogen and carbon. Changes in soil fertility.	The built environment may be expected to allow for food growing more effectively.	High (Potentially positive)	Chapin et al. (2000), Diaz et al. (2006), Lambin et al. (2001), Loreau et al. (2001), Rutledge et al. (2010), Chivian and Bernstein (2008).
	Human work force and inhabitants may be negatively affected and impact indirectly on the viability of the built environment.	High	
	Building materials such as timber may be affected.	Medium	
Changes to precipitation patterns and water availability and quality. Warmer, drier climates. ⁴⁰	Increased cooling loads.	High	Chapin et al. (2000), Lambin et al. (2001), MEA (2005a).
	Reduction of water availability.	High	
	Increased cost of water.	Medium	
	Increased requirement for buildings to catch and store rainwater.	Medium (potentially positive)	

⁴⁰ This can occur through increasing replacement of many land types with pasture for example.

	Changes in the ability of built environments in certain areas to support human life.	High	
Loss of provision of ecosystem services (such as fuel, structural materials, etc.).	Changes in the viability of some urban environments to support human life.	High	Balvanera et al. (2006), Diaz et al. (2006), WWF (2010), Chapin et al. (2000), Lambin et al. (2001), Naeem et al. (1994)
	More expensive construction costs.	Medium	
	Changes in availability and costs of materials.	Medium	
Negative impacts on animal, plant and human physical health ⁴¹ .	Changes in capabilities to design, construct, and maintain the built environment.	High	Chapin et al. (2000), Diaz et al. (2006), Rutledge et al. (2010), Rockstrom et al. (2009), Chivian and Bernstein (2008).
	User capabilities and expectations of the built environment may change.	Medium	
Increased social dislocation, marginalisation, poverty and loss of income particularly of indigenous and poor communities.	Increased urban populations through rural migration.	Medium	Chapin et al. (2000), Diaz et al. (2006), MEA (2005a).
	Poorer quality of building stock.	Medium	
Increased local and international emigration and immigration (likely to be immigration into New Zealand).	Changes in expectations of the built environment to accommodate different and possibly increased numbers of users.	Medium	Diaz et al. (2006), Howden-Chapman et al. (2010), MEA (2005a).
	Changes in population and activity patterns will affect expectations of and viability of parts of the built environment.	Medium	
Changes in global and regional economies.	Shifts in money and resources available for construction.	Medium	Asafu-Adjaye (2003), Chapin et al. (2000), Diaz et al. (2006), MEA (2005a), Rockstrom et al. (2009), TEEB (2011a).
	Changes in costs to run/build the built environment will affect design and expectations of it.	Low	
Increase in regulations to protect	Changes in construction methods ⁴² .	Medium	McKinney (2002), Rands et al.

⁴¹ This can be caused by reduced air, soil and water quality, particularly where biomass is removed for example, along with amplified climate change impacts. MEA (2005a).

⁴² For example removing all biomass and top soil as is typical when beginning the construction of greenfield developments may be actively discouraged to maintain pre-development vegetation (McKinney, 2002).

biodiversity.	Changes in materials available, suitable and desirable for construction ⁴³ .	Medium	(2010).
	Changes in development zones.	Medium (potentially positive)	
	Greater skill and knowledge required to design.	Low (potentially positive)	
	More vegetation in urban areas.	Potentially positive	
	Increased multidisciplinary collaboration.	Potentially positive	
	Increased use of the precautionary principle.	Potentially positive	
Reduction in air quality and increase in acid rain.	Damage to building materials and integrity and infrastructure.	Medium	Chapin et al. (2000), MEA (2005a).
Decline in human mental health.	Changes to workforce available to build and maintain the built environment.	Medium	Diaz et al. (2006), Kellert and Wilson (1993), Kellert et al. (2008), MEA (2005a).
	Desire to have more vegetation in urban areas.	Low (potentially positive)	
Loss of 'option value' ⁴⁴ , and the 'insurance effect' ⁴⁵ through increased extinctions or biodiversity loss.	Less ability to develop responses to future changes that could affect the built environment.	Medium	Chapin et al. (2000), Diaz et al. (2006), Loreau et al. (2001).

⁴³ Materials that are used in construction may change due to the need to protect biodiversity. For example, it may become illegal or undesirable to purchase timbers from rainforest sources.

⁴⁴ Option value is *'the value of attaining more knowledge about species and their contribution to human wellbeing in order to make informed decisions in the future'* (Chapin et al., 2000).

⁴⁵ See section: 3.5.4.7.

ecosystems (made up of biodiversity), because humans are entirely dependent upon ecosystem services for survival (Díaz et al., 2006, Tilman, 2000). Species that are important to the functioning of ecosystems and therefore to ecosystem services often only become apparent after they have been removed in high proportions and when an ecosystem becomes significantly altered. This means biologists and ecologists cannot currently provide lists of the species humanity should conserve in order to maintain specific ecosystem services, and which species can become extinct without consequence to overall ecosystem health (Mills et al., 1993). Biodiversity loss that results in extinction of specific species is of course irreversible (Chapin et al., 2000). It is apparent that many of the indirect impacts of climate change described in table 2 are similar to impacts of biodiversity and ecosystem changes shown in table 3. This further demonstrates the reinforcing or synergistic nature of climate / ecosystems / biodiversity relationships.

1.4.2 RESPONSES TO ECOSYSTEM DEGRADATION IN THE BUILT ENVIRONMENT

Typical responses to addressing the loss of biodiversity in a built environment context are:

1. Protection or conservation of remnant ecosystems through covenants or nature reserves.
2. Provision of connections between remnant habitats to reduce fragmentation.
3. Restoration of degraded ecosystems.
4. Management of urban vegetation and/or structure to increase biodiversity.

These responses will be explored below. Actions that target education, policy changes, and economic penalties or rewards can also result in biodiversity benefits but are considered to be outside the scope of this thesis⁴⁶.

⁴⁶ Several researchers point out that although urban dwellers tend to place more value on natural habitats and landscapes than rural counterparts, there is a lack of understanding that preservation of ecosystems or restoration of them is more than an aesthetic or altruistic ideal and is actually intrinsically linked to human health and well-being (Brook et al., 2008, Rands et al., 2010). Increasing knowledge of this relationship is, they argue, a key to change. Hanski (2005) provides reasons for a lack of public understanding of the importance of biodiversity including: the time lag of extinctions and consequences of biodiversity loss compared to the

Footnote continued on next page...

1.4.2.1 PROTECTION OF EXISTING ECOSYSTEMS

The global network of protected areas has grown by approximately 2.5% per annum between 1992 and 2009 in total area, and 1.4% per annum in number of actual sites (an overall increase of 42%), but many sites may be poorly managed (Rands et al., 2010, UNEP, 2011). WWF (2010) state that:

'In 2009, there were over 133 000 nationally designated protected areas covering a total of nearly 19 million square kilometres of land and sea, or 12.9 per cent of the Earth's land area and 6.3 percent of the Earth's territorial seas'.

Habitat preservation is thought to be the cheapest and most effective long term way to reduce biodiversity loss (McKinney, 2002) and potentially stores carbon long term (Gitay et al. 2002). Native species richness increases with the area of habitat available, particularly for plants, birds and mammals (McKinney, 2002). The built environment itself cannot effectively mimic or become areas of protected ecosystems akin to non-human integrated ecosystems, but built environment policy and regulations could contribute to the protection of biodiversity through effective land-use management. Strategies include:

- Defining zones that are inappropriate to build in (i.e. existing or recovering native ecosystems). This may involve introducing ecological knowledge into urban planning practices to increase understanding of the composition and patterns of urban biodiversity through biotope mapping for example (Niemelä, 1999, Pickett et al., 2008, page 106, Mathieu et al., 2007).
- Maintaining and adding to existing protected ecosystems areas in or adjacent to urban places (McKinney, 2002).
- Preventing road building or other activities that lead to fragmentation within protected areas (Hanski, 2005).

causes of it, biased portrayals of natural habitats in the media, and a lack of personal experience of natural habitats.

- Defining set boundaries for urban sprawl through the use of ‘green belts’, and preservation of pre-development biodiversity in greenfield development⁴⁷ (Niemelä, 1999).
- Integrating suitable human activities into protected zones to reduce competition between the needs of recreation for urban dwellers and the preservation of habitat (Niemelä, 1999).
- Carefully considered densification of urban settlements to minimise sprawl and land transformation outside current urban boundaries (McGranahan et al., 2005, page 817)⁴⁸.

The built environment also has a part to play in mitigating the causes of biodiversity loss aside from land-use change through: avoiding pollution of ecosystems; avoiding overharvest (through unsustainable forestry, the hunting of certain animals, and collection of firewood); careful materials selection (purchasing building materials with certain certification labels such as the Forest Stewardship’s FSC sustainable timber mark could contribute to preventing biodiversity loss in places remote to the urban environment in question); reducing fire risk; and reducing GHG emissions (due to the negative impact climate change will have on ecosystems). These interacting causes of change should be planned for to avoid negative cascading effects of multiple interacting drivers (Brook et al., 2008, McKinney, 2002).

1.4.2.2 PROVISION OF CONNECTIONS BETWEEN REMNANT HABITATS TO REDUCE FRAGMENTATION

Maintaining or creating connectivity can relate to the creation of ‘wildlife corridors’ or ‘greenways’⁴⁹. This facilitates the movement of species between remnant

⁴⁷ As mentioned in table 3, typical construction practices often result in the removal of all vegetation and even topsoil before commencing development. This reduces costs by allowing easy access of machinery to sites, but is devastating to local biodiversity. Preserving biodiversity is cheaper in the long term and preferred by residents of new developments (McKinney, 2002). An appreciation of the presence of urban biodiversity is reflected in higher property prices near vegetated areas (Niemelä, 1999).

⁴⁸ But refer to section 1.3.2.1 for other factors than need to be taken into account when considering such a strategy.

patches of habitat, reduces the effects of fragmentation, potentially enables seasonal migrations to continue, and may enable some species to better adapt to climate change (Heller and Zavaleta, 2009).

Connectivity routes are typically created through providing a piece of suitable land that physically connects one piece of habitat to another. Other architectural design concepts that could potentially contribute to increasing connectivity include green roof design (Lundholm, 2006), green infrastructure design (Gill et al., 2007), and potentially some forms of urban agriculture (Bakker et al., 2000). Corridors and greenways should be managed for the benefit of native (rather than exotic) species and should not become substitutes for the protection of large intact nature reserves within urban, suburban, or periurban settings (Niemelä, 1999).

1.4.2.3 RESTORATION OF DEGRADED ECOSYSTEMS

The restoration of degraded ecosystems can add to biodiversity health and therefore increase the health of ecosystem processes, ecosystem services and bio-capacity. Restoration of degraded urban ecosystems often takes the form of citizen or council initiated clean ups of streams and beaches, re-planting of previously removed vegetation, and pest and weed eradication schemes on degraded land. It may also include in some locations improving land tenure, as well as sustainable land, water, and agriculture management.

A growing body of research and design strategies, termed here 'ecological design', have as their basis a motivation to restore biodiversity or the health of ecosystems through various built environment design methods. Regenerative design is one aspect of this. This is examined in more depth in section 1.6.1. Other examples of design that could potentially contribute to the restoration of biodiversity are: ecologically designed urban landscapes, and 'Eco-revelatory Design' where ecological processes are made visible as a way to educate people about them

⁴⁹ The success of wildlife corridors or greenways is highly dependent on site specific conditions, type of species using the corridor, and presence of remnant existing remnant ecosystems. Their use can be controversial and a detailed analysis should be undertaken for each proposed corridor to determine benefits or disadvantages of such proposals (Simberloff et al., 1992).

(Eisenstein, 2001); 'Building Ecology' with an emphasis on education of building professionals about relationships between the built environment and ecosystems and a system approach to design (Graham, 2003); 'Biophilic design' based on the concept that humans have an innate affinity with the living world that can be reflected in design (Kellert et al., 2008); 'Construction Ecology' where ecosystems provide energy and material flows in urban areas and humans provide nutrients to ecosystems (Kibert et al., 2002); 'Bioregionalism' with an integrated understanding of deep ecology concepts (Lomba-Ortiz, 2003); Integrating human social and ecological processes (Lyle, 1994, Van Der Ryn and Cowan, 2007); 'Cradle to Cradle' design where materials use is connected in cycles, thus eliminating waste and pollution (McDonough and Braungart, 2002); and using ecological processes to remediate pollution or degradation of ecosystems (Todd and Todd, 1993).

1.4.2.4 MANAGEMENT OF URBAN VEGETATION AND STRUCTURE TO INCREASE NATIVE BIODIVERSITY

Urban environments typically include large areas of parks, play grounds, vacant plots, road sides, street plantings, residential backyards, community and botanical gardens, and sports grounds (McGranahan et al., 2005, pages 807-808). Managing the vegetation within this open or green space to assist native plants and fauna may make a significant contribution to biodiversity conservation or restoration (McKinney, 2002). It may also contribute to connectivity strategies. Several difficulties with maintaining urban biodiversity and further discussion of this concept along with examples are provided in section 5.3.1.3. The trend in many industrialised nations is towards increasing amounts of vegetation in urban areas (McGranahan et al., 2005, page 808), though private ownership of green spaces (such as residential gardens) may mean control is fragmented and that management for the benefit of biodiversity is difficult (Goddard et al., 2009). At the individual scale of a building it is important that landscaping is done with sensitivity to increasing native biodiversity or to preserving or enhancing local ecosystem services.

Preserving rare species within urban environments through active management can also contribute to the protection of biodiversity (McKinney, 2002, Niemelä, 1999, Gitay et al., 2002). There is evidence that rare species occur in some urban environments at surprisingly high rates, and can be found most commonly in parks, cemeteries, by railway tracks, or in vegetated areas under power lines and in other public rights of way that are protected from development (Niemelä, 1999). Although it is not clear if this applies to all climates, or types of urban areas, this suggests it is important that knowledge about what species exist in a particular place is gained before green or brownfield development is approved.

Urban habitats are typically at early successional stages because regular disturbances occur, such as mowing, trimming, and pruning (McGranahan et al., 2005, page 808). Natural succession increases species diversity and there is some evidence that it increases native diversity and reduces non-native species in some locations (McKinney, 2002). This means older residential neighbourhoods that have experienced some natural succession tend to be more bio-diverse than newer ones (Tratalos et al., 2007). ‘Benign neglect’⁵⁰ therefore is an option to maintain high species diversity and richness of habitat types in some urban settings (McKinney, 2002).

Several researchers discuss the difficulty of restoring environments to be similar to local ecosystems and instead advocate the use of ‘ecological engineering’ to create habitat on or in urban structure (such as on walls, seawalls, or other kinds of structure) (Francis, 2011, Chapman and Blockley, 2009, Goddard et al., 2010). This is linked to ‘reconciliation ecology’ and ‘ecosystem analogue’ theories (Rosenzweig, 2003, Lundholm and Richardson, 2010).

⁵⁰ This entails leaving some areas unmanaged, lightly managing others, and actively intervening in others. The variation of management strategies produces a diverse urban ecology with areas in different states of succession and rich in habitat niches (Niemelä, 1999).

1.5 THE RELATIONSHIP BETWEEN RESPONSES TO CLIMATE CHANGE AND BIODIVERSITY HEALTH IN A BUILT ENVIRONMENT CONTEXT

Climate change has become accepted as a significant issue that humanity must address (Walther et al., 2005). Although action to prevent significant future climate change is at present inadequate (IPCC, 2007c, page 97), more emphasis is currently placed on climate change and its impacts than on biodiversity loss and its impacts (Sala et al., 2000). This is despite there being less controversy about the reality, causes and impacts of biodiversity loss (Lord May of Oxford, 2005)⁵¹, and the fact that both issues are important and related (Gitay et al., 2002, Asafu-Adjaye, 2003). Consequently, policies, laws and strategies to improve the environmental performance of the built environment and the activities of humans, focus more on climate change mitigation and adaptation than on reducing biodiversity loss.

Action taken to mitigate the causes of biodiversity loss and adapt to its impacts is also at an inadequate level to address the problem (MEA, 2005a, 2005b, Thomas et al., 2004, Chapin et al., 2000). Since 1992 there has been an overall decrease in money dedicated to environmental aid including biodiversity protection from bilateral and multilateral donors (UNEP, 2011)⁵². As Chapin et al. (2000) state:

‘Despite convincing scientific evidence, there is a general lack of public awareness that change in biodiversity is a global change with important ecological and societal impacts and that these changes are not amenable to mitigation after they have occurred’.

Rands et al. (2010) suggest however that there is evidence of growing political recognition of the need to protect biodiversity. They provide a summary of political actions and initiatives that have been taken up until 2010 and also give reasons for

⁵¹ Some biodiversity issues do cause controversy among scientists (Loreau et al., 2001).

⁵² Most of this environmental aid is dedicated to energy conservation, renewable energy initiatives and environmental governance (UNEP, 2011).

the difficulty in addressing biodiversity loss. These include the fact that agents of damage are often far away from victims of impacts in space and time so political boundaries are crossed, and damage remains invisible to those causing it. McGranahan et al. (2005, pages 820-821) provide a summary of similar barriers to action that effectively addresses ecosystem degradation. The establishment of the Intergovernmental Platform on Biodiversity and Ecosystems Services (IPBES) may help to close knowledge gaps and facilitate change in this area (Rands et al., 2010)⁵³.

Responses to climate change and the loss of biodiversity vary. It is important that responses are complimentary rather than antagonistic in addressing these two issues. Site selection and management practices are crucial to determining if climate mitigation related activities such as land-use change, reforestation or conservation, and renewable energy generation will affect biodiversity positively or negatively (Gitay et al., 2002). It is key that responses take into account interactions between drivers of change over long time periods to ensure that actions are beneficial in reducing climate change and maintaining biodiversity. Management of single drivers is unlikely to be adequate (Brook et al., 2008), while the effectiveness of strategies can be enhanced when they are part of broader approaches to address other impacts of global change (Gitay et al. 2002). For example, increases in the production of biofuel can be positive from a climate change mitigation agenda because biofuel can replace fossil fuels in some instances and therefore reduces GHG emissions, but from a biodiversity point of view, increased crop production of a variety of oils and fuels has meant the destruction of existing ecosystems to provide land for the crops (UNEP, 2011). This has had severe negative biodiversity implications for certain places in Asia (Rands et al., 2010). In contrast, protecting or regenerating native forest or afforestation on degraded land to provide carbon sinks is likely to have biodiversity benefits if these are considered at the planning stage. The creation of carbon sinks

⁵³ Discussions to fully operationalise IPBES began in 2012. See: <http://www.ipbes.net/about-ipbes.html>. Significant progress in assigning value to biodiversity and ecosystem services has been recently made, adding to tools available to affect change (TEEB in Local Policy, 2011, TEEB in Business, 2011, TEEB Foundations, 2010, TEEB, 2011a).

does not address the use of fossil fuels, or provide an alternative to their use however.

Gitay et al. (2002) examine cases of mutualisms and antagonisms between climate change responses and biodiversity in depth. Some points of most relevance for the built environment are:

- Conservation of biodiversity is not always consistent with high carbon storage goals on the same piece of land, because plantation timbers tend to grow faster and sequester more carbon in the short term⁵⁴. Considering biodiversity alongside climate change may mean an emphasis on retaining or regenerating native ecosystems alongside focusing on planting fast growth exotic trees for maximum carbon sequestration. Careful consideration would need to be given to the amount of land available to achieve both aims (section 5.4.1).
- Changes to water sheds should be carefully considered when planning afforestation to avoid negative impacts.
- The building of physical barriers (like levees and sea walls) to enable urban areas to adapt to climate change impacts may lead to loss of biodiversity and maladaptations in some species to future climate change. Regulatory measures such as enforced building setbacks, enhanced building codes and increased insurance coverage may lead to less perceived need to build physical barriers.

1.6 A SYNERGISTIC RESPONSE: ECOLOGICAL REGENERATION THROUGH THE BUILT ENVIRONMENT

Because there is a synergistic relationship between the climate and ecosystems (Gitay et al., 2002, Araújo and Rahbek, 2006, Chapin et al., 2000), additional strategies to address the causes and impacts of climate change may be found by reducing the loss of biodiversity and working to restore the health of ecosystems.

⁵⁴ More frequent harvesting of plantation timbers compared to long term protection of native forests in terms of carbon sequestration and storage results over time is an issue in this regard. See section 5.3.4.2.

This would at the same time restore or create ecosystem services and add to resilience (Chapin et al., 2000, Rands et al., 2010).

Many current climate change mitigation and adaptation strategies can be described as 'sustainable'. This is an improvement on design that does not consider environmental impacts at all however 'sustainable' design ultimately still results in negative environmental impact (Reed, 2007). Through incremental steps the ultimate goal of such an approach is neutral environmental impact as demonstrated in figure 6. Until this goal is reached, the built environment continues to degrade the ecosystems and climate humans are dependent upon for well-being, wealth, and basic survival. Under many current definitions sustainable design seeks to minimise pollution rather than achieving clean air, soil and water. It minimises energy use, rather than using energy from non-damaging renewable sources. It minimises waste rather than eliminating it altogether by creating positive cycles of resource use (McDonough and Braungart, 2002, page 62). Within this paradigm, no attempt is made to remediate past damage. Most urban environments are built in such a way that the outcome is detrimental to climate, ecosystems, and to people (Newman, 2006), rather than nearing even approximate 'sustainability', even if the original meaning of the term (to continue indefinitely) is implied.

The goals of creating neutral environmental outcomes in terms of energy use, carbon emissions, waste generation, and water consumption are worthy but difficult targets to meet in architectural and urban design. Given the urgency of the changes needed, and the severe outcome for humans should efforts not go far enough to reduce damage, the built environment may need to go beyond efforts to limit negative environmental outcomes. Instead, positive environmental outcomes should perhaps be the goal (Rees, 1999, Reed, 2007, Birkeland, 2008, page xi, Pawlyn, 2011, page 2). This implies that the built environment should contribute more than it consumes to ecosystems while simultaneously remediating past and current environmental damage. Because it is not possible to replace the entire built environment, individual or small scale regenerative developments may have to cease, reduce, counter and reverse not only their own negative impacts but also

those of existing buildings in a given urban environment. The feasibility of this is examined in chapter five.

FIGURE 6 TRAJECTORY OF ENVIRONMENTALLY RESPONSIBLE DESIGN (SOURCE: REGENESIS 2000-2012). 'BUSINESS AS USUAL' IN NEW ZEALAND PART ADDED BY AUTHOR.

Development that enables ecosystems to recover so they are in a state where they are as healthy as they were before humans disturbed them, and could return to being self-sustaining, could be termed 'regenerative' (Cole, 2012b, du Plessis, 2012, Reed, 2007). The practical task of how to create such built environments or enable them to evolve must be considered, particularly given the scarcity of built examples that are able to reach even a 'neutral' status.

1.6.1 REGENERATIVE DESIGN

Regenerative design seeks to address the continued degradation of ecosystem services by designing and developing the built environment to restore the capacity of ecosystems to function at optimal health for the mutual benefit of both human and non-human life (Cole et al., 2012, Cole, 2012a). Crucial to regenerative design

is a systems-based approach (Reed, 2007). Buildings are not considered as individual objects, but are designed to be parts of larger systems. Buildings are considered as nodes in a system, much as organisms form part of an ecosystem. The intention of this is that it may enable complex and mutually beneficial interactions between the built environment, the living world, and human inhabitants to occur.

Regenerative design is holistic in nature. The social or community aspects of a project are enmeshed with ecological health in terms of both physical and psychological well-being (Kellert et al., 2008, Berkebile and Hoxie, 2012, Mang and Reed, 2012). It is acknowledged that for a development to become truly regenerative, the relationship between ecosystems and human society needs to be understood and utilised to ensure maximum well-being for both.

This thesis focuses on the ecological aspect of regenerative design only. This is not because human well-being is thought to be separate from the positive benefits of ecological regeneration, or because the need to understand and develop positive relationships between humans and ecosystems is not essential (Mathews, 2011), but is to narrow the scope of the research and to complement parallel investigations into other aspects of regenerative design. These include: community engagement and generating a 'sense of place' (Hoxie et al., 2012); exploring relationships between 'green', 'sustainable', and 'regenerative' design and the types of discussions these approaches generate amongst people involved in a project (Cole 2012b); the historical and philosophical development and implications of regenerative design (du Plessis 2012); the ability of regenerative design to strengthen an understanding of natural systems (Cole 2012b); the relationship of regenerative design to changing world views ('mechanistic' to 'ecological') (Mang and Reed, 2012, Svec et al., 2012, du Plessis, 2012); developing regenerative design practices (Mang and Reed, 2012); and the development of regenerative design tools (Plaut et al., 2012, Cole et al., 2012, Svec et al., 2012).

FIGURE 7 REGENERATIVE DESIGN IMPACTS

Figure 7 demonstrates the idea that if regenerative design is possible and if regenerative design strategies replace conventional ones in the built environment, human caused biodiversity loss may be reduced⁵⁵ if matched by changes in other aspects of human behaviour. At the same time generation of additional ecosystem services may be provided either directly by the built environment, or by integrating it effectively with ecosystems. Regenerative design works to reduce the causes of climate change through increasing biomass and thus potentially increasing the storage or sequestration of carbon⁵⁶. Cessation of the use of GHG emitting energy sources as part of a regenerative development paradigm would also contribute to reducing the causes of climate change. This means the impacts of climate change would be reduced, particularly over the long term. Increasing the health of ecosystems also increases the resilience of ecosystems⁵⁷ and potentially human urban environments if integrated into them (Gitay et al. 2002) as an adaptation response to climate change (Chapin et al., 2000). An additional benefit of a regenerative design strategy is that regeneration of ecosystems may reduce some of the causes and ameliorate certain impacts of climate change and therefore loss of biodiversity, dampening the positive feedback loop described earlier. Chapin et al. (2000) state:

‘The diversity-stability hypothesis suggests that diversity provides a general insurance policy that minimises the chance of large ecosystem changes in response to global environmental change’.

The impacts of climate change and significant loss of biodiversity are occurring and will occur despite any actions humans take collectively now (IPCC, 2007d, page 12, Rockstrom et al., 2009, Chapin et al., 2000, Gitay et al., 2002), so arrows representing this remain on figure 7. This inevitable change is due to historic and current emissions of GHGs and disruption of ecosystems and species extinctions that have already occurred.

⁵⁵ This is demonstrated in specific detail in chapter five.

⁵⁶ The differences between sequestration and storage of carbon and the changing nature of these over time when biomass is the medium are discussed in section 5.3.4.

⁵⁷ One example of how this happens is that conserving biodiversity ensures a larger gene pool is available for adaptations to environmental or climate change (Gitay et al. 2002).

A shift from a built environment that is degenerating ecosystems to one which restores local environments and regenerates capacity for ecosystems to thrive, will not be a gradual process of improvements, but will require fundamental rethinking of architectural and urban design (Cole, 2012b, Reed, 2007) (figure 8). Even with such a change in design thinking, wide scale change in human behaviours and consumption patterns would also need to be addressed. While the time scale illustrated in figure 8 may seem ambitious, this reflects the urgency of the needed change and is based on research from Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), that states that a global collapse in human population and economic systems may occur before 2050 if a 'business as usual' paradigm is followed. Such a collapse would be due to the limits of planetary ecological systems being exceeded because of continued growth in the global economy (Turner, 2008).

While the philosophical basis of regenerative design would appear to be a logical goal for development given continued degradation of the planet's systems (Carpenter et al., 2009; MEA, 2005b), it is difficult to find successful built examples or guidance about how to begin and then work through a process of regenerative design⁵⁸. The aim of this thesis is to describe a potential starting point for regenerative design in terms of ecological health, and to discuss how this could be used in an urban environment. It begins by investigating ecosystem services in general and then identifies potential key ecosystem services that are applicable to a built environment context. It examines how ecosystem services analysis might be applied to urban settings, and what benefits and difficulties are inherent in such an approach to design, or re-design of urban environments.

The goal of the research is to identify whether regenerative design is possible in urban settings, and to determine where key leverage points for system change may be within the built environment, to move towards a regenerative urban environment. A potential starting point for regenerative design in terms of ecological health is described and then tested.

⁵⁸ A special issue of the Building Research and Information Journal published in 2012 (Volume 40, issue 1) presents research providing a synthesis of current thinking, understanding and practice of regenerative design and development that begins to address this.

FIGURE 8 MOVING FROM CONVENTIONAL DEVELOPMENT TO REGENERATIVE DEVELOPMENT OVER TIME (ADAPTED FROM: PEDERSEN ZARI AND JENKIN 2009).

1.6.2 MIMICKING THE LIVING WORLD

Some regenerative design literature implies that understanding organisms or ecosystems could be an important part of such an approach to design (Reed, 2007, du Plessis, 2012, Svec et al., 2012). This is because an ecosystem that has not been degraded or significantly altered by human activities is likely to be an example of effective organisation of life in terms of environmental performance (Carswell et al., 2008, Benyus, 1997, pages 2-3, 7, Kibert et al., 2002, page 7). The modern building industry appears to be modelled on human industrial processes developed since the industrial revolution (McDonough and Braungart, 2002, chapter one). Such processes tend to be linear and use large amounts of energy to function, in comparison to the system of cyclic, integrated and low energy processes that typify a healthy ecosystem (Kibert et al., 2002, page 7, Pawlyn, 2011, page 91). Ecosystems are resilient, resourceful, and opportunistic, and utilise existing relationships for symbiotic advantage. They adapt and evolve, are resilient to disturbance and importantly, they create conditions conducive to on-going life (chapter three). Ecosystems then, in a given location and climate, may provide a model or a set of performance targets, for urban areas in the same location and climate.

The mimicry of organisms and ecosystems is often termed 'biomimicry'. Biomimicry is the emulation of strategies seen in the living world as a basis for human design. This may include design of urban environments, objects and materials, as well as the design of social and economic systems. It is the mimicry of an organism, an organism's behaviour, or an entire ecosystem, in terms of forms, materials, construction methods, processes, or functions⁵⁹. The emphasis with such an approach is to see the living world, not just as a resource for exploitation, but as a system that provides models worthy of examination for applicability to a human context. The investigation of biomimicry therefore may provide a means to

⁵⁹ Most biomimicry is not understood in relation to the classifications devised in this thesis, leading to potential misunderstandings about the most effective kinds of biomimicry to employ if the goal is to increase the sustainability of the built environment as will be discussed in chapter two. Most researchers or commentators on biomimicry tend to use Benyus' categories of form, process and system (Benyus, 2008, page 40). See for example Pawlyn (2011).

contribute to regenerative design theory and add to the strategies available to designers to respond to climate change and the decline in biodiversity health.

As discussed, regenerative design requires that humans understand the built environment differently. The central thesis of this research is that biomimicry could provide a suitable vehicle for such a shift in thinking because it requires people to understand that humans are not separate from ecosystems but are in fact dependent upon them for survival, so the human-ecosystem relationship fundamentally changes (Mathews, 2011)⁶⁰. Regenerative design also sees human systems, including the built environment, and social, economic, and cultural systems, as indivisible from ecosystems (Mang and Reed, 2012, du Plessis, 2012).

Literature and case studies examining biomimicry tend to be 'ad hoc' and in need of critical review and theoretical definition (Mathews, 2011, Vincent et al., 2006). Biomimicry in relation to architectural design is explored in depth in chapter two to determine whether it is a strategy worth employing in the built environment, if more sustainable or regenerative environmental performance is a goal. A categorisation method for biomimicry is devised in order to analyse existing biomimetic technologies and ideas and to determine, which, if any, kind of biomimicry is most suitable for design focused on improving ecological performance. Chapter two goes on to critique biomimicry for its potential to improve sustainability outcomes related to climate change and biodiversity health and establishes which kind of biomimicry may be more likely to result in long term effective sustainable outcomes.

In light of the conclusions reached during the course of this initial research, the thesis goes on to develop, explore and test long term biomimetic responses that mimic ecosystems and utilise synergies between the need to mitigate the emission of GHGs and loss of biodiversity, and strategies to adapt to direct climate change impacts and loss of ecosystem services in the built environment. The foundations

⁶⁰ Humans should be seen not as stewards or controllers of ecosystems (a power-over relationship), but reconsidered as elements in a complex system, whose survival depends entirely on the health of the ecosystems they exist in.

of the theory needed to implement such a response from a design point of view are presented in chapters three and four and are tested in chapter five.

1.7 RESEARCH METHODOLOGY

As discussed, this thesis seeks to investigate an understanding of ecosystems and distil that into knowledge useful in the design disciplines in the creation of regenerative built environments that synergistically respond to climate change and biodiversity issues. A broad spectrum of information about climate change, ecosystems, regenerative design, biomimicry and urban built environments, is drawn together and analysed, and forms the basis of the research. In order to create the theoretical underpinnings of a practical approach to urban design, which this thesis argues is necessary, such a broad initial approach was needed. This implies that the research will interpret and redefine relationships in existing research, in order to bring about new insights and devise new theory.

The research paradigm to which this research belongs can be described as 'emancipatory', or belonging to a 'critical thinking approach'. This implies that the research: relates to a particular time and place; aims to 'erode ignorance' (adds new knowledge); and has a 'transformational impulse' (aims to create a change in thinking) (Groat and Wang, 2002, pages 40-41)⁶¹. The ontological⁶² assumption of such an approach is that there are multiple perceived realities shaped by social, political, and cultural values, and that perceived reality changes depending on how people understand and interpret a situation (Groat and Wang, 2002, page 32). The research attempts to reveal a generalised ecological reality that can be used to determine goals for architectural and urban design. Because humans do not experience one common perceived reality due to their different cultural values and historical context, a realisation that there is a common ecological reality existing independently of human political or cultural values, may serve as a mechanism to

⁶¹ Although several other sources were initially consulted while conducting research for this section (Creswell, 2003, Denzin and Lincoln, 2005, Knight and Ruddock, 2008, Laurel, 2003, Sanoff, 1991), this section relies primarily on Groat and Wang (2002) because their publication 'Architectural Research Methods' remains essentially the most comprehensive and authoritative source of discussion about research methodologies used in an architectural context.

⁶² This refers to the research's stance on the nature of reality and existence.

alter the perception of how the built environment should be designed and lived in and interact with ecosystems. This is true if the goal is to evolve regenerative built environments that are resilient and address climate change issues.

Although it is the position of the author that ecological reality does exist⁶³, the very nature of design as an act of human cultural expression means that the ways people respond to this ecological reality will be varied and will reflect the values of their own culture. Understanding this could enable multiple human realities to co-exist and flourish in different times and places without depleting the ecological base which all humans and other species ultimately depend on for survival.

The epistemological assumption⁶⁴ of this thesis is that there is an interactive link between researcher and that being researched and that knowledge is therefore socially and historically situated. Such a stance is often applied to social research where the 'researcher' may influence the 'subject', blurring traditional research boundaries where a neutral and impartial starting point is typically demanded. Although this research has not affected ecosystems themselves, the understanding of ecosystems existing in the realm of human knowledge is subject to layers of human interpretation. This occurred first when ecological research this thesis draws upon was initially carried out and then subsequently by the author's interpretation of it from the viewpoint of a designer rather than an ecologist.

The theory presented here is historically situated relative to current understandings of ecosystems and climate change. Knowledge in the field of ecology and the understanding of climate change is changing rapidly. Changes in ecological knowledge will have to be reflected in subsequent generations of the concepts and findings of this research therefore.

⁶³ It is acknowledged that the variety to be found in and between ecosystems is vast. Common underlying traits are typically shared however. Differences also exist between developing and mature ecosystems. This research draws predominantly upon mature ecosystems as is discussed in chapters three and four.

⁶⁴ Epistemological refers to the ways that knowledge is acquired.

1.7.1 A LOGICAL ARGUMENTATION APPROACH

The generation of original research in this thesis is achieved primarily through a 'logical argumentation' research approach⁶⁵. Groat and Wang (2002, page 301) point out that:

'...Logical argumentation... can be provisionally defined as making sense of some aspect of the cosmos in a systematically rational manner. The human mind often encounters a seemingly disparate group of factors or phenomena that it somehow senses to be interconnected into an explanatory system. Once this system is framed, it gives clarity to those disparate elements under a general heading.'

Groat and Wang (2002, page 302) state that the aim of logical argumentation is to *'frame logical conceptual systems that... interconnect previously unknown or unappreciated factors in relevant ways'*. In the case of this research, the aspects being connected are ecosystem processes and functions, and architectural and urban design. Ecosystems are evaluated for their suitability for contribution to regenerative design theory, specifically as a means to establish ecological performance goals. Such goals are investigated for their relevance in evaluating existing built environments and in directing the design or re-design of urban environments. Exact mechanisms and elements of ecosystem processes and functions are still controversial in much ecology and biology literature, but general understandings exist. It is this knowledge, with the exception of a small body of work, which appears to be unappreciated or misunderstood in the disciplines of architectural and urban design. Such an observation is deduced in relation to the dearth of built examples or even architectural discourse reflecting such an understanding. This is discussed further in chapters three and four.

⁶⁵ Logical argumentation originates from Aristotle's (384 BC – 322 BC) 'The Organon', a grouping of his works of logic (Maginn et al., 2008, McKeon, 1941). In the 1960s and 70s several influential argumentation researchers perceived and then described a disconnection between prescribed formal methods of argumentation and those employed on an everyday basis in less formal situations. In response they sought to produce new descriptions of argumentation techniques. Many of these are now used in logical argumentation research processes and thus in this thesis. Perelman and Olbrechts-Tyteca (1969) called this 'new rhetoric' while Toulmin produced the earlier 'uses of argument' theory in 1958.

A logical argumentation project is often set within a larger 'transcendental venue' such as 'nature', 'the machine', or 'morality' (Groat and Wang, 2002, page 303). This thesis sees 'nature' as a system or model which works well within the planet's ecological operational limitations and functions in a way which is potentially useful for humans to learn from. The logical groundwork for living within ecosystems without degrading them and regenerating them is assumed to be found within understanding ecosystems and then translating this knowledge into a human context. This philosophical stance is discussed further in section 2.2.4.

1.7.2 STAGES OF LOGICAL ARGUMENTATION THROUGHOUT THE THESIS

A logical argumentation approach implies that the project has the following traits: broad systemic applicability, paradigmatic innovation, and testability (Groat and Wang, 2002, pages 308-311). The rest of the thesis is divided into parts following these traits⁶⁶.

Part one of the thesis is a primary logical argumentation treatise because it argues for a new way of conceiving the built environment (broad systemic applicability) and then provides analytic frameworks and matrix tools (paradigmatic innovation). Primary logical systems can be described as 'innovative' because they work at the level of paradigm discourse. A paradigm exists within a cultural and historical context, so most primary logical systems have connections to previously expressed concepts which may not have been connected before (Holm, 2006). Rather than predict future events or outcomes, the research seeks to explain facts already existent, or to make relationships clear between existing facts, thus revealing larger patterns.

'Primary logical systems... have the ability to... uncover reality at a deeper level than what is seen on the empirical surface of things. And the reality

⁶⁶ The success of such research within a logical argumentation paradigm is seen in its adoption by a community (Groat and Wang, 2002, pages 310-311), in this case architectural designers and related building professionals, as a design method or as a way of understanding interactions between people and the built environment, and between the built environment and the greater ecosystems in which it exists. Measurement of the success of the theory generated in this thesis therefore will not be apparent until sometime after it is published, and the theory is explored, adapted, adopted or discredited.

that is uncovered reveals connections that unify the stuff at the surface.'
(Groat and Wang, 2002, page 309).

Part two can be understood as a secondary or applicative treatise because it tests the primary theory described in part one. It applies this to an existing urban setting to establish the validity of the concepts discussed and to provide an example of how the frameworks could be practically applied as a design motivation, method, goal, and evaluation technique. A number of specific research methods are used that draw from both quantitative and qualitative traditions. This is because some aspects of the research lend themselves to measurement while others are more subjective and thus require qualitative research investigations. Testing is carried out using a variety of correlational research strategies such as mapping exercises, particularly in the comparison of ecosystem services to urban built environments (chapter five). This testing also occurs through case studies and through analysis of ecology literature where appropriate. An explanation and justification of the specific research methods employed will be given in the body of the thesis as they occur. Implications of the findings from this testing are discussed and a series of recommendations are made to conclude part two of the thesis.

Part three of the thesis forms the conclusion. Possible alterations and revisions of the initial framework are discussed and an explanation of how the framework could work in a larger context is offered. Figure 9 maps these three stages of the research against the actual chapter headings.

1.8 CONTRIBUTION TO KNOWLEDGE

The contribution to knowledge this thesis provides is a comprehensive exploration of the potential of applying ecological strategies to the built environment in order to find solutions to problems associated with climate change and biodiversity loss. Well-grounded approaches that build upon and strengthen regenerative design methodologies or concepts may be useful to design professionals and governing bodies as they address climate change impacts in the built environment. The thesis suggests that a rethinking of how the built environment could interact more effectively with ecosystems, rather than a plethora of new technologies that are

FIGURE 9 LOGICAL ARGUMENTATION AND THE STRUCTURE OF THE THESIS.

added to buildings, could be a useful way forward (Mitchell, 2012). Although this research focuses on the New Zealand context and Wellington specifically, in order to test and refine the ideas generated, it is expected that findings, particularly the theoretical underpinnings of the practical application of ecosystem based biomimicry, will be relevant in an international context.

This research differs from most existing biomimicry research because it explores long term systemic approaches to architectural design afforded by understanding ecosystems, rather than the typical exploration of new technologies devised by mimicking a single organism. This latter approach is shown to be less likely to result in improved environmental performance in chapter two. The body of knowledge of regenerative design is also increased, through clarifying and testing original theoretical frameworks for ecosystem service based design through the case study discussed in chapter five.

Other aspects of this research that contribute to the body of knowledge are the comparison of ecosystem processes and functions described by ecologists and biologists, to those described by designers, architects and industrial ecologists. Such research is important in creating robust ecosystem biomimicry theory based on scientific knowledge rather than abstracted translations of ecosystems by designers. A set of case studies of biomimetic architecture and building technologies is also produced and demonstrates a relationship between the type of biomimicry that is employed and possible sustainability outcomes.

The ecosystem based design and evaluation strategies suggested in the research could be employed by teams of designers and ecologists as well as urban planners, policy-makers or ecological economists at regional levels. Practitioners or policy makers seeking well-grounded research to argue for and implement a shift to systems-based and potentially regenerative built environments will likely find the research useful. In addition, biomimicry related researchers as well as those in the field of ecology may find relevance in the work because it expands pre-existing research in those areas and applies it to the built environment and to climate change and biodiversity issues specifically.

1.9 DETERMINING THE SCOPE AND LIMITATIONS OF THE RESEARCH

This section describes the scope and limitations used to define the research. The subject areas that the research draws upon and limitations of the research are illustrated in figure 10.

FIGURE 10 FIELDS OF RESEARCH DRAWN FROM (BLUE CIRCLES) AND LIMITATIONS (RED CIRCLES) OF THE RESEARCH.

The thesis investigates climate change impacts on new and existing urban built environments and focuses on Wellington, New Zealand in order to provide a context for the research. It is important that testing the concepts explored in this thesis is situated in a specific place, due to the wide range of ecosystem types and climate

change impact scenarios across the globe. Regenerative design is also by nature inherently site specific (Reed, 2007).

Urban environments were chosen, due to increasing human population density and changing human habitation patterns. This has resulted in a trend towards urbanisation of the population in New Zealand (Statistics New Zealand, 2006b) and globally (UNEP, 2011). Urban environments are also responsible for a large proportion of negative environmental impact caused by humans (Rojstaczer et al., 2001, McDonald and Patterson, 2003) as discussed in section 1.2.

There is a focus on both new and existing elements of urban environments in this research. New building and development projects provide substantial opportunities for initiating and demonstrating change, but most buildings that will still exist when the effects of climate change become more acute have already been built in most urban centres. New Zealand exemplifies the point. Buildings are required to last for at least 50 years under the New Zealand Building Code, while homes last for an average of 80 years and some for up to 150 years (O'Connell and Hargreaves, 2004). This means that many of the buildings in New Zealand that will be occupied until at least 2090, when the effects of climate change will be more apparent, have probably already been built. The rate of constructing new buildings (approximately 1500 per month (Bascand, 2011)) is also far less than the rate of demolition of existing buildings⁶⁷. This, combined with increased population in urban centres suggests that the built environment is expanding as well as being replaced incrementally through demolition and new construction (Storey et al., 2004). The existing built environment will also need to be part of a long term solution to climate change because buildings have relatively long lives and slow rates of renewal compared to consumer items such as clothing or electronic equipment. An increased understanding of the problems associated with current methods of disposing of demolition waste, may also mean that buildings or their components will be more likely to be reused in the future (Storey et al., 2003, Falk and Guy, 2007, Manuel, 2003).

⁶⁷ Increased demolition and construction activity caused by the 2011 Christchurch earthquakes are likely to alter national New Zealand statistics in this regard. The underlying trend remains, especially outside of the Canterbury region.

Reasons for limitations of specific aspects of the research have been explained throughout the thesis as they occur. It should be noted that because this research seeks to relate to a future context many uncertainties remain. Future climate change impacts on the built environment and the response of ecosystems to these same changes are explored by numerous researchers (Hunt and Watkiss, 2011, Wilby, 2007, Parmesan, 2006), but findings are often based on uncertain climate predictions and other drivers of change. Assumptions have, therefore, been made in order to progress the research. These assumptions are discussed throughout the research as they occur.

The social, psychological and aesthetic implications of an approach to architectural or urban design utilising an understanding of ecosystems are not explored in this thesis. The potential relationships with biophilia (Kellert et al., 2008, Wilson, 2006), evolutionary psychology (Heerwagen, 2005) and integration with non-human dominated ecosystems are however acknowledged and are worthy of future research.

1.10 CONCLUSIONS: CHAPTER ONE

The urban built environment is already experiencing and will continue to experience significant impacts caused by climate change and the decline of biodiversity health. As the physical climate changes, these impacts will affect not only the fabric of buildings and infrastructure, but also the social and economic context the built environment exists in, as well as wider ecosystems and hinterlands that cities depend on. Coupled with climate change, other significant drivers of change are likely to converge in the 21st century that will affect the built environment. While responding to only the direct impacts of climate change in the built environment may be easier for built environment professionals to comprehend, it is important to consider the built environment in its wider ecological context and to understand and respond to the social and economic context that also impacts on the built environment (Howden-Chapman et al., 2010)⁶⁸.

⁶⁸ Hunt and Watkiss (2011) and Allan and Tait (2011) provide a framework for city-scale climate change risk assessment that takes some of these issues into account.

Because of the great variation of impacts in different locations, responses to climate change and biodiversity loss should be tailored to specific urban environments. Responses to climate change impacts in the built environment typically fall into two categories: those aiming to mitigate the causes of climate change, and those seeking to adapt to the anticipated changes. Considering these two goals in tandem may ensure that strategies employed do not conflict but instead create mutually beneficial outcomes. Responses to climate change and to biodiversity issues also need to be considered together so that actions taken are beneficial for both climate and ecosystems.

It has been suggested in chapter one that regenerative design could be investigated for its ability to enable the built environment to positively address both climate change and the loss of biodiversity. Incorporating an understanding of biology and ecology into regenerative design is important to ensure that outcomes have measurable positive effects on climate and ecosystems. The transfer of biological and ecological knowledge into a design context can be termed biomimicry. Defining biomimicry more precisely forms the basis of chapter two.

2.0 CHAPTER TWO: DEFINING A THEORETICAL FRAMEWORK FOR INCORPORATING BIOMIMICRY INTO REGENERATIVE DESIGN

'Imitating nature is more than flattery on the part of human kind, it is also copying systems that function in an extraordinarily successful fashion.'

(Kibert et al., 2002, page 22).

This chapter determines which kinds of biomimicry, if any, might be useful as strategies for transforming built environments so that overall environmental performance is increased. To do this, a framework is established to examine and analyse if mimicking organisms or ecosystems could be an effective means to address biodiversity issues, to mitigate the built environment causes of climate change, or to adapt to its impacts.

Two possible options for an architectural response to climate change that employs an understanding of the living world are investigated. The first is integrating biomimetic technologies into or onto buildings that are able to mitigate GHG emissions. The second is using biomimicry to adapt to the direct impacts of climate change on the built environment. Biomimicry's potential for this over the short, medium and long terms is examined. Documented successes and potential benefits and difficulties inherent in such approaches are discussed. As well as a reduced or potentially negative carbon footprint for the built environment, this chapter analyses further significant benefits that may occur, including positive impacts on biodiversity. Several issues with, and disadvantages of, using biomimicry to address climate change or biodiversity through the medium of the built environment are discussed.

2.1 INTRODUCTION

To be able to examine biomimicry's potential effectiveness or failure as a means to achieving greater sustainability and regenerative goals in the built environment, and as a useful strategy in the architectural or urban context with regards to climate

change, it is first necessary to understand and define what biomimicry is and what different kinds of biomimicry exist. This is important because a substantial amount of discourse about biomimicry is in general very enthusiastic and passionate about the potential of biomimicry as a means to increase sustainability outcomes (see: Berkebile and McLennan, 2004, Koelman, 2004, Pawlyn, 2011), but is uncritical in its investigation of measurable successes or failures of the concept. This could lead to biomimicry being criticised as being a potential ‘green-wash’⁶⁹ mechanism (Mathews, 2011, Bensaude-Vincent et al., 2002, Birkeland, 2008, pages 17-18).

Through an examination of contemporary and historic examples of biomimicry a framework is suggested for analysing how it has been used in design, and particularly architectural and urban design, and how it might be employed if the motivation for learning from living organisms and the systems they create is to increase the sustainability of the built environment, specifically addressing climate change and biodiversity loss.

2.2 UNDERSTANDING BIOMIMICRY

‘I thought there couldn’t be anything as complicated as the universe until I started reading about the cell’ (de Silva as quoted in Forde, 2006).

2.2.1 A BRIEF HISTORY OF THE TERM ‘BIOMIMICRY’

The portmanteau term ‘biomimicry’ originates from the work of multidisciplinary scientist Otto Schmitt (1913-1998). ‘Bio’ comes from the Greek ‘bios’ meaning life, and ‘mimicry’ is from ‘mimesis’ meaning imitation (Benyus, 1997, front matter). Harkness (2002) says of Schmitt:

‘He was able to draw potent connections between disciplines, which others might see as distinctly unrelated to reach insightful conclusions’.

⁶⁹ ‘Green-washing’ is the act of describing a behaviour, group, concept, or product as being more environmentally sustainable than it actually is to enhance its public reputation, and/or increase financial profits.

Schmitt's doctoral research, defended in 1937, detailed his production of an electronic device that mimicked the electrical action of a nerve (Harkness, 2002). It is unclear exactly when the term 'biomimetic' was coined, but an early record is the title of a 1969 paper '*Some interesting and useful biomimetic transforms*' (Schmitt, 1969). Bensaude-Vincent et al. (2002) suggest 'biomimicry' might have been used in academic writing as early as 1962. In 1974 the term 'biomimetics' appeared in Webster's Dictionary (Vincent et al., 2006), and was defined as:

'The study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesising similar products by artificial mechanisms which mimic natural ones.'

'Biomimicry' was popularised in the 1997 book '*Biomimicry - Innovation Inspired by Nature*' by biologist Janine Benyus. She described biomimicry in three parts: using 'nature's models' as inspiration for designs that seek to solve human problems; using ecological standards to judge the effectiveness of innovations; and finally, using biomimicry as a way to redefine how humans relate to nature (Benyus, 1997, front matter).

2.2.2 CONTEMPORARY BIOMIMICRY

Mimicking organisms or ecosystems is an expanding field of research in both academic and design discourse (Hesselberg, 2007, Pawlyn, 2011, page 2, Bensaude-Vincent et al., 2002, Manuel, 2003). Hesselberg (2007) demonstrated that the percentage of papers published with the term biomimetic published each year is increasing. This is confirmed by Gebeshuber et al., (2009) who add that most publishing activity in the area of biomimicry comes from the research disciplines of bioengineering, chemical engineering and engineering physics. Rapid increase in memberships of biomimetics related research networks (such as the UK BIONIS and the German Biokon Network) and the recent appearance of peer reviewed technical journals on the subject is also recorded by Bonser and Vincent (2007) as a further indication that activity in this area is increasing.

Benyus (1997, page 6) suggests that biological knowledge is doubling every five years. This increases human capacity to understand and mimic nature in more meaningful ways and has been crucial to the emergence of biomimicry as a research area. Humans are now able to explore and analyse the very molecules of the living world as well as global and extra-terrestrial phenomena more accurately (Manuel, 2003). There is also more capability through technological advancements and computer and nanotechnology⁷⁰ to engineer the complicated forms, mechanisms and chemical reactions seen in nature at molecular scales (Dickinson, 1999), although whether such innovation would be beneficial in the context of increasing sustainability outcomes is debatable (Clark and York, 2005).

For researchers and designers there are three main motivations behind investigating biomimicry. Firstly, biomimicry can be seen as a source of innovation in the creation of new materials and technologies. Most biomimetic research and patents relate to this factor and are not necessarily concerned with improving the ecological performance of human technology. Rather, they are about novel approaches to technical problems, increased performance capabilities, or the ability to increase profit margins (Wahl, 2006, Reap et al., 2005). A considerable body of research details scientific experiments and technological innovation particularly in robotics, computing and materials technologies that have no focus on sustainability issues (Allen, 2010, page 9, Garrod et al., 2007, Nakrani and Tovey, 2004, Manuel, 2003). Bhushan (2009) lists the following properties of biology as of particular commercial interest and relating to current research: molecular scale devices, super-hydrophobicity, self-cleaning, drag reduction in fluid flow, high adhesion, reversible adhesion, aerodynamic lift, materials and fibres with high mechanical strength, biological self-assembly, antireflection, structural coloration, thermal insulation, self-healing, and sensory-aid mechanisms.

Secondly, there is a rise in interest in the potential of biomimicry as a way to create more sustainable materials, products, built environments, and engineering solutions. While the idea that biomimicry can radically improve the environmental performance

⁷⁰ Nanotechnology refers to manipulating matter on an atomic or molecular scale. The principles of quantum mechanics apply at this scale. For discussion on the application of nanotechnology to architecture see: Pacheco-Torgal and Jalali (2011).

of human technologies and the built environment is often discussed with great passion (Berkebile and McLennan, 2004, Reap et al., 2005, Wahl, 2006, Pawlyn, 2011) there is little quantitative evidence to suggest that the act of mimicking an organism in design is in itself a means to achieve greater sustainability (Reap et al., 2005).

Finally, the third motivation for exploring biomimicry comes from a group of researchers who examine whether design based on an understanding of the living world could contribute to increasing human psychological wellbeing, due to its inherent relationship to the concept of biophilia (Kellert et al., 2008, Benyus, 2008, Kellert, 2005, Heerwagen, 2003). Biophilia is explained in more detail in section 2.2.3.3.

This motivation for engaging with biomimicry as a means to increase sustainability outcomes is the subject of the research presented in this thesis. Gebeshuber et al. (2009) investigate how biomimicry might contribute to addressing global challenges, including sustainable development, in a fifty year time frame. They see probable tangible advancement in the areas of materials science (including the development of composite and smart materials), energy conversion technologies, energy production systems and materials recycling systems. Again, such a discussion of innovation or new technologies as a means to increase sustainability is not set within a wider context where technological advancements on their own are unlikely to result in a human society with less negative ecological impact (Clark and York, 2005, Mitchell, 2012).

Confusion between the first kind of biomimicry and the second is caused when some of the examples of biomimicry that are cited by people advocating it as a method to increase the sustainability outcomes of design, have been sourced from the group of researchers and designers who employ biomimicry only as technical innovation, without a focus on improving sustainability outcomes. Some biomimicry related to innovation has resulted in products or materials that do not appear to be related to a larger sustainability agenda (Marshall, 2007b) but are more aligned with increasing the unsustainable exploitation of, or perpetuating damage to, both ecosystems and people. Examples include the design of undetectable surveillance equipment based

on insect eyes (Duparré and Wippermann, 2006); the design of spacecraft based on flying insects, beetles, cockroaches and worms (Scott and Ellery, 2004); several new military technologies based on a variety of animals (Bar-Cohen, 2006, Bar-Cohen, 2010); the creation of new consumer items such as cars, clothing, and paint based on understandings of various fish, trees, and flowers (Pawlyn, 2011, page 5); and the design of echolocation technologies to detect areas suitable for mineral mining based on bats and dolphins (Allen, 2010, pages 9, 84).

Some of these examples have been criticised as ‘biomimicry green wash’. Examples include Lotusan paint, the ‘Bionic car’, or even Velcro, all of which are common examples given by people advocating biomimicry-for-sustainability but none of which are good examples of radically more sustainable design (see sections 2.4 and 2.5). This contributes to people dismissing biomimicry as a shallow trend in design, or an exercise in adding high-tech ‘eco-bling’⁷¹ to buildings, rather than a method to contribute to more sustainable design thinking and practice (Armstrong, 2009 and 2011, Brikeland, 2008, pages 17-18).

One of the key differences between biomimicry-for-sustainability and biomimicry-for-innovation, which are not always mutually exclusive, is that biomimicry-for-sustainability tends to recognise the importance of mimicking not just organisms but also the underlying processes, strategies and systems of ecosystems, to lead to more sustainable outcomes. Biomimicry-for-sustainability is not focused solely on the creation of new and novel technologies, but on the altering of the underlying foundations of design. It is possible that not all people interested in biomimicry-for-sustainability understand this important philosophical difference. It is vital to be clear about which kind of biomimicry in terms of motivation a researcher or designer is interested in from the outset of projects (Wahl, 2006, Wahl and Baxter, 2008).

⁷¹ ‘Eco-bling’ describes the practice of adding often expensive and highly visible pieces of technology to otherwise conventional buildings to improve sustainability outcomes. Examples are wind turbines, solar panels, green roofs, and rainwater tanks. While some of these technologies may in fact be beneficial in some circumstances, often their effectiveness is not analysed from a whole life-cycle perspective and their use does not necessarily challenge the underlying thinking behind the practice of designing and building (Mithraratne and Vale, 2007, Gerhardt and Vale, 2010, Mithraratne, 2009).

2.2.3 BIO-MUDDLERY: RELATED TERMS

Analogies between ecosystems and living organisms, and architectural design, referred to here as bio-inspired design, are explored in many different ways (Kibert et al., 2002, Allen, 2010, Gruber, 2011, Todd and Todd, 1993, Van Der Ryn and Cowan, 2007, Vogel, 1998). Biomimicry is one aspect of bio-inspired design. Figure 11 illustrates different kinds of bio-inspired design that have significance in an architectural context. It maps elements of bio-inspired design onto the three drivers for biomimicry described earlier: technological innovation; increased sustainability; and increased human wellbeing. This diagram reveals possible underlying meanings and motivations behind the various terms used⁷². Intersections are also uncovered which may prove useful in future research. For example, aspects of design that biophilia (for human well-being) and biomimicry (for increased sustainability) have in common might determine important factors in regenerative development, where the goal is both increased human and ecological health.

There are some subtle but important distinctions between several of the terms used in relation to design inspiration from organisms or ecosystems. The ones most commonly confused with biomimicry are explored in brief below. It is accepted that the interpretation of their meaning here may be controversial. In some cases the different terms are used to mean the same thing and vary most obviously between researchers in the United States, where 'biomimicry' is more common, and Europe, where 'bionics' is often used. Often the terms 'biomimicry' and 'biomimetic' are interchangeable (Marshall, 2007b). The term 'biomimicry' does however often bring with it an inference that it encompasses ideals of sustainability, whether true or not, while bionics, and biomechanics do not.

2.2.3.1 BIONICS

The term 'bionics' has been used since 1958 to describe technologies that have been developed based on an understanding of biology (Hesselberg, 2007). The term

⁷² Although not explicit in figure 11, some kinds of regenerative design, permaculture and ecological design require human behaviour changes alongside design strategies in order for lower environmental impact systems to function effectively.

FIGURE 11 TERMS TO DESCRIBE DESIGN APPROACHES THAT MIMIC ASPECTS OF NATURE.

was coined by the United States Air Force engineer Major Jack Steele (Wahl, 2006). In English 'bionics' is now more commonly associated with the mechanical replacement or enhancement of body parts (Marshall, 2007b), but German and Italian speaking sources still use the term 'bioniks' (Schäfer, 2003, Hesselberg, 2007, Anon., 2005, Gebeshuber et al., 2009). This is largely because of the work of Werner Nachtigall, a German Zoologist, who since the 1970s has developed bionics into a support discipline for engineers where *'learning from nature [is] an inspiration for independent technical design'* (Wahl, 2006). Italian designer Carmelo di Bartolo, should also be acknowledged for founding the Istituto Struttura Naturali at the Istituto Europeo di Design school in Milan in the 1970s (Anon., 2005).

'Bionics' is often a more technologically oriented approach to designing from nature not generally concerned with broader sustainability issues or positively changing the relationship between humans and ecosystems. According to Wahl (2006) the latter is implicitly encompassed by the term 'biomimicry':

'Without acknowledging the complex context of sustainability and ecological and social interactions, bionics...will ultimately perpetuate unsustainable practices, as it ignores the complex interplay of diverse social, cultural, economic and ecological factors that have to be brought into synergy in order to create sustainable solutions and design'.

2.2.3.2 BIOMECHANICS

'Biomechanics' as described by Steven Vogel, Professor of Zoology at Duke University, *'looks at the technology of life and the mechanical world of nature'* (Vogel, 1998, page 9). 'Biomechanics' relates primarily therefore to the transfer of mechanical solutions in biology to an engineering context. This again denotes that 'biomechanical' solutions are typically innovative for the sake of technological advancement rather than for increasing the sustainability of designed artefacts and habitats. The term 'functional morphology' is also used to describe 'biomechanics' (Dickenson, 1999).

2.2.3.3 BIOMORPHIC / ZOOMORPHIC / ORGANIC / BIOPHILIC DESIGN

Architecture that is biomimetic does not necessarily translate into a new aesthetic. Vincent et al. (2006) emphasise that biomimicry involves an interpretation, adaptation or derivation from biology. This process of translation often results in designs that are not immediately similar to the organism that inspired them, but utilise the same functional concepts. Biomimicry therefore is not the same as organic, biomorphic or zoomorphic architecture, which are concerned with the aesthetic mimicry of organic form in design (see for example: Feuerstein, 2002, Aldersey-Williams, 2003, Pearson, 2001, Portoghesi, 2000). Buildings that mimic nature for the purpose of becoming more sustainable should imitate how the living world is able to function rather than just its form (Mathews, 2011, Gruber, 2011, Aldersey-Williams, 2004). They should consider the working systems of the built environment and their relationship to the wider ecosystems and cultural contexts in which they are situated.

Biomimicry is also distinct from biophilic design which is more concerned with forms, spatial relationships, and the appearances of buildings and interiors to enhance human wellbeing⁷³. The term biophilia means *'the tendency to focus on life, and life-like processes'* (Wilson, 1984, page 1). Biophilic design seeks to incorporate an understanding of the processes of human psychological connection with the perceivable living world. It combines evidence and theories from the areas of environmental psychology, evolutionary psychology, ecological psychology, and neuroscience. Much of the evidence that biophilic design draws on comes from the premise that because the human mind evolved in the natural world, survival behaviours and responses related to certain organisms, landscapes and natural forms are genetically inherited, and affect the human sense of belonging and wellbeing (Kellert, 2005, Kellert et al., 2008). Evidence suggests that people feel less stressed, are able to concentrate better, and are even able to physically and psychologically heal more rapidly, when they have a connection with the living world

⁷³ It is possible that with a greater understanding of the living world, architectural form will change. Research suggests the way buildings look affects the sense of well-being and can tap into a biological need to be connected to the living world (Kellert et al., 2008, Ulrich, 1984). This is separate to pleasure derived from participating in the aesthetics of fashion trends.

(Lohr et al., 1996, Ulrich, 1984, Faber Taylor et al., 2002, Tennesen and Cimprich, 1995). Several researchers provide lists of elements of biophilic design along with explanations of their scientific basis (Kellert et al., 2008, Kellert, 2005, Academy of Neuroscience for Architecture, 2003). There is increasing research detailing people's needs and preferences to be near nature or images of nature (Kellert et al., 2008, Kellert, 2005). The first most common manifestation of biophilic design is that elements of the living world, particularly plants, should be brought into urban landscapes and building interiors (Salingaros and Masden, 2006). An example of this is seen in the Genzyme Headquarters in Massachusetts, designed by Behnisch and Behnisch in 2004 (Kellert, 2005). Extensive use of gardens, running water, and natural light and materials are employed. The second manifestation is that to increase psychological wellbeing, the built environment should mimic the geometry or morphology of natural form. One example of this is the investigation into the psychological benefits of fractal architecture, where similar forms repeat themselves at varying scales (Joye, 2007, Taylor, 2006). Fractal patterns may be attractive to humans, because they mimic human cerebral organisation (Salingaros and Masden, 2006). An example of fractal patterns used in architecture is René Binet's entrance to the 1900 Paris World Exposition, based on Ernst Haeckel's fractal drawing of a radiolarian (Ball, 2001). Frank Lloyd Wright's Palmer House in Michigan (1950), also exemplifies the concept with its fractal floor plan, where the triangle is repeated at several different scales. Steven Holl's Simmons Hall (2002) which mimics the openings in a sea sponge is also likened to fractal design (Joye, 2007).

Although biomimicry is different from biomorphic, organic, zoomorphic or biophilic architecture and design, there is no reason why a building or development which is biomimetic could not also draw upon these other strategies for its design aesthetic.

2.2.3.4 BIO-UTILISATION / BIO-ASSISTED DESIGN / ECO-INTEGRATION

'Bio-utilisation' describes the act of using living organisms in human systems. This is also termed 'bio-assistance'. An example is John and Nancy Todd's Living Machines where the process of waste water treatment in ecosystems is mimicked through the use of complex plant communities (Todd, 2004, Todd and Josephson, 1996). The Australian developed Biolytix system is also an example. It mimics soil based

decomposition to treat grey and black water and integrates worms and soil microbes into the process (Allen, 2005, Baumeister, 2007b). A strictly biomimetic approach would look at how worms are able to digest food scraps and emulate that without using worms themselves.

The idea of integrating with ecosystems, so that human built form is more sympathetic to and responsive to natural ecosystems for the mutual benefit of both, is also not strictly speaking biomimicry. Various aspects of 'ecological design' explore how such integration could occur and what the effects would be (Eisenstein, 2001, Van der Ryn and Pena, 2002, Berkebile and McLennan, 2004, Alberti et al., 2003). Much like biomorphic design there is no reason why bio-utilisation techniques cannot be employed as part of a biomimetic design particularly at the ecosystem level (Pawlyn, 2011, page 53). The examples given in this section are in fact biomimetic at the ecosystem level.

2.2.4 THE PHILOSOPHICAL BASIS OF BIOMIMICRY AS PART OF REGENERATIVE DESIGN

Tools and technology always exist within the context of an ideology and are used generally to further or maintain its intentions (Benyus 1997, page 8). Advocating the use of the living world as a source of inspiration can have very different philosophical foundations and ultimately different ideological aims and political goals. This exposes the importance of analysing the philosophical roots of biomimicry and its projected end aspirations.

For example, Kevin Kelly (1994), a business motivational expert, advocates a mimicking of natural systems he calls 'biologic'. Kelly's ideas are closely aligned with a '*government-off-your-back*', '*crypto-libertarian*' (Best and Kellner, 1999) ideology which does not consider environmental destruction or social injustice to be problems. Rather, present economics and the capitalist system are equated with a natural ecosystem which must be, according to Kelly, in a dynamic flux and on the edge of chaos to function and endure. Likening capitalism to an ecosystem naturalises and justifies the current economic system. This relates to the idea that the law of supply and demand will naturally regulate prices and competition in an economic

marketplace situation⁷⁴. Kelly has also been criticised for his views on competition in nature, with critics arguing this is used to support his specific political viewpoint:

‘Like Social Darwinists and their principle of ruthless competition, Kelly reads social metaphors into nature and then back into society, thereby eternalising contingent relations and ideas and legitimising the current organisation of society through a cosmic metaphysics’ (Best and Kellner, 1999).

This demonstrates that while biomimicry and biologic may both be about applying an understanding of biology to design and business models respectively, the motivations and political outcomes are very different. It is important therefore to avoid the assumption that because an object, material, system or building mimics nature in some way, it is inherently more sustainable. As Gebeshuber et al. (2009) point out, the intention to make a design more sustainable is largely independent of design method and comes instead from societal and cultural values and norms.

The anthropocentric view, cemented in westernised cultures over the past 500 years⁷⁵ seeks to understand nature in order to extract as many ‘resources’ as possible for human industry, and to control, exploit or conquer its complexity and diversity rather than work with it. Wahl (2006) traces the advent of such a *‘reductionist science of detached objectivism’* to Galileo Galilei (1564-1642) who regarded the measurable quantitative aspects of an understanding of nature as more important than qualitative ones, Francis Bacon (1561-1626) who advocated that humans should be masters of nature, and René Descartes (1596-1650) who created a philosophical separation of humans and nature, body and mind, and subject and object, thus transforming these into dualistic mutually exclusive categories. Nature was seen as wild, dangerous, hostile and in need of taming and civilising (McDonough and Braungart, 2002, page 26). Wahl (2006) explains the implications of such a view:

⁷⁴ This is closely linked with Adam Smith’s invisible hand metaphor coined in *The Wealth of Nations*, 1776 (Smith, 1776).

⁷⁵ Extensive discussion of the origins of the anthropocentric view going back to Plato and Aristotle can be found in Bosworth et al. (2011).

'The root cause of the utter unsustainability of modern civilisation lies in the dualistic separation of nature and culture. It is in nature that all peoples and all species unite into a community of life. Yet culture is commonly conceived of as apart from nature, rather than a part of nature. Since the Industrial Revolution, reductionist science has enabled us to design a whole host of powerfully manipulative technologies, which have transformed the planet.'

The shift needed is from taking from ecosystems as inexhaustible stores of resources for the use of humans, to understanding that humans live within them and are entirely dependent upon them for survival (Alberti et al., 2003, Daily, 1997). In architecture this emerging shift might be represented by a move away from the metaphor of a house as a machine for living in (Le Corbusier, 1923), to an ideal of design where human environments are symbiotically integrated with ecosystems and contribute to rather than harm ecosystem health (Reed, 2007, Cole, 2012a, Cole, 2012b, Cole et al., 2012, du Plessis, 2012).

This is also symbolised by a greater interest in biology among designers. This is seen by some adherents of an anthropocentric view as 'dangerous' and 'negative'. Kaplinsky (2006) asserts that the increasing interest in biology demonstrated by some architects and designers is a direct affront to the ideals of the human-centric world associated with the Enlightenment (18th Century) and demonstrates that there is a lack of meaning in human society in general. His vision of '*a city transformed into jungle [as] a powerful symbol of collapsed and lost civilisation where nature has overthrown the human order*' (Kaplinsky, 2006), brought about by embracing the natural world, demonstrates his research falls into a paradigm of seeing the world through a human-nature relationship lens that assumes nature is threatening, and something to be conquered.

Humans have always studied nature, drawing guidance and inspiration from it to better understand themselves and their relationship to the world around them (Vogel, 1998, page 18-19). Leonardo da Vinci and Otto Lilienthal are described as some of history's most famous biomimics (Pawlyn, 2011, page 5). However, the philosophy behind the emergence of the biomimicry-for-sustainability movement, particularly

since the 1990s⁷⁶, with its roots in the deep ecology movement⁷⁷, is perhaps part of the beginnings of an important shift in the general western cultural stance on the natural world (Mathews, 2011, Benyus, 1997 pages 7-10, Pawlyn, 2011, page 108, Altomonte, 2008a, Dollens, 2005, Berkebile and McLennan, 2004). Such a change in thinking is paralleled in other aspects of human culture and economy. For example, biological and ecological knowledge is being explored in many areas of research such as; ecological economics (Krishnan et al., 1995); ecological philosophy or ecosophy⁷⁸ (Drengson and Inoue, 1995, Guattari, 2000); and ecological education (Smith and Williams, 1999). This implies a desire to understand more thoroughly and integrate more effectively with ecosystems. Biomimicry is one aspect of this application of ecological and biological knowledge to human endeavours that seems to pertain more to design, architecture and engineering. Allen (2002) points out that:

'Much as organisms are particularly comfortable and useable in biology because of their tangibility... buildings may have a similar role to play in concretising abstractions about the human social condition. Thus buildings may be a particularly useful intellectual device for furthering our understanding of energetics and the interface between biology, sociology, and economics.'

While there is evidence that a small minority of people call for and participate in new ways of thinking at the paradigm level in design (Mathews, 2011, McDonough and Braungart, 2002, Reed, 2007, Wahl, 2006, Birkeland, 2008), translation of this into a

⁷⁶ It was the 1997 publication of *'Biomimicry. Innovation Inspired by Nature'* by Benyus that popularised biomimicry as a means to increase sustainability. This also cites some examples of biomimicry that seem to be purely technological innovation driven biomimicry rather than biomimicry related to a sustainability agenda.

⁷⁷ Proponents of deep ecology argue that all organisms and living systems have a right equal to humans to exist and flourish on the planet, not because of their value to humanity but simply because they exist. There is also an emphasis on the importance of ecosystems and natural processes (Mathews, 2011, Drengson and Inoue, 1995). The development of the philosophy inherent in biomimicry-for-sustainability has also been traced to the activities of McHarg (McHarg, 1992, Steiner, 2006), and Todd, Jack-Todd and McLarney of the New Alchemy Institute (Todd and Todd, 1993) in the 1960s and 70s with their *'holistic, participatory'* worldview and *'ethically responsible'* approach to ecological design (Wahl, 2006). This is closely related to the 'Bioneers' movement. *'The Bioneers (biological pioneers) are a network of scientists, writers, economists, artists, and other leaders with practical and visionary solutions for our most pressing environmental and social challenges'* (Ausubel, 2004).

⁷⁸ The term 'ecosophy' can be related to the work of Norwegian Arne Næss and his 'deep ecology' ideas (Drengson and Inoue, 1995) and to the French philosopher Félix Guattari (Guattari, 2000). The two different sets of concepts are related but at times are contradictory.

slowing or even stabilisation of the rate of human caused drivers of negative environment change is not yet apparent.

The underlying philosophy behind biomimicry-for-sustainability is inherently respectful of organisms and of ecosystems (Wahl, 2006). Benyus suggests ‘a *humbling that allows us to be attentive to nature’s lessons*’ should accompany the endeavour of biomimicry (Benyus, 1997, page 8). This points again to the importance of understanding at a holistic level how and why people design the built environment, why the planet is in a degraded state, and how humans need to reassess their expectations of lifestyle, including the motivations behind designing, producing, building and consuming. This matches discussions about the philosophy of regenerative design and the idea that it is unlikely to be a raft of new technologies⁷⁹ that creates or evolves regenerative built environments, but rather a change in perception (Reed, 2007). An understanding of this is one of the key things that separate biomimicry-for-sustainability and biomimicry solely as a method for generating technological innovation.

Parallel to the idea of respect for nature, the ideal of active stewardship also comes through in biomimicry with a sustainability motivation. That organisms and ecosystems can inspire developments in human design and engineering is cited as a reason to preserve or regenerate ecosystems (Kellert and Wilson, 1993, Kellert, 2005, Benyus, 1997, pages 292-295)⁸⁰. This different way of approaching the human / nature relationship is exemplified in the ‘Innovation for Conservation’ scheme managed by the Biomimicry Institute⁸¹ where a percentage of the payments made for

⁷⁹ Just considering the estimated changes needed to stabilise the climate at a level of only 2 degrees of warming (an 80% reduction in CO₂ emission levels by 2100), a reliance on technology alone will not be enough without corresponding policy changes governing consumption, economic growth, and population growth (Mitchell, 2012). Global CO₂ emissions increased by at least 2.4% per annum between 1996 and 2006, Aggregated global gross domestic product (GDP) increased by 3.1% per annum, while technological improvements only accounted for a 0.7% per dollar off set of emissions growth (Mitchell, 2012).

⁸⁰ Biophilic design is an aspect of bio-inspired design that echoes this sentiment. Wilson and Kellert outline the basis for a conservation ethic as it relates to biophilia (Kellert and Wilson, 1993). They argue that living forms must be preserved because of the ‘neurological nourishment’ they provide to humans (Wilson, 1984, page 119-140). This is echoed by Heerwagen and Orians, who state that ‘a *biologically impoverished planet will not only reduce humanity’s economic options, it will diminish our emotional lives as well*’ (in Kellert and Wilson, 1993). See also section 2.2.3.3.

⁸¹ The Biomimicry Institute is a non-profit organisation founded in 2005 by Janine Benyus. It is the educational and philanthropic part of Benyus’ biomimicry network of organisations (www.biomimicryinstitute.org).

Biomimicry Guild⁸² research contracts goes to *‘on the ground effective conservation efforts’*, in an attempt to ‘pay’ the organisms for their inspiration by protecting their habitat. Companies that use the services of the Biomimicry Guild are encouraged to provide on-going royalties to the organisms through the Innovation for Conservation scheme by way of profits gained or savings made (Biomimicry Institute, 2011). A ‘bio-inspired inventor’s guide’ has also been developed by the Biomimicry Institute, part of which reads:

‘By signing this Accord, we signal a new ethic amongst bio-inspired inventors, an ethic that embraces engagement with our study subjects and rejects the notion that benefits from the environment should flow in a single direction only. By signing this Accord, we hereby establish that we can and should take an active, responsible stance towards the conservation of threatened biodiversity, in direct proportion to the benefits we derive from being able to study life on Earth.’

These two initiatives signal another clear distinction between the kind of biomimicry advocated by researchers and designers based on an underlying ethic of sustainability, compared to biomimicry used just as a means to develop new and novel products or technologies. Further development and clarification of a biomimicry ethic will need to occur to avoid unwanted consequences. The importance of this is discussed by Gebeschuber et al. (2009) who state:

‘Now that we begin to understand the language and concepts of life itself, careful selection between what is possible, but harmful, and what is possible and useful has to be made. Cyborgs, devices made from synthetic biology, bioinspired self-replicating systems and the like do not go through millions of years of natural selection, and therefore might show unforeseen outcomes. People will have to establish ethical codes of conduct for using novel

⁸² The Biomimicry Guild is the for-profit research consultancy part of Benyus’ network of biomimicry organisations and initiatives. It was co-founded in 1998 by Benyus and Baumeister (www.biomimicryguild.com). There are other consultancy firms that use an understanding of biology to find design solutions. Examples include BioTRIZ in the UK (footnote 92), Biomimietik of the Netherlands, Swedish Biomimetics 3000, and Biomimetic Connections LLC of the United States.

technologies especially outside of the protected space of the laboratory. In some cases it might be advantageous not to follow some routes at all.'

2.3 DRAWBACKS AND PITFALLS OF A BIOMIMETIC DESIGN APPROACH

This chapter began with a discussion of the enthusiastic but unqualified claims that biomimicry is the key to increasing the sustainability of human design products and how this could lead to biomimicry being used as a green-washing mechanism. The undefined and 'ad hoc' (Mathews, 2011) current approach to biomimicry is also a drawback that the framework presented here (see section 2.5) aims to address. Aside from these two issues, there are several other potential pitfalls to using an understanding of biology or ecology in design that must be considered for it to become a useful tool for designers in the pursuit of sustainability.

2.3.1 THE ROMANTICISATION OF NATURE AND EVOLUTION

It is true that ecosystems and the organisms they are made of do provide an extraordinary number of examples of how living systems are energy effective, materials efficient, and extremely innovative at solving problems (Manuel, 2003). Because many aspects of biological entities as well as ecosystems are not fully understood, there is a tendency to romanticise nature as a perfect system (Vogel, 1998, page 19, Kaplinsky, 2006). This tendency is criticised by various scientists (Vincent et al., 2006, Vogel, 1998, pages 18-19) and reinforces the need to acknowledge that not all solutions arrived at through evolutionary processes found in organisms will be perfect, or suitable for a human context.

A related issue is that ecosystems and therefore organisms evolve within climatic and local constraints. Evolution, the natural process of experimentation with form and function, started at least 3 billion years before the first human experimentations with wood, bone and stone (Dickinson, 1999). Although the process of evolution through natural selection is a method of change and development that normally appears extremely slow by human cultural standards (Vogel, 1998, page 31), more refined examples of function, structure and organisation can in many but not all

cases be found in ecosystems than in human products. The process of evolution in some instances has led to adaptations in organisms that are not examples of great efficiency. The giraffe (*Giraffa camelopardalis*) illustrates the point (Kaplinsky, 2006). It has evolved to have a long neck to reach leaves from tall trees⁸³. The laryngeal nerve in the neck loops down the neck, under the throat and back up the neck because the ancestor of the giraffe had a much shorter neck (or none at all). The seemingly inefficient arrangement is a result of gradual modification of the nerve and artery arrangement over time through evolution rather than a re-engineering to produce an artery arrangement more effective for a long-necked tetrapod (Zimmer, 2009). This example illustrates that evolution is usually linear in nature, though there is genetic drift. Humans have the ability to source inspiration and materials from a wide range of sources, leading to solutions not possible from a simple linear evolutionary approach to design. Humans can design objects, systems or concepts without referring in any way to a previous model or version.

There is a tendency in organisms and ecosystems for mechanisms and materials to be multifunctional and not optimised for one specific function. Hesselberg (2007) uses the example of a spider's web. Its primary function is to catch prey and retain it. It also acts as a communication mechanism and camouflage strategy. These multiple functions mean the web may not be optimised for strength and stickiness, which might be of most interest to human designers. As will be explained in chapter three, multi-functionality is an important and useful trait of organisms or ecosystems to mimic, however there is a need to mimic organisms or ecosystems critically and ensure appropriate adaptation occurs in the translation process to a human context.

2.3.2 THE COMPLEXITY OF NATURE: MISUNDERSTANDINGS

While some organisms have been studied thoroughly and are well understood by biologists, many are not. This has led to some 'bio-mythologically-inspired' design (Pawlyn, page 78). Examples are wall systems developed based on the incorrect idea that polar bear (*Ursus maritimus*) hair is hollow and conducts sunlight through it

⁸³ Not all biologists agree with this hypothesis (Holdrege, 2003).

to the black skin beneath the white fur as a kind of heat gathering adaption⁸⁴ (Pawlyn, page 78), and buildings based on an outdated understanding of how termite mounds work to regulate internal thermal environments (Turner and Soar, 2008). This latter example is explored in more detail in section 2.4.1. This might not be a problem if design based on a misunderstanding of biology still produces more sustainable outcomes (Pawlyn, 2011, page 78).

The complexity of ecosystems and the difficulty in understanding them is an issue, particularly for designers. Critics believe that because humans do not fully understand how ecosystems work as dynamic systems, using them as a basis for design leads to problematic situations. For example, there is the tendency to simplify ecosystems and use the idea of the ecosystem as a metaphor, rather than a quantifiable metric and goal in design and development (Kibert, 2006). This means that built examples may not exhibit the full potential of design based upon a thorough understanding of ecosystems. As Korhonen (2001) points out:

‘One may face the risk of abstracting too much from actual ecosystem operation, which obviously should be the focus point of sustainable development discussion in general...’

2.3.3 IMPROVING UPON NATURE: ‘ARTEFACTUALISATION’

It is not in fact known if ecosystems are always examples of the most effective system as discussed above, and it is important for designers to question the fitness of their models for human contexts. Although Vincent (2010) makes the point that *‘...there is no evidence that any other system [referring to the biological system of the planet] would provide us with the resources we need for survival, at least on Planet Earth’*, this has led Kibert et al. (2002, page 17) to pose the following questions:

⁸⁴ The system referred to consisted of a black painted wall with a layer of transparent insulation and then glass. Controllable louvers were used on the outside to prevent overheating. The whole system proved to be expensive and was not widely adopted (Pawlyn, 2011, page 78).

‘Do natural systems in fact use resources optimally or can technology actually improve on the energy and matter utilisation of Nature, perhaps through observing Nature itself? Are there limits to using the natural system metaphor for industrial systems..?’

Mathews (2011) describes some of the philosophical dangers of the idea of human technology or built form achieving higher levels of environmental performance than previously existing ecosystems in the same place. Biomimicry is part of a larger philosophical movement that calls for humans to learn from and integrate with nature in order to regenerate it, rather than seeing humans as separate from ‘nature’ as has been the case in westernised societies (see section 2.2.4)⁸⁵. Matthews argues that the philosophical separation of humans from the non-made or non-built (i.e. ‘nature’) and the tendency to see the ‘natural’ as something to leave alone and protect as uniquely different from human is problematic. It is argued that for humans to become better at living on the planet without disturbing or destroying ecosystems, the organisms within them, and planetary biochemical cycles, the dualistic idea of nature as separate from human must be challenged. If humans are seen as a part of ecosystems, it could follow that human made items or technologies are ‘natural’. Understanding humans as ‘natural’ would signal a philosophical shift in thinking that could pave the way to societal change in relationship to ecosystems. This does not mean that human activities and products become any less damaging to the biosphere however. It could mean that human activities that harm the natural environment are considered ‘natural’ and therefore acceptable. The argument that humans should integrate more with nature and base technologies on it could also lead to the idea (as exemplified by Kibert’s questions) that if a human made artefact is an expression of nature, nature could be improved upon by human design, so that nature as it exists undisturbed by humans will cease to be something to value (Mathews, 2011). There is a certain anthropocentric arrogance in this that should be examined⁸⁶, and if left to its natural conclusion could result in a completely human made world devoid of ‘nature’.

⁸⁵ Mathews (2011) discusses this and cites other philosophers that explain these distinctions and traces their emergence through time.

⁸⁶ Bensaude-Vincent et al. (2002) discuss this same problem in relation to past aspirations of some chemists.

The issues explored in this section do not mean that human designers cannot learn anything from studying how biology or ecosystems work to become more able to live within them without negative effects, but findings suggest that there is a need both to explore and respect solutions seen in the living world along with tested and successful strategies that humans have devised, and to understand the differences between them. This is important in order to make decisions about what is and is not appropriate in terms of design, so that sustainability is increased, and so that the greater philosophical or ethical implications of biomimicry-for-sustainability are not ignored.

2.4 APPROACHES TO EMPLOYING BIOMIMICRY

Through a comparative literature review, and an examination of existing biomimetic technologies, this section defines distinct approaches to biomimetic design. As part of using a critical theory research methodology, terms for these distinctive approaches have been established. Approaches to biomimicry as a design process typically fall into two categories. The first is termed here: ‘design referencing biology’. This is when a human need or design problem is defined first, and then the ways other organisms or ecosystems solve this is explored. The second approach is termed ‘biology influencing design’. This refers to biomimicry where a particular characteristic, behaviour or function in an organism or ecosystem is identified, and is then translated into a human design context.

2.4.1 DESIGN REFERENCING BIOLOGY

When designers look to organisms or ecosystems for solutions they are first required to identify problems and then to match these problems to organisms that have solved similar issues. Biologists, zoologists, ecologists and related scientists in the field of biomechanics or systems biology are generally the keys to accessing this vast encyclopaedia of biological and ecological knowledge, so design teams may need to be multi-disciplinary⁸⁷. This approach is effectively still led by designers

⁸⁷ Biomimicry research tends to be multidisciplinary in nature. Groups have included collaborations between chemists, physicists, philosophers, engineers, architects, designers, and computer scientists (Fratzl, 2007, Forde, 2006, Hesselberg, 2007). Some of these researchers suggest it is the multi-disciplinary nature of biomimicry
Footnote continued on next page...

identifying initial goals and parameters for the design. Design referencing biology is the most common approach to biomimicry and is favoured particularly by those focusing on medicinal, computer, and robotic applied science, as well as the development of new materials (Hesselberg, 2007).

An industrial design example of this approach is DaimlerChrysler's⁸⁸ 2005 prototype Bionic Car (figure 12). The large volume, small wheel base concept Bionic Car, was based on the hydrodynamic and strength characteristics of the boxfish (*Ostracion meleagris*). This resulted in the design of a more fuel efficient car with the low drag co-efficient of 0.19, and panels with 40% more rigidity than a standard car (Anon., 2005). The chassis and structure of the car were also biomimetic, having been designed using a computer modelling method designed by Claus Mattheck that mimics how trees are able to grow in a way that minimises stress concentrations⁸⁹ (Pawlyn, 2011, page 21, Mattheck, 1998, Mattheck et al., 1996). The resulting car structure looks almost skeletal (figure 12). Total car weight was reduced by at least a third, because material was allocated only to the places where it is most needed (Vincent et al., 2006). This process was abandoned because according to the car manufacturers it was too time intensive (Vincent, 2010).

A possible implication for architectural design when biological analogues are matched with human identified design problems, is that the fundamental approach to solving a given problem omits examining the issue of how buildings relate to each other and the ecosystems they are within. The underlying causes of a non-sustainable built environment are not necessarily addressed when mechanisms and structures found in biology are incorporated into an existing inherently unsustainable engineering or architecture paradigm (Vincent, 2010). This is typical of most current attempts at architectural or engineering biomimicry⁹⁰ (Vincent, 2010) and could be a

research that helps to contribute to innovation, though this is not quantified. Several other examples of multi-disciplinary teams working on innovation based biomimicry are detailed by Vincent et al. (2006).

⁸⁸ The Bionic Car is also referred to as the 'Mercedes Bionic Car' (Pawlyn, 2011, page 5). Mercedes Benz is part of the DaimlerChrysler group.

⁸⁹ Pawlyn (2011, page 23) describes this process and suggests the computer programme could be used in structural building applications.

⁹⁰ For examples of this see Pawlyn (2011).

reason for the lack of measurable improved sustainability outcomes attributable to biomimicry either architecturally or generally.

FIGURE 12 DAIMLERCRYSLER'S BIONIC CAR INSPIRED BY THE BOXFISH AND TREE GROWTH PATTERNS (CAR: PHOTO BY RYAN SOMMA. BOXFISH INSERT: PHOTO BY RICHARD LING).

The Bionic Car (figure 12) again illustrates the point. Compared to a standard non-biomimetic car, it is efficient in terms of fuel use because the body is more aerodynamic due to the mimicking of the box fish. It is also more materially efficient through mimicking tree growth patterns to identify the minimum amount of material needed in the structure of the car. The car itself, however, is not a new approach to transport. Instead, small improvements have been made to existing technology without a re-examination of the idea of the car as an answer to personal transport. It is also no more fuel or materials efficient than ultra-efficient cars designed without employing biomimicry. Because the impression is given that because it looks fish-like, it is somehow more sustainable, the car has been criticised for being an example of biomimicry green-wash (Gebeshuber et al., 2009, Armstrong, 2011).

Another related issue with this approach to biomimicry is that designers are able to research potential biomimetic solutions without an in depth scientific understanding or collaboration with a biologist or ecologist. With a limited scientific understanding translation of such biological knowledge to a human design setting has the potential to remain at a shallow level. It is in some cases easy to mimic forms and certain mechanical aspects of organisms but difficult to mimic other aspects, such as chemical processes, without scientific collaboration (Bensaude-Vincent et al., 2002).

An architectural example of this is Mick Pearce's Eastgate building. This is perhaps the most often cited example of architectural biomimicry (see for example: Koelman, 2004, Zhao and Xu, 2010, Pronk et al., 2008) and is discussed in more depth in section 2.5.2. Turner and Soar (2008) discuss how early examples of architecture based on the mimicking of termite mounds are simplistic and in fact incorrect. In depth scientific analysis since Eastgate was designed has revealed that termite mounds interact with the environment in a much more sophisticated way to regulate temperature than was previously thought (Pawlyn, 2011, page 84). This has led to suggestions that a new generation of 'living' biomimetic buildings could utilise a more accurate understanding of the termite mound as a multipurpose extension of termite physiology more analogous to the function of lungs (Turner and Soar, 2008). This is an example of how architects and designers are able to use a metaphor of how organisms work with a shallow understanding of the actual science behind the mechanism. This demonstrates the importance of working with ecologists and biologists to avoid 'bio-mythologically-inspired' design (Pawlyn, 2011, page 78).

An example of a building which attempts to take advantage of this new understanding of termite mounds (but perhaps does not fully exploit it) is the 2006 Davis Alpine House by Wilkinson Eyre, Dewhurst MacFarlane and Atelier Ten located in Kew Gardens, London, England (Pawlyn, 2011, pages 86-88) (figure 13). The building was designed to avoid energy intensive refrigeration typically needed for the display of alpine plants, and instead uses a stack effect to cool the interior passively, while essentially remaining a glass house with high rates of air circulation (Pawlyn, 2011, pages 87-88). A removable shading sail is included in the design to prevent too much sunlight reaching the plants. The stack effect is enhanced through the high internal space created by the double arches, sequential apex venting as

temperature increases, by vents at the bottom of the glass structure, and through a Barossa termite (*Isoptera* order) inspired decoupled thermal mass labyrinth below the building. The concrete block labyrinth is set between a double concrete slab that also acts to resist the forces exerted by the tension rods that support the glass ceiling (Bellew, 2006). The air that is cooled within the labyrinth is recirculated so it cools the low level plants. The labyrinth is vented at night to take advantage of cooler temperatures. The mass remains at a temperature usually cooler than that required for the space itself.

'The system is arranged so that a small fan can drive the air through the labyrinth tunnels and expel it outside at night, so that the structure is cool in the morning. As the building starts to heat up the outdoor air is directed straight into the glasshouse, via vertical pipes that terminate with directional outlets within the plant beds. As the outdoor temperature continues to rise above 18°C the air is diverted through the labyrinth where it is cooled before passing through the same pipes to cool the plants. This is cooling without refrigeration' (Bellew, 2006).

This form of cooling allows more effective control, and in the way termites open and close vents within mounds to regulate temperature, the 'coolth' can be drawn upon or rejected. The economic payback period calculated for the labyrinth cooling system was nine years (Pawlyn, 2011, page 88).

A similar system has been installed by Atelier Ten in the atrium-like Federation Square space in Melbourne, Australia (figure 14). Mechanical cooling was eliminated⁹¹ and the energy needed to power the system's fan is only 10% of a conventional overhead cooling system. If the atrium is at a comfortable temperature excess 'coolth' is diverted to adjoining museum galleries (Bellew, 2006).

⁹¹ The question of why a building in Melbourne should need active cooling mechanisms could be posed.

FIGURE 13 DAVIS ALPINE HOUSE, LONDON, ENGLAND (PHOTO BY PAUL GALLETTY).

As touched upon, design referencing biology as an approach to biomimicry requires the formation of multidisciplinary teams that include specialist skills in both biology and engineering, or the employment of expert biology or ecology consultancy firms. As databases of biological information relevant to design and engineering contexts are developed, this may change (Hesselberg, 2007, Gebeshuber et al., 2009). At least two such databases, AskNature developed by the Biomimicry Guild and BioTRIZ developed by researchers at the University of Bath, have recently been developed⁹².

⁹² 'AskNature' was developed by the Biomimicry Institute in the United States. This became available online in 2008 and is free to the public. It is a database of biological literature organised by function where users can search for organisms by function (www.asknature.org). The second is a database of 'biological patents' based upon the Russian Theory of Inventive Problem Solving (TRIZ). The development of this was led by researchers Nikolay Bogatyrev, Olga Bogatyreva and Julian Vincent at the University of Bath's Centre for Biomimetic and Natural Technologies (Vincent and Mann, 2002, Craig et al., 2008b, Bogatyreva et al., 2003, Vincent et al., 2005). The BioTRIZ database appears to be available only through BioTRIZ Ltd. formed in 2008 (www.biotriz.com). An example of using BioTRIZ in architectural design to devise a new system for passive radiative cooling of building roofs is detailed by Craig et al. (2008b). Craig et al. (2008a) discuss the same infrared transparent insulation as well as a starch based concrete formwork product also developed using BioTRIZ. A third database was developed in the form of a multi-level biological phenomena database by the Advanced Systems Team of the European Space Agency. This database enables a '*search for biological phenomena according to specified parameters and keywords*' (Gebeshuber et al., 2009). This was accessible online for people with the publicly available correct passwords in 2006 but at the time of this research appears no longer available.

FIGURE 14 FEDERATION SQUARE, MELBOURNE, AUSTRALIA (PHOTO BY: ROBYN FLETT).

Despite some of the disadvantages with this approach to biomimicry, it is the most common (Vincent, 2010). It could form one component of a way to begin transitioning the built environment from an unsustainable to an efficient and effective paradigm (McDonough and Braungart, 2002, pages 68-91). Leading thinkers on regenerative design (Reed, 2007, Cole, 2012a, du Plessis, 2012, Mang and Reed, 2012) argue that a shift from a built environment that ultimately is degenerating ecosystems to one which regenerates will not be a gradual process of improvements but will in fact require a fundamental rethinking of how architectural design is approached however. In this regard, this kind of biomimicry may not help to produce the required shift in thinking unless typical design paradigms are also challenged (Vincent, 2010).

2.4.2 BIOLOGY INFLUENCING DESIGN

When biological knowledge influences human design, the collaborative design process is initially dependent on people having knowledge of relevant biological or ecological research, rather than on determined human design problems. The translation from a biological context can be intentional or accidental (Hesselberg, 2007). The perhaps most well-known example of this kind of accidental biomimicry is the 1948 development of Velcro by Swiss engineer George de Mestral. He was walking his dog and after seeing how burrs stuck to the dog's coat and his clothing he examined them under a microscope. From his observations he developed the hook and loop system now known as Velcro. The study of gecko feet (of the *Gekkonidae* family) is an example of a more intentional study of biology for human application and has led to experiments aiming to create strong dry adhesion tapes that are reusable, referred to as 'Gecko Tape' (Hesselberg, 2007). Several groups of researchers and scientists have tried to mimic the minute fibre structure on the toe pads of the gecko that create van der Waal forces and enable it to walk on and cling to vertical surfaces and the undersides of surfaces (Eadie and Ghosh, 2011, Geim et al., 2003, Maeno, 2009, Konopka, 2008). The examples given in this section are revisited in more detail in section 2.5 to examine their contribution to increasing sustainability.

Similarities between human design solutions and tactics used by other species are surprisingly few considering they exist in the same context and with the same available resources (Vogel, 1998, page 298). Vincent et al. (2006) suggest the overlap is as small as 12%. Although human and natural design strategies are different for sound reasons in many cases (Vogel, 1998, page 291, Bensaude-Vincent et al., 2002), an advantage of this approach is that biology may influence human design in ways that might be outside a predetermined human design problem. This could result in new technologies or systems or even approaches to design solutions. The potential for true shifts in the way humans design exists with such an approach to biomimetic design (Vincent et al., 2005).

A disadvantage from a design point of view is that biological research must be conducted and then identified as being of relevance to a design context. Biologists and ecologists must be able to recognise the potential application of their research to a human context, which may be new. It also relies on good communication networks to disseminate research between disciplines, and for engineers or designers to be able to understand biological research at a basic level, even if it has not been translated into a human design context. The earlier described biological function databases may go some way towards addressing these issues.

An example of biology influencing a design approach to biomimicry is the scientific analysis of the lotus flower (*Nelumbo nucifera*) emerging clean from swampy waters. This led to development of Lotusan paint manufactured by Sto AG, which enables buildings to be self-cleaning (figure 15). By studying the nanostructure of the lotus leaf, scientists observed that due to its rough texture, water is forced to bead on the leaves, which draws dirt from the leaf as the droplets roll off. Lotusan paint, which contains particles, does not look like the lotus in any way, but allows surfaces to be self-cleaning in a way similar to the lotus. This 'lotus effect' has been utilised not only in paint, but in other products such as tiles, plastic food containers, spray on surfaces and stainless steel bathroom fixtures (Baumeister, 2007b). While it can be argued that reducing the need to wash buildings may save water, reduce the need to use toxic cleaning chemicals, and could protect building facades from damage caused by the build-up of surface pollutants, the use of Lotusan paint, while innovative, is unlikely to lead to more sustainable outcomes in the built environment. This example illustrates the need to have a clear sustainability focused intention behind biomimicry to increase the chances of outcomes being more sustainable.

FIGURE 15 THE LOTUS EFFECT (PHOTO BY: RQ1959).

2.5 A FRAMEWORK FOR UNDERSTANDING BIOMIMICRY FOR DESIGN

This section attempts to clarify the various levels and dimensions of biomimicry and propose a framework for understanding its application at different levels. It also attempts to examine biomimicry's potential as a tool to increase the regenerative capacity of the built environment. By defining the kinds of biomimicry that have evolved, this framework may allow built environment designers who wish to employ biomimicry for more sustainable outcomes to identify an effective way to begin by narrowing down the initial parameters of biomimicry type. The framework described here is applicable to both approaches to biomimicry (design looking to biology, and biology influencing design) as described previously. A framework is important because much biomimicry literature presents biomimicry and examples of biomimetic design in a piecemeal and illogical way without a sound description of its different levels and dimensions, and a clearly defined approach to biomimicry useful for designers (Mathews, 2011, Glier et al., 2011, Vincent et al., 2006, Hesselberg, 2007). This, along with the absence of a comprehensive and rigorous general theory

of biomimicry as applied to architectural design processes and their outcomes over building lifecycles is understood to be a barrier in the application of biomimicry generally (Vincent et al., 2006), and perhaps therefore to regenerative design paradigms.

The first part of the framework determines which aspect of 'bio' has been 'mimicked'. This is referred to here as a 'level'. Three kinds of biomimicry that may be applied to a design problem are typically given as '*form, process and ecosystem*' in biomimicry literature (Biomimicry Guild, 2007a). 'Form' and 'process' are aspects of an organism or ecosystem that could be mimicked. 'Ecosystem' however is the entire collection of organisms and their relationships, so these three terms seem to be an illogical way of describing biomimicry. Through an examination of existing biomimetic technologies it is apparent that there are three levels of mimicry; the organism, behaviour and ecosystem. The organism level refers to a specific organism like a plant or animal and may involve mimicking a part of or the whole organism. The second level refers to mimicking behaviour, and may include translating into human design an aspect of organism behaviour, or relationship to a larger context. The third level is the mimicking of whole ecosystems and the common principles that allow them to work successfully, or their actual functions. Within each of these levels, a further five possible 'dimensions' of scale of mimicry exist. The design may be biomimetic in terms of what it looks like (form), what it is made out of (material), how it is made (construction), how it works (process) or what it is able to do (function)⁹³. This more logical and specific way of understanding biomimicry is illustrated in table 4. The differences between each kind of biomimicry are described and exemplified by looking at how different aspects of a termite, or a termite ecosystem, could be mimicked.

⁹³ Glier et al. (2011) suggest a different way of understanding the scales of the organism: cellular, organ, whole organism and behaviour based on common scales used in biology literature. In the framework presented in this thesis, examining the 'process' dimension at the 'organism level' would encapsulate cellular and organ scales of an individual organism. The terms used here relate more closely to terms used by designers of the built environment.

TABLE 4 LEVELS AND DIMENSIONS OF BIOMIMICRY. A FRAMEWORK FOR UNDERSTANDING BIOMIMICRY

Level:	Dimension:	Example: A building that mimics termites.	Potential specific demonstration:
Organism level (Mimicry of a specific organism)	form	The building looks like a termite.	A replica of a termite.
	material	The building is made from the same material as a termite.	A material that mimics termite exoskeleton / skin.
	construction	The building is made in the same way as a termite.	It goes through various growth cycles.
	process	The building works in the same way as an individual termite.	It produces hydrogen efficiently through meta-genomics.
	function	The building functions like a termite in a larger context.	It recycles cellulose waste and creates soil.
Behaviour level (Mimicry of how an organism behaves or relates to its larger context)	form	The building looks as if it was made by termites.	A replica of a termite mound.
	material	The building is made from the same materials that termites builds with.	Using digested fine soil as the primary material.
	construction	The building is made in the same way that termites would construct it.	Piling earth in certain places at relative to sun angles.
	process	The building works in the same way as a termite mound would.	By utilising careful orientation, shape, materials selection and natural ventilation, or it mimics how termites work together.
	function	The building functions in the same way that it would if made by termites.	Internal conditions are regulated to be optimal and thermally stable. It may also function in the same way that a termite mound does in a larger context.
Ecosystem level (Mimicry of an ecosystem)	form	The building looks like a termite ecosystem.	A replica of a termite ecosystem.
	material	The building is made from the same kind of materials that a termite ecosystem is made of.	It uses naturally occurring common components, and water as the primary chemical medium.
	construction	The building is assembled in the same way as a termite ecosystem.	Principles of succession and increasing complexity over time are used.
	process	The building works in the same way as a termite ecosystem.	It captures and converts energy from the sun, and stores water.
	function	The building is able to function in the same way that termite ecosystems do and forms part of a complex system by utilising relationships between processes.	It is able to participate in the hydrological, carbon, and nitrogen cycles in a similar way to an ecosystem and provides ecosystem services.

It is expected that some overlap between different kinds of biomimicry exists and that each kind of biomimicry is not mutually exclusive. For example, a series of interacting elements like an ecosystem would be functioning at the ecosystem level of biomimicry. The individual details of such a system may be based upon a single organism or behaviour mimicry, much as a biological ecosystem is made up of the complex relationships between multitudes of single organisms⁹⁴.

By using a framework as suggested here, it is anticipated that distinctions between the different kinds of biomimicry and their regenerative potential can be made more easily. The examples provided in table 4 demonstrate the deepening levels of biomimicry in terms of regenerative potential from form biomimicry at the organism level to functional biomimicry at the ecosystem level (figure 16).

FIGURE 16 DEEPENING SUSTAINABILITY POTENTIAL OF TYPES OF BIOMIMICRY.

A building that exhibits form biomimicry, which is stylistically or aesthetically based on an organism⁹⁵, but is made and functions in an otherwise conventional way, is

⁹⁴ Although other authors of biomimicry literature do not use this particular framework, the idea that different kinds of biomimicry can overlap is discussed or inferred (Pawlyn 2011, page 58).

unlikely to be more sustainable than a non-biomimetic building. An example is the sheep and dog buildings in Tirau, New Zealand⁹⁶ (figure 17). A building that is able to mimic natural processes and can function like an ecosystem in its creation, use and eventual end of life has greater potential to be part of a regenerative built environment. Both buildings could be termed biomimetic, but the potential for increased sustainability would obviously be quite different.

FIGURE 17 DOG BUILDING, TIRAU, NEW ZEALAND (PHOTO BY: ALLAN HARRIS).

Although this discourse tends to the theoretical at present with many ideas yet to be tested in built form, it is suggested that if biomimicry is conceived as a way to increase the sustainability of an architectural project, mimicking general ecosystem principles should be incorporated into the design at the earliest stage and used as an evaluative check throughout the design process.

⁹⁵ Form biomimicry at the organism level relates more to biomorphic or zoomorphic design (described in section 2.2.3.3). Most explanations of biomimicry will distance biomimicry from biomorphic design (Pawlyn 2011, page 2).

⁹⁶ Tirau's 'Big Dog Information Centre' was constructed by a local craftsman in 1998 (Tirau i-SITE Visitor Centre, 2011).

2.6 BIOMIMICRY AND ARCHITECTURAL DESIGN

'Designers looking to natural systems to discover analogues useful in the design of the built environment have an extremely large field of potential information to absorb. We are only at the beginning of the learning curve, shifting the guiding metaphor in architecture from thinking of buildings as static machines or works of sculpture to conceptualising them as dynamical living systems that are the very nature of Nature' (Van der Ryn and Pena, 2002, page 231).

Specific research into mimicking biology or ecology for architecture is limited but is expanding (Aldersey-Williams, 2004, Altomonte, 2008a, Armstrong, 2009, Berkebile and McLennan, 2004, Birkeland, 2008, Dollens, 2005, Dollens, 2006, Genovese, 2005, Gruber, 2011, Kibert et al., 2002, Kibert, 2006, Pawlyn, 2011). Although recent advances in both biological knowledge and technology have enabled more complicated manifestations of bio-inspired design, meaningful, systematic translation of ecological and biological scientific knowledge into a built environment context remains infrequent (Armstrong, 2009). Examples of biomimicry that have progressed past the concept and development stage are typically of products or materials, rather than buildings or building systems, and tend to mimic an aspect of a single organism. Most architectural biomimicry remains in the realm of the proposed rather than the built and tested (Vincent and Mann, 2002, Faludi, 2005). Discussions about biomimetic architecture typically draw on a few celebrated examples of mimicking termites for increased thermal performance in buildings (by the architect Mick Pearce) and mimicking the ability to use tension as structure like spider webs (by the architect Frei Otto) (Pawlyn, 2011, page 5). Aldersey-Williams (2004) and Pawlyn (2011) do provide several contemporary examples of biomimetic architecture and Aldersey-Williams (2003) details a number of buildings that mimic animals in various ways, although most do not go beyond mimicking form. A number of historic examples of biomimetic architecture and architectural technologies are detailed by Vincent et al. (2006) and Vogel (1998, pages 249-275).

The rest of this section follows the framework described in section 2.4 and presents a selection of brief case studies of biomimetic buildings. It is not the intention to describe every known example of biomimetic architecture, but rather to select a series of documented examples and analyse these for their contribution to sustainability.

2.6.1 ORGANISM LEVEL

Life in various different forms has been evolving for approximately 3.8 billion years (Birkeland, 2009, Pawlyn, 2011, page 1). Existing organisms on Earth have survival mechanisms that have withstood and adapted to constant changes (Spiegelhalter and Arch, 2010). As Baumeister (2007b) points out, *'the research and development has been done'*. Humans therefore have an extensive pool of examples to draw on to solve problems experienced by society that organisms may have already addressed, usually in ways that are energy and materials efficient. This is helpful as more is understood about the consequences of the negative environmental impact that current human activities have on many of the world's ecosystems (Alberti et al., 2003, Rojstaczer et al., 2001, Parmesan, 2006), and as changes in the climate and in access to resources (through reaching peaks of oil, and certain metals and minerals) continue.

Nicholas Grimshaw & Partners' 1993 design for the now unused Waterloo International Terminal demonstrates an example of form and process biomimicry at the organism level using a design referencing biology approach (figure 18). The terminal needed to be able to respond to changes in air pressure as trains enter and depart. The pangolin (*Manis* genus) and the snake (suborder *Serpentes*) do not have to deal with internal air pressure changes, but after determining that a flexible building was needed, the architects studied the scale arrangements of the pangolin and various snakes to understand what makes them flexible. They used this to design the fixing arrangement of the panels of the terminal. The irregular shaped glass panel fixings that make up the structure are designed so that each panel is fixed at only one point. This enables the panels to move and flex by sliding over or away from each other in response to the imposed internal air pressure forces (Aldersey-Williams, 2003, Kirkland, 2002).

Although the approach to dealing with large forces through a flexible skin taken in this building could be argued as a way to reduce materials, this is more accurately an example of technological innovation derived from biology rather than biomimicry specifically for the purposes of increasing sustainability.

FIGURE 18 WATERLOO INTERNATIONAL TERMINAL, LONDON, ENGLAND (PHOTO BY: SOUTHEASTERN STAR) AND THE PANGOLIN (PHOTO BY: GUILLAUME AND PAULINE).

Another architectural example of process biomimicry at the organism level but this time using a biology influencing design approach is the mimicking of the Namib desert beetle (*Stenocara gracilipes*) by Matthew Parkes of KSS Architects / Atlas Industries⁹⁷ with his fog-catcher design for the Hydrological Centre for the University of Namibia (figure 19) (Killeen, 2002). The beetle lives in a desert with negligible rainfall but with short infrequent morning fogs. It is able to capture moisture from the fog that moves swiftly over the desert by tilting its body into the wind. Water condenses on the surface of the beetle's back because its shell is cooler than the surrounding air. Droplets form on the shell, and the alternating hydrophilic, hydrophobic surface of the beetle's back and wings enables the drops to roll down into its mouth (Parker and Lawrence, 2001, Garrod et al., 2007).

⁹⁷ The project was proposed when Parkes was a Masters student at Oxford Brookes University (Killeen, 2002).

FIGURE 19 HYDROLOGICAL CENTER FOR THE UNIVERSITY OF NAMIBIA (SOURCE OF IMAGES: M PARKES) AND THE STENOCARA BEETLE (PHOTO BY: JAMES ANDERSON).

While the building form obviously references the beetle, and the idea of collecting water in the desert comes from the beetle, it is not clear if the design transcends this basic metaphor, or if the fog catcher design is in any way distinct from other non-biomimetic fog catcher concepts (see for example: Suau, 2010). Parkes proposed that a nylon-mesh sail be used to intercept the fog. This mesh would hold the moisture until it began to roll downwards under gravity into an underground storage tank. A seawater desalination process, powered by photovoltaic panels placed on the building's roof is added to the scheme suggesting that the water collected by the fog would need to be supplemented.

If built, the building would be likely to be more sustainable than a standard counterpart because it produces or harvests some of its own water, although opportunities to challenge conventional building strategies or understand the beetle in biological terms appear not to have been taken up. Research conducted in the United Kingdom has shown that surfaces based on the beetle's shell are several times more effective at harvesting fog than typical methods using nets (Trivedi, 2001). Ravilious (2007), Garrod et al. (2007) and Knight (2001) discuss a more specific material biomimicry at the organism level of the same beetle, where its shell surface has been studied and mimicked to be used for other applications such as clearing fog from airport runways and improving dehumidification and distillation equipment. Another Grimshaw project, the proposed Teatro del Agua in the Canary Islands, also mimics the Namib desert beetle but in a different way (section 2.7.2.1).

Mimicking an organism without also mimicking how it is able to participate in and contribute to the larger context of its ecosystem, has the potential to produce designs that remain conventional or even below average in terms of environmental impact (Reap et al., 2005). An example given by Baumeister (2007b) is Velcro. While Velcro mimics how burrs of certain plants attach to animal fur, the product itself is made from petrochemicals and is not typically recycled or recyclable (figure 20), nor does it take into account any of the other principles of ecosystems. Although Velcro is biomimetic, it is not necessarily more sustainable than other fasteners such as zips or buttons.

Because mimicking of organisms tends to be of a specific feature, rather than a whole system, biomimicry could become a technology that is added onto buildings rather than being integral to them (Armstrong, 2009), particularly if designers have little biological knowledge and do not collaborate with biologists or ecologists during the early design stages. While this may result in new and innovative building technologies or materials, methods to increase sustainability are not necessarily explored.

FIGURE 20 ILLUSTRATION OF THE LIFECYCLE OF VELCRO COMPARED TO THE LIFECYCLE OF A BURR.

2.6.2 BEHAVIOUR LEVEL

In behaviour level biomimicry, it is not the organism itself that is mimicked, but its behaviour or strategies for survival. A great number of organisms encounter the same environmental conditions as humans and therefore need to solve similar issues. There are for example, organisms than can build thermally stable habitats, that can harness sun, wind and rain for various purposes, and that can survive extremes of weather. Organisms tend to operate within the environmental carrying capacity of a specific place and within limits of energy and material availability (Reap and Bras, 2008). These limits, as well as pressures that create ecological niche adaptations in ecosystems, mean not only well-adapted organisms continue to evolve, but also the well-adapted organism behaviours and relationship patterns

between organisms or species (Reap et al., 2005). It may be possible to mimic the relationships between organisms or species in a similar way.

Several authors provide examples and details of organisms altering their own habitats while facilitating the presence of other species, increasing nutrient cycling, and creating mutually beneficial relationships between species (Jones et al., 1994, Wright and Jones, 2006, Jones et al., 1997). Organisms that can directly or indirectly control the flow of resources to other species and who may cause changes in biotic or abiotic materials or systems, and therefore habitats, are called 'ecosystem engineers' (Jones and Lawton, 1995, Rosemond and Anderson, 2003). Examples are beavers (*Castor* genus) and woodpeckers (*Picidae* family) (see section 3.5.2.3). The building behaviour of other species is often termed 'animal architecture' and research into this may provide further examples of ecosystem engineers (von Frisch and von Frisch, 1974, Hansell, 2007, Hansell, 2005, Gould, 2007, Turner, 2000, Bontha et al., 2002, Pallasmaa, 1995a, Hersey, 1999, Pallasmaa, 1995b). Humans are undoubtedly effective ecosystem engineers, but may gain valuable insights by looking at how other species change their environments while creating more capacity for life to continue in that system.

An architectural example of process and function biomimicry at the behaviour level is demonstrated by Pearce's Eastgate Building in Harare, Zimbabwe (figure 21). Eastgate was designed to have a relatively thermally stable interior environment with minimal mechanical cooling. This resulted in reductions in energy use of between 17% and 52% compared to similar buildings in Harare (Baird, 2001, Smith, 1997), and therefore also reduced GHG emissions. Pearce based the design in part on principles of induced flow and the use of thermal capacity to regulate temperature observed in termite (*Macrotermes michaelseni*) mounds of southern Africa, although the correctness of the science has been disputed (Turner and Soar, 2008). The temperature regulation in the mounds is achieved through careful orientation, spatial organisation and techniques of passive ventilation. It is not therefore the termite that is mimicked, but the results of its mound building behaviour. Although Eastgate is perhaps the most often cited example of biomimetic architecture, biomimicry at the behaviour level is much less common than biomimicry at the organism level.

FIGURE 21 EASTGATE BUILDING IN HARARE, ZIMBABWE (PHOTO BY: GARY BEMBRIDGE) AND TERMITE MOUND IN AFRICA (PHOTO BY: DAVID SIU).

Behaviour level mimicry requires ethical decisions to be made about the suitability of what is being mimicked for the human context. Not all organisms exhibit behaviours that are suitable for humans to mimic and the danger exists that models of consumption or exploitation could be justified on the basis of how other species behave. For example, mimicking the building behaviour of termites might be appropriate for the creation of passively regulated thermally comfortable buildings, while mimicking the social structure of termite colonies would not be suitable if universal human rights are valued. Without careful consideration it may be more appropriate to mimic specific building and survival behaviours that will increase the sustainability and regenerative capacity of human built environments rather than traits to be applied in the social or economic spheres (Best and Kellner, 1999). In this regard, mimicking whole systems rather than single organisms may be most prudent.

2.6.3 ECOSYSTEM LEVEL

The mimicking of ecosystems is an integral part of biomimicry (Benyus 1997, page 7, Vincent 2007). The term 'ecomimicry' has also been used to describe the mimicking of ecosystems in design (Lourenci et al., 2004, Russell, 2004). Marshall (2007a, 2007b, 2009) uses 'ecomimicry' to mean a sustainable form of biomimicry where the

objective is the wellbeing of ecosystems and people, rather than '*power, prestige or profit*'. Ecomimicry is a kind of biomimicry where flora and fauna of a particular place are studied to find technologies or methods that will fit best to the unique conditions of the site. This is because they are most likely to be optimally suited to a particular place because they have evolved to work within a given set of climatic conditions and local resource constraints (Marshall, 2007b). This is similar to the 'Genius of Place' idea from the Biomimicry Guild where local biology or ecology is studied to find solutions for site specific design challenges (Peters, 2011, Biomimicry Guild, 2011). Other design ideas or strategies related to ecosystems and architecture are discussed in chapter three.

The most important advantage of such an approach to biomimetic design may be the potential positive effects on overall environmental performance. Bio-inspired buildings are likely to have better sustainability outcomes if they mimic the process strategies (how they work) and/or the functions (what they do) of ecosystems, rather than simply the form or material properties of individual organisms (Reap et al., 2005). Ecosystem biomimicry can operate at both a metaphoric level and a functional level. At a metaphoric level, general ecosystem processes (based on how most ecosystems work) are able to be applied by designers with little ecological knowledge. If the built environment were designed to be a system and expected to behave like an ecosystem, even if only at the level of metaphor, its environmental performance might increase, even if only certain aspects were mimicked, such as the fact that ecosystems adapt and evolve, and create conditions conducive to ongoing life (Korhonen, 2001, Kibert et al., 2002, page 16). Process level ecosystem biomimicry is explored more thoroughly in chapter three.

The danger exists that simplified lists of how ecosystems work can be misunderstood by designers and fail to address the problems of the built environment, leading to small gradual improvements in sustainability outcomes rather than paradigm shifts (Mathews, 2011). Although some noteworthy and environmentally successful projects (section 2.7.2.2) use an understanding of how ecosystems work, many focus simply on the waste cycling aspects of ecosystems and miss investigating some of the other lessons that ecosystems afford (Allenby and Cooper, 1994).

Function biomimicry at the ecosystem level could mean that an in-depth understanding of ecology drives the design of a built environment so that it is able to participate in the major biogeochemical material cycles of the planet (hydrological, carbon, nitrogen) in a reinforcing rather than damaging way. If the living world is to give designers insights into architectural design that improves the sustainability of the built environment, buildings should be considered as parts of a living system and an understanding of ecosystems could be used to set goals for a project, drive design solutions, and evaluate successes or failures of the design. Function level ecosystem biomimicry is explored in more depth in chapters four and five.

Architectural or urban design that mimics entire ecosystems at present tends to be in the realm of the theoretical. Mithūn Architects and GreenWorks Landscape Architecture Consultants' proposed Lloyd Crossing project for Portland, Oregon displays aspects of an approach that employs function biomimicry at an ecosystem level (figure 22). The project began with a detailed study of how the ecosystem had functioned on the site before development, termed by them 'Pre-development Metrics'. This was used to set goals for the ecological performance of the project over a 46 year time span and gave them a proven

FIGURE 22 LLOYD CROSSING PROJECT, PORTLAND, USA (SOURCE MITHŪN).

working model of a system that had worked in a highly refined and successful way on the same site (Portland Development Commission, 2004).

The stated goals of the project included: preserving urban density; achieving carbon balance; achieving a water neutral development; and living within the site's solar budget, for its energy production and use. The ecosystem analysis proved it was possible to meet such goals at that location and also provided a successful example to emulate in achieving the goals. Projected benefits include: increased local biodiversity; reduction of the heat island effect; reduced demand for new potable and waste water systems; increased quality of public infrastructure; and increased local renewable energy generation including 10MW of photovoltaic and 1.4MW of wind turbine capacity making it a net energy producer (Portland Development Commission, 2004).

Assuming that the project is built, and that built performance is close to predicted levels, this project illustrates that an advantage of an ecosystem based biomimetic design approach is that it is applicable to a range of temporal and spatial scales (Reap et al., 2005) and can serve as an initial benchmark for what constitutes sustainable or even regenerative design for a specific place. A further advantage of designing at this level of biomimicry may be that it can be used in conjunction with other levels of biomimicry (organism and behaviour). It may also be possible to incorporate existing established sustainable building technologies or methods that are not specifically biomimetic, such as bio-assisted systems (section 2.2.3.4), where human and non-human systems are merged to the mutual benefit of both (Pawlyn, 2011, page 2). At the time of writing this thesis, the absence of regenerative developments using an understanding of ecosystems as their basis that have been built, tested and measured for their ecological performance over time means additional benefits or drawbacks have not been ascertained⁹⁸.

⁹⁸ See Issue 1 of Volume 40 Building Research and Information Journal (Special Issue on Regenerative Design) particularly Hoxie et al. (2012) and Mang and Reed (2012) for brief details of some projects that claim to be regenerative. Ruthen (2012) discusses the recently completed Centre for Interactive Research on Sustainability, at the University of British Columbia, Vancouver, Canada.

2.7 CAN OR DOES BIOMIMICRY ADDRESS CLIMATE CHANGE IN THE BUILT ENVIRONMENT?

As professionals of the built environment need to solve more urgent and difficult problems related to mitigating and adapting to climate change, it may be useful to examine examples of how the same problems have been solved by other living organisms or ecosystems. If not providing full and easily transferable solutions this may provide new areas of exploration (Altomonte, 2008a). Looking to plants or animals that are highly adaptable or ones that survive in extreme climates or through climatic changes may provide insights into how buildings can or should function. Examining the qualities of ecosystems that enable them to be resilient may also offer potential avenues to follow (see section 3.6).

2.7.1 MITIGATING GREENHOUSE GAS EMISSIONS FROM THE BUILT ENVIRONMENT

Several contemporary examples of biomimetic architecture or technologies that can assist the built environment in climate change issues will be examined to ascertain whether biomimicry can be used to address climate change, and if so in what way. As discussed in chapter one, common mitigation strategies in a built environment context include: increasing the density and limiting sprawl of urban form to reduce building energy use and emissions from vehicles⁹⁹; creating or maintaining urban forest and green space; design for energy conservation; provision of renewable energy sources; and carbon storage or sequestration. The first two strategies relate to urban planning and represent long term climate change adaptation strategies. This section, therefore, will deal with the latter three, and most common (Steemers, 2003b), categories.

The first category examined is biomimetic examples that mimic the energy efficiency or effectiveness of living organisms and systems. The impetus is that by being more

⁹⁹ Although this is a common mitigation strategy in the context of the built environment (Reisinger et al. 2011) it is not necessarily advocated as a suitable solution in the context of this thesis. There is growing evidence that increasing the density of cities may not contribute to mitigating the causes of climate change and that it negatively affects several other environmental performance aspects of cities, such as flood risk, storm water issues, habitat provision and building energy efficiency, and energy generation potentials (section 1.3.2.1).

energy efficient, less fossil fuel is burnt and therefore fewer GHGs are emitted. The second approach is to devise new ways of producing energy to reduce human dependence on fossil fuels, and their associated GHGs. Various biomimetic technologies and products have been developed for the purposes of improving energy efficiency and exploring new energy generation possibilities. A third biomimetic approach to mitigating GHG emissions is investigating organisms or ecosystems for examples of processes within them that can sequester and store carbon. This is to prevent emission of GHGs through human activities causing additional climate change. Examples are investigated in the following sections.

2.7.1.1 BIOMIMICRY FOR ENERGY EFFICIENCY

There are numerous examples of living organisms and systems that are highly energy effective and that may yield an understanding of how humans could carry out their activities without a dependence on fossil fuels (Allen, 2010, page 169, Pawlyn, pages 91-101). Some well-known examples of biomimicry fit into this category, such as DaimlerChrysler's Bionic car (2005) and the Eastgate building in Harare, Zimbabwe (1996), as discussed earlier. Though both examples make contributions to energy efficiency it is doubtful that they are more energy efficient than comparable counterparts with similar energy efficiency results

FIGURE 23 EVAPORATIVE COOLING IN TERMITE MOUNDS (SOURCE: BELLEW, 2006).

achieved without the use of biomimicry.

In the 2006 Council House 2 (CH2) in Melbourne with which Pearce was involved, 100 000 litres of water is extracted and cleaned from the sewers beneath the building and used to condition the air. This is reminiscent of how certain termite species use the proximity of aquifer water as an evaporative cooling mechanism. African Barossa termites (*Isoptera* order) make tunnels tens of metres deep to reach the water table, so that its cooling effect can be used in extreme heat to keep the mound within a one degree temperature fluctuation range (Bellew, 2006) (figure 23).

In CH2 (figure 24) some of the cleaned water is passed through shower towers on the outside of the building. This cools the water, particularly at night. The water passing through the shower towers also cools surrounding air which is then used to ventilate the commercial premises on the ground floor. The water continues to the basement where it passes through a system that stores the 'coolth' by using phase change materials. The water is then used in a closed loop in chilled beams that provide cooling to the building interior.

FIGURE 24 CH2 BUILDING, MELBOURNE, AUSTRALIA
(PHOTO BY: WOJTEK GURAK).

In combination with the effects of additional sustainability features¹⁰⁰, CH2 is reported to use 85% less energy, reduce GHG emissions by 87%, and use 70% less water than typical comparable buildings (Tan, 2007, Jones, 2008), although these estimates have not been verified. CH2 is a 6 star Australian Green Star building. It was built at a cost premium of 22.1% (Aranda-Mena et al., 2008), but due to productivity increases of 10.9% from staff attributed to the new building (Paevere et al., 2008, Paevere and Brown, 2008), as well as substantial energy savings, pay back was between 5 and 7 years (Bond, 2010). These results suggest that the building is successful and performs better than conventional buildings.

FIGURE 25 60L, MELBOURNE, AUSTRALIA (PHOTO SOURCE: SPOWERS ARCHITECTS).

Other Australian buildings achieve similar or better results and are not biomimetic, however, such as the 2009 The Gauge by Land Lease (by architect Darren Kindrachuk), also a 6 Green Star building in Melbourne. This claims to recycle 92% of its water onsite, and to produce 25% of its own energy. The 2008 Workplace6 (Sydney, also 6 Green Star rated by architects Nettleton Tribe)

reports 90% water savings, 70% reduction in carbon footprint, and 45% energy savings (Bond, 2010)¹⁰¹. Even Melbourne's 60 Leicester St (60L), built in 1870 and retrofitted using non-biomimetic strategies and technologies in 2002 by Spowers Architects (figure 25), was estimated to use a third of the energy (Bond 2010)¹⁰²,

¹⁰⁰ The building generates much of its own energy through wind turbines, photovoltaic panels and co-generation (Tan 2007, and Melbourne City Council at: <http://www.melbourne.vic.gov.au/info.cfm?top=171&pg=1943>).

¹⁰¹ Both The Gauge and Workplace6 hold two 6 Green Star ratings, one based on the design and one 'as built'. This means estimations of performance given above are based on the building after construction, not just on the design. Values however are still based on simulations rather than measured performance. Bond (2010) discusses some of the issues between estimations given by simulations and actual measured performance that can lead to quite different results. Performance estimates given above should therefore be treated with caution.

¹⁰² 60L does not have a green building rating. The performance estimates above are based upon simulations. Verified measured results were not available.

produce 66% fewer carbon emissions¹⁰³, and use 90% less mains water than comparable conventional buildings (Australian Conservation Foundation, 2004). Nine years after the retrofit, actual performance results showed that the building was less successful in terms of environmental impact than what the designers had envisaged, however the building was reported to use approximately a third of the energy use of similar conventional buildings, and 95% less mains water (Anon., 2011). The black water recycling system was difficult to run and was discontinued in 2011.

Improving general energy efficiency is an important part of addressing climate change, but should be regarded as an intermediate step (McDonough and Braungart, 2002, page 62). Improving efficiencies helps to reduce the intensity of GHG emissions but does not challenge assumptions about how and why technologies are made and used. Nor does it address the underlying causes of climate change such as dependence on fossil fuels. Other researchers also detail increased rather than decreased energy use as a result of energy efficiency initiatives. This is referred to as 'Jevons Paradox' (Jevons, 1865). Simplistically, as efficiencies increase, the price of a technology goes down often resulting in a net increase in consumption (Turner, 2008). Improving energy efficiencies does allow positive incremental changes to be made to existing technologies and buildings rather than assuming the only way forward is a complete rebuild of the built environment (which is not possible). Energy efficiency could, therefore, be important in the short term for the built environment becoming better able to address climate change.

2.7.1.2 BIOMIMETIC ENERGY GENERATION FOR MITIGATING THE CAUSES OF CLIMATE CHANGE

Several biomimetic technologies or systems aim to replace the use of fossil fuels as the primary human energy source. Looking to the living world for inspiration is appropriate in this regard, because almost all organisms source energy from renewable sources, which predominantly is directly or indirectly from contemporary

¹⁰³ The estimates of reduced GHG emissions are based on modelling rather than measured performance. Estimated GHG emissions are offset through offsite tree planting in Western Australia (Australian Conservation Foundation, c. 2004) but the time periods are unclear.

sunlight¹⁰⁴ (Kibert et al., 2002, page xxiv). Examples of biomimetic systems for development of alternative energy sources include mimicking the process of artificial photosynthesis in solar energy cell technology (Moore et al., 2004, Collis et al., 2005, Davidson, 2003. See also the work of the Australian Artificial Photosynthesis Network (AAPN)), microbial fuel cells generated from electron donors in waste water, biomass conversion systems, radiosynthesis¹⁰⁵ based systems (Gebeschuber et al., 2009), and the development of ocean energy technologies that mimic how sea kelp (*Laminariales* order) or certain fish move efficiently in water (Allen, 2006). The Australian company BioPower has, for example, developed under water power generators called BioWAVE that oscillate in ocean waves and currents rather than rotate like turbines (figure 26). Baker (2011) says of the technology:

'The BioWave system sits on the floor of the ocean with three buoyant blades extending from the base. These buoyant blades, which can reach heights of 25 meters and 19.5 meters wide (for all three blades combined), sway back and forth with the motion of the waves. These blades reach almost to the top of the water where the flow of the water is most powerful. The motion of the blades drives an on-board generator to produce electricity, which is then transported from the system to the shore through cables on the seabed.'

Through the use of permanent magnet motors, the low-speed high-torque oscillation is converted into high-speed low-torque rotation. Units are anchored to the ocean floor by the use of a series of small root-like devices to avoid extensive, damaging and complicated drilling and installation. The generators rotate freely to orient themselves towards currents and in the same way can lie flat in storm events to avoid damage (BioPower Systems, 2011, Finnigan and Caska, 2006). The units are

¹⁰⁴ There are chemosynthetic communities of animals and bacteria living on the ocean floor that are sustained by chemical nutrients in the form of dissolved gases rather than directly or indirectly by photosynthesis. These communities occur in a variety of deep ocean environments including methane and oil gas rich areas called cold seeps, or near hot hydrothermal vents (Barry, 2006, Sassen et al., 1999). These communities do not source energy from contemporary sunlight, living as they do in the aphotic (no light) zone of the oceans. They are indirectly powered by ancient sunlight. It should be noted that these non-photosynthesis communities may have evolved before or at the same time as photosynthesis communities (Xiong and Bauer, 2002), so some may not be reliant on ancient photosynthesis, particularly the sulphur based thermal vent deep ocean ecosystems. The vast majority of ecosystems and organisms on Earth are however directly dependant on contemporary sunlight to sustain food webs.

¹⁰⁵ Radiosynthesis refers to the process of melanin in micro-organisms capturing high-energy electromagnetic radiation to generate metabolic energy (Gebeschuber et al., 2009).

made from lightweight, non-corrosive, durable composite materials. They are more lightweight than comparable wave power systems and possibly more material and cost effective (Baker, 2011). A 250kW four year grid-connected pilot study of the technology, funded in part by the Victorian Government in Australia, will be conducted in 2012 near Port Fairy. BioPower state they have independent verification of the viability of their systems but as yet there are no results available (see however: Gonzalez et al., 2009 for a technical report of BioWave testing). Once in operation the energy generated is claimed to be cost competitive with that from typical wind farms (BioPower Systems, 2011). BioPower has also developed tidal power conversion systems based on the efficient propulsion mechanisms (termed 'thunniform motion') of species such as shark (*Elasmobranchii* subclass), tuna, and mackerel (both in the *Scombridae* family) called BioSTREAM (Gebeshuber et al., 2009).

FIGURE 26 IMAGE OF BIOWAVE UNIT (SOURCE: BIOPOWER SYSTEMS 2011).

Finding methods to replace fossil fuels with renewable energy sources is a long term solution to climate change (Atkinson, 2007a). This is potentially problematic given the time available to find alternatives to the use of fossil fuel before more irreversible damage is done to the climate (Turner, 2008). Due to the economic and social impacts of climate change (Stern, 2006, Howden-Chapman et al., 2010) it is possible

that resources to research and develop alternatives to fossil fuels will become more scarce (Mitchell, 2012). It should also be remembered that despite new developments in energy generation technologies, the uptake of such technologies is hindered because industrialised countries still tend to subsidise fossil fuels, hampering research into renewable energy alternatives. One study estimated that the subsidy is as high as \$US200 billion per year (Gebeschuber et al., 2009).

While reducing or ceasing to use fossil fuels as an energy source would prevent creation and release of additional GHG emissions, biomimicry has also been investigated to find ways to remove excess CO₂ already in the atmosphere.

2.7.1.3 BIOMIMETIC SEQUESTERING AND STORING OF CARBON

There are several organisms and processes in nature that are able to store, sequester or recycle carbon. Understanding how they do this could be used in the development of technologies for industrial processes and the built environment.

In Quebec, CO₂ Solutions is developing carbon sequestration technology which mimics certain chemical processes that occur in the bodies of mammals (Geers and Gros, 2000). The technology mimics the enzyme carbonic anhydrase which is able to convert CO₂ into bicarbonates. This enzyme enables mammals to manage CO₂ during respiration. The process works at atmospheric pressure and ambient temperatures (Fradette, 2007). It generates bicarbonate which can be used to neutralise certain industrial wastes, store CO₂, or can be transformed into carbonate compounds such as limestone to be used in processes in cement works or paper mills. The aqueous solution, where the conversion of CO₂ to bicarbonate occurs, is reused in a closed loop (figure 27). The technology can be retrofitted on to existing facilities such as power plants, cement works, aluminium smelters and oil sands operations, or integrated into new ones (Atkinson, 2007b, CO₂ Solution, 2008).

The process is more energy effective, and therefore cost effective, than conventional carbon capture technology that use monoethanolamine, with energy savings in the order of 30% (Carley, 2012). The enzymes used allow the use of different solvents (such as tertiary amines, carbonates and amino acids) that are also less toxic,

corrosive and volatile than those used in similar non-biomimetic systems. For example this system does not result in the emission of the known carcinogen nitrosamine which is the case in systems that use piperazine (a chemical promoter used to accelerate CO₂ absorption) (Carley, 2012).

FIGURE 27 CO₂ SOLUTIONS PROCESS DIAGRAM (SOURCE: CO₂ SOLUTIONS).

Initial testing on an Alcoa aluminium smelter in Deschambault, Quebec indicated removal of 80% of CO₂ that would otherwise have been emitted into the atmosphere (Hamilton, 2007). The CO₂ emissions are combined with waste bauxite residue, which is difficult to manage and potentially dangerous, to neutralise it and create a product that has secondary uses and revenue generating potential (Carley, 2012). A larger pilot project on a power plant (for a company wishing to keep the project confidential) was conducted in 2011. CO₂ Solutions reported positive but as yet unquantified and unpublished results. Discussions of pilot projects in cement works and with major oil producers in Alberta are underway to tailor the technology to these sectors (Carley, 2012).

FIGURE 28 CALERA CARBON SEQUESTRATION PROCESS (SOURCE OF IMAGE: CALERA).

A similar example of biomimetic carbon sequestration technology can be found in Stanford University research. Brent Constantz¹⁰⁶ investigated how coral (*Anthozoa* class) creates its hard aragonite exoskeleton of calcium and magnesium carbonate and bicarbonate minerals by using minerals, sea water and CO₂. Based on his discovery of how calcite and aragonite (polymorphs of calcium carbonate) are nucleated by the marine organisms and subsequent replication of that in a laboratory, in 2007 he formed the company Calera. Calera is developing technology that sequesters carbon from industrial flue gas emissions, adds it to brine wastewater, sea water, manufactured alkaline solutions, or brines extracted from geological deposits, and from this process converts the gas first to carbonic acid, and then to stable solid minerals (figure 28). These materials are used to produce high reactive cements that do not require the calcining of the carbonate typically required to produce conventional Portland cement. The resulting Calera cement process results in fewer CO₂ emissions than conventional cement production (Calera, 2012).

¹⁰⁶ Constantz also developed a biomineralisation process in the 1990s that is now used extensively in a medical context to grow artificial bone to repair fractures (Constantz et al. (1995).

The technology has been applied at a demonstration level to California's Moss Landing gas fired electricity power plant in the Monterey Bay area. Here seawater is used, along with 92% of the plant's 3.5 million tonnes of annual CO₂ emissions and some of the waste heat and fly ash from the flue to create cement (Lovins and Cohen, 2011, page 285). Further independent analysis of the Calera process confirms that up to 90% of carbon emissions could be captured if the system was applied to other suitable plants (Andersen et al., 2011). The same report from the Institute for Governance and Sustainable Development states:

'The advantage of the Calera process relative to other proposed CCS [carbon capture and storage systems] is that: it is available near-term at a lower estimated cost, it is [a] modular retrofit to existing power plants making it scalable, and it has the potential to capture carbon while producing a useful product'.

Every tonne of cement made in the process sequesters between 0.5 and 1.0 tonnes of CO₂. This supposedly eliminates additional carbon emissions caused by producing and transporting cement (Lovins and Cohen, 2011, page 285, Nidumolu et al., 2009, Andersen et al., 2011). The seawater used in the process is not polluted and can be returned to the ocean or used as pre-treated water to make drinking water through desalinisation because the hardness is removed (McKeag, 2010). Trace metals in emissions are also removed during the process and mercury is captured and converted into a non-leachable form (Calera, 2012). Calera has developed several new processes to enable their system to work, one of which is a process to create the alkaline solution needed for the electrochemical part of the system. This uses one third to one fifth of the energy of comparable state of the art practices. Testing began in 2011 on the suitability of the products of the Calera process for building and construction processes¹⁰⁷ and cement based products have been used in several demonstration projects. Non-structural applications (foot paths, tiles) are likely to be end uses for the cement (Calera, 2012).

¹⁰⁷ Compressive strength data is available on the Calera website: <http://calera.com/> (accessed June 2012).

The company has considered using a completely different business model to other cement producers in that it would give away cement to customers while charging polluters a fee for removing their emissions (Nidumolu et al., 2009). Some criticism of the science behind Calera's process and the suitability of the resulting cement can be found online but in un-citeable blog postings¹⁰⁸.

A final example of efforts to increase the sequestration of carbon using biomimicry is illustrated by research conducted by Dr Jeffrey Brinker at the Sandia National Laboratories in the United States, investigating how the abalone or paua (*Haliotis* genus) is able to grow a crack resistant shell approximately 200% harder than human ceramics using only seawater and a series of proteins (Brinker et al., 1999). The research could lead to lightweight, extremely strong, optically clear building materials (Sellinger et al., 1998) or to alternatives to concrete. Cement production accounts for approximately 5% of the world's anthropogenic CO₂ emissions (Vanderley, 2003). This process of bio-mineralisation stores carbon much like the growing of forests locks carbon into the structure of the trees and soil until released. The concept of a new material able to grow through self-assembly over a structure, with the simple additive of seawater, by activating proteins on the structure imitated from the abalone has been investigated, but results are not available (Koelman, 2004). Biomimetic biomineralisation is also discussed by Vincent (2010) and Armstrong (2009).

The utilisation of detritus, or waste, is an important part of the process of cycling nutrients and is a fundamental part of maintaining the health of an ecosystem (section 3.5.3.6 and 3.5.4.6). In using biomimicry to address excess carbon in the atmosphere it may be possible to use carbon as a resource rather than it being a source of pollution or waste. The obvious example from biology is how plants utilise CO₂ during the photosynthesis process, converting it into the products needed for plant growth and development, such as cellulose. For plants, CO₂ in the correct quantities is a necessary resource, rather than a pollutant.

¹⁰⁸ See: <http://www.hcn.org/issues/42.7/skeptical-of-calera> (accessed June 2012).

A company formed out of research by Dr Geoff Coates at Cornell University called Novomer is mimicking this aspect of carbon sequestration in plants, by using CO₂, mostly captured as factory emissions, as a resource for new carbon-based polymers (McKeough, 2009) (figure 29). The resulting plastics are 50% to 65% transformed CO₂ by weight and could be used as coatings for building materials or foam insulation (Fister Gale, 2008, McKeough, 2009). The zinc-based¹⁰⁹ catalyst that is needed for the process works at ambient temperature and low pressure (150psi), and the process is therefore less energy intensive and expensive than conventional bio-plastics production (Greenemeier, 2007). The use of CO₂ and carbon monoxide (CO) as feed-stocks, rather than corn or starch as in bio-plastics, means the carbon-based plastic does not compete with food production, and both captures and stores carbon, while reducing demand on oil reserves (if the result is less production of conventional oil based plastics). On-going research suggests that the stored carbon in the carbon-based plastic is released upon decomposition, although depending on the exact nature of the feedstock and catalyst, the biodegradability of the carbon-based polymers can be varied to enable longer term carbon storage (Patel-Predd, 2007a, Gerngross and Slater, 2003).

FIGURE 29 NOVOMER PLASTICS (SOURCE OF IMAGE: NOVOMER).

In recent advances within Novomer, acrylic acid, acrylate esters, butanediol and succinic anhydride have been synthesised cost competitively from bio-based feedstocks using existing technology. These materials can be combined with

¹⁰⁹ Some sources report that the catalyst is cobalt based (Novomer (2010)).

Novomer's catalyst to make materials and chemicals with a potentially negative carbon footprint, with the suggestion that such a process could lead to plastics which sequester CO₂ over the product lifecycle, while being 30% cheaper than conventional plastics to manufacture (Novomer, 2010).

An issue with this approach to addressing climate change impacts is that sequestering carbon does not examine or solve the problem of excessive burning of fossil fuels. Nor does it take into account the depletion of oil reserves. Rather, sequestration is another interim step in the development of a more sustainable human society and economy, possibly creating time to develop technology which does not just pollute less, but instead does not pollute at all. There are several additional logistical, economic, technological, and environmental problems with current attempts at carbon sequestration (Schiermeier, 2006). Technologies that allow polluting practices to continue for longer, even if at decreased rates, may distract people from the necessary task of re-organising human industry, and with it consumption at a fundamental level, and may instead perpetuate a 'business as usual' paradigm that could make the eventual highly probable collapse of such systems more difficult for people. It is likely that transitions to non-polluting and non-fossil fuel based ways of making energy and products, including buildings, would be easier and less disruptive ecologically and economically if done before there was no other option due to ecosystem collapse or the end of cheap fossil fuels. If such a scenario is allowed to occur, it is possible that the impacts would be so great, that transition may not be possible (Turner, 2008). The benefit of using biomimicry as a means to capture or sequester carbon, however, is that such techniques may help to retrofit and adapt existing building infrastructure, while addressing GHG emissions in the short to medium term.

Several of the examples of a biomimetic approach to carbon sequestration or storage discussed here reveal that useful secondary products related to a built environment context can be made from wastes without toxic by-products and without using high amounts of energy. There may also be important restorative capacity in lowering the amount of atmospheric carbon by using CO₂ as a feedstock for new materials. As discussed earlier, the built environment uses approximately 40% of the materials consumed by the global economy (Rees, 1999). Building materials that

store carbon long term, or that are made from CO₂ and do not release all this upon biodegradation, and are durable and safe, could make a contribution to mitigating climate change or even lowering levels of atmospheric carbon over the long term, if combined with other initiatives. It should be remembered that most of the built environment that will exist for the next 90 years (in New Zealand at least) has already been built, so there is a limit to how much of an impact new kinds of materials can make within a timeframe that would allow the built environment to address GHG emissions before the impacts of climate change prevent large amounts of additional building.

2.7.2 BIOMIMETIC STRATEGIES FOR ADAPTATION TO CLIMATE CHANGE IN THE BUILT ENVIRONMENT

There are several examples of biomimicry being employed as a strategy that professionals of the built environment can harness to adapt buildings to climate change. The first and most common category of examples are those that respond to anticipated direct impacts of climate change on the built environment (see table 1). The second is a more comprehensive approach to altering the built environment so it becomes more adaptable and resilient as a whole system.

2.7.2.1 RESPONDING TO DIRECT IMPACTS OF CLIMATE CHANGE

The living world is made up of numerous organisms that effectively solve the same problems that the built environment will face as climate change continues. While the potential impacts of climate change are numerous and dependent on local conditions, the list of organisms and ecosystems that manage similar issues effectively is also long. There are approximately 1.8 million species on the planet that have been described and categorised. Estimates of the total number of species range from 2 to 100 million, with a 'best guess' of 14 million (Purvis and Hector, 2000). There are many organisms and ecosystems that manage frequent overheating, high winds, and erosion. Organisms may be specifically tailored to these conditions because they are part of their habitat niche. Other organisms demonstrate strategies to adapt to changes on a temporary basis that could be

useful for humans to study, while others adapt over the longer term or over generations, through the processes of evolution.

Several architectural biomimicry projects respond to direct impacts of climate change. The architecture discussed here may form a suitable response to changes in precipitation patterns and projected water shortages for example.

Grimshaw Architects in collaboration with Charles Paton of Seawater Greenhouse have taken an understanding of the Namib desert beetle and proposed a unique desalination process that will form part of a large outdoor theatre called Teatro

FIGURE 30 TEATRO DEL AGUA (SOURCE OF IMAGE: GRIMSHAW ARCHITECTS).

del Agua on the Canary Islands (figure 30). The Teatro del Agua mimics aspects of the beetle (see section 2.6.1) by passing seawater over a series of evaporative grilles. As the sea breeze moves through these grilles, some of the water evaporates leaving salt behind. The moist air then continues until it hits pipes holding cool seawater, pumped up from the nearby ocean. As the warm moist air touches the cool pipes, condensation forms and clean fresh water trickles down the outside of the pipes and is collected. The seawater pumps are powered by wind turbines using the same uni-directional sea breeze. The building is projected to be self-sufficient in water with surplus being transferred to neighbouring buildings and landscapes (Pawlyn, 2011, page 70).

A more established example of bio-mineralisation than that described in section 2.7.1.3 that could relate to climate change adaptation and may have application to the building industry is called Biorock. Biorock was developed by marine biologist

Thomas Goreau and engineer Wolf Hilbertz in the 1970s to restore coral reefs (Pawlyn 2011, page 50) (figure 31). Frames of steel are placed on to ocean floors, and low voltage current that is not harmful to marine life is passed through the frames. This encourages minerals dissolved in the seawater to crystallise. A layer of minerals appears on the frames within a few days upon which coral can be attached. Accretion rates are up to 50mm per year with a load bearing strength of between 24 and 80MPa (concrete's compressive strength is typically between 17 and 28MPa) (Goreau, 2010, Pawlyn, 2011, page 50). The

FIGURE 31 BIOROCK STRUCTURE AT PEMUTERAN BAY, BALI, INDONESIA (PHOTOS BY: RANI MORROW-EUIGK).

process continues for as long as the current moves through the metal substrate. The resulting material has self-repairing characteristics. The exact makeup of the material is dependent on the type of seawater it grows from.

The original intent of the technology was to develop low cost structures on land (Pawlyn, 2011, page 50). Suggestions have been made that integrating Biorock with off shore wind turbines or ocean energy power generators by diverting small currents to foundations could be used to regenerate surrounding marine ecosystems (Pawlyn 2011, page 50). The physical presence of the frames, the low voltage currents, and an environment suitable for coral attract other marine life, and over time diverse ecosystems mature. Coral and oysters grow three to five times faster on Biorock and have a survival rate in higher ocean temperatures caused by climate change of 16-50 times higher than background rates (Goreau, 2005). Biorock has been used since

1975 in at least 20 countries (Goreau, 2010). This is an example of a biomimetic technology focused on adapting to climate change, and reducing biodiversity loss that is regenerative of ecosystem health. Goreau (2005) points out that:

‘Large-scale application of Biorock reef restoration technology may offer... long-term hopes for coral reefs, [because changes caused by] global warming, pollution, and new diseases are now beyond control... Biorock reefs not only keep corals alive where they would die, they allow us to grow reefs where natural recovery is impossible...’

Responses to the direct impacts of climate change have a number of benefits and associated difficulties. They are helpful for a gradual response to the impacts of climate change, particularly if the financial resources needed to research, develop and test technologies continue to be available. They require accurate knowledge of what the impacts of climate change will be for a given site over time, which is difficult to predict accurately in many cases. A benefit of this approach is that technologies and architectural responses to direct impacts may be transferable to other places with similar issues. The biomimetic system based on the Namib beetle described above may be useful for small island communities or coastal areas that have difficulties sourcing fresh water, exacerbated by climate change. An additional benefit of the process of developing technological solutions for individual buildings is that it fits into the current method of extending and renewing the built environment, which is typically a building by building or addition by addition process over time (Brand, 1994). This means it may be suitable for a gradual retrofitting of the existing built environment.

Developing individual technologies or even whole buildings to deal with the myriad of direct climate change impacts on the built environment does not however ready the built environment for unpredicted changes or indirect climate change impacts (table 2). Focusing solely on adapting the built environment to the direct impacts of climate change also does not address multiple concurrent impacts. The challenge of other related drivers of change is also not tackled, which may in the long run be of greater consequence to the built environment and to humanity as a whole (Atkinson, 2007a). Understanding local built environments as whole systems in terms of their strengths

and weaknesses and utilising these to create greater resilience may be a more effective way to plan for unpredictable future climatic changes.

2.7.2.2 SYSTEMIC IMPROVEMENT OF THE BUILT ENVIRONMENT

Ecosystems are typically resilient and many are able to move through infrequent abrupt changes while still supporting the survival of organisms (Gunderson and Holling, 2002). The ability of ecosystems to adapt to the rapid changes that may come about due to climate change is difficult to predict (Parmesan, 2006, Walther et al., 2002)¹¹⁰. Despite this, mimicking ecosystems may offer insights into how the built environment could function more like a system than a set of unrelated object-like buildings, and thus become better able to adjust to change. An aspect of ecosystems which enables them to adapt to constant change comes from the fact they are made up of organisms and processes that are in close relationships. High diversity in terms of the relationships between organisms typically leads to increased system redundancy, and results in a greater ability for the whole system to adapt to change. This is discussed in depth in chapter three (sections 3.5.2.2, 3.5.2.4 and 3.5.4.7). Systems based climate change adaptation challenges conventional architectural design and procurement thinking, particularly the typical boundaries of a building site and design time scales. By mimicking process strategies in ecosystems, designers may have successful models to follow in devising how systems in buildings or urban environments should be put together and how they should work.

Research into intensive aquaculture systems stretching back several decades demonstrates in several cases the advantages of mimicking ecosystem processes to create resilient and effective systems (Hutchinson, 2005). Typically, such systems mimic the process in ecosystems where waste becomes a resource for another component of the system, or where energy is shared ensuring the system becomes cyclic and eliminates duplication of effort. The Happy Shrimp Farm in the Netherlands is strategically located next to E.ON Benlux's pulverised coal fired

¹¹⁰ Evolutionary responses to recent climate change have been documented in some insects but there is little evidence that indicates that observed changes in genetic traits are of the kind, speed or magnitude needed to prevent wide spread species extinctions caused by climate change (Parmesan, 2006). This point is echoed by (Sohn, 2011) using the specific case of the North American rattlesnake (*Crotalus* and *Sistrurus* genera).

power station in Rotterdam's Maasvlakte (a part of the city's harbour and industrial area). Greenhouse enclosed basins for raising shrimp are kept at a steady 30°C by a 2.5km pipe which transfers heat from the power plant's waste coolant water (60°C) through a heat exchange system to the farm. Previously this warm water was discharged directly into the sea. The 5000m² farm also supports the growth of algae. This algae feeds on the nitrogen rich waste produced in the shrimp farming process and becomes in turn feed for the shrimps, while helping to keep the basins clear. This results in productivity up to 200 times higher than if traditional feeds were used (Braungart et al., 2008). Samphire (a name given to several species of edible coastal growing plants) and sea lavender (*Limonium* genus) thrive in the conditions and are grown in the shrimp waste in cases suspended above the basins. Growing orchids may also be added into the system in the future, utilising more of the waste as a resource and creating further revenue streams (Koeleman, 2007, Baas, 2008).

Well known examples of successful industrial ecology such as Denmark's Kalundborg industrial region also illustrate how the process of cycling materials in ecosystems can be mimicked, even between diverse companies. In Kalundborg this sharing of waste as resource results in a reduction of 30 million m³ of groundwater used, and a reduction of 154 000 tonnes of CO₂ and 389 tonnes of mono-nitrogen oxides (NO_x) emitted. Five companies and one local municipality make up the industrial park where twenty different bi-product exchanges occur (Jacobsen, 2006). The UK Cardboard to Caviar (or ABLE) Project created by Graham Wiles of the Green Business Network in Kirklees and Calderdale and the design of a zero emissions beer brewery near Tsumeb, Namibia demonstrate similar concepts of mimicking the waste cycling of ecosystems and both projects report significant beneficial social outcomes (Pawlyn 2011, page 45, Mathews, 2011). Analysis of further ecosystem processes other than cycling of wastes or sharing of energy, suggests additional strategies for the built environment to mimic (Korhonen, 2001, chapter three). The elimination of toxins and pollutants that lead to the degradation of ecosystems is also addressed with such an approach.

Mimicking the functions of ecosystems is different from mimicking their processes. The former suggests that in a similar way to the functioning of an ecosystem, a building or development could be designed to form a system, or be part of a system

that: produces food; produces renewable energy; produces raw materials for the future built environment; collects and purifies water; purifies air and soil; regulates climate through mitigating GHG emissions and the heat island effect; contributes to soil formation and fertility through careful cycling of bio-degradable wastes and recycling of non-biodegradable wastes; and deliberately provides habitat for species suitable for co-inhabitation with humans in the urban built environment. Such new regenerative developments in turn could act as filters (mechanisms that purify air and water), producers (of food and materials) and generators (of energy) for the rest of the built environment which is still degrading ecosystems and is likely to persist for at least another 50 years (O'Connell and Hargreaves, 2004). If these regenerative nodes became part of the built environment and start to perform even small aspects of ecosystem functions, it is possible that built environment caused climate change (section 1.3) would be to some extent mitigated, and at the same time the built environment could become more adaptable to climate change, while creating beneficial biodiversity outcomes.

Similar ideas are discussed by proponents of eco-effectiveness (McDonough and Braungart, 2002). The difference between those concepts and the ecosystem level biomimicry proposed here is that the measurable targets such as emissions levels, carbon storage, water catchment, energy production and resource production, are determined through an understanding of suitable ecosystems or the pre-development ecosystem of the site, and thus are based on ecological reality, rather than human political needs or trends. The Lloyd Crossing Project (section 2.6.3) demonstrates aspects of the concept. A benefit of mimicking the functions of ecosystems is that, through careful urban planning and an integrated and multidisciplinary design method, buildings as part of a larger system, able to mimic ecosystem processes and/or functions in their creation, use, and eventual end of life, may have the potential to adapt more readily to climate change.

Whole system adaptation of built environments using an understanding of ecosystems may have the potential to address climate change impacts and biodiversity changes concurrently, but the concept needs to be better understood and further developed. Further analysis of ecosystem biomimicry at the process and function levels occurs in chapters three and four, and a comprehensive analysis of

how ecosystem functions could specifically be supplemented by the built environment forms the basis of the case study presented in chapter five.

2.8 EXAMINING THE IMPACT OF A BIOMIMETIC APPROACH TO ARCHITECTURE OVER TIME

As demonstrated by examples given earlier in this chapter, different kinds of biomimicry might form short, medium and long term responses to climate change, some of which are likely to be more effective than others. Biomimetic approaches to climate change mitigation and adaptation in the built environment are diverse and are not preventative of other non-biomimetic approaches being employed.

FIGURE 32 TIME LINE OF APPROACHES TO CLIMATE CHANGE IN THE CONTEXT OF THE BUILT ENVIRONMENT

While existing technologies and techniques will be crucial in the short and medium term, approaches that contribute to regenerative developments could form an important part of long term solutions to climate change and biodiversity loss. Biomimicry could be useful as part of strategies designed to replace the use of fossil fuels, to develop technologies or techniques to address direct climate change impacts on the built environment and in the systemic improvement of the built environment using ecosystem biomimicry as investigated in this chapter (figure 32).

Technologies that increase energy efficiencies and can sequester or store carbon may form part of an important short to medium term approach, but should be seen as intermediate steps. As well as a reduced or potentially negative carbon footprint for the built environment, examples of biomimetic technologies reveal approaches that use current excess CO₂ as a resource for new materials. Biomimetic technologies that address direct climate change impacts and biomimetic technologies or systems that prevent further GHG emissions have also been examined and could be implemented alongside wider systemic change in the built environment (including a consideration of people's consumption behaviour and life-style expectations).

2.9 SUMMARY: CHAPTER TWO

The aim of this chapter was to clarify the various types of biomimicry that commonly exist or could be explored in the future, so that distinctions between different kinds of biomimicry and their potential sustainability outcomes could be made. In order to do this, a framework for understanding how biomimicry can be applied to design and what sustainability outcomes could be predicted from their application was devised.

Biomimicry is often described as a tool to increase the sustainability of human designed products, materials and the built environment (Berkebile and McLennan, 2004, Benyus, 1997, Pawlyn, 2011). It should be noted that a lot of biomimetic technologies or materials are not inherently more sustainable than conventional equivalents and may not have been initially developed with such goals in mind (Marshall, 2007b, Reap et al., 2005, Gebeshuber et al., 2009), and many examples of technologies or strategies that have achieved high ecological performance have

been developed outside of a biomimicry paradigm. Biomimicry is not the only plausible way forward in terms of increased environmental performance of the built environment, and should not be thought of as a '*global panacea*' (Gebeshuber et al., 2009). Through this examination of existing biomimetic technologies, architecture and the literature in general, it is clear that markedly different approaches to biomimetic design have evolved and can have different outcomes in terms of overall sustainability.

Commonly given examples of successful biomimicry are typically products or materials rather than buildings or building systems, and tend to mimic a single organism. Mimicking aspects of organisms can produce innovations that address sustainability issues in some cases (Pawlyn, 2011), but without an understanding of the ecological context of these organisms, such innovations can too easily become simple technological add-ons to conventional buildings. These could fall into the category of 'green-wash', if buildings remain average in terms of overall sustainability performance over whole lifecycles (Armstrong, 2009). Such solutions also miss an opportunity to examine the possibility of systemic change in the built environment and to re-evaluate the nature of the relationship between people, their built environment the ecosystems they exist in (Mathews, 2011).

The case studies examined in this chapter suggest that ecosystem based biomimicry at the process and function levels may be the most effective kind of biomimicry to respond to climate change impacts and utilise synergies between mitigation and adaptation strategies, as well as address biodiversity issues. This is also the least explored aspect of biomimicry in built form. Positive integration with ecosystems leading to a regenerative rather than damaging effect on them may contribute to maintaining biodiversity and the ecosystem services that humans are dependent upon for survival, particularly as the climate continues to change. Such a concept goes beyond encouraging a basic understanding of ecological processes over time, as is increasingly advocated in recent publications and in educational institutions (Mitchell and Mueller, 2011, Graham, 2003, Rowe, 2007, Orr, 2002, Birkeland, 2008). Instead it is the thorough integration of ecological knowledge into architecture and urban design to alter how buildings function fundamentally in relation to ecosystems and to each other. Buildings are expected to become active contributors

to ecosystems and social systems, rather than remaining unresponsive agents of ecosystem degeneration. Because this ecosystem aspect of biomimicry seems to have the most potential for creating a new way of conceiving, building, analysing and retrofitting the built environment, exploring this concept becomes the focus of the rest of the thesis.

3.0 CHAPTER THREE: EXAMINING ECOSYSTEM PROCESSES FOR A BUILT ENVIRONMENT CONTEXT

'It is clear that industrial systems and biological systems are deeply similar. Indeed it is clear that both are complex systems, and that in general, they evolve to maintain themselves over time without discontinuous change... Considerable care must be taken not to let attractive similarities blind one to significant differences, especially where an understanding of those differences can be equally valuable.'

(Allenby and Cooper, 1994).

3.1 INTRODUCTION

Mimicking ecosystems, rather than aspects of individual organisms, is important in biomimicry that seeks to increase the sustainability of the built environment and contribute to a regenerative design paradigm. In chapter two it was established that ecosystem biomimicry at the process or function level may have greater potential for long term effective GHG mitigation and adaptation to climate change impacts, while enabling the built environment to become an agent of ecosystem regeneration and a provider of ecosystem services. This chapter will explore this finding further and will build upon the framework presented in chapter two, by examining and defining ecosystem biomimicry at the process level in greater depth. Ecosystem biomimicry at the function level will be examined in chapter four. This and the subsequent chapter aim to provide an integrated set of principles that could form the theoretical underpinnings of a practical ecosystem biomimicry approach to regenerative design.

This chapter begins with a general overview of ecology, ecosystems, and their relationship to humans and then examines the relationship of ecology to architecture. Different understandings of ecosystem processes from various disciplines are analysed to define general principles for ecosystem biomimicry at the process level.

The methodology used to devise the generalised ecosystem principles is described, and each principle is briefly elaborated. The results are presented as both a simplified list and an organisational matrix diagram where the relationships between principles become apparent. Those aspects of ecosystem processes that are particularly relevant to climate change adaptation or mitigation are identified in order to form an understanding of how ecosystem based biomimicry could be harnessed to address climate change and biodiversity loss impacts on the built environment.

Ecosystem processes have not before been mapped to demonstrate relationships and hierarchies, providing an overall view of how ecosystems work, in an architectural or design context. The significance of such research is that it provides a thorough and comprehensive basis for the development of biomimicry for architecture and urban environments seeking to move into highly sustainable or potentially regenerative paradigms. The research presented here aims to move attempts to mimic ecosystems from the shallow, and misunderstood (Kibert et al., 2002, page 41, Paton, 1992, Korhonen, 2001), to the more insightful, meaningful, and measurable levels that may be possible when knowledge from ecology and biology is thoroughly integrated into architectural design (Birkeland, 2008, page 17, Gebeshuber et al., 2009).

3.2 ECOLOGY, ECOSYSTEMS AND HUMANS

The term ‘*oekologie*’, from the Greek *oikos*, meaning ‘household’ (Hermansen, 2006) was coined in 1866 by the German Ernst Haeckel. This became ‘*ecology*’ in English and in 1870, Haeckel defined it as:

‘...The body of knowledge concerning the economy of nature – the investigation of the total relations of the animal both to its inorganic and to its organic environment including... relations with those animals and plants with which it comes directly or indirectly into contact... Ecology is the study of all those complex interactions...’ (in Costanza, 1996).

The science of ecology evolved from the discipline of biology and on a practical level became the study of the living world that does not include humans. This traditional

approach to ecology meant that living systems tended to be studied as unaffected by and separate from human influence (Costanza, 1996). As discussed in chapter one, it may be impossible to look at non-human ecosystems as separate from human systems, or to consider humans as separate from the 'natural world' (Alberti et al., 2003, Orr, 1999, Orr, 2002). Odum pointed out as early as 1969 that including humans as part of the study of ecology is crucial when trying to understand environmental impacts:

'Until recently mankind has more or less taken for granted the gas exchange, water purification, nutrient cycling and other protective functions of self-maintaining ecosystems, chiefly because neither number nor environmental manipulations have been great enough to affect regional and global balances. Now of course it is painfully evident that such balances are being affected, often detrimentally. The 'one problem, one solution' approach is no longer adequate and must be replaced by some form of ecosystem analysis that considers man as part of, not apart from, the environment' (Odum, 1969).

It is well known that humans are affecting ecosystems and evolutionary processes at great rates and in multiple ways and that all major anthropogenic drivers of ecosystem degradation continue to grow¹¹¹ (Vitousek et al., 1997, Imhoff et al., 2004, Carpenter et al., 2009). Despite the general negative environmental impact of humans, most urban environments still contain elements that contribute to ecosystem processes and functions, such as areas of tree planting, maintained landscapes, lakes, and streams (Bolund and Hunhammar, 1999, MEA, 2005a).

Although there may be few ecosystems that are truly unaffected by humans (Pickett et al., 2008, page 100), and humans are inherently part of the natural world, there are some obvious and essential differences in the way that non-human-dominated and human-dominated systems work (Vincent, 2010, Pawlyn, 2011, page 54, Vogel, 1998, pages 289-29 Vogel, 2003). The initial premise of this research was that by investigating how ecosystems are able to be robust, resilient and capable of

¹¹¹ Major drivers include anthropogenic caused climate change, land use change, the introduction of invasive species, over exploitation of 'resources', pollution, human population increase, and economic growth and development (Carpenter et al., 2009).

adapting to constant change (Gunderson and Holling, 2002), strategies and techniques that could be transferable to the built environment may be elucidated. This is to aid the creation, or evolution of a human habitat that is able to integrate with and contribute to, rather than damage, ecosystems as a means of concurrently addressing climate change and biodiversity loss.

3.3 ECOSYSTEMS AND ARCHITECTURAL DESIGN

Dinur (2005) points out that the key distinction of architecture that is a true reflection of ecological understanding, is not found in creating an object (or building) that *looks* as though it has emerged from a living process, but instead is the creation of architecture that *becomes* a living process and system. It is crucial that designers understand both how ecosystems work and how to avoid shallow interpretations of natural processes. Ecosystems provide designers with examples of how life can function effectively in a given site and climate and offer insights into how the built environment could function more like a system than as a set of individual unrelated object-like buildings. An understanding of ecosystems operating formatively in setting the initial goals and in establishing the performance standards by which the appropriateness of changes to the built environment are evaluated, may have the potential to create a significantly more sustainable and ultimately regenerative built environment.

Various interrelated methods for incorporating an understanding of ecosystems into architectural or urban design have been advocated. For example, Van der Ryn and Cowan (2006) and Todd and Todd (1993) examine aspects of what they term 'ecological design', while Graham (2003) discusses 'building ecology' and draws upon several ecological principles including the laws of thermodynamics and the importance of understanding change over time. Lyle (1994) lists different strategies and technologies for regenerative design that draw upon a variety of ecological concepts. Gruber (2011) examines mimicking the processes of ecosystems in an architectural context, also touched on by Pawlyn (2011). Design that incorporates an understanding of 'life's principles' is advocated by the Biomimicry Guild (Peters, 2011). Birkeland (2008) presents the concept of 'Positive Development' based on an understanding of 'eco-services' to increase the ecological base of urban

developments. McDonough and Braungart (2002) assert that ‘waste equals food’ as part of their ‘Cradle to Cradle’ vision, a concept derived from understanding how ecosystems work. Precedents and extensions of their ideas can be found within industrial and construction ecology research (Kibert et al., 2002, Hermansen, 2006). Concepts contained within research investigating permaculture (Mollison, 1988, Copeman, 2008), ecological engineering (Bergen et al., 2001, Mitsch and Jørgensen, 2003), and green infrastructure (Benedict and McMahon, 2007a) in relation to the design of the built environment also come from an understanding of ecosystems and have links with the concepts discussed above.

There is considerable value to be found within these ideas when considering how to use an understanding of ecosystems in architectural design that aims for regenerative environmental outcomes. Kibert (2006) cites a number of these authors and criticises many of these kinds of approaches to design due to the difficulty in understanding and modelling ecosystems. He asserts that ‘...*the mimicking of nature in human designs is one dimensional [and] non-complex...*’ Complexity may be one of the most significant difficulties of linking an understanding of ecosystems with design.

Design projects tend to be led by architects, planners, or designers without an ecology background, with potentially limited time and resources to acquire that knowledge (either directly or through incorporating ecologists into design teams), and who are under significant time and financial pressure to finish projects quickly and cheaply. This may lead to enthusiastic dabbling in biomimicry in architectural design, because the potential of biomimicry to improve the sustainability of the built environment is easy to grasp and, perhaps, overstated (Gebeshuber et al., 2009). The unfortunate result is simplistic form based biomimicry that may fall short in improved sustainability performance (Armstrong, 2009).

3.4 UNDERSTANDING ECOSYSTEM PROCESSES FOR A DESIGN CONTEXT

By mimicking process strategies in the living world, designers have a successful model to follow in determining how systems in buildings or urban environments

should be put together and work. Ecology literature does not typically offer sets of generalised principles of how ecosystems work but instead tends to explore the complexities of certain aspects of ecosystems. While there is considerable overlap in how ecosystems are described between sources, not all authors are in agreement. There are a number of controversial theories in ecology literature, such as the processes and mechanisms of evolution and the processes of ecological succession (Kay and Schneider, 1994, Martin and Embley, 2004).

Descriptions of the processes of ecosystems are varied in their format (Klijn and Udo de Haes, 1994). There is, therefore, a significant number of ways of organising a collection of ecosystem processes. This is also evidenced by the diversity in aspects of ecosystem processes that authors in different disciplines discuss. In light of this a list, as well as a relationship matrix, has been devised here to illustrate ecosystem processes that designers could mimic in architectural or urban design. The methodology for devising the list and the matrix as well as their benefits and drawbacks will be discussed in the following sections. Brief explanations of each ecosystem process are presented in section 3.5.

3.4.1 REPRESENTING ECOSYSTEM PROCESSES: LIST FORMAT

‘In the broadest sense, we generalise by building mental models about nature that attempt to explain an observed pattern or process by simplifying the complexity of the real world’ (Vepsäläinen and Spence, 2000).

To address the problem of disparate lists and groupings of ecosystem process, and to capture a cross-disciplinary understanding of how ecosystems work, a comparative analysis was initially conducted of explanations of ecosystem processes in the disciplines of ecology, biology, industrial ecology, and ecological design, as well as the ‘life’s principles’ discussed in biomimicry literature (Benyus 1997, page 7). Such a process served as a checking mechanism to ascertain that information related to ecosystem processes provided in design oriented literature was in fact in line with that discussed in the fields of ecology and biology.

Drawing upon techniques used in phenomenological research (Denzin and Lincoln, 2005), a matrix was formulated to compare various explanations of generalised ecosystem principles. This, along with lists of all sources drawn upon can be found in appendix two. From this matrix exercise, an inventory was compiled encompassing as much of the information as possible. Additional sources, typically from the discipline of ecology, have been used to expand upon the description of each process in section 3.5.

TABLE 5 ECOSYSTEM PROCESSES LIST

Ecosystem Processes (How Ecosystems Work):
1. Ecosystems adapt and evolve within limits at different levels and at different rates.
2. Ecosystems enhance the capacity of the biosphere to support life, and functioning and processes in ecosystems and within organisms tend to be benign.
3. Ecosystems are resilient. They can persist through time even as components within them change.
4. Ecosystems are diverse in species, relationships and information.
5. Ecosystems are self-organising, decentralised and distributed.
6. Ecosystems function through the use of complex feedback loops or cascades of information.
7. Organisms within ecosystems operate in an interdependent framework.
8. Ecosystems and the organisms within them optimise the whole system rather than maximising components.
9. Ecosystems and organisms are dependent upon and responsive to local conditions.
10. Living organisms within ecosystems are resourceful and opportunistic. Abundances or excesses are used as a resource.
11. Ecosystems and the organisms within them have the capacity to learn from and respond to information and self-assemble.
12. Ecosystems and the organisms with them have the capacity to self-heal within limits.
13. Ecosystems often have in-built redundancies.
14. Variety can occur through emergent effects (rapid change).
15. Variety can occur by recombination of information and mutation (gradual change).
16. Ecosystems are organised in different hierarchies and scales.
17. Ecosystems and organisms use cyclic processes in the utilisation of materials.
18. Parts of ecosystems and organisms are often multifunctional.
19. The form of ecosystems and organisms is often a result of functional need.
20. Living organisms that make up ecosystems are typically made from commonly occurring elements.
21. Ecosystems and the organisms within them gather, use and distribute and energy effectively.
22. Local energy / resources become spatial and temporal organisational devices.

A second method to devise an overview of ecosystem processes (described in full in section 3.4.3.1) was employed to provide a cross checking method to ensure robust results. The outcomes of the two methods were combined to produce the initial list of

ecosystem processes, shown in table 5. It should be noted that the ecosystem processes provided here are proposed as a set of generalised norms for the way most ecosystems operate rather than absolute laws.

Many discussions of how ecosystems work culminate in a list of ecosystem process components without consideration of the relationships between components. A list, such as table 5 could initially be useful for designers who are unfamiliar with ecology to use at the design stage. This is because the information is presented simply, and if brief descriptions of each process are available, the designer may be able to utilise the concept of each process during the early design stages of a project with the potential to improve the sustainability performance of the resulting design (Korhonen, 2001). This is somewhat uncertain however and an analysis of how the processes are related to each other may provide further insight.

3.4.2 RELATIONSHIPS BETWEEN ECOSYSTEM PROCESSES

Although the initial list of ecosystem processes presented in table 5 is a simple and easily understandable way to describe ecosystem processes, it lacks the ability to illustrate relationships between each process. This in turn reduces understanding the information in a way which is useful for spatial design and complex situations, such as those involving time dimensions. Vepsäläinen and Spence (2000) state that simple linear generalisations of ecosystems are often not helpful and can be inaccurate because each phenomenon in ecosystems has multiple interconnected causes and effects. They suggest that the development of general explanatory frameworks may be more effective. Those that can illustrate the relationships between patterns and processes can become powerful research or explanatory tools at several levels (Hoeller et al., 2007). This could also apply to design. Establishing connections between elements of a system helps people to reduce, through abstraction, the complexity of the system and understand how the elements come together to form a whole. Therefore, an examination of the relationships between each ecosystem process may have the potential to offer additional insights into how human design could be based on ecosystems.

Ecosystems are made up of non-linear and interconnected processes (Peterson, 2000). They are incredibly complex and are made up of large numbers of diverse components (both in terms of organisms and processes), scale multiplicity, and spatial heterogeneity (Wu and David, 2002). This means it is difficult to organise generalised principles into a neat list which encapsulates the complexity of the relationships between each process or between sets of processes accurately. This ultimately reflects the nature of ecology, which is the study of relationships between organisms and their contexts (Costanza, 1996).

One of the processes of ecosystems is that diversity is linked to resilience in a system that is constantly changing (section 3.5.2.2). Part of this diversity is found in the complex networks that exist in ecosystems, between organisms, and also between ecosystem processes (Ratzé et al., 2007). Part of the resilient nature of living systems related to diversity is that if one aspect of an ecosystem fails (a particular function, process or organism), then typically other ways of ensuring the continuity of the system as a whole exist. Just as ecosystems are difficult to compartmentalise accurately because they are complex systems, so too are the processes of ecosystems. It is not surprising that in mapping ecosystem processes, a relationship diagram reveals that each principle is a part of and is related to many others.

3.4.3 REPRESENTING ECOSYSTEM PROCESSES: RELATIONSHIP MATRIX

A 2007 iteration of the Biomimicry Institute's 'Life's Principles' remains the only other non-linear model of ecosystem processes of which the author is aware (Biomimicry Guild, 2007b). Baumeister (2007a) explained that the evolution of the diagram of what is termed 'Life's Principles' involved a process of trying to map relationships between aspects of the principles. This diagram focuses on the processes of living organisms in general rather than ecosystems. The more recent 'Life's Principles' of 2009 and 2011 from the same group are in a circular format, which is basically still a list but without an obvious end or beginning (appendix three). These are based on a combination of processes within individual organisms and within larger systems. Miller (2008) points out that it is a common misconception to assume that all significant aspects of ecology can be described by processes associated with

individual organisms rather than ecosystems themselves. The following relationship matrix differs from these other attempts therefore because it focuses on describing the processes of ecosystems rather than organisms.

3.4.3.1 METHODOLOGY

In order to expand the research to include an understanding of relationships and to ensure that no information had been left out, the author took each list of ecosystem processes provided by different sources (appendix two) and broke these into their individual components. Each component was recorded on a separate piece of paper. This provided a pile of papers with all the components from all of the lists. The components were then physically sorted into clusters of ecosystems processes. Many researchers discussed the same phenomena in ecosystems but used different terms. Clustering all these similar terms into one group enabled the opportunity to devise suitable single terms for each group¹¹².

The clusters were taped together and then secured to a white board, where lines could be drawn between clusters to represent relationships. During this process it became apparent that each cluster related to other clusters in different ways. For example, some clusters of ecosystem processes were entirely dependent on others, while others provided the conditions that enabled further clusters of processes to exist. White board marker lines joined each cluster into a complex network of relationships. The nature of each relationship was also recorded. This information was then transferred back to a computer where the clusters, which were renamed so each had a single term, could easily be manipulated in space while retaining their relationship lines to other clusters.

¹¹² This technique draws upon phenomenological research methods where large amounts of information must be analysed for patterns (Lester, 1999). The method also relates to the aspect of logical argumentation research that requires new categories of information, or new terms to be devised to reorganise information and therefore understand it in a different way (Groat and Wang, 2002, pages 322-323).

3.4.3.2 ORGANISING THE INFORMATION

Initial iterations of the resulting matrix diagram explored non-hierarchical formats (figure 33). It was found that this did not represent the different kinds of relationships between each process well. It also did not allow the processes to be understood from the most general to the more specific. During this process of simplifying the relationship network diagram, it became apparent that the relationships themselves were ordering mechanisms for understanding ecosystem processes. This is in line with what several ecosystem modelling experts have observed (Miller, 2008). The nature of relationships between ecosystem processes has been described as hierarchical (Ratzé et al., 2007) and Miller (2008) suggests that:

‘This fundamental hierarchical organisation is easy to detect in nature but has been undervalued by ecologists as a source of new insights about the structure and development of ecosystems and as a means of understanding the crucial connections between ecological processes and large-scale evolutionary patterns’.

Wu and David (2002) point out that a hierarchical perspective is crucial to understanding complex ecosystem dynamics and that non-hierarchical complex systems cannot be fully described. Hierarchical nested processes make up ecosystems, so it stands to reason that presenting the information in this way is not only more suitable to portray the processes accurately, but may also contribute to a potential change in patterns of thinking about ecosystems, particularly among non-ecologists, such as built environment professionals¹¹³ (Ratzé et al., 2007).

¹¹³ Even basic actions to reduce the environmental impact of the built environment, such as specifying insulation levels above the building code (in New Zealand at least), or even orienting buildings correctly relative to heating and cooling needs, are still not wide spread among all building design professionals. Expecting this group to understand ecosystems in a thorough way, therefore, is probably ambitious and unlikely in the near future. Rapid changes in practices and the thinking behind built environments do need to occur (see chapter one), so information about ecosystems as presented here could be useful if it was part of wider and comprehensive efforts to enable built environment professionals to move towards creating regenerative (or even just ‘greener’) urban environments. Even if only a few people within the area of building and urban design can engage with the complexity of ecosystems to the level suggested here, it could prove to be useful in the short term.

FIGURE 33 NON-HIERARCHICAL MATRIX FORMAT.

The use of a hierarchical relationship matrix diagram to portray ecosystem processes may at first seem to complicate things, especially for a design rather than ecology context. Elredge (1985, page 9) points out however that:

'Hierarchies at first glance seem to make matters much more difficult, providing no help at all in managing complexity because they are themselves so complex. But hierarchies actually deal with complexity by teasing it apart; it is as if hierarchies are more honest in their simple recognition that a system is complex than is an approach that seeks unity in characterising the system in simple terms...'

From a design perspective a non-linear format is useful because it provides an overview of how each process, once mimicked, could relate to others in a potentially reinforcing way. Miller (2008) discusses understanding ecosystem processes in terms of hierarchies as a means both to broaden the ability to generalise about 'how

life works' as well as to *'forge new and mutually enriching connections to related disciplines'*. While it is doubtful that he may have had architectural or urban design in mind, it is apparent that ecological information is being applied to more and more disciplines and that these disciplines seek to understand ecosystems in ways relevant to their fields (see section 2.2.4).

Understanding ecosystems is a complex matter, and if ecosystem processes are to inform architectural design, such complexity may need to be embraced and explored (Allen, 2002, pages 118-120). Hierarchy theory¹¹⁴ emphasises the importance of both bottom up as well as top down interactions as generators of change and stability (Wu and David, 2002, Lane, 2006). This means that elements of lower levels may cause aspects of a higher level, and that higher levels are made up aspects of the lower levels. It is the relationships, or causation pathways that the ecosystem processes matrix presented here seeks to represent (figure 34).

'Hierarchy' here does not mean a higher level process is better or more important, but rather that it encompasses the others below it in a series of nested and connected systems¹¹⁵. Ecosystem processes overlap, enabling multiple causations for phenomena to exist and rendering efforts to identify single isolated factors in ecological systems difficult (Vepsäläinen and Spence, 2000). So although the diagram (figure 34) depicts each process on each level as separate or modular, they are often closely related both horizontally and vertically in the matrix. This will become apparent during section 3.5 that provides brief explanations of the processes.

In Simon's (1962) foundation paper describing hierarchy theory, the idea of near-decomposability was introduced:

¹¹⁴ Hierarchy theory comes from research in different disciplines such as management science, psychology, biology, economics, and systems science (Allen, 2009, Wu and David, 2002).

¹¹⁵ Although the term 'hierarchy' is used for the sake of clarity, a more appropriate term to use to encapsulate what is being described would be 'rhizome' after Deluze and Guattari's definition (1988). Rhizome refers to the fact there are multiple entry and exit points in the data, and that relationships are non-linear in nature throughout the matrix.

'If systems were completely decomposable, then there would be no emergent whole, because the parts would exist only separately. The 'near' in near-decomposable allows the upper level to emerge from the fact that the parts are not completely separate.'

The ecosystem processes matrix diagram (figure 34) is composed of interacting components that are near-decomposable vertically into levels of organisation, and horizontally into holons (Wu and David, 2002). A holon is an entity in a grouping that is a whole process in its own right and at the same time a part of others¹¹⁶. Ratzé, et al (2007) point out that such organisation reflects nested ecological hierarchies and go on to state that:

'A holarchically integrated system is a dynamic and adaptive entity, reflecting its own functioning in the patterns of change over all levels of the system'.

Nested hierarchies refer to systems where each higher tier actually encompasses all the objects (processes) in the tiers below it. The ecosystem processes matrix diagram (figure 34) represents an overlapping, branching, nested hierarchy, which is convenient in terms of representing the information, but crucially also reflects how actual processes in ecosystems work. This means that each process commonly has two or more 'parents' in the tier above it, and a number of 'children' below it, as well as several 'siblings' in the same tier. Each level in figure 34 should be understood as being nested in the one above (figure 36).

¹¹⁶ Holons were first described by Koestler (1967).

FIGURE 34 ECOSYSTEM PROCESSES RELATIONSHIP MATRIX DIAGRAM.

FIGURE 35 NON-EXISTANT OR LESS OBVIOUS RELATIONSHIPS BETWEEN ECOSYSTEM PROCESSES (REPRESENTED BY GREY LINES).

Many human engineered systems are also nested hierarchies in that each higher level contains the systems of the level below it. For example, an electrical system is part of a room and connects to other rooms. A series of rooms make up a building, a building can be part of a neighbourhood, a series of neighbourhoods make up a suburb or a section of a city, these in turn make up the fabric of a city, a grouping of urban and rural environments make up a district, area or state, and a series of these make up a country. Architectural designers already understand the nested hierarchical aspects of building processes. Mapping ecological processes on to these or integrating or mimicking them may not, therefore, be as great a leap as in some other disciplines for understanding the nested hierarchy aspect of ecosystem processes.

FIGURE 36 LEVELS OF HEIRARCHY

Although it may appear that everything is connected in figure 34, figure 35 illustrates that not all processes have a clear, obvious or as important connection. This may aid designers to make decisions about which processes to focus on initially, particularly if

there is a specific performance goal that must be met. This is discussed further in the next section (figures 37, 38, and 39).

3.4.3.3 DESCRIPTION OF THE ECOSYSTEM PROCESSES MATRIX DIAGRAM

The most difficult part of devising the ecosystem processes matrix was determining where level boundaries should fall. This was done by determining the number of relationship interactions (the lines between processes in the matrix) both to the levels above and below for each process. A similar process is described and advocated by Klijn & Udo de Haes (1994). Vepsäläinen & Spence (2000) point out that boundaries between hierarchies or levels are often set by the human mind to enable deeper understanding, rather than existing discreetly in ecosystems.

Two clear ecosystem operating parameters seem to exist and form the top level of the matrix (coloured green in figure 34) (Biomimicry Guild, 2007b, Mathews, 2011). The first is that the context life is in is constantly changing. The second is that living entities that make up ecosystems generally work to remain alive. These conditions have led to the evolution of a set of strategies for enabling the on-going existence of organisms within ecosystems in a dynamic context of change.

Other researchers have tried to define similar top level operating conditions for ecosystem processes (Biomimicry Group, 2011, Biomimicry Guild, 2007b and 2009 , Mathews, 2011). The Biomimicry Guild and Group's 'Life's Principles' diagrams (appendix three) suggest that the fact that 'life creates conditions conducive to life' and 'life adapts and evolves' are overarching, or more important principles, though the reasoning behind this is not clear. Both of these ecosystem principles appear in the matrix presented here as tier two processes because they relate to a strategy ecosystems use to function, rather than to underlying conditions to which ecosystems respond.

Some biomimicry researchers (Mathews 2011) also discuss the need to find the deeper underlying principles in ecosystems. Matthews posits that there may be many such principles, but argues that the ‘principle of conativity’¹¹⁷ and the ‘principle of least resistance’ are two. Conativity means the will or impulse of the individual to maintain and increase existence. This is the same as the idea that ‘living entities that make up ecosystems generally work to remain alive’. This idea does not replace natural selection as the mechanism of determining the form and functionality of organisms but is rather an outcome of it and an essential requirement of the process according to Mathews (2011).

Mathews’ ‘principle of least resistance’ relates to the idea that organisms will chose the least energy intensive way to go about the business of living as a means to promote their own survival and also that of those around them (because this increases their own chances of survival). This process is represented in the matrix diagram (figure 34) as ‘ecosystems and the organisms within them gather, use and distribute energy effectively’ in tier four. The significance of this process is discussed further in section 3.5.4.10. While obviously a very important part of how ecosystems work, it is a product of the fact that living entities that make up ecosystems generally work to remain alive, and the constantly changing context in which ecosystems and organisms exist. If this constantly changing context was removed, organisms would essentially not have to move or adjust to changes and would not have to pursue a path of least resistance. For this reason it is not considered an overall operating parameter here.

The two principal ecosystem operating parameters presented in figure 34 – the fact that life exists in a constantly changing context, and living entities that make up ecosystems work to remain alive – create the next layer (coloured blue in figure 34). This layer consists of four ecosystem processes:

- Ecosystems adapt and evolve within limits at different levels and at different rates.

¹¹⁷ This is also termed ‘autopoiesis’ in contemporary systems theory (Mathews, 2011).

- Ecosystems are resilient in that they can persist through time even as components within them change.
- Ecosystems enhance the capacity of the biosphere to support life and functioning, and processes in ecosystems and within organisms tend to be benign¹¹⁸.
- Ecosystems are diverse in species, relationships and information.

These four main processes are supported by several ecosystem processes which form the third tier (red):

- Ecosystems are self-organising decentralised and distributed.
- Ecosystems function through the use of complex feedback loops or cascades of information.
- Organisms within ecosystems operate in an interdependent framework.
- Ecosystems and organisms are dependent upon and responsive to local conditions.
- Ecosystems and the organisms within them optimise the whole system rather than maximise components.
- Organisms within ecosystems are resourceful and opportunistic (abundances or excesses are used as a resource).

This third tier is in turn supported by a fourth tier (orange) which begins to become much more specific in terms of design strategies. Processes contained within this third tier are as follows:

- Ecosystems have the capacity to learn from and respond to information and self-assemble.
- Ecosystems and the organisms with them have the capacity to heal within limits.
- Variety can occur through emergent effects (rapid change).

¹¹⁸ 'Benign' here is after the definition in medicine or pathology meaning that no harm is done. This meaning of benign is also used in some ecology literature.

- Variety can occur by recombination of information and mutation (gradual change).
- Ecosystems are organised in different hierarchies and scales.
- Ecosystems and organisms use cyclic process in the utilisation of materials.
- Ecosystems often have in-built redundancies.
- Parts of ecosystems and organisms are often multi-functional.
- Local resource or energy sources become spatial and temporal organisational devices.
- Ecosystems and the organisms within them gather, use and distribute and energy effectively.
- The form of ecosystems and organisms is often a result of functional need.
- Organisms that make up ecosystems are typically made from commonly occurring elements.

The lines connecting each ecosystem process represent direct relationships. Each process is the consequence of and, in most cases, causes many others. For example, the fact that ecosystems are self-organising, decentralised and distributed, that they function through the use of complex feedback loops and cascades of information, that living organisms operate in an interdependent framework, that ecosystems and organisms are responsive to and dependent upon local conditions, that whole systems rather than parts are optimised, and that organisms within ecosystems are resourceful and opportunistic, all contribute to the fact that ecosystems are resilient (figure 37). Using the matrix diagram in this way can show which aspects of ecosystems might be important focus on when trying to increase the resilience of the built environment as a response to climate change. An analysis of how ecosystems are able to adapt could also contribute to finding strategies useful for enabling the built environment to adapt to climate change (figure 38). Examining a further level of detail (the fourth tier of ecosystem processes) would reveal further ecosystem processes to mimic.

FIGURE 37 ASPECTS OF ECOSYSTEMS THAT CONTRIBUTE TO RESILIENCE.

FIGURE 38 ASPECTS OF ECOSYSTEMS THAT CONTRIBUTE TO ADAPTABILITY.

FIGURE 39 THE CYCLIC USE OF MATERIALS PROCESS AND ITS RELATIONSHIPS.

What the matrix reveals is that even if a design team decides to focus on one particular ecosystem process, several other ecosystem processes, if employed, will probably support this (shown in the tier above), and that one process will be likely to cause or have repercussions for other lower tier or same tier processes. As discussed, industrial ecology is a term often given to the practice of mimicking, in industrial situations, the ecosystem process of cyclic materials use (section 2.7.2.2). What figure 39 shows is that the scales and hierarchies of the various materials are likely to be important when considering how to mimic the process of cyclic materials use (process 4.5 in figure 39). Careful consideration of feedback loops and information sharing processes (process 3.2 in figure 39), optimisation of the whole system rather than individual components within it (process 3.5 in figure 39), and ensuring processes are set up to enable an interdependent network between organisations in the system (process 3.3 in figure 39) may help to ensure that materials cycling works more effectively. Such a system may help to: increase the ability of the network to adapt at different times and in different ways to changes (2.1); be more resilient (2.2); enhance the capacity of the network to support living organisms (2.3); and be diverse (2.4). This would add to the ability of such a network to continue to exist even as conditions change (1.1 and 1.2).

Although issues of scale and time are important when discussing complex ecosystem dynamics (Peterson, 2000, Vepsäläinen and Spence, 2000), scale and time are not represented in the ecosystem processes matrix diagram (figure 34) and could be an area for further exploration. In the context of presenting generalised ecosystem processes for potential mimicry in a design context, such issues may be less relevant and may further complicate representations of ecosystem processes. While systems which exist at a micro scale may be different from those at a macro level (Ratzé et al., 2007), Klijn and Udo de Haes (1994) offer a different perspective:

‘...The only organisational ‘reality’ which deserves looking at, is the ecosystem which can be understood as a tangible whole of interrelated biotic and abiotic components. The term ecosystem thus becomes scale independent, implying

that there are small ecosystems as well as large ones, made up of smaller geophysically related systems...'

It should be noted that the author is not an ecologist, but rather is a designer trying to understand ecology principles so that they can become useable and tangible guides in design processes for built environments with regenerative environmental outcomes. It may be that such a matrix is not useful for ecologists who may understand the intricacies of each ecosystem process more thoroughly. Mapping the relationships between each process enables designers, many of whom think visually and spatially (Bertel, 2005), and have the ability to understand complex relationships, to incorporate into their designs a series of ecosystem processes that are self-reinforcing or symbiotic.

The relationship matrix diagram proposed here should be taken as a work in process, particularly as the study of ecology is constantly evolving and with it, human understanding of the living world. It may not be an absolute true and accurate reflection of ecosystem processes due to their complex nature, but it could enable designers to engage with mimicking such processes in design, and allow testing of the value of such a method. Once evaluation processes begin, feedback loops, if deliberately created could enable the refinement of the matrix.

'Useful generalisations may... propose relationships among classes of parameters that are not explicitly connected to specific systems. These generalisations are not at all 'testable' in any particular system because part of the challenge is to connect the abstraction to measurable elements in each system... such highly abstract generalisations are essential frameworks for asking more specific questions about nature' (Vepsäläinen and Spence, 2000).

What Vepsäläinen and Spence demonstrate here is that even if generalisations are not completely accurate, their value is in enabling people to think in a different way and to discover 'truths' through devising tests of a proposed generalisation. Such

generalisations are in their opinion more effective when people have minimal working knowledge of the phenomena in question. In the case of designers trying to understand ecology, this is likely to be the case.

3.5 DESCRIPTIONS OF ECOSYSTEMS PROCESSES

The descriptions of each ecosystem process presented here are not intended to be comprehensive and complete explanations of the way ecosystems work and cannot encapsulate the myriad opinions, the finer details and exact mechanisms of ecosystem processes discussed in ecology literature¹¹⁹. It should be noted that the following explanations are brief and that in most cases there are exceptions to each ecosystem process principle. The processes discussed relate to mature ecosystems, such as forests or prairies. Biological systems display different characteristics depending on their stage of maturity (Allenby and Cooper, 1994, Odum, 1969)¹²⁰.

Table 6 takes the ecosystem processes (from figure 34) and illustrates them in table form. This enables the nature of the relationships between the different hierarchical levels to be understood clearly. For example, the conditions in tier one directly cause the processes in tier two. A brief description of each ecosystem process follows using the numbering system in table 6. The links are also illustrated in figure 34 in the form of lines connecting processes. Possible relationships to architectural and urban design that an understanding of these principles could have are illustrated in table 7, following the brief ecosystem processes descriptions below.

¹¹⁹ For a discussion on the processes, laws or phenomena that may govern ecosystem processes as a whole such as metabolic rates (the metabolic theory of ecology) and patterns of least resistance flow (constructal theory) see: Bejan (2000) and Brown et al. (2004).

¹²⁰ Allenby and Cooper (1994) point out that *'a sharpening of the analogy to include contrasts between developing versus mature biological communities – could be useful in further developing the industrial ecology concept.'* The same could be true of ecosystem biomimicry.

TABLE 6 ECOSYSTEM PROCESSES ORGANISED INTO HIERARCHIES

Ecosystem Processes:
Tier One. Ecosystem Context:
1.1 The context that life exists in is constantly changing.
1.2 Living entities that make up ecosystems generally work to remain alive.
Tier Two. Therefore:
2.1 Ecosystems adapt and evolve within limits at different levels and at different rates.
2.2 Ecosystems are resilient. They can persist through time even as components within them change.
2.3 Ecosystems enhance the capacity of the biosphere to support life, and functioning and processes in ecosystems and within organisms tend to be benign.
2.4 Ecosystems are diverse in species, relationships and information.
Tier Three. The implications of this are that:
3.1 Ecosystems are self-organising decentralised and distributed.
3.2 Ecosystems function through the use of complex feedback loops or cascades of information.
3.3 Organisms within ecosystems operate in an interdependent framework.
3.4 Ecosystems and organisms are dependent upon and responsive to local conditions.
3.5 Ecosystems and the organisms within them optimise the whole system rather than maximise components
3.6 Organisms within ecosystems are resourceful and opportunistic. Abundances or excesses are used as a resource.
Tier Four. This is supported by the fact that:
4.1 Ecosystems have the capacity to learn from and respond to information and self-assemble.
4.2 Ecosystems and the organisms within them have the capacity to heal within limits.
4.3 Variety can occur through emergent effects (rapid change).
4.4 Variety can occur by recombination of information and mutation (gradual change).
4.5 Ecosystems are organised in different hierarchies and scales.
4.6 Ecosystems and organisms use cyclic process in the utilisation of materials.
4.7 Ecosystems often have in-built redundancies.
4.8 Parts of ecosystems and organisms are often multi-functional.
4.9 Local energy / resources become spatial and temporal organisational devices.
4.10 Ecosystems and the organisms within them gather, use, and distribute and energy effectively.
4.11 The form of ecosystems and organisms is often a result of functional need.
4.12 Organisms that make up ecosystems are typically made from commonly occurring elements

3.5.1 TIER ONE

The elements in tier one (constant change and the effort to survive) refer to the context in which ecosystems exist. This context directly affects the way that ecosystem processes work.

3.5.1.1 THE CONTEXT THAT LIFE EXISTS IN IS CONSTANTLY CHANGING

Climate and weather; the changing tilt of the earth causing seasons; gravitational effects of the moon causing tides; and growth and decay cycles mean living organisms and therefore the systems they create and are part of, need to adapt constantly. Ecosystems must respond to different temperatures, climatic conditions, gas ratios, water and mineral availability, and threats or mutualisms from other systems or organisms. Change and constant movement creates a need for constant adaptation to circumstances and constant cycling or movement of energy and materials in ecosystems. This suggests ecosystems are not equilibrium systems but in fact are '*far from equilibrium*' systems (Allen, 2002). Ecosystems are essentially in a constant state of flux. It is this very state of flux that keeps an ecosystem dynamically stable (Gunderson and Holling, 2002, Levin 1999). Allenby & Cooper (1994) point out that:

'Mature communities [are] highly dynamic systems, and many subsystems will be in flux at any given time... Maturity is not stasis'.

Loreau et al. (2001) also state that:

'Most of the classical equilibrium approaches [in ecology research] may be inadequate to understand stability properties such as resilience and resistance at the ecosystems level...'

Kibert et al. (2002, page 17) state that no natural system can be said to be 'sustainable' over the long term, if 'sustainability' refers to a static state.

'Changes in natural systems reflect experiments that shift the composition of processes, functions, and species, both independently and in response to novelty of system composition or of context (changing conditions). Evolutionary history is studded with unprecedented leaps of novelty that rendered unsustainable many systems that had endured for eons.'

FIGURE 40 FEEDBACK MECHANISMS IN ECOSYSTEMS. MARINE BIOGENIC SULPHUR (SOURCE OF IMAGE: NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION).

There is evidence to suggest that the processes of ecosystems and the living organisms they are made up of actually affect the dynamic system of the planet (Harding, 2001) (figure 40). The Gaia hypothesis proposed by Lovelock and Margulis in the late 1970s (Lovelock, 1979, Lovelock and Epton, 1975), and the Daisyworld model¹²¹ created by Lovelock shortly afterward, posit that living communities

¹²¹ The Daisyworld model was created to counter claims that the Gaia hypothesis was teleological (an argument for deliberate design and purpose in the universe often linked to evidence of a 'creator' or 'God'). It was designed to be a simplistic model of the Earth, to illustrate that in principle, planetary regulation *could* be an emergent property of a system comprised of interacting living and abiotic parts (Wilkinson, 2003). While there are a number of proponents of the Gaia hypothesis and the Daisyworld model as detailed by Harding (2001), with numerous academic papers using it to test theories and examine how life may interact with planetary regulation, these tend to be by physicists and climatologists rather than ecologists (Wilkinson, 2003).

influence their microclimate and that they may not be passively dependent on the local environment but actually be a part of creating it as an emergent phenomenon of their initial adaptation to it. The tendency of organisms to work towards survival may, therefore, cause and perpetuate the dynamic nature of the context in which organisms live. Organisms use interdependencies and diversity to maximise their ability to adapt to changing conditions (sections 3.5.2.4 and 3.5.3.3).

Ecosystems function cyclically (section 3.5.4.6) but also exist in a continually cyclic context. They function in the context of longer term cycles such as weather patterns and in the past, temperature fluctuations¹²².

3.5.1.2 LIVING ENTITIES THAT MAKE UP ECOSYSTEMS GENERALLY WORK TO REMAIN ALIVE

Coupled with the fact that the context in which life exists is constantly changing, is the observation that living organisms generally work to stay alive (Mathews, 2011). This effort may be as an individual (a moth will try to swim out of water to avoid drowning) or as part of a colony or family group¹²³.

Another aspect of this process is that the activities of living with which organisms engage tend not to use non-renewable resources, but instead use excesses as resources. This leads to processes involving materials being essentially cyclic, ensuring that the potential to use resources is not lost for future generations. Within this context, living organisms use freely available and easily accessible energy and

¹²² Temperature fluctuations may have been relatively cyclic on the planet until the influence of human industrial processes leading to increases in the concentration of GHGs in the atmosphere. This was due to factors such as the Milankovitch cycles. Serbian engineer and mathematician Milutin Milanković, theorised that variations in eccentricity, axial tilt, and precession of the Earth's orbit could be related to its climatic fluctuations. This was confirmed in 1976 by the work of scientists studying deep sea cores (Hays et al., 1976, IPCC, 2007d, page 9).

¹²³ Although some behaviour in plants and animals can be interpreted as suicidal, this is often associated with reproduction or protection of a colony or herd and so ensures the continuation of genes rather than individuals. For example, certain ants (*Camponotus*) will cause a rupture in their body allowing internal chemicals to mix when attacked. The mixture of chemicals causes the ant to explode and coat enemies with its toxic chemicals. This protects the colony's territory (Jones et al., 2004). Another example is efforts by females of certain octopus species (*Octopoda* order) to nurture eggs and young which ultimately results in her death through malnutrition (Wang et al., 2006). This ensures the continuation of her gene lines through her offspring.

resources, such as sunlight, wind currents, and commonly occurring minerals, typically found locally.

As a result of interdependencies between organisms, diverse ecosystems are created. These systems tend to be highly adaptive due to complex feedback loops in a context of constant change and the drive towards maintaining life (Gunderson and Holling, 2002). The complexity that arises from multiple relationships, feedback loops, and diversity allows emergent effects and decentralised self-organisation to exist in ecosystems (Allen, 2002). This is another mechanism to ensure on-going life in the face of constant change (Shear McCann, 2000).

3.5.2 TIER TWO

Tier two elements of the matrix are consequences of tier one conditions.

3.5.2.1 ECOSYSTEMS ADAPT AND EVOLVE WITHIN LIMITS AT DIFFERENT LEVELS AND AT DIFFERENT RATES

Adaptation and evolution allow organisms and whole ecosystems to persist through their locally unique and constantly dynamic, cyclic environment. Reap et al. (2005) describe adaptation as the means by which an organism adjusts behaviourally and physically to change throughout its lifetime. Evolution is referred to as the process by which genetic changes happen through successive generations in species or ecosystems through the medium of the gene (Korhonen, 2001, Darwin, 1859). As is typical in the biological sciences, debate about the exact mechanisms and functions of the process of evolution exists (Martin and Embley, 2004, Ruse, 2000). Evolution is the process of gradual change, while emergence is a more rapid mode of change in complex systems (sections 3.5.4.3 and 3.5.4.4).

Biological components impose limitations on the intensity of flows in systems. This is closely related to the concept that ecosystems tend to create conditions conducive to sustained life. The process of emergence in ecosystems is also linked to the

combination of excess energy and natural limits in systems (Allenby and Copper, 1994, Allen, 2002, page 110). Benyus (1997, page 7) suggests it is the physical limits of energy and climate that bind animals and plants and that drives the evolutionary change that enables them to 'fit' into a particular niche. These limits become one cause of adaptation and evolution¹²⁴.

3.5.2.2 ECOSYSTEMS ARE RESILIENT. THEY CAN PERSIST THROUGH TIME EVEN AS COMPONENTS WITHIN THEM CHANGE

Resilience here is defined after the explanation given by Harding (2001) as *'the speed with which a community returns to a former state having been displaced by perturbation'*. Resistance is defined as *'the ability to avoid such displacement'*, while stable communities *'are those with high resilience and resistance'*. As ecosystems shift from development stages to mature stages¹²⁵ over time and through the combined activities and interactions of organisms within them, they tend to become more resilient, able to adapt to change, and able to support more organic matter as well as organisms with longer and more complex life cycles (Odum, 1969, Faludi, 2005).

Mature ecosystems tend to retain nutrients stored in biomass for longer periods (Odum, 1969) and are made up of organisms with more complex life cycles and webs of relationships than those in developing systems (Allenby and Cooper, 1994). As systems reach maturity and total biomass is dynamically stable, typically inputs into the ecosystem almost match outputs, and the transfer of elements from organisms to soil will be near equal to the biological uptake of elements (Vitousek and Reiners,

¹²⁴ A related issue is proportion, which is crucial to living organisms because they must grow, and therefore are much more limited than human designers and engineers. *'Nature in effect, must transmute a motorcycle into an automobile while providing continuous transportation. The need for growth without loss of function can impose severe geometric limitations'* (Vogel, 1998, page 23). If the proportion of an organism is radically changed, its strength is affected and its internal dynamics altered. Some organisms do however change shape and proportion radically such as insects through their various life cycles. Doczi (1985) examines the limits of proportion found in various species of flora and fauna and links them to rules of golden proportion. He suggests there are proportional limits in nature and that proportions themselves are shared limits. Faludi (2005) alludes to the fact that nature uses self-similarity to plan for several scales at once, with his assertion that *'nature designs fractally'*. Fibonacci spirals are an example as although they grow, they retain the same proportions.

¹²⁵ There has been considerable debate about the mechanisms of succession among ecologists (Kay and Schneider (1994).

1975). This means that nutrients are not retained for increased growth in mature systems as they would be in ecosystems of intermediate development (Vitousek and Reiners, 1975). Exact ecosystem processes, therefore, adapt and change relative to the stage of ecosystem development.

Moderation in processing rates (Allenby and Cooper, 1994, Benyus, 1997, page 262), 'flux' (Kibert et al., 2002, page 15) or 'throughput of materials' (Korhonen, 2001) combined with complexity in spatial patterns of growth, decay, or destruction in ecosystems leads to their ability to be dynamically stable and may explain why very old ecosystems tend to lose fewer nutrients than they take up (Vitousek and Reiners, 1975).

Even in developing systems, where pioneer species¹²⁶ (Kibert et al., 2002, page 17) colonise a disturbed area¹²⁷ and cycle nutrients to such an extent that the habitat changes and longer life¹²⁸ species take over (Kibert et al., 2002, page 17), these pioneers add to the ability of the local environment to support more organisms over time, thus creating conditions favourable to a more complex and stable ecosystem (Faludi, 2005). This is despite the fact that they alter the environment to the extent they can often no longer survive there¹²⁹.

¹²⁶ Pioneer species are also referred to 'r-strategists'. Kibert et al. (2002, page 17) describes r-strategists in the following way: *Their strategy of maximum mobility and reproduction involves investing all of their energy in seeds and rapid growth and minimises investments in structure. R-strategists are mobile, surviving by being the first at the scene of a disturbance and securing resources before they are eroded away*.

¹²⁷ This may be from a natural disturbance such as a fire or earthquake or human caused disturbance such as forest clearing.

¹²⁸ Such species (sometimes termed 'k-strategists') spend less energy on reproduction (including producing seed) and instead use energy for more complex root systems to allow them to survive for longer periods and through changes (Kibert et al. 2002, page 17).

¹²⁹ Price (1995) discusses how humans can be likened to a pioneer species.

3.5.2.3 ECOSYSTEMS ENHANCE THE CAPACITY OF THE BIOSPHERE TO SUPPORT LIFE, AND FUNCTIONING AND PROCESSES IN ECOSYSTEMS AND WITHIN ORGANISMS TEND TO BE BENIGN

The growth and activities of ecosystems and the organisms within them tend not to damage the ability of the overall system of which they are a part to exist and continue (Rosemond and Anderson, 2003). Ecosystems do more than avoid polluting and in fact tend to regenerate, and strengthen the system as organisms live and die within it (section 3.5.1.2). Rosemond and Anderson (2003) point out that classifying the effects of species in ecosystems as beneficial or detrimental is largely a subjective human interpretation, but in this context, beneficial effects may include facilitating the presence of other species, increasing nutrient cycling, and creating mutually beneficial relationships between organisms.

FIGURE 41 BEAVER DAM (PHOTO BY: ANON.) AND BEAVER (PHOTO BY: STEVEHDC).

Because mature ecosystems tend to contain more nutrients and water (Odum, 1969), they may be responsible for creating, preserving or changing the nature of the local environment that supports life. Ecosystems and the organisms in them appear to have the capacity to change their immediate environment, as well as adapt to it by interacting with the physical world as a selection measure. This is in addition to internal selection pressures (Harding, 2001). Baskin (1998), and Jones & Lawton (1995) detail various examples of 'ecosystem engineers' that create or change

habitats. Ecosystem engineers do this either through their own structure¹³⁰ (such as coral (*Anthozoa* class)) or through mechanical or other means¹³¹ (such as woodpeckers (*Picidae* family) which use their beaks to access resources from trees).

The example of the North American beaver (*Castor canadensis*) (figure 41) demonstrates how through its altering of the landscape, wetlands are created and nutrient retention and plant and animal diversity is increased, helping in part to make the ecosystem more resilient to disturbance (Rosemond and Anderson, 2003).

FIGURE 42 SAND DUNE IN ALAMOSA (PHOTO BY: YOTUT).

Vitousek & Reiners (1975) use a different example of an unoccupied sand dune (figure 42), with no means of conserving nutrients:

¹³⁰ This is termed *autogenic*. (Rosemond and Anderson, 2003).

¹³¹ This is termed *allogenic* (Rosemond and Anderson, 2003).

'The development of biomass through succession provides a mechanism for elemental uptake and, more importantly, establishes compartments, or pools for elemental storage in biomass. As plants become established on the sand dune, elements essential to plants will accumulate in the organic matter of this simple ecosystem.'

Von Frisch & von Frisch (1974) and Hansell (2005) also provide numerous examples and details of organisms altering their own habitats with beneficial results termed '*animal architecture*'. Such examples may be useful for exploring behaviour level biomimicry for a design context (section 2.5.2).

Functioning and processes in ecosystems and within organisms tend to be benign. Chemicals, including nutrients, can be toxic in natural systems if in high concentrations. Ecosystems typically, therefore, do not have spatial clusters of high energy and material transformations, and avoid high fluxes in the use of energy and materials (Allenby and Copper, 1994).

Materials (both internal such as organs and external such as shells) are produced at ambient temperature and often use water as the chemical medium (Vincent, 2010). Benyus (1997, page 105 and 261), contrasts this with the human tendency to produce materials in high energy, pressure, and chemically intensive conditions; the '*heat, beat and treat*' approach, rather than allowing '*the physics of falling together and falling apart – the natural drive towards self-assembly*' to do the work.

Organisms must manufacture or process the materials or chemicals they utilise in their same environment. Concentrated toxins, such as snake venom, tend to be used and produced locally and must be produced in the body of the snake (*Serpentes* suborder).

3.5.2.4 ECOSYSTEMS ARE DIVERSE IN SPECIES, RELATIONSHIPS AND INFORMATION

'Natural systems are sustained by the emergence of surprise... and novelty... and by the diversity of information found in genetic codes, which instruct the fabrication and operation of organisms. This diversity is present at several levels: within each population of a species, across all populations of a species and across all species in communities...' (Kibert et al., 2002, page 18).

Mature ecosystems tend to be diverse, highly structured, complex and made up of numerous relationships between organisms and species (Allenby and Cooper, 1994). The diversity of nature (biodiversity), in terms of the number, identity, locations, and interactions of species that make up functional ecosystems, fulfils various roles crucial to the support of all life (Naeem, 1999). A diverse system can be described as a robust one capable of adapting to change (Vincent et al., 2006). Korhonen (2001) points out that diversity can be seen as a *'long term survival strategy of ecosystems as a consequence of permanently changing conditions.'* It should be noted there is considerable historical debate about the relationship between diversity, complexity, resilience, and stability in ecosystems (Baskin, 1998, Hermansen, 2006, Wu and Loucks, 1995). Results observable at different trophic levels¹³² of an ecosystem tend to be wide ranging, adding to the debate (Loreau et al., 2001).

While a number of experimental results exist (Loreau et al., 2001), much knowledge of the relationship between biodiversity and ecosystem functioning and dynamic stability is in the realm of ecological theory. More research is required, particularly in determining the role of diversity in mutualistic interactions and relationships, in relation to sustaining ecosystem processes (Loreau et al., 2001). What is clear from the literature is that it is the number and strength of relationships (termed 'interaction strength') between species in systems that is of paramount importance to dynamic stability and system resilience, rather than actual numbers of species (Shear

¹³² 'Trophic level' refers to the place an organism occupies in a food chain. Ecosystems can be broken into trophic levels such as the first and largest level of producers (green plants) and smaller upper levels of carnivores.

McCann, 2000). By creating more cooperative links in an ecosystem, rather than simply more elements, it may become more adaptable and better able to persist through change.

FIGURE 43 NATIVE NEW ZEALAND TŪĪ (PHOTO BY: DIGITALTRAILS).

For example a species of bird that only eats one type of insect will lose its food source if the insect becomes extinct or scarce, and may become extinct itself. It would then not be available as a food resource to other animals. Birds that eat a variety of insects would be less affected by one kind of insect disappearing. An example of this is found in New Zealand, where the predation of certain introduced species such as the possum (*Trichosurus vulpecula*), stoat (*Mustela erminea*) and rat (*Rattus exulans*, *Rattus norvegicus* and *Rattus rattus*) on certain native bird species such as the Tūī (*Prothemadera novaeseelandiae*) (figure 43), Kererū (*Hemiphaga novaeseelandiae*) and the now extinct Huia (*Heteralocha acutirostris*) means fewer birds exist to eat berries from certain native trees, such as the New Zealand Kauri

(*Agathis australis*). This means fewer seeds from these trees are distributed and grow into new trees. This in turn means there are fewer trees providing food for the remaining birds. This is an example of what Shear McCann (2000) describes as a strong resource interaction relationship. This particular example also demonstrates the potentially wide ranging indirect impacts small changes, or losses in biodiversity, can have on existing ecosystems.

Diversity in terms of high numbers of species does not necessarily increase the stability of populations (the number of individuals in a species in a system), but is often related to keeping total numbers of individuals in a community (made up of many different species) in a dynamic balance. So, stability and resilience are related to how diverse an ecosystem is in terms of relationships, but are not a direct result of high numbers of species. It would appear however, that ecosystems with large numbers of species may be less vulnerable to disruption in terms of overall ecosystem function over the long term (Baskin, 1998, page 221). There is also evidence that decreased biodiversity affects the stability of ecosystems and that it is difficult to predict which species are 'keystones'¹³³ or ecosystem engineers (WWF, 2010).

3.5.3 TIER THREE

The implications of the processes described in tier two become manifest in tier three.

3.5.3.1 ECOSYSTEMS ARE SELF-ORGANISING DECENTRALISED AND DISTRIBUTED

Ecosystems tend to be made up of distributed and decentralised networks of feedback loops dependent on relationships between organisms, and between the living system and the rest of the environment, making them rapidly responsive and adaptable to change (Vincent et al., 2006, Harding, 1999). This means there is no

¹³³ 'Keystone' species are ones, such as the beaver, whose removal dramatically changes a whole ecosystem (Rosemond and Anderson, 2003).

centralised organising factor in ecosystems, such as a single super computer or brain entity that controls everything within them. Allenby & Cooper (1994) and Kay (2002, pages 76-79) describe this aspect of how ecosystems work as 'self-organisation'. This kind of organisation tends to incorporate high amounts and transfer rates of information because it is based on multiple feedback mechanisms (Allenby and Cooper, 1994).

3.5.3.2 ECOSYSTEMS FUNCTION THROUGH THE USE OF COMPLEX FEEDBACK LOOPS OR CASCADES OF INFORMATION

Ecosystems have internal feedback mechanisms as well as external ones. When a population becomes too large, less food is available for individuals to eat and support reproduction. This results in the population of a given area eventually reverting to a number that enables the organism's supporting organisms (such as the plants and animals a population feed on) to persist through time. Feedback mechanisms, or the way that changes in one part of the ecosystem are communicated throughout the entire community in a cascade of information, are acknowledged as a further factor in the ability of ecosystems to adapt and evolve (Allenby and Cooper, 1994). The fact that feedback mechanisms are numerous in mature systems is related to the dynamic stability of the overall system (Allenby and Cooper 1994, Peterson 2002, pages 128-137), adding to the fact the diversity of relationships and interactions within a system is a factor in the ability of ecosystems to persist through time (Shear McCann, 2000).

3.5.3.3 ORGANISMS WITHIN ECOSYSTEMS OPERATE IN AN INTERDEPENDENT FRAMEWORK

In complex ecosystems, both cooperation and competition between individuals and species are important (Vincent and Mann, 2002, Kibert et al., 2002, page 18) and is still debated, although a shift from seeing the world as inherently 'dog eat dog' to one that is also made up of cooperative interdependencies has occurred (Faludi, 2005, Wu and Loucks, 1995). An example of the variety of opinions is the theory of natural

selection and competition between species and individuals as the driver for evolution as advocated by Darwin (1859) and Dawkins (1976)¹³⁴, compared to the more recent 'endosymbiotic theory' proposed by Margulis (1998), where life colonised the planet not through fighting and competition, but by cooperation and networking.

In mature ecosystems, cooperation is important, as demonstrated by the way organisms will occupy non-competing niches. Species in the same niche may use other tactics such as defining territories or having non-overlapping feeding times to avoid competition.

'When we find many animals apparently sharing a food supply, we do not talk of struggles for survival; we watch to see by what trick the animals manage to be peaceful in their coexistence... A perfectly fashioned individual of a Darwinian species is programmed for a specialised life to be spent for the most part safe from competition with neighbours of other kinds. Natural selection is harsh only to the deviant aggressor who seeks to poach on the niche of another. The peaceful coexistence between species, which results from evolution by natural selection, has to be understood as an important factor in the workings of the... ecosystems around us' (Colinvaux 1979, pages 131-132).

Reap et al. (2005) discuss their theory that life exists in a cooperative framework due to *'the diverse web of interactions that effect populations, facilitate resource transfers, ensure redundancy and generally maintain the biosphere'*. This idea is similar to the work of Lovelock (1989), who advocates that the Earth is a living self-regulating system, where organisms of the planet, together with abiotic components such as rocks, clouds and oceans interact in such a way to slow or prevent the increase of entropy, and thus keep conditions on the planet favourable to continuing life.

¹³⁴ Intra and inter-species competition is a crucial part of Darwin's *'Theory of Evolution'*, allegedly driving the process of natural selection and adaptation to environment and therefore evolution (Darwin, 1859). Other noted biologists such as Dawkins discuss evolution as driven by competition between individual genes (Dawkins and Krebs, 1979, Dawkins, 1976), although critics argue that genes must cooperate to survive (Wilson & Wilson, 2007).

3.5.3.4 ECOSYSTEMS AND ORGANISMS ARE DEPENDENT UPON AND RESPONSIVE TO LOCAL CONDITIONS

'Biological communities are by and large, localised or relatively closely connected in time and space. Many linkages... in nutrient cycles in fact depend on natural energy fluxes and close proximity...' (Allenby and Copper, 1994).

Living organisms adapt to local environments, pointing to ecosystems and the organisms within them being attuned and suited to their climate and environment¹³⁵. Species that make up ecosystems tend to be linked in various relationships with other organisms in close proximity (Allenby and Cooper, 1994, Korhonen, 2001). Typically they utilise resources and local abundances from their immediate range of influence, and tend to be well adapted to their specific microclimatic conditions (Reap et al., 2005). Functions required for an ecosystem to continue and remain in dynamic balance, including the cycling and production of materials, are usually carried out by species within the system, which exist in specific niches (Kibert et al., 2002, page 18).

Because species co-evolve with others in an ecosystem, they are specifically adapted to each other (Colinvaux, 1979). This increases individual survival, and ensures the effective use of an individual's own energy by occupying niches, reducing competition, and using their evolved capabilities in the most effective way. Reap et al (2005) point out that:

'Local shortfalls created evolutionary pressures that promoted the persistence of organisms with more efficient means of using local resources.'

The native New Zealand Kiwi (*Apteryx* genus) (figure 44) is an example of a species with unique features that allow it to use certain resources from its local environment. It is nocturnal to match the activities of its insect diet and has a specially shaped

¹³⁵ This is likely to change with the advent of further climate change (Parmesan 2006).

beak to access specific native forest insects. It is able to digest what it sources from its environment, and has defensive behaviour and 'cryptic' colouring to guard itself and its eggs from attack from native predators¹³⁶

(Holdaway et al., 2001). FIGURE 44 LOCALLY ADAPTED BROWN KIWI (PHOTO BY: FLORENCE_CRAYE).

These include the weka

(*Gallirallus australis*), also a flightless bird that predares on kiwi eggs and the now extinct Haast's eagle or pouakai (*Harpagornis moorei*). Kiwi eyes, olfactory and tactile capabilities are suited to nocturnal forest feeding including nostrils located at the end of its beak (Martin et al., 2007).

As discussed, local resources and nutrients are generally kept within mature ecosystems for longer periods (Odum, 1969, Vitousek and Reiners, 1975). There are obvious exceptions to this with certain birds cycling marine nutrients to land environments and migrating animals transporting nutrients and seeds. An illustration of this is the important marine derived elements found in Canadian riparian forests. It was discovered that salmon (*Oncorhynchus* genus) migrating from oceans up streams, were caught by bears (*Ursus* genus) or other predators and their subsequent transportation into the forest accounted for the significant transfer of nutrients and minerals (figure 45) (Reimchen et al., 2002, Gende et al., 2007).

¹³⁶ 'Cryptic' colouring conceals or disguises an animal's shape. These strategies are not effective against introduced predators such as the stoat, rat, and possum.

FIGURE 45 ALASKAN COASTAL BROWN BEAR TRANSPORTS MARINE NUTRIENTS INTO FORESTS (PHOTO BY: ALAN VERNON)

3.5.3.5 ECOSYSTEMS AND THE ORGANISMS WITHIN THEM OPTIMISE THE WHOLE SYSTEM RATHER THAN MAXIMISE COMPONENTS

'Plants and animals always try to use materials and energy efficiently, because for them energy and material costs are the only costs. Successfully minimising mass and energy use requires thorough optimisation to the problem at hand, so organism structures are highly information driven' (Faludi, 2005).

Organisms in ecosystems need to balance the multiple functions they must perform with the energy that is easily available to them. The whole is privileged over a part in terms of matter used by individual organisms. What would appear to be inefficiency in individual organisms can sometimes equate to effectiveness for the entire system. McDonough and Braungart's (2002, page 72) example of a cherry tree (*Prunus* genus) illustrates the point (figure 46). Korhonen (2001) points out that in environments with seemingly unchanging conditions, where severe resource

constraints exist, the ecosystem is optimised through organisms diversifying to occupy niches. He offers the example of coral reefs and tropical rain forests.

'Consider the cherry tree: thousands of blooms create fruit for birds, humans, and other animals, in order that one pit might eventually fall to the ground, take root, and grow. Who would look at the ground littered with cherry blossoms and complain: 'How inefficient and wasteful!' The tree makes copious blossoms and fruit without depleting its environment. Once they fall on the ground, their materials decompose and break down into nutrients that nourish microorganisms, insects, plants, animals, and soil. Although the tree actually makes more of its 'product' than it needs for its own reproductive success in an ecosystem, this abundance has evolved (through millions of years of success and failure)... to serve rich and varied purposes. In fact the tree's fecundity nourishes almost everything around it' (McDonough and Braungart, 2002, pages 72-73).

FIGURE 46 CHERRY TREES IN BLOSSOM (PHOTO BY: TITUS TSCHARNTKE).

3.5.3.6 ORGANISMS WITHIN ECOSYSTEMS ARE RESOURCEFUL AND OPPORTUNISTIC. ABUNDANCES OR EXCESSES ARE USED AS A RESOURCE

Organisms tend to be opportunistic and resourceful in that they use freely available and local resources, such as 'free energy' (Baumeister, 2007b). Examples include plants producing wind dispersed seed pods that exploit air currents, or marine

mammals using ocean currents to aid migration (Thomson et al., 1992, Greene and Johnson, 1995). Ultimately this resourceful use of 'free' energy is harnessing converted energy from the sun in means other than directly through photosynthesis (or indirectly through the food chain). Such opportunism often becomes the evolutionary and emergent drivers of change as systems and organisms constantly adapt to a dynamic context (Schneider and Kay, 1994).

Processes in ecosystems tend not to damage the ecosystem itself or use resources that cannot be replaced. Instead the excesses, or wastes from earlier processes that are freely available tend to be used. This aspect of ecosystems ensures the ability of consequent generations of organisms to be able to use similar resources. One of the most obvious examples of this aspect of ecosystem processes is that energy in ecosystems is sourced from solar radiation. Solar radiation is the only input into the closed loop ecosystem of earth and, except for the gravitational effects of the moon¹³⁷, is the only source of energy either directly or indirectly available to organisms. Oxygen production, the hydrological cycle, wind currents, and drivers for certain ocean currents and other cycles are all caused by, or intimately linked with, solar radiation¹³⁸.

¹³⁷ The moon is responsible for the Earth's ocean tides, which are a potential source of energy and are a timing mechanism in some tidal plants and animals (Palmer, 2002).

¹³⁸ A by-product of capturing solar energy through photosynthesis is the release of oxygen, a vital life sustaining element on earth for both animals and plants. Oxygen is used during the respiration process, enabling food energy to be used in plants. Animals take in oxygen through lungs and gills, while plants take it in through stomata. Oxygen is also vital to the aerobic environment needed for healthy cell function in animal bodies and to certain microbiotic processes. Xiong (2002) discusses the importance of photosynthesis: '*Oxygen-evolving photosynthesis has generated most of the atmospheric oxygen that is used for respiration as well as formation of an ozone layer to shield Earth from UV radiation*'. Oxygen also assists in the breakdown of biodegradable wastes, the cycling of which, through decomposition and re-absorption is crucial to the function and maintenance of many mature ecosystems (Odum, 1969). Forests are an example, where rotting trees and leaf matter are absorbed and eaten by insects, animals and other plants as well as microbes and soil dwelling organisms. These plants and animals are reabsorbed by other organisms after their death, creating a constant cycling of nutrients.

Water is evaporated from the oceans by the sun to form clouds. Wind carries the water vapour powered by the sun) where it eventually rains or snows, beginning the cycle again. So the fresh water component of the survival of many natural ecosystems is also in part dependent upon the sun. Most land areas of the planet have some amount of annual rain or snowfall as part of the global water cycle. Animals and plants in river, lake and wetland systems obviously rely on this water cycle also. Snow or glaciers which melt and rain water eventually finds its way to the oceans while replenishing the river and lake systems of the land. Most ecosystems (including some in the ocean) rely on fresh water for survival. Even in low or no rainfall areas there are adaptations in plants and animals that allow them to survive on very little water or indirect water. Some cacti (*Cactaceae* family), with their shallow roots and water storage stem with no leaves, and kangaroo rats (*Dipodomys* genus) and camels (*Camelus* genus), with little sweat loss and absorption of water from scarce food resources in the desert are examples (Guterman, 2002).

Most plants are able to harness the sun's energy as light and with CO₂ and water through the process of photosynthesis, transform it into simple sugars (carbohydrates), proteins, starch and fats for health and growth. These photosynthesisers store the starch and sugars within their bodies. These are then used by other life forms when they eat (or absorb) the plants. Other species then eat them and so on to create a functioning food web. The energy sustaining the ecosystem is still ultimately converted or stored sunlight in the form of biomass (Kibert et al., 2002, page 18). This is true for almost all communities of life on the planet¹³⁹ from whales (*Cetacea* order) which feed on fish and krill (*Euphausiacea* order), fed by plankton grown through photosynthesis, through to tiny slow growing Antarctic lichens (*Buellia* genus), which feed on rock and harness the six months of sunlight a year (Ahmadjian, 1993, page 81). In contrast, humans currently source a large proportion of energy from ancient sunlight in the form of fossil fuels.

3.5.4 TIER FOUR

Tier four aspects of how ecosystems work support or enable the processes in the three upper levels.

3.5.4.1 ECOSYSTEMS HAVE THE CAPACITY TO LEARN FROM AND RESPOND TO INFORMATION AND SELF-ASSEMBLE

This ecosystem process relates closely to the idea of self-organisation and response to feedback loops discussed earlier. A trait of ecosystems and the organisms within them that differs substantially from human technology is that natural materials and systems self-assemble without externally imposed operating instructions. This is possible through the medium of DNA and also because of the chemically benign and energy non-intensive processes of assembly seen in nature. It is added to by the fact that commonly occurring elements are typically used (section 3.5.4.12). Self-

¹³⁹ See footnote 104.

assembly is being explored for further potential in new materials technology (Vincent 2010).

3.5.4.2 ECOSYSTEMS AND THE ORGANISMS WITHIN THEM HAVE THE CAPACITY TO HEAL WITHIN LIMITS

Ecosystems, particularly complex ones, are (within limits) able to persist through change and after damage (Korhonen, 2001). An example would be regeneration of a forest after a fire or flood. Such damage events may actually form important parts of cycles of nutrient replenishment in soils¹⁴⁰ or reproduction of certain tree species, where seed germination only occurs during temperatures created by fire (Bradstock and Auld, 1995, Auld, 1996). This self-healing seen in ecosystems is a response to a dynamic context and is facilitated by succession processes (White, 1979).

Almost all organisms are characterised by an ability to heal certain kinds of damage to their systems or structures. Some materials produced by organisms are structured in such a way to prevent damage and to self-heal. Examples are abalone or paua (*Haliotis* genus) shell and rhino (*Rhinocerotinae* subfamily) horn (Vincent, 2010). A keratine matrix in the horn, and a similar ‘mortar’ in the shell interrupts cracks coming from one direction and redistributes stress, resulting in high torsional strength (Benyus, 1997, page 143). In rhino horns, which may not be made of any living tissue, cracks are filled with a polymer through a de-polymerisation and then re-polymerisation process¹⁴¹.

¹⁴⁰ It should be noted that human intervention in the fire cycle of certain forests may damage soil fertility and health (Tiedemann et al., 2000).

¹⁴¹ The process is not well understood at present (Benyus, 1997, page 140). Self-healing plastics and concrete have been developed as detailed by Benyus in an interview with Leonard (2003): ‘*We basically put [in concrete] little capsules of an epoxy, of a gluelike material, that when the concrete flexes will break and pour into the crack. It’s an exciting but crude approximation of the amazing process that goes on in rhino horns*’. Research by Scott White at the University of Illinois is also cited (Leonard, 2003). Vincent (2010) provides further examples of materials that have similar properties and Patel-Predd, 2007b details a similar idea for plastics.

3.5.4.3 VARIETY CAN OCCUR THROUGH EMERGENT EFFECTS (RAPID CHANGE)

Some of the most recent work on ecosystems is based on the second law of thermodynamics¹⁴² which states that *'a closed system will run down to equilibrium'*, (Allen, 2002, page 109) interpreted by Schneider and Kay (1994) as meaning that *'systems running down to disorder is a trivial matter compared with the elaborate things that happen and persist if the system is not allowed to run down'*. One of these 'elaborate things' is the phenomenon of emergence.

Emergence in ecosystems is the occurrence of new, and sometimes novel and unexpected rapid organisation in complex systems (Vincent et al., 2006, Wu and Loucks, 1995). A common yet controversial example is of human consciousness. Neurons, blood, and electrical pulses are parts of the brain. Cognition is an emergent property of these interactions. The brain in turn is an organ interacting with many others in a body. 'Consciousness' exists in the body but it cannot be found as an independent part, yet most humans know it as something which exists. It is an emergent phenomenon of a complex system (Goleman, 1997, page 60).

Emergence occurs as a result of resistance to disequilibrium (a limit in a natural system) and pressure against that limit exerted by an excess of energy or material in a system. Allen (2002, pages 111-114) asserts that it is through new relationships of control and constraint that emergence appears, allowing systems to become more complex. Allen et al. (1999) differentiate between complex systems and complicated systems as follows (figure 47):

'As a system becomes more complicated, more parts are added or more connections develop between parts. When a system becomes more complex,

¹⁴² Ecosystem approaches that use the first law of thermodynamics, which states that energy must always be conserved, tend to assert that fluxes through a system should be balanced. An example applying this to the built environment is that as materials and energy are fed into a building, the objective is to minimise loss of that material or energy to the wider environment (Allen, 2002, page 118).

new asymmetrical relationships arise, such that some components at a higher level become the context of others at a lower level in the system’.

FIGURE 47 COMPLEXITY VS. COMPLICATEDNESS (SOURCE: ALLEN ET AL., 1999).

Emergence is a way that systems become more complex. An energy base is needed to shift organisation to another level, which happens by a rapid or sudden process of feedbacks, rather than as an incremental and gradual process of change over time (Allen, 2002, page 113, Allen et al., 1999).

3.5.4.4 VARIETY CAN OCCUR BY RECOMBINATION OF INFORMATION AND MUTATION (GRADUAL CHANGE)

Complex systems evolve over time and do not start as complex¹⁴³. Evolution can be a slow process of gradual changes caused by adaptations in individuals to conditions and through the process of recombination of genetic material and mutation through

¹⁴³ An example is mature old growth forests. If this is cut down, planting new trees will not simply regenerate the forest, which has evolved to be complex. In New Zealand, although few trees were taken (on average) per acre in ‘sustainably’ managed temperate rainforest logging on the west coast of the South Island in the late 1990s, lines of trees taken from ridgelines meant wind was able to enter the forest and damage it. The strong sunlight able to reach the forest floor once the tall trees had been felled meant certain species were unable to thrive and new seedlings planted to replace the old trees could not grow easily in the conditions. Regeneration of forests is a slow process where pioneer species must grow and alter the conditions to ensure the survival of longer life species.

sexual reproduction. Change occurs often by rearranging information that already exists. This compares to the human tendency to search for completely novel technologies to solve problems rather than to reframe the problem itself.

Dramatic events such as floods, earthquakes, volcanic eruptions, storms, or human interventions can also shape and alter ecosystems in a matter of minutes rather than millennia. An ecosystem may begin or permanently end after such events if they are extreme enough, or they may form part of the cycle of continual dynamism and change in an ecosystem.

3.5.4.5 ECOSYSTEMS ARE ORGANISED IN DIFFERENT HIERARCHIES AND SCALES

Dynamic hierarchical structures in ecosystems (Klijn and Udo de Haes, 1994, Miller, 2008) are linked with increased dynamic stability, therefore enabling them to adapt more rapidly and persist through time in various states (Peterson, 2000) (section 3.4.3).

Organisms in natural systems operate at different scales. These are governed by different principles of physics (Vogel 1998, pages 39-57, Thompson, 1942). What works on small scales for a living organism might not work or be appropriate for human technology (Vogel 1998). Human mechanisms operate at a different scale from most of nature though there are large

FIGURE 48 DRAGONFLY (PHOTO BY: ROB BARBER).

overlaps (Vogel, 2003). Nature typically employs diffusion, surface tension, and laminar flow while gravity, thermal conductivity and turbulence are used more frequently in human technologies, which typically are larger. Flight is a good example

of the issue of scale. A dragonfly (*Anisoptera* Infrorder) (figure 48) or bird scaled up to a size useful for human aircraft will simply not work¹⁴⁴. Both Galileo Galilei and D'Arcy Thompson¹⁴⁵ studied and recorded the effects of scale on organisms extensively (Vogel, 1998, page 39).

3.5.4.6 ECOSYSTEMS AND ORGANISMS USE CYCLIC PROCESSES IN THE UTILISATION OF MATERIALS

Processes in ecosystems tend to be cyclic and related to, integrated with, and have an influence on larger geochemical cycles such as the hydrological cycle, the nitrogen cycle and the carbon cycle (Harding, 2001). Because of the cyclic nature of ecosystems and the complex relationships and feed-back mechanisms between organisms and between organisms and the overall system, non-reusable or non-absorbable waste is avoided (Kibert et al., 2002, page 19). Ecosystems tend to recycle materials or matter so that the wastes of one organism become the nourishment of the next.

Odum (1969) and Allenby & Cooper (1994) discuss the critical importance of detritus, or waste as part of food webs and as a method for nutrient cycling in mature ecosystems. Organisms whose function is to recycle waste in a system are critical to the health of the entire community (Allenby and Cooper, 1994). Kibert et al. (2002, page 16) point out that natural systems exist in connected, different scales and that once a life cycle of birth, living and death has occurred at one scale, the material used can be metabolised and reused at another. This is a point closely linked with the fact that mature ecosystems tend to enhance the capacity of the biosphere to support life.

¹⁴⁴ Despite issues with scale several researchers and scientists examine various insects as models for flying craft and spaceships (Allen, 2010, page 162, Scott and Ellery, 2004).

¹⁴⁵ D'Arcy Thompson is an often cited reference in biomimicry literature for his 1942 work 'On Growth and Form'. Vogel (1998, page 41) refers to Thompson's work as: '*Unquestionably the best known work on mechanical aspects of biology*'. He further states: '*As biology it is strange and anachronistic, a search for a kind of geometric perfection in nature to which evolution by natural selection is largely irrelevant. Non-biologists such as architects often assume that 'On Growth and Form' is in the mainstream of biology or biomechanics. So I hasten to explain that Thompson is a much-loved godfather rather than someone whose intellectual genes we proudly carry.*'

3.5.4.7 ECOSYSTEMS OFTEN HAVE IN-BUILT REDUNDANCIES

In both ecosystems and individual organisms there may be a level of redundancy to allow for adaptation to changing conditions at different rates. Some ecologists describe this as the 'insurance effect' (Loreau et al., 2001). It is the (once) vast bank of species that forms this 'insurance' for the continuation of ecosystem functions. Shear McCann (2000) states that:

'An ecosystem's ability to buffer perturbations, loss of species and species invasions is dependent on the redundancy of the species having important stabilising roles, as well as on the ability of the species in the community to respond differentially to perturbations...'

Although it is thought that not every species in an ecosystem plays a crucial role in its functions, it is accepted there is a generally poor understanding of the precise roles most species or groups of species have in the processes and functions of healthy ecosystems, from erosion prevention and nutrient cycling, to formation of precipitation and wind patterns. Even rare species in ecosystems may have special traits necessary to ecosystem function that come to the fore only in times of disturbance, upheaval, or gradual change in other species or in the ecosystem itself (Baskin, 1998, Levin, 1999, page 167).

In individual organisms there are many examples of certain internal redundancies, such as extra bones, ribs or organs. Double organs, such as eyes, ears, and kidneys, ensure the function they provide continues, even if less effectively, in the event of damage to one of the organs.

This 'insurance' works at a larger scale, where each element in an ecosystem is supported by several others. An example is an epiphyte in a forest (figure 49). The epiphyte is supported by a tree or several trees and is fed by rainwater, sunlight, decomposing insects, and other nutrients it can source. It may be dependent on

FIGURE 49 FOREST EPIPHYTES (PHOTO BY: BREWBOOKS).

wind, birds, or insects to distribute its seeds. It provides habitat for insects within specific ecosystem niches, may catch and store water, makes and holds soil, feeds insects and possibly birds with its fruit, seeds and leaves, and feeds the tree, soil and additional insects when its parts decompose and become part of the food web. Just as the epiphyte needs various elements from its environment to survive, so does the wider ecosystem need it to support in part, other elements in the system.

3.5.4.8 PARTS OF ECOSYSTEMS AND ORGANISMS ARE OFTEN MULTI-FUNCTIONAL

In an example of both material and energy effectiveness, organisms in ecosystems tend to use materials for more than one function. This means less energy is expended and can be used for other functions such as health, growth and reproduction. If materials can constantly adapt to changes, then less material has to be grown or utilised for survival.

For example the surface of a leaf has several functions (Koch et al., 2009). It may enable the exchange of gases, protection from contamination and pathogens, signals to be given to other organisms, transportation or limitation of uncontrolled water loss or leaching, self-cleaning properties, reduction of attachment or movement of insects,

protection against solar radiation, resistance against mechanical stress (caused by wind), gathering of energy (photosynthesis), and reduction of surface temperature by increasing turbulent air flow over the boundary air layer (figure 50).

FIGURE 50 MULTI-FUNCTIONS OF PLANT SURFACES (SOURCE: KOCH ET AL., 2009).

FIGURE 51 WETLAND IN THE MINGO NATIONAL WILDLIFE RESERVE, MISSOURI (PHOTO BY: ANON.).

Parts of ecosystems themselves are also multi-functional. A wetland (figure 51) will provide habitat for certain organisms but can also retain nutrients, sequester carbon, contribute to improved air and water quality, maintain species diversity, reduce storm water run-off, retain sediments, stabilise shorelines, recharge groundwater, and treat and recycle 'wastes', among other functions (Turner et al., 2008).

3.5.4.9 LOCAL ENERGY SOURCES AND RESOURCES BECOME SPATIAL AND TEMPORAL ORGANISATIONAL DEVICES

Local resources or energy sources, of which the sun is normally the most predominant, act as timing and directional orientation or spatial organisation mechanisms in ecosystems. Biological rhythms such as diurnal and annual (or longer) cycles are determined by factors including the sun's gravitational effect and the rotation of the earth. The Earth's yearly journey around the sun and its axial tilt create the condition of annual seasonal changes. Animals and plants are typically able to respond to these changing conditions¹⁴⁶. Migration and hibernation patterns or flowering seasons in some species, in response to these cycles, are examples of the role the sun (or the Earth's relative position to it) has in timing mechanisms in ecosystems (Palmer, 2002).

Palmer (2002) describes experiments proving that plants respond to the length of nights (the absence of light) to adjust their flowering seasons. Carl Linnaeus, the noted biologist who devised the common system of binomial nomenclature¹⁴⁷, designed an intricate flower clock or 'horologium florum' in 1751¹⁴⁸ (figure 52). He

¹⁴⁶ Jeffrey Palmer, a chronobiologist, and Professor of Biology, asserts that plants, animals and even individual organs have biological clocks. He states that: *'All plants and animals have... timepieces; living clock control is ubiquitous throughout the organic world. Thus if we are to truly understand living things we must comprehend their clocks. Until this task is accomplished, humanity will lack an exceedingly important key to understanding life.'* (Palmer, 2002, page xii). Guy Warman of the University of Auckland also explores this (Putterill, Stockum, and Warman, 2009).

¹⁴⁷ This is the formal system of naming species of living things using two words based on Latin grammatical rules.

¹⁴⁸ Linnaeus published his findings in *Philosophical Botanica* in 1751. He found three groups of flowers: 1) Meteorici flowers which change their opening and closing times according to weather conditions; 2) Tropici flowers which change their opening and closing with the length of the day; and 3) Aequinoctale flowers which have fixed times for opening and closing. His theory was that if Aequinoctale flowers were arranged in a certain way it would be possible to read the time.

Plants and animals are able to sense the time of day, without necessarily seeing or feeling the sun, enabling greater efficiencies and even survival. Examples are found in diurnally vertical migrants¹⁴⁹ in seashore situations (Palmer, 2002). Many tidal zone plants and animals live by cycles relative to tides and therefore the moon. Examples include crabs (*Brachyura* infraorder)

and tiny marine creatures that have tidal vertical migration patterns relative to tide and the diurnal day/night cycle (Manuel and O'Dor, 1997).

FIGURE 52 LINNAEUS FLOWER CLOCK AT WINTERBOURNE BOTANICAL GARDENS, BIRMINGHAM (PHOTO BY: DEFINING MOMENTS IMAGES).

FIGURE 52 LINNAEUS FLOWER CLOCK AT WINTERBOURNE BOTANICAL GARDENS, BIRMINGHAM (PHOTO BY: DEFINING MOMENTS IMAGES).

¹⁴⁹ This refers to animals that move up or down in the sand over the course of a day.

FIGURE 53 EUROPEAN ROBIN (PHOTO BY: LEE HAYWOOD).

In addition to being a timing mechanism to set biological clocks in nature, the sun also functions as a directional orientation or spatial mechanism. There are noted scientific experiments that conclude that some birds use the relative position of the sun in the sky, in combination with an internal biological clock to navigate. This is often referred to as 'sun compass

orientation' (Palmer, 2002, pages 100 - 102). Some birds are thought to navigate by a combination of the sun, and the earth's magnetic field. Pigeon (*Columbidae* family) beaks for example contain magnetite, which may help them use the Earth's magnetic field. Other birds such as the European Robin (*Erithacus rubecula*) (figure 53) have special proteins on their eyes called magnetoreceptors that can detect magnetic fields¹⁵⁰ (Plicher, 2004). Similar strategies for navigation can be found in certain fish species such as salmon (*Oncorhynchus nerka*), who have small iron deposits in their heads (Yano and Aoyagi, 2008).

Many plants grow or move leaves towards (or away) from the sun, enabling greater photosynthesis efficiency or other advantages. Some leaves are able to follow the path of the sun over a day. This is termed diaheliotropism, paraheliotropism, or heliotropism depending on the exact movement and mechanisms involved. The sun acts at times as a beacon for sensory mechanisms in plants, organising growth direction. Indoor plants are an excellent example of this. If a plant is moved to a different place, the plant will gradually twist itself round or change growth direction to face the sun.

¹⁵⁰ Some birds follow highways and use landmarks in journeys they have made before in addition to solar and magnetic navigation methods. It is thought that although following roads and railway lines adds distance to their journey, it may be mentally easier, allowing them to focus on other tasks such as watching out for predators (Lipp et al., 2004).

FIGURE 54 KIRCHER'S FLOWER CLOCK (SOURCE: CHEMICAL HERITAGE FOUNDATION OTHMER LIBRARY AND SPECIAL COLLECTIONS).

Perhaps one of the most famous, though not a totally scientifically accurate example of this phenomenon, is another kind of flower clock created by Athanasius Kircher (figure 54). The German Jesuit priest lived in the 15th Century and invented a clock where he:

'Floated a potted sunflower in a vat of water and stuck a needle in the stem, which then pointed to the hour marked on the edge of the device as the plant rotated freely to follow the sun across the sky' (McLeemee, 2002).

Wind and rain patterns, which are dependent on solar radiation, are also important

organisational factors in ecosystems, determining where and in what formation organisms are able to inhabit a microclimate in an effective and least energy consuming way. Some leaves, for example, will curl in response to strong winds to minimise damage to them (Vogel, 1998, pages 96-97).

3.5.4.10 ECOSYSTEMS AND THE ORGANISMS WITHIN THEM GATHER, USE AND DISTRIBUTE ENERGY EFFECTIVELY

Although matter and nutrients can be cycled in ecosystems, energy cannot, as governed by the second law of thermodynamics. The second law encompasses the

concept that the total entropy of isolated thermodynamic systems increases over time, approaching a maximum value (Allen, 2002, page 109). This means that although energy cannot be lost according to the first law of thermodynamics because it changes form, every transformation of energy causes a part of the energy to be converted to heat that then dissipates. This means energy must be constantly fed into a system and that energy cannot be cycled for an infinite number of uses in a system, as matter potentially can. Energy is not cycled but rather is cascaded through a system (Korhonen, 2001).

Solar energy is transformed by plants through photosynthesis into sugars and carbohydrates. What is available to the next step up in the food chain (herbivore) is about 10% of the energy initially captured by the plant. The amount of energy available to the level after that (carnivore) diminishes again by 90% (Benyus, 1997, page 261). The fact that the energy available diminishes as it cascades through the food chain (upwards) is a factor explaining why plants tend to make up the vast proportion of biomass in most ecosystems and why large carnivorous animals are rare (Colinvaux, 1979).

Biological systems degrade energy in a large number of small steps, rather than in a small number of large steps as tends to be the case in human systems. These pathways of dissipation tend to be highly deliberate and important to the overall system. This allows energy left after one organism (or part of an organism) has done work to be utilised by another, so effective energy use is maximised.

'If there is free energy left after some work has been done, then biological systems will get more work out of that energy, gradually lowering the quality of the energy so as to extract as much work as possible. In fact, the structure of complex... systems often reflects that process of eking out more work for the passage of materials or energy down the gradient' (Allen, 2002, page 119).

Allen (2002, page 119-120) uses the example of the counter-current heat exchange organisation of blood vessels in a wolf (*Canis lupus*) (figure 55):

'The warm blood leaving the core of a wolf to its feet is run beside cold blood returning from the wolf paw. By the time that blood reaches the foot it is already cold, and so loses less heat to the ice and snow. The blood in the paw has already donated its heat to warm the returning blood. The transfer of the heat is passive, and comes about because of carefully organised juxtapositioning of veins against arteries.'

FIGURE 55 WOLF (PHOTO BY: PETER BOND).

When the predominant energy source for ecosystems (sunlight converted by photosynthesis) is considered¹⁵¹, it is apparent that the drive to be energy efficient or effective in natural systems is different from the need for humans to be energy efficient. Because solar energy, converted by photosynthesis into usable foods for plants and animals, essentially forms the basis for the entire ecosystem network on the planet, it

is not problematic or damaging to use more energy to produce, for example, abundant amounts of seed pods and blooms where fewer would have been sufficient for a particular plant's reproductive success. Being less energy efficient in this way does not impact on the amount of energy available for other uses, nor does it pollute

¹⁵¹ The earth itself receives an estimated one or two-billionth of the energy emitted from the sun daily. Of this, roughly one third is reflected back into space. In one minute the earth receives more energy from the sun than used by the entire human population in one year (Sen, 2004). Albert Einstein is attributed with the quote: 'The amount of sunlight reaching the earth's surface is 6,000 times the amount of energy used by all human beings worldwide. The total amount of fossil fuel used by humans since the start of civilization is equivalent to less than 30 days of sunshine'. Land and water is warmed by the sun's energy as it changes from light into heat. The entire hydrologic cycle runs on approximately 25% of available energy; wind and ocean currents are powered by 1% of available energy (Benyus, 1997) and photosynthesis (which is 95% efficient at converting sunlight into usable energy) uses 0.1% of available energy from the sun (Sen, 2004). The small amount of energy utilised for photosynthesis is still ten times greater than worldwide human energy consumption.

(figure 47). Despite this, organisms and flows in nature (such as the movement of water and air for example) generally follow paths of least resistance to minimise energy expenditure, or energy loss (Bejan, 2000, Mathews, 2011). The importance of this is explained by Mathews (2011):

‘Organisms that succeed in fulfilling their conative ends [impulse to stay alive] while least provoking resistance on the part of others will be those best able to conserve their own energy, leaving them with greater energy to invest in other forms of self-maintenance and self-increase relative to organisms whose activity provokes greater resistance. They will also best conserve their environment, in the sense that their activities will least compromise the conativities of the other elements of their life-support system. The path of least resistance is in this sense the logical path for conative entities to follow, so it is the path that will be naturally selected for them: They evolve an existential disposition that leads them to favour this modality’.

Another aspect of effective energy use in natural systems is related to the specific use of energy, particularly in contrast with human energy use. Ecosystems tend to use energy for growth, maintaining health and reproduction. This relates closely to the fact ecosystems tend to enhance the life carrying capacity of the surrounding environment rather than damaging it as they function (section 3.5.2.3). Noted physicist Amory Lovins sums up the implications of mimicking this aspect of ecosystems:

‘If I were to come back in fifty years’ time and find that we had extremely efficient factories making napalm and throwaway beer cans, I’d be very disappointed, because it would mean that we hadn’t addressed a parallel agenda of what’s worth doing with all that energy’ (Benyus, 1997, page 262).

3.5.4.11 THE FORM OF ECOSYSTEMS AND ORGANISMS IS OFTEN A RESULT OF FUNCTIONAL NEED

Reap et al. (2005) describe the characteristic of form fitting function as:

'The use of limited materials and metabolic energy to create only structures and execute only processes necessary for the functions required of an organism in a particular environment.'

Biological evidence for this is cited in Reap et al. (2005) from the protein, cellular and macroscopic level in plants and animals. The geometry and relative proportions found in nature as related to function were offered up as examples of material and energy efficiency by Buckminster Fuller (Baldwin, 2007). Honeycomb is an often given example of a natural form using the least amount of material to facilitate a necessary function (Hersey, 1999, page 65). Further examples are found in Vogel (1998) and Dcozi (1995).

FIGURE 56 PEACOCK (PHOTO BY: PEDRO MOURA PINHEIRO).

Ecosystems and organisms tend to use materials effectively for a specific function. There are some flamboyant forms in nature, such as a peacock's (*Pavo* genus) fan (figure 56), or bower birds' (*Ptilonorhynchidae* family) elaborately decorated nests. Although not necessarily an example of the most efficient use of materials, the display in both cases helps to attract mates for reproduction (von Frisch and von

Frisch, 1974, pages 221-250). Similar examples are found in defensive strategies in some organisms. The overall use of material in a blowfish (*Tetraodontidae* family)

(figure 57) may not efficient but when the body is inflated, the fish appears to be larger and this forms an effective defence mechanism to scare off predators. Although inefficient on one level, such apparent overuse of material is effective in terms of an organism's overall success in reproduction to ensure genetic survival. Excessive materials used are easily incorporated back into the food chain for the use of other organisms at other scales.

Another example of material effectiveness is the use of structure to make colour rather than pigment. In animals such as the Morpho butterfly (*Morpho* genus) (figure 58), beetles, and some shells, such as the abalone (paua), colour is created by colourless crystalline structure within the surface of the material. This means that, unlike colour created by pigment, it will not fade over time or in ultra violet light (Pawlyn, 2011, page 37). Using structure to make colour also ensures the colour is able to change relative to a viewer's position, working like an optical prism. The colour is created by the size of the crystals and is able to shift and change with light (Vukusic et al., 2000). This means less pigment and less material is required to replace faded pigment (Pawlyn, 2011, page 37).

FIGURE 57 BLOWFISH (PHOTO BY: ALANA LEW).

FIGURE 58 MORPHO BUTTERFLY (PHOTO BY OPENCAGE).

3.5.4.12 ORGANISMS THAT MAKE UP ECOSYSTEMS ARE TYPICALLY MADE FROM COMMONLY OCCURRING ELEMENTS

Living organisms tend to be made up of commonly occurring elements such as carbon, hydrogen, nitrogen, and oxygen. Sulphur, calcium, phosphorus, iron, and sodium are also utilised in lesser amounts (Adriano, 2001, Vincent, 2010). Such trace elements are generally sourced from the surrounding environment in the form of nutrients from food, soil or water.

Much of the structure of organisms is made up of proteins (polypeptides) such as collagen, elastin and keratin. Proteins are made of amino acids most of which are carbon, hydrogen, nitrogen and oxygen in different formations. Different arrangements of these simple elements make up the huge variety of bones, horns, feathers, beaks, shells, hair, fur and hooves as well as cartilage and connective tissue seen in living organisms. Other proteins serve motility functions in bodies such as myosin, kinesin and dynein (Matthews and van Holde, 1990). Once used, materials can be reabsorbed in a cycle of growth and decay without the accumulation of poisons in the system, or the expending of energy to obtain rare elements. The majority of non-human chemistry takes place in water. Levin (1999, page 31) points out that water was necessary for the development and evolution of early life forms and that water remains necessary for maintaining the conditions humans (and other life forms) need for survival.

3.6 ECOSYSTEM PROCESSES THAT MAY CONTRIBUTE TO CLIMATE CHANGE AND LOSS OF BIODIVERSITY RESPONSES IN THE BUILT ENVIRONMENT

Although many aspects of ecosystems may be suitable for designers to investigate in the creation of regenerative built environments, features of ecosystems that make them resilient and adaptable could be specifically useful in the context of adapting to climate change. By using the relationship matrix chart of ecosystem processes (figure 34), these were identified and are represented in figure 59.

FIGURE 59 ECOSYSTEM PROCESSES OF ADAPTATION AND RESILIENCE.

FIGURE 60 THE ECOSYSTEM PROCESSES OF THE CAPACITY OF THE BIOSPHERE TO SUPPORT LIFE.

Aspects of the processes of ecosystems that could add to strategies to mitigate the causes of climate change and address loss of biodiversity relate to the fact that ecosystems enhance the capacity of the biosphere to support life, and functioning and processes in ecosystems and within organisms tend to be benign. Processes that contribute to this are represented in figure 60.

These two examples illustrate how the relationship matrix diagram can be used to target specific issues. They also demonstrate that because processes in ecosystems are linked, focusing on one specific process at a higher level inevitably means most lower level processes are important. It is not surprising for example that many ecosystems processes enable ecosystems to be adaptable, because a constantly changing environment is the context that ecosystems must respond effectively to in order to survive and thrive (Gunderson and Holling, 2002).

3.7 APPLYING ECOSYSTEM PROCESS TO A BUILT ENVIRONMENT CONTEXT

Table 7 lists ecosystem processes and suggests how these might be interpreted in a built environment context. Ecosystem biomimicry at the process level provides a clear and logical framework to apply existing technology or design strategies for a more thorough approach to increasing the sustainability of the built environment, if it can be proven that a built environment that works like an ecosystem will be more sustainable in the long term. Potential case studies and additional research sources are also suggested in the table. Table 7 makes implicit the further potential of processes level ecosystem biomimicry and demonstrates (along with descriptions in section 3.5) that the development of new technologies might not be needed to create regenerative built environments that incorporate an understanding of ecosystem processes. This means designers can use the myriad of existing technologies and design methods available. For example if designers were to attempt to base a project on the ecosystem process of being dependent upon and responsive to local conditions, they could draw upon several established design techniques or concepts

TABLE 7 ECOSYSTEM PROCESS STRATEGIES FOR THE BUILT ENVIRONMENT TO MIMIC

Ecosystem process strategies for the built environment to mimic:		Climate change / biodiversity implications:	Additional sources / case studies of built environment design that include an understanding of this process:
1. Ecosystems adapt and evolve within limits at different levels and at different rates.	<ul style="list-style-type: none"> Re-define when developments are considered as finished and design them to be more dynamic over time. Plan for and allow constant change. Design systems that incorporate a level of redundancy to allow for added complexity to evolve over time. Increase the ability of the built environment to be able to respond to new conditions, preferably passively. 	<ul style="list-style-type: none"> Planning for change allows for easier adaptation. Less pollution of ecosystems and atmosphere related to demolition and construction waste may occur. Less pollution or habitat destruction caused by production and transportation of new materials. 	Altomonte (2008), Gill et al. (2007), Hamin and Gurrán (2009), Hunt (2004), Nottage et al. (2010), Roaf et al. (2005), Steemers (2003), Walker et al. (2004).
2. Ecosystems enhance the capacity of the biosphere to support life and functioning and processes in ecosystems and within organisms tend to be benign.	<ul style="list-style-type: none"> Production and functioning should be environmentally benign. Employ the precautionary principle when there is doubt. The development should enhance the biosphere and community as it functions. Consider the built environment as a producer of energy and resources, and adapt it over time to nurture increased biodiversity in the urban environment. Integrate an understanding of ecosystems and systems in general into decision making processes. Use only biodegradable or recyclable materials (be aware of composite materials that mix the two). 	<ul style="list-style-type: none"> Healthier ecosystems mean better life support systems for humans and greater potential to adapt as the climate changes (Kibert et al., 2002). Buildings that contribute to the regeneration of the atmosphere so that acid rain and extreme weather is reduced means less damage to people, buildings and infrastructure and therefore less waste of energy and materials. Less pollution or habitat destruction caused by production and transportation of new materials and 'waste'. 	Benedict and McMahon (2006), Birkeland (2008), Busby et al. (2011), Cole et al. (2012), Gill et al. (2007), Kibert et al. (2002), McDonough and Braungart (2002), Todd et al. (2003).
3. Ecosystems are resilient. They can persist through time even as components within them change.	<ul style="list-style-type: none"> Plan for change over time. Create performance goals related to different time scales. Integrate built environments with ecosystems to sustain or increase resilience. 	<ul style="list-style-type: none"> More effective human adaptation to some of the impacts of climate change. Less destructive human disturbance of ecosystems. Increased opportunities for humans to interact with and possibly begin to restore local ecosystems. 	Brand (1994), Folke, 2006), Kibert et al. (2002), Newman et al. (2009), Portland Development Commission (2004).
4. Ecosystems are diverse in species, relationships and information.	<ul style="list-style-type: none"> Increase diversity to increase resilience. Create and foster a variety of relationships in the development and with groups outside it. Utilise opportunities to create self-organising and distributed systems. Translating this ecosystem process into the built environment implies a systems approach to architectural design where the facilitation of relationships between buildings, components, people and ecosystems is as important as designing the individual buildings themselves. 	<ul style="list-style-type: none"> More robust built environment and community able to adapt to climate change. Decisions based on a broader knowledge base are likely to be more sustainable (Wahl and Baxter, 2008). 	Berkebile and Hoxie (2012), Cole et al. (2012), Hoxie et al. (2012), Plaut et al. (2012), Svec et al. (2012), Gifford (2007), Walker et al. (2004), Moffatt and Kohler (2008), Pickett et al. (2008), Alberti et al. (2003), Leaman et al. (2010), Francis (1999).
5. Ecosystems are self-organising, decentralised and distributed.	<ul style="list-style-type: none"> Decision making could become more localised and independent to reflect local changes and conditions. Power generation and distribution may become more decentralised. 	<ul style="list-style-type: none"> More awareness of local ecology and climate issues and opportunities to address them. Less use of fossil fuels to generate energy and fewer GHG emissions. 	Allen (2002), Allen et al. (1999), Allen (2010), Gruber (2011), Kibert et al. (2002).
6. Ecosystems function through the use of complex feedback loops or cascades of information.	<ul style="list-style-type: none"> Building systems and systems connecting buildings should be designed to incorporate some level of redundancy to allow for added complexity to evolve over time, increasing the ability of the built environment to respond to new conditions throughout time and become partially self-maintaining. 	<ul style="list-style-type: none"> A built environment more able to adapt to changing conditions may last for longer periods, reducing pollution and habitat destruction created by new building. A more rapidly responsive built environment to local conditions may be less damaging to ecosystems. 	Allen (2002).
7. Organisms within ecosystems operate in an interdependent framework.	<ul style="list-style-type: none"> Applying this ecosystem process to the built environment would require a redefinition of building boundaries to ensure a cooperative system emerges. 	<ul style="list-style-type: none"> More effective integration of human systems with ecosystems to the mutual benefits of both. 	Rees (1997), Kibert et al. (2000), Newman (1999).
8. Ecosystems and the organisms within them optimise the whole system rather than maximise components.	<ul style="list-style-type: none"> Cycle matter and transform energy effectively. Materials and energy should have multiple functions. A built environment that mimicked this aspect of ecosystems through multifunctional use, closed loop functionality and overall system optimisation to ensure effective material cycles and careful energy flow would beneficially challenge conventional attitudes to building boundaries and the idea of waste. 	<ul style="list-style-type: none"> Reduced use of energy and materials. Reduced need for mining/growing/production of new materials and energy. Reduced waste, all of which lead to reduction of GHG emissions and less ecosystem disturbance. 	Allenby and Cooper (1994), Bisch (2002), Bogunovich (2002), Graedel (1999), Hermansen (2006), Bringezu (2002), Jacobsen (2006), Kay (2002), Korhonen (2001), Newman (1999).

Ecosystem process strategies for the built environment to mimic:		Climate change / biodiversity implications:	Additional research sources / case studies of built environment design that include an understanding of this process:
9. Ecosystems and organisms are dependent upon and responsive to local conditions.	<ul style="list-style-type: none"> Source and use materials locally and use local abundances or unique features as design opportunities. A thorough understanding of a particular place would be required and local characteristics of ecology and culture should be seen as drivers and opportunities in the creation of place. 	<ul style="list-style-type: none"> Reduced transport related GHG emissions. Potentially less disruption to ecosystems and biodiversity if impacts of mining / deforestation are visible and understood by people driving demand for the products of those activities. More robust local communities and economies able to adapt to climate change impacts. 	Copeman (2008), Eigenbrod et al. (2011), Francis (1999), Hoxie et al. (2012), Leaman (2010), Mang and Reed (2012), Mathieu et al. (2007), Oliver (1997), Reed (2007), Swaid et al. (1993), Yeang (1994),
10. Living organisms within ecosystems are resourceful and opportunistic. Abundances or excesses are used as a resource.	<ul style="list-style-type: none"> Source energy from current sunlight, or other renewable sources. Understand locally available materials sources or geographical or climatic features than can aid in the design of regenerative urban environments. Design to enable buildings (or urban environments) to respond more effectively to ecological cycles and climatic conditions. 	<ul style="list-style-type: none"> Increased energy effectiveness leading to a reduction of GHG emissions used to operate buildings. Less damage done to ecosystems. 	Allen (2010), Benyus (1997), Eigenbrod et al. (2011), Twin (2003).
11. Ecosystems and the organisms within them have the capacity to learn from and respond to information and self-assemble.	<ul style="list-style-type: none"> Design to enable the building (or people with in it) to respond to changing conditions (preferably passively). Allow for adaptable and diverse user control (ability to open windows). Buildings should be able to respond to changing social conditions. Feedback mechanisms such as post occupancy evaluations are important. Consider use of materials or building systems that have more rather than less value as they age. 	<ul style="list-style-type: none"> More cared for and utilised buildings will last longer resulting in less waste of materials. This could translate into fewer GHG emissions (through transporting and manufacturing materials) and less disturbance to ecosystems (through mining, pollution, and land use changes to source new materials and through pollution attributed to waste). 	Armstrong (2009), Gebeschuber (2009), Gruber (2011), Kibert et al. (2002).
12. Ecosystems and the organisms with them have the capacity to heal within limits.	<ul style="list-style-type: none"> Integrate user or building feedback mechanisms into building maintenance regimes. Consider self-repairing or cleaning materials if appropriate. 	<ul style="list-style-type: none"> More cared for and utilised buildings will last longer resulting in less waste of materials. Potentially more energy and materially effective built environments. 	Allen (2010), Armstrong (2009), Benyus (1997), Gruber (2011), Pawlyn (2011).
13. Ecosystems often have in-built redundancies.	<ul style="list-style-type: none"> Redundancies for future changes need to be balanced against energy and material effectiveness considerations of the present. Consider possible future societal needs or technological changes. Plan for multiple energy generation possibilities and the utilisation of multiple energy sources. Consider adding some redundancy to structural capacity if there is a possibility for addition over time or if buildings are designed to be perdurable or exist when climate change impacts become more severe. Design to facilitate easy adaptation and transformation in use of space over time. Allow for generous, non-programme specific allocation of space if possible. 	<ul style="list-style-type: none"> A more adaptable and resilient built environment as the climate continues to change. Reduced negative environmental impact from the built environment. Reduced pressure on ecosystems distant from urban areas to provide certain ecosystem services (such as energy generation). 	Brand (1994)
14. Variety can occur through emergent effects (rapid change).	<ul style="list-style-type: none"> Design for increased complexity rather than complicatedness. Create or utilise positive (reinforcing) feedback loops within organisations, and buildings. Include factors external to a localised system (i.e. building) when planning organisational models. Such factors may include wider societal issues and wider climatic and ecological issues. Consider information based (digital?) relationships between elements rather than solely mechanical ones. Allow interior environments to be dynamic (consider temperature, light levels etc.). 	<ul style="list-style-type: none"> A built environment able to adapt to changes more rapidly (such as climate change impacts). A more energy and materially effective built environment. More psychologically healthy human population. 	Allen (2002), Allen (2010), Gruber (2011), Kibert et al. (2002).
15. Variety can occur by recombination of information and mutation (gradual change).	<ul style="list-style-type: none"> New architectural and urban design should build upon the successes of the best examples of sustainable architecture and sustainable building technologies rather than repeat patterns of conventionally performing buildings. Successes from vernacular or traditional forms of building should be examined because many of these rely on passive techniques rather than high amounts of external energy to function. Buildings and urban environments should be designed to enable gradual change over time. 	<ul style="list-style-type: none"> More adaptable built environment in terms of climate change. Less generation of waste as buildings become obsolete or unsuitable would have positive climate change mitigation implications as well as biodiversity health implication because less mining and transportation would need to occur to produce building materials. 	Altomonte (2008b), Gill et al. (2007), Hamin and Gurrán (2009), Hunt (2004), Nottage et al. (2010), Roaf et al. (2005), Steemers (2003b), Walker et al. (2004).

Ecosystem process strategies for the built environment to mimic:		Climate change / biodiversity implications:	Additional research sources / case studies of built environment design that include an understanding of this process:
16. Ecosystems are organised in different hierarchies and scales.	<ul style="list-style-type: none"> The built environment is already good at understanding different scales. Match the intensity of building activities with cycles of ecosystems (for example use long lasting materials and construction methods where buildings will remain long term). Plan for changes, additions, new uses, increased performance over short, medium and long time frames. 	<ul style="list-style-type: none"> A more adaptable and less energy and materially intensive built environment will have positive implications for both climate and biodiversity within ecosystems. 	Allen (2010), Gruber (2011), Pawlyn (2011), Vogel (1998, 2003), Vincent (2010).
17. Ecosystems and organisms use cyclic processes in the utilisation of materials.	<ul style="list-style-type: none"> Buildings should be constructed to allow for future reuse or recycling in separate nutrient streams (i.e: decomposition in the biosphere and closed loop recycling in the 'technosphere'). Design for deconstruction. Buildings should utilise reused or recycled building materials. Minimise the use of composite materials and the number of materials in buildings. Records should be kept of which materials are used when buildings are constructed (so these can be identified later at the end of the building life). Consider the entire life-cycle of a material when specifying it. Consider 'take back' schemes relevant for a built environment context. Buildings should facilitate easy circulation of materials that people use within them. 	<ul style="list-style-type: none"> More effective material use would have a positive impact on both mitigating the causes of climate change and on ecosystem health. Less generation of waste could mean less pollution of ecosystems. 	Allenby and Cooper (1994), Baas (2008), Bisch (2002), Bogunovich (2002), Derochers (2001), Graedel (1999), Gruber (2011), Hermansen (2006), Jacobson (2006), McDonough and Braungart (2002), Nakajima (2000), Pawlyn (2011), Spiegelhalter and Arch (2010), Wernick (2002).
18. Parts of ecosystems and organisms are often multifunctional.	<ul style="list-style-type: none"> Consider how space can be used more effectively by allowing for different activities to occur at different times of the day/night or year. Plan for adaptive or transformational responses to the different needs of people. Allow for future adaptive reuse. Consider buildings not just as shelters of humans but also providers of energy and food, purifiers of air and water, sequesters of carbon, providers of habitat for non-humans. 	<ul style="list-style-type: none"> More effective use of materials and energy could translate into less GHG emissions and less ecosystem disturbance (due to sourcing and distributing both energy and materials). A more adaptable built environment may be better suited to future climate change impacts. Less pressure on ecosystems to provide humans with ecosystem services. 	McDonough and Braungart (2002), Gruber (2011), Vogel (1998).
19. The form of ecosystems and organisms is often a result of functional need.	<ul style="list-style-type: none"> Consider reducing the amount of material or energy in designs that results in a stylistic or aesthetic response to fashion trends. Consider psychological human well-being in design. 	<ul style="list-style-type: none"> Reduced GHG emissions through energy use and transportation of materials Reduced ecosystem damage through materials use 	Allen (2010), Heerwagen (2003, 2005), Kellert (2005), Kellert et al. (2008), Mattheck (1998), Pawlyn (2011).
20. Living organisms that make up ecosystems are typically made from commonly occurring elements.	<ul style="list-style-type: none"> Materials used in built environments should be non-toxic (to use or make), benign, and made from materials that are not rare or difficult to extract and are renewable unless they can be recycled indefinitely. 	<ul style="list-style-type: none"> Reduced mining / extraction of difficult to source materials and therefore fewer disturbances to ecosystems. Reduced pollution of ecosystems through toxic waste / emission. Healthier and therefore more resilient biodiversity (and humans). 	Allen (2010), Benyus (1997), McDonough and Braungart (2002).
21. Ecosystems and the organisms within them gather, use and distribute and energy effectively.	<ul style="list-style-type: none"> Attention should be given not just to energy efficiency and the generation of energy within urban environments but also to how energy is moved, shared and dissipated to ensure maximum effectiveness. Consider using 'free energy' or 'waste' energy from one process to power another. Elaborations to harness this energy (preferably passively) may become structural or more physically apparent within or between buildings. 	<ul style="list-style-type: none"> Reduced GHG emissions from the burning of fossil fuels for energy. Reduced pollution / damage of ecosystems through mining, drilling and emissions from sourcing fossil fuels. 	Allen (2002), Allen et al., (1999), Gruber (2011), Kibert et al. (2002), McDonough and Braungart (2002)
22. Local energy / resource become spatial and temporal organisational devices.	<ul style="list-style-type: none"> Energy should be sourced from contemporary sunlight (including wind, hydro and biomass sources). Built environments should be sited and organised according to climate, utilising if possible unique features of the site to improve environmental performance outcomes. 	<ul style="list-style-type: none"> Reduced GHG emissions. Reduced energy use. Physical and psychological benefits (Kellert, 2005). Development more suited to a local context and less reliant on heating or air conditioning devices. 	Copeman (2008), Francis (1999), Hoxie et al. (2012), Oliver (1997), Leaman et al. (2010), Mang and Reed (2012), Reed (2007), Swaid et al. (1993), Yeang (1994).

such as: permaculture (Copeman, 2008); bioclimatic design (Swaid et al., 1993, Yeang, 1994); vernacular design (Oliver, 1997); participatory or integrated design (Francis, 1999); post occupancy evaluation techniques (Leaman et al., 2010); regenerative design strategies to develop a sense of place (Hoxie et al., 2012, Mang and Reed, 2012, Reed, 2007); and local ecology/geography/climate modelling (Dymond and Shepherd, 2004, Mathieu et al., 2007).

This is not to say that some examples of individual organism based biomimetic technologies do not have significant improved sustainability outcomes (section 2.7), but so do non-biomimetic sustainable technologies. The issue is not that humans need new technologies to solve problems regarding climate change and the loss of biodiversity (among other serious environmental problems) but rather that people need to apply what has already been developed, and reassess their consumption behaviour and relationship to ecosystems, so that the idea of sustainability becomes physically manifest in the built environment.

3.8 CONCLUSIONS: CHAPTER THREE

In this chapter a theoretical framework for the use of ecosystem biomimicry at the process level was devised and ecosystem processes were explored for their potential to become part of an understanding of ecology that could contribute to architectural or urban design. Key findings are that more work has been done in terms of translating ecosystem processes into a design context than on ecosystem functions (as explored in the next chapter), but that ecosystem processes may be complicated both to understand and use in a design context. Mimicking the processes of ecosystems may be difficult for designers because of the large amount of complex ecological information that has to be understood to do this meaningfully (Kibert, 2006).

Although several researchers advocate using an understanding of the processes of ecosystems in biomimicry (Benyus, 1997, Hoeller et al., 2007, Peters, 2011, Reap et al., 2005, Gruber, 2011) and industrial ecology literature (Hermansen, 2006, Graedel,

1999, Korhonen, 2001, O'Rourke et al., 1996, Nakajima, 2000) as well as in related fields (Kibert et al., 2000, McDonough and Braungart, 2002, Todd and Todd, 1993, Van Der Ryn and Cowan, 2007) its use is not wide spread. This is evidenced by a lack of examples that go beyond mimicking the materials cycling process of ecosystems (section 2.7.2.2). Some of the processes of ecosystems are still to an extent controversial within ecology literature. This adds an additional barrier to designers being able to use the processes of ecosystems as a basis for regenerative design.

Table 7 suggests that ecosystem biomimicry at the process level could be a way to give order and coherence to the myriad of methods used in the creation of sustainable architecture. This is because process level biomimicry is not prescriptive of specific technologies or design techniques, or strategies. Rather it provides goals regarding how built environments should work at an overall level of organisation. This means any suitable existing method or technology can be used to meet those goals. In a similar way, a built environment that utilised ecosystem biomimicry at a process level would not have set outcomes in terms of style or aesthetics. This means there is room for cultural expression to remain a part of architectural and urban design¹⁵².

If the mimicking of ecosystems to improve the sustainability outcomes of the built environment is the motivation for incorporating an understanding of ecosystems into design, then it is the outcomes, or functions of ecosystems, that should be the focus, not specifically how ecosystems work. Mimicking the processes of ecosystems could potentially result in better sustainability outcomes (Gebeschuber et al., 2009) but the danger exists that such efforts may remain at a shallow level. For example, a development that cycles matter, gathers and uses energy effectively and is able to adapt to changing conditions might be based upon an understanding of ecosystem processes. It may not have environmental performance outcomes that are any better overall than other 'sustainable' buildings or even conventional ones. Mimicking the

¹⁵² Fashion trends that result in the use of extra energy or materials and lead to waste due to demolitions to create them or when they become outmoded (Brand, 1994) rather than functionally obsolete, as is currently the case, would be prevented by a thorough ecosystem biomimicry approach because such practices would be specifically excluded from any ecosystem based and/or regenerative approach to design.

functions of ecosystems may also be easier because they are readily comprehensible and because many aspects of ecosystem functions are measurable and, if used as a basis for built environment design, may be easier when it comes to documenting positive results. Because of this the rest of the thesis will focus on understanding the functions of ecosystems rather than their processes (see: section 2.5 and table 4) for incorporation into a built environment context.

4.0 CHAPTER FOUR: EXAMINING ECOSYSTEM FUNCTIONS FOR A BUILT ENVIRONMENT CONTEXT

'Most industrial societies tend to disregard and devalue ecosystem [services], opting instead for a technological fix whenever environmental services falter. Lost services are replaced not with natural mimics but with engineering solutions: dams, reservoirs, waste treatment plants, air scrubbers, air conditioners, synthetic pesticides and fertilisers, and water filtration systems. Replacing natural systems that work for free with engineered systems powered by fossil fuels is enormously expensive, often problem plagued, and commonly impractical, especially in developing countries. Furthermore these systems seldom attempt to replace the full array of services supplied by the natural system.'

(Baskin, 1998, page 212).

4.1 INTRODUCTION

This chapter continues the research that began in chapter three examining ecosystem based biomimicry for its potential to contribute to the evolution of regenerative built environments. This chapter begins with the intention to ascertain whether analysing the urban built environment from the perspective of how ecosystems function could be a significant step towards the creation of a built environment where positive integration with, and restoration of, local ecosystems could be realised. The aim is to define ecosystem biomimicry at the function level and organise aspects of the theory in such a way that it becomes useful as a practical tool for research, evaluation of existing built environments and design of new developments or retrofits. The significance of such research is that it could provide a thorough and comprehensive basis for the development of ecosystem based biomimicry that is practical, measurable and has multiple potential benefits.

The chapter begins by examining the concept of ecosystem services, and then analyses different understandings of these to define a framework for ecosystem biomimicry at the function level. A list is presented to describe ecosystem services. Relationships between each ecosystem service are then examined to form a relationship network matrix. Brief descriptions of each ecosystem service follow. Through a ranking research exercise, this chapter attempts to identify key ecosystem services that may be of most benefit to focus on in a built environmental context. The ecosystem biomimicry at the function level framework devised and presented in this chapter becomes the basis for investigations in chapter five where a real world situation (Wellington City, New Zealand) is evaluated as a means to test the usability and relevance of the ideas presented here.

4.2 ECOSYSTEM SERVICES

Ecosystem services are the benefits that humans derive, either directly or indirectly from the functions of ecosystems (Costanza et al., 1997). They have been described as *'the aspects of ecosystems consumed and utilised to yield human well-being'* (Turner and Daily, 2008). These are aside from the intrinsic value some people believe ecosystems have, independent of the ability of humans to exploit them¹⁵³. Although these ecosystem services are determined by people's ability to use them, for the context of this thesis they are understood as the functions of ecosystems that could be potentially be provided by the built environment¹⁵⁴.

¹⁵³ As Heal et al. (2005) point out: *'Many people believe that ecosystems have value quite apart from any human interest in explicit goods or services... The fact that ecosystems exhibit emergent behaviours and operate to sustain themselves is sufficient to argue that they have value to their components. Although comprehending this intrinsic value does not trouble most individuals, assessing it is problematic.* Farber et al. (2007) state, *"As humans are only one of many species in an ecosystem, the values they place on ecosystem functions, structures and processes may differ significantly from the values of those ecosystem characteristics to species or the maintenance (health) of the ecosystem itself."* Proponents of deep ecology also believe that ecosystems have value aside from their functional or economic value to humans (Drengson and Inoue, 1995).

¹⁵⁴ In ecology literature distinction is often made between ecosystem 'services' and ecosystem 'functions'. 'Services' are human derived benefits, while 'functions' are *'the habitat, biological or system properties or processes of ecosystems'* (Costanza et al., 1997). Ecosystem functions are independent of human defined value. The ecosystem service of 'nutrient cycling' corresponds to the ecosystem function of 'storage, internal cycling, processing and acquisition of nutrients', while the ecosystem service of 'climate regulation' relates to the ecosystem function of 'regulation of global temperature, precipitation, and other biologically mediated climatic

Footnote continued on next page...

The functions of ecosystems (what they do), are much less controversial in ecology literature than their processes (how they do it). A focus on ecosystem 'services' has been widely adopted among ecology and policy professionals (Carpenter et al., 2009) and formalised by the United Nations' Millennium Ecosystem Assessment of ecosystems and human wellbeing (Alcamo et al., 2003, MEA, 2005a, 2005b).

Several ecologists define and list ecosystem services (Daily et al., 2000, de Groot et al., 2002, MEA, 2005a, Cavanagh and Clemons, 2006, Costanza et al., 1997). The services that humans receive from ecosystems can be divided into: provisioning services such as food and medicines; regulation services such as pollination and climate regulation; supporting services such as soil formation and fixation of solar energy; and cultural services such as artistic inspiration and recreation. Daily (1997) provides scientific details of each function, which are also discussed in section 4.4.

Human use of ecosystem services is expanding due to human population increases as well as rises in per capita rates of consumption (Turner, 2008). Ecosystem services are fundamental to basic human survival and human well-being (MEA, 2005b, TEEB in Local Policy, 2011) (figure 61). In their seminal paper, Costanza et al. (1997) estimated that although humans would not be able to replace the ecosystem services they utilise, if these services had to be paid for in monetary terms, the cost would have been almost twice the entire global gross national product at the time of the research. Many of these services could not be replaced with current technology (Norberg, 1999), though approximately 60%, including 70% of all regulating and supporting services, have now been degraded by human activities (MEA, 2005b). The global condition of most ecosystem services except for the provisioning of food and raw materials has declined over the past fifty years (Carpenter et al., 2009, MEA, 2005c). In fact, ecosystems have changed more in the last fifty years than in any other period of human history (MEA, 2005b). Several studies have also proven that in most cases, the costs of ecosystem conservation

processes at global or local levels'. Costanza et al. (1997) provide a table listing ecosystem services and ecosystem functions. While services compared to functions is an important distinction in ecology and ecological accounting research, it is less important in the context of this research where the purpose of understanding ecosystems is to measure current and future environmental performance of the built environment and devise design goals.

are far outweighed by the net benefits generated by healthy intact ecosystems (Turner and Daily, 2008).

FIGURE 61 RELATIONSHIPS BETWEEN ECOSYSTEM SERVICES AND HUMAN WELLBEING¹⁵⁵ (SOURCE: MEA, 2005A).

The ecosystem services concept is currently the subject of intensive international research and policy development initiatives in an attempt to define values for them so

¹⁵⁵ The constituents of well-being as proposed by the Millennium Ecosystem Assessment authors do not appear compatible with the current dominant operating paradigm with its overall aim of increasing financial profit and unlimited growth, that forms the economic frameworks of industrialised nations (Turner, 2008). The ability of these constituents to be realised without a reassessment of the way human society operates is acknowledged as being (at best) difficult. Carlisle et al. (2009) critiques the modern paradigm with a proposal that increased ecological understanding may be an important way to increase wellbeing within it (i.e. society typical of industrialised nations) because it can: 'Counter trends towards materialism, individualism and consumerism, and in so doing could also contribute to our health and wellbeing, as individuals and as social beings in a finite... world'. Hawken et al. (1999) also provide a critique of current industrial capitalism and propose ways to alter it.

they (and possibly biodiversity¹⁵⁶) will be preserved (Naidoo et al., 2008, Daily, 1997). Understanding ecosystem services also aids in the setting of policy and development of tools to determine how much polluters should pay or how much protectors and regenerators of ecosystem services should be compensated (Carpenter et al., 2009, TEEB in Local Policy, 2011, TEEB in Business, 2011, TEEB, 2011a, TEEB Foundations, 2010). Examples of the many schemes incorporating an ecosystem services approach that have emerged in the last decade include: direct compensation paid to land owners for ecosystem services; conservation banking; tradable habitat rights; debt-for-nature swaps; insurance schemes; and tax relief programmes¹⁵⁷. Some proponents of such schemes point out that it is unlikely that economic incentives alone will change human behaviour so that people value and adopt environmental stewardship practices (Turner and Daily, 2008).

4.2.1 URBAN ENVIRONMENTS AND ECOSYSTEM SERVICES

‘By considering ecosystem services, cities have the opportunity to make some very positive changes, saving on municipal costs, boosting local economies, enhancing quality of life and securing livelihoods’ (TEEB, 2011b).

Most cities are increasingly dependent on the services of distant ecosystems for their resources (Doughty and Hammond, 2004) and have been described as *‘intensive nodes of consumption’* (Rees, 1999). Because of the built environment’s increasing appropriation of the goods and services of natural ecosystems (Rees, 1999), vital ecological services for human society (and other species) such as climate regulation, salinity control, soil formation, nutrient cycling, the hydrological cycle, photosynthesis, pollination, and waste assimilation are negatively affected (Shepherd et al., 2002, Vitousek et al., 1997, Vitousek et al., 1986, Balmford et al., 2002, Baik et al., 2001, Daily et al., 2000, Costanza et al., 1997).

¹⁵⁶ Turner and Daily (2008) and Naidoo et al. (2008) discuss the apparent lack of a correlation between areas identified as important for preserving ecosystem services and areas of high value biodiversity.

¹⁵⁷ See Turner and Daily (2008) for case studies.

In urban environments, ecosystem services are thought to not occur at all or be negligible except for human cultural services (Costanza et al., 1997). Doughty & Hammond (2004) also point out that many cities are now primarily sites for cultural expression and the facilitation of trade, rather than for the production of physical resources or the generation of services that produce physical health, either of ecosystems or humans. In many instances the systems and activities taking place in urban environments have a negative effect on non-cultural ecosystem services (Rees, 1999, Newman, 2006).

Although urban environments may present some unique benefits for restoring ecosystems (for example a high concentration of people equates to a high potential volunteer and resource base, and the absence of grazing animals and other threats to rare plants enables more effective regeneration) it should also be noted that urban environments are typically representative of highly disturbed ecosystems and are generally not good sources of seeds, or fertile soil (Wellington City Council, 2007a, Given and Meurk, 2000). Vinton (2008) points out that:

'[Environments in cities do] not have enough time to equilibrate through succession before being modified again... Ecological 'rules' such as those driving diversity, density, dispersal, and distribution in urban areas are different from those of more natural landscapes.'

However, Clarkson et al. (2007a) state that:

'Urban environments offer opportunities to reverse ecosystem degradation and biodiversity loss in a meaningful way through human engagement in ecological restoration'.

4.3 UNDERSTANDING ECOSYSTEM FUNCTIONS FOR A BUILT ENVIRONMENT CONTEXT

Mimicking ecosystem services as described in this thesis, suggests a design strategy based on a systematic transfer of scientific ecological knowledge into a built environment context, rather than design based on analogies of ecosystems as defined by designers. Architectural and urban designers have adopted terminology from life sciences, such as 'metabolism', 'genetic design' and 'evolutionary design' (Tsui, 1999, Chu, 2006, Newman, 1999), without necessarily adopting the scientific basis of the original meaning of the terms (Gruber, 2008). This may have led to design that is celebrated from an aesthetic perspective, however as this chapter will demonstrate, there may be opportunities to move beyond semantics and aesthetic metaphors to incorporate a more thorough understanding of ecology into architectural design to improve the environmental performance of the built environment (see also: Mlade, 2007).

Disaggregating the functioning of ecosystems into discrete 'services' is philosophically as well as practically difficult, and a concentration on parts of ecosystems, rather than ecosystems as whole entities, could undermine the holism that is central to regenerative design. Therefore, ecosystem services analysis should be used in concert with other aspects of regenerative design that focus on the development of relationships between humans, the built environment and wider ecosystems (Plaut et al., 2012, Hoxie et al., 2012, Mang and Reed, 2012, Reed, 2007, du Plessis, 2012, Cole et al., 2012, Cole, 2012a).

Applying the concept of ecosystem services to built environments is potentially useful as a way to demonstrate the limits to regenerative design. Utilising ecosystem services analysis enables ecological regeneration goals for a built environment context to be devised and makes the performance of design interventions easier to measure. This is important to ensure that regenerative design has scientific credibility, particularly if it is not to simply become a vehicle for the creation of

developments with high ideals that, nevertheless, fail to tangibly improve the environmental performance of the built environment.

As pointed out in chapter three, biomimicry literature typically offers up sets of organism processes, rather than ecosystem functions or services, as aspects to mimic in ecosystem biomimicry. The author is unaware of any lists, matrices or comprehensive design theory of ecosystem services that have been devised for the use of designers. In order to relate ecosystem services to a design context, a similar methodology was followed to that used to determine the ecosystem processes as detailed in section 3.4. This was done to ensure that a thorough understanding of ecosystem services was achieved. This also ensured that the vast variety of formats for presenting ecosystem services as discussed by Heal et al. (2005) were taken into account.

4.3.1 REPRESENTING ECOSYSTEM SERVICES: LIST FORMAT

A comparative analysis was conducted of known ecosystem services from a variety of sources (appendix four). Through this process, a group of ecosystem services was formulated, aiming to capture understandings provided by different researchers. Ecosystem services are first presented in a list format (table 8). The benefit of presenting the information in this simplified format is that it becomes an easily usable set of generalised ecosystem services that provides an overview for designers with limited background knowledge in ecology.

The ecosystem services provided here are proposed as a set of generalised examples of the benefits ecosystems provide to humans rather than absolute laws. Heal et al. (2005) note that certain ecosystem services were only recognised when ecological knowledge increased, therefore it is likely that the list of known ecosystem services may also evolve in the future. Lists of ecosystem services could develop further because they are determined not just by the functions of ecosystems but also by human ingenuity in deriving benefit from them.

TABLE 8 ECOSYSTEM SERVICES

1.Provisioning Services	2.Regulating services (human time scale)	3.Supporting Services (long time scale)	4.Cultural Services
1.1 Food - Human (land / fresh water / marine) - Forage	2.1 Pollination and seed dispersal	3.1 Soil -formation -retention -renewal of fertility -quality control	4.1 Artistic inspiration
1.2 Biochemicals -Medicines -Other	2.2 Biological control -Pest regulation -Invasive species resistance -Disease regulation	3.2 Fixation of solar energy -primary production / plant growth (above ground, below ground, marine, fresh water)	4.2 Education and Knowledge
1.3 Raw materials -Timber -Fibre -Stone -Minerals / ores	2.3 Climate regulation -GHG regulation -UV protection - Moderation of temperature	3.3 Nutrient cycling -Regulation of biogeochemical cycles -Retention of nutrients	4.3 Aesthetic Value
1.4 Fuel / energy -Biomass -Solar -Hydro -Other	2.4 Prevention of disturbance and moderation of extremes -Wind / wave force modification -Mitigation of flood / drought -Erosion control	3.4 Habitat provision -refugium function ¹⁵⁸ -nursery function ¹⁵⁹	4.4 Cultural Diversity and history
1.5 Fresh water -Consumption -Irrigation -Industrial processes	2.5 Decomposition -Waste removal	3.5 Species maintenance -biodiversity -natural selection -self organisation	4.5 Recreation and tourism
1.6 Ornamental resources	2.6 Purification -Water / air / soil		4.6 Spiritual inspiration
1.7 Genetic information			4.7 Creation of a sense of place
			4.8 Relaxation and psychological wellbeing

¹⁵⁸ Defined as suitable living space for wild plants and animals (de Groot et al., 2002).

¹⁵⁹ Defined as suitable reproduction habitat (de Groot et al., 2002).

Table 8 is very similar to tables of ecosystem services provided by ecologists and those given by the authors of the Millennium Ecosystem Assessment. While some terms, such as the provisioning service of fuel / energy and the supporting service of fixation of solar energy may seem to overlap from the point of view of a designer, important distinctions between the services will be elucidated in section 4.4.

4.3.2 RELATIONSHIPS BETWEEN ECOSYSTEM SERVICES

Many discussions of how ecosystems function result in lists of unrelated services, much like ecosystem processes discussed in chapter three (section 3.4.2). Lists may be useful in preliminary stages of design if design teams are unfamiliar with ecosystem services, but showing where services are potentially linked may give designers insights into how to design buildings or spatial environments to provide or support multiple ecosystem services that positively reinforce each other (Haines-Young and Potschin, 2008). It also illustrates that when affecting one ecosystem service others need to be considered, so that when improving one, another is not degraded (Daily and Matson, 2008). For example increasing the carbon sequestration potential of an area can impact negatively on biodiversity (species maintenance) if both services are not considered in tandem. This could happen for example if trees are planted in an attempt to sequester carbon without an understanding of the tree species necessary in that area to provide habitat for other locally occurring organisms (Gitay et al., 2002).

4.3.3 REPRESENTING ECOSYSTEM SERVICES: RELATIONSHIP MATRIX

It is easier to categorise ecosystem services than it is to differentiate and understand relationships between ecosystem processes. Each service is connected with others in a variety of ways, and it is clear that an examination of the relationships between each service is important in devising theory to support the practical application of ecosystem biomimicry at the function level. A matrix diagram that can do this is

useful in a design context for several important reasons as discussed in sections 4.6 and 4.7.

The mapping of ecosystem services differs from the mapping of ecosystem processes (figure 34) in two important ways. Firstly because ecosystem services relate to the values humans place on ecosystem functions, the four categories (provisioning services; regulation services; supporting services; and cultural services) could not be arranged hierarchically. For these reasons the ecosystem services matrix relationship diagram is non-hierarchical in format.

Although social and ecological systems are intimately linked (Berkebile and Hoxie, 2012, Folke, 2006, Health Council of the Netherlands and RMNO, 2004, Young et al., 2006, Azar et al., 1996), and proponents of the biophilia hypothesis argue that ecosystem health both affects and is affected by human psychological health (Kellert et al., 2008), for the purposes of this research cultural services¹⁶⁰ are thought to have less direct or obvious links to improved ecosystem health than the other categories, and therefore the actual provision of regulating, supporting and provisioning ecosystem services. Also, many of these cultural services are not fulfilled by ecosystems exclusively. Artistic inspiration may be as equally found in a city of character as in a forest for example.

Furthermore, following a 'strong' model of sustainability (figure 62) where a healthy economy is dependent on societal sustainability, which in turn depends on ecological health (Pollock, 2009, Ott, 2003, Neumayer, 2003), suggests that focusing on the regeneration of ecosystem services related to maintaining not only human physical and economic wellbeing but the wellbeing of all living creatures and planetary cycles is a good long term strategy to regenerate human and social wellbeing. The decline of regulating services is of particular concern because it indicates future declines in other ecosystem services (Shelton et al., 2001). For these reasons the category of

¹⁶⁰ Cultural services are listed in table 8. Many aspects of ecosystems are consumed not just for physical survival or to create functional objects but also for psychological or cultural benefits. An example is the creation of gardens for pleasure and relaxation. Such designed landscapes rely on the on-going survival of ecosystems to provide and maintain populations of plants, animals and insects that are then arranged by humans for their own benefit.

cultural services and the provisioning service of ornamental resources are not considered further in this context. In light of this, the ecosystem services matrix (figure 63) illustrates relationships between provisioning, regulating and supporting services only.

FIGURE 62 STRONG MODEL OF SUSTAINABILITY.

The second difference in representing ecosystem functions relative to representing ecosystem processes is that the ecosystem processes relationship matrix (figure 34) describes a nested system of processes going from the general to the specific. The ecosystem services described here are all at one level, without the inclusion of sub-services. For this reason the ecosystem services relationship matrix is not organised into a nested hierarchy.

What this signifies is the services of ecosystems are complex and numerous but all are necessary to ensure the on-going health of ecosystems, as well as the life (human and non-human) that occurs within them (Costanza et al., 1997).

It is clear that ecosystem services experience non-linear changes through multiple feedbacks between biotic, abiotic and human drivers (Levin, 1999, pages 30-31). While the relationship matrix (figure 63) does not illustrate the complex variety of potential feedbacks as drivers of change, it does reflect more accurately the physical reality of ecosystem services operating in a dynamic changing context than the simple list presented in table 8.

FIGURE 63 ECOSYSTEM SERVICES RELATIONSHIP MATRIX.

FIGURE 64 NON-EXISTANT OR LESS OBVIOUS RELATIONSHIPS BETWEEN ECOSYSTEM SERVICES (REPRESENTED BY GREY LINES).

The ecosystem services relationship matrix diagram (figure 63) illustrates a complex web of relationships. The relationship lines are coloured to reflect dominance or strong causation. For example the line between the provisioning service of 'food' and the supporting service of 'soil' is coloured red (figure 65). Because supporting services are colour coded as red in the matrix diagram, this signifies that it is the supporting service of fertile soil that enables the service of providing food. Arrows are not used because, although there is strong causation one way in the relationship, food provision also contributes to soil building due to the ecosystem process of cycling of nutrients (from food waste and sewage) and the processes of decay and decomposition. Dotted lines signify relationships between services in the same category. Although it may look as if all services are connected to each other in figure 63, figure 64 illustrates the places where there are no links, or where relationships may be less important, direct, or obvious (represented by grey lines).

FIGURE 65 RELATIONSHIPS BETWEEN ECOSYSTEM SERVICES.

By examining the relationship matrix diagram of ecosystem services (figure 63), it is apparent that although not all ecosystems services are directly connected in the diagram, provisioning services are dependent on both regulating and supporting services, but supporting or regulating services tend not to be dependent on provisioning services. Because of this, it is important that any ecosystem service based design methodology or evaluation technique does not ignore regulating or supporting services, although these are more difficult to measure and quantify (Daily, 1997). The provision of food for example is the provisioning service that appears to have the most dependent links to other ecosystem services. Because the ecosystem service of provision of food is fundamental to the continuation of the human species, this highlights the importance of considering individual ecosystem services in the context of their relationships to other services rather than in isolation, even if the goal is regeneration or provision of a particular individual service.

As the understanding of relationships between ecosystem services and human well-being develops, and different values are assigned to different services, the relationship matrix may need to be refined. Determining the exact levels of causation and representing additional complexities of the relationships depicted is beyond the scope of this research, and would complicate the matrix's potential as a design or evaluation tool. Causal patterns are described as being complex, rarely linear and an important part of future ecology research, needed to progress the understanding of ecosystem services (Carpenter et al., 2009). Indicating where important or obvious relationships exist (figure 63) however may be useful in a design context.

FIGURE 66 CLIMATE REGULATION SERVICE CONNECTIONS.

The relationship lines in figure 63 indicate to designers which additional services they need to investigate when planning to provide, regenerate or integrate with a specific ecosystem service. This is needed to mitigate damage to other ecosystem services and harness strategies for symbiotic relationships between services. Relationship lines may also provide pathways to investigate whether development could be used to provide 'bundles' of related services. Such a methodology has been called for by Carpenter et al. (2009). For example if a design goal was to maintain or regenerate climate regulation services the two additional regulation services of

biological control and prevention of disturbance would have to be considered (figure 66). The provision of food and water would also be affected. Likewise, the supporting services of species maintenance, habitat provision and nutrient cycling are affected. This shows how just one service is closely related with seven others. When considering each service to which these seven are connected, all of the other services quickly become additional important considerations.

4.4 DESCRIPTIONS OF ECOSYSTEMS SERVICES

A brief description of each ecosystem service follows using the numbering system in table 8. If descriptions of each service are available, the designer may be better able to utilise the concept of providing ecosystem services through the development or regeneration of the urban environment at early design stages. A full explanation of the current state of each ecosystem service is beyond the scope of this thesis however The Economics of Ecosystems and Biodiversity studies (TEEB, 2011a, TEEB, 2011b, TEEB Foundations, 2010) provide further insights, case examples and specific details of each ecosystem service. The Millennium Ecosystem Assessment publications (MEA, 2005a, 2005b, 2005c) provide detailed information about the current state of each ecosystem service.

4.4.1 PROVISIONING SERVICES

Provisioning services are those which provide some kind of tangible resource to humanity. They provide for the nutritional, medicinal, shelter, and evolutionary (through genetic material) needs of people to survive at the most basic level, and for the great variety of technologies, products, chemicals, and energy needs of humans at another. This great range of goods and services extracted from ecosystems is largely based on the diverse amounts of biomass found on the planet, formed through photosynthesis (de Groot et al., 2002). Daily (1997) points out that these ecosystems 'goods' are a familiar and integral part of traditional forms of human economic systems.

4.4.1.1 FOOD

The provision of food includes sources from terrestrial, marine and aquatic ecosystems for humans directly and also as forage or feed for domesticated livestock. It includes hunting, gathering, subsistence farming and larger scale agricultural, horticultural and commercial fishing activities (Costanza et al., 1997). While the provision of food has increased greatly since

FIGURE 67 COMMON FRUIT AND VEGETABLES (PHOTO BY: MUAMMEROKUMUS).

the late 1960s due to the 'green revolution' (Evenson and Gollin, 2003), this has come at the expense of a decrease in regulation and supporting services (Carpenter et al., 2009, Mooney et al., 2009). Food production rose by 45% between 1992 and 2009. This exceeded the increase in population for the same period which was only 26% (UNEP, 2011).

Although natural ecosystems provide the conditions for growing food in agricultural ecosystems¹⁶¹, the current form of global food production based on transported products of large scale agricultural businesses, rather than the more traditional small scale local farms that existed before the 'green revolution', is entirely dependent on the use of fossil fuels. Over time this diminishes the ability of land to produce food without them (Pfeiffer, 2006), while impacting negatively on other ecosystem

¹⁶¹ They provide the ecosystem services of pollination, biological pest control, maintenance of soil structure and fertility, nutrient cycling, and hydrological services on which agricultural systems depend (Power, 2010).

services (such as habitat provision, water provision and regulation, and soil fertility) and often on biodiversity (Power, 2010, UNEP, 2011). For plant-based foods, fossil fuels are used to plant seeds (through the use of fuel consuming machinery), promote growth (through the use of fertilizer), maintain crops (through the use of pesticides and herbicides), harvest them (using of fuel consuming machinery), process them (again by use of energy intensive machinery) and finally to transport foods to market (using fossil fuel consuming vehicles).

The current calculated energy content of food, based on the fossil fuels used to produce it, exceeds by more than seven times on average the calorific energy content of the food (Eshel and Martin, 2006). Food production accounted for at least 10.5% of total global fossil fuel use in the mid-2000s and 17% in the United States in 2002. This proportion of energy use is growing and is projected to peak in 2020 (Eshel and Martin, 2006). This means food production and the dietary choices of individuals¹⁶² contribute significantly to climate change, and that without the input of fossil fuels the current model of food production that most of the world's people depend on would cease to be viable (Pfeiffer, 2006).

4.4.1.2 BIOCHEMICALS

Biochemical services primarily allow for the provision of medicines, either directly in the form of traditional medicines, or indirectly through the pharmaceutical industry. They also provide other chemical products related to: preservation (found mostly in foods), cleaning (of bodies and homes), fashion (cosmetic products) and entertainment (paint, fireworks and hobby materials). Again, such resources are used by humans and also for livestock (mostly in terms of medicines).

¹⁶² Discussion about specific dietary choices in relation to an individual's ecological footprint and contribution to climate change can be found in Vale and Vale (2009, pages 40 and 46), and Eshel and Martin (2006) and section 5.3.7. Essentially, plant based diets rather than a diet based on meat have a significantly lower overall ecological and climatic impact.

The search for useful biochemicals is frequently cited as a reason for conservation of certain ecosystems, particularly tropical rainforests such as the Amazon (Shanley and Luz, 2003). A 1997 estimate places the value of currently undiscovered pharmaceuticals in tropical forests at \$US109 billion (Beattie et al., 2005). 80% of people in the world are dependent on traditional herbal medicine (TEEB, 2011b) and more than 50% of modern prescription medicines were originally discovered in plants (Beattie et al., 2005). Most biochemicals are either substantially processed or synthesised and also require specialist facilities that may not be available within a given locality. For specific information relating the bio-prospecting industry to biodiversity and ecosystem services see: Beattie et al. (2005).

FIGURE 68 CHINESE HERBAL MEDICINE PHARMACY (PHOTO BY: ANON.).

4.4.1.3 RAW MATERIALS

The raw materials ecosystem service includes the provision of timber, fibre, stone, earth, sand, and minerals for human activities (de Groot et al., 2002). As human technology has progressed, it has been possible to extract more raw materials from ecosystems to meet the assumed needs of an increased population and increased culture of consumption (Mitchell, 2012). Like food production, this ecosystem service has increased since the industrial revolution, but has meant the degradation of other services over time such as climate regulation, erosion prevention, and provision of fresh water. (Carpenter et al., 2009, Mooney et al., 2009).

Many of the negative effects of an increase in the provision of raw materials are hidden because people do not generally understand the less tangible, measurable, or visible ecosystem services (particularly those in the regulating and supporting categories) that are damaged as a result of increased extraction of raw materials (Daily, 1997). Also, many of the locations where ecosystem services are degraded due to increased extraction of raw materials are not near to populations demanding, transporting, paying for, and consuming the same raw materials (Rees, 1999). For example, the international demand for timber (along with the equally pressing drive to procure more farmland, in order to produce more food, often for export) has led to deforestation in many parts of the Earth, particularly in tropical rainforests such as the Brazilian Amazon (Parayil and Tong, 1998) (figure 69)¹⁶³.

FIGURE 69 DEFORESTATION IN THE AMAZON (PHOTO BY: NATIONAL WILDLIFE FEDERATION INTERNATIONAL TEAM).

Because of the interconnected nature of ecosystem services, increasing the ecosystem service of provision of raw materials is not as simple as sanctioning new

¹⁶³ Primary forest area has decreased by 300 million hectares since 1990 (an area approximately 11 times larger than New Zealand) mostly due to deforestation in Latin America and Africa (UNEP, 2011).

timber plantations or increased mining of minerals without a consideration of the overall impact such activities will have on other ecosystem services both locally and remotely.

4.4.1.4 FUEL / ENERGY SOURCE

Fuels and energy derived from biomass, biofuels, plant oils, and wind, hydro and solar energy¹⁶⁴ are an essential ecosystem service¹⁶⁵. As human technology changes, different kinds of energy sources are needed and can be accessed, expanding the scope and scale of this ecosystem service. Recent advances or emerging technologies in the development of ocean powered energy generation (including wave, tidal and ocean thermal energy conversion) (Ben Elghali et al., 2007, Pelc and Fujita, 2002), and artificial photosynthesis (Moore et al., 2004, Pace, 2006) are examples.

It is currently difficult for renewable energy sources to compete with cheap and established fossil fuel energy sources (Pelc and Fujita, 2002) due to the on-going subsidisation of conventional energy, which encourages greater use of fossil fuels and consequent emissions of GHGs and further climate change (MEA, 2005c). Such subsidies were estimated to be \$US250 to 300 billion in the mid-1990s (MEA, 2005c).

¹⁶⁴ Most researchers, including the Millennium Ecosystem Assessment, that provide lists of ecosystem services (appendix four) do not include non-renewable energy sources (fossil fuels) as part of provisioning ecosystem services because they are not dependent on the living components of current ecosystems. Hoda (2007) suggests that the ecosystem service of collecting and storing solar energy as fossil fuels over long time periods should be acknowledged and factored into legal and economic frameworks of valuation, because fossil fuels are non-renewable and currently are not *'managed sustainably'*. He argues: *'It is necessary to value the ecosystem services that manufactured fossil fuels, and to find a legal mechanism to internalise that value into the marketplace, either as a cost on the fossil fuel resource or a subsidy on renewable energy alternatives that seek to collect solar energy and convert it into a usable form'*. 'Geosystem services' which are a consequence of 'geodiversity' are terms that have been used since 1993 to describe the abiotic (non-living) components and resulting services of ecosystems (Gray, 2011). Gray (2011) considers the provision of fossil fuels to be a part of the provision of geosystem services and discusses the interdependent nature of ecosystem and geosystem services.

¹⁶⁵ Some researchers include the provision of fuel with the provision of raw materials (see for example: TEEB, 2011b, Costanza et al., 1997).

4.4.1.5 FRESH WATER

Ecosystem services related to water include the regulation of hydrological flows as well as the storage, purification and retention of water (de Groot et al., 2002). Water is consumed for human needs by both humans and their livestock to ensure survival and health. It is also consumed in large amounts for crop irrigation (Hoff et al., 2010) and to a lesser extent by industrial processes, such as milling (Oki and Kanae, 2006) (figure 70).

FIGURE 70 GLOBAL HYDROLOGICAL FLUXES AND STORAGES WITH NATURAL AND ANTHROPOGENIC CYCLES (SOURCE: OKI AND KANAE, 2006).

Water can be considered as both a provisioning and a regulating service (Costanza et al., 1997). In terms of regulation, local ecosystems have a large influence on retaining water, managing the volume and timing of eventual run off, recharging of

aquifers, control of flooding, and quality of drinking water (Winz, 2005). All of these regulation aspects also impact directly on the provisioning service of water.

4.4.1.6 GENETIC INFORMATION

FIGURE 71 BELGIAN BLUE BULL (SOURCE OF IMAGE: THE BRITISH BLUE CATTLE SOCIETY).

Ecosystems produce genetic information that is either directly used by humans or used indirectly to support the maintenance of healthy ecosystems. Genetic information enables on-going evolution and therefore the potential

for adaption in the constantly changing context of life. It ensures the continued health of populations of flora and fauna and plays an important role in maintaining or establishing resiliency (Levin, 1999, page 127). This may be important in terms of climate change adaptation. If a population is more diverse there are more likely to be individuals that can adapt to changes in conditions (Baskin, 1998).

Both selective breeding and genetic engineering are examples of how humans use genetic information from ecosystems as a resource. Humans have long used the genetic variety of both flora and fauna to manipulate the breeding of food crops and livestock for desirable characteristics. For example the Belgian Blue cattle breed (a variant of *Bos taurus*), an extremely large, lean and muscled cattle farmed for meat, exists due to a history of human selective breeding, beginning in the nineteenth century, for a mutated myostatin gene in the cattle (figure 71). The mutation results in accelerated muscle growth in the animals (McPherron and Lee, 1997).

Genetic engineering is a newer form of manipulating organisms and differs from selective breeding as it can result in organisms that would not have been able to appear naturally, even through a process of human selective breeding. For example, in the United States in 2001 a rhesus macaque / monkey (*Macaca mulatta*), named ANDi was 'created' containing a jellyfish gene (of the *Medusozoa* subphylum), so the monkey's offspring would glow (Forster et al., 2007, Anon., 2005). Crossing the species barrier in such a manner is highly controversial ethically (Riess and Straughan 1996, Ausubel, 2004).

4.4.2 REGULATING SERVICES

Regulating services relate to the cycling of nutrients at a local and global scale, and the filtering and transformation of pollutants and wastes. These services ensure the regulation and maintenance of the essential functions of ecosystems that support health and growth, and involve interactions between biotic and abiotic elements of ecosystems (Norberg, 1999). Many of these services are less direct in nature than provisioning services in that they do not lead to tangible products for human consumption, and consequently are more difficult to assign value to (TEEB Foundations, 2010). However, these services are fundamental to the survival of all species. Because of their interlinked nature (figure 63) small changes in one can affect others in a myriad of ways. The multiple effects of climate change (section 1.3.1) are an example of this phenomenon.

The built environment will not be able to replace regulating services entirely (Costanza et al., 1997), but might be capable of making contributions to these rather than damaging them, if careful consideration is given to planning.

4.4.2.1 POLLINATION AND SEED DISPERSAL

Pollination refers to the role that ecosystems have in facilitating the transfer of genetic material between plants (usually through bees or other insects but also through some birds and bats) allowing them to flower and fruit and then reproduce. Seed dispersal refers to the process of geographical or spatial transfer of material

relating to the reproduction of plants (through birds, other organisms, and wind and ocean currents).

FIGURE 72 POLLINATION INTERACTION BETWEEN A FLOWER AND A BEE (PHOTO BY: SNAP).

The importance of pollination to the on-going survival of plants and animals (including humans) is discussed by Kevan and Viana (2003), while a global 'pollination crisis' caused by anthropogenic drivers of change such as fragmentation of habitat, land use changes, modern agriculture (including the use of pesticides and

herbicides) and invasions of non-native plants and animals, is examined by Kearns et al. (1998). 76% of the most common and important global food crops depend upon insect and bird pollination (TEEB, 2011b).

4.4.2.2 BIOLOGICAL CONTROL

Biological control refers to the influence ecosystems have on regulating organisms or pathogens that lead to disease in humans or livestock (Patz et al., 2005), or ones considered to be pests by humans involved in crop production and livestock rearing. Birds, bats, flies, wasps, frogs, fungi, and other predators and parasites within ecosystems all contribute to this ecosystem service (TEEB, 2011b).

This service also encompasses the aspect of resistance to invasive species that ecosystems provide. Local pests and diseases are in general kept to manageable levels through a network of complex feedback mechanisms (Kay and Schneider, 1994). An example of the importance of maintaining the service of biological control is that an increase in the prevalence of the bacteria that cause Lyme disease in North America in ticks (*Ixodidae* or *Argasidae* families) (figure 73) has been

attributed to biodiversity loss caused by habitat fragmentation (Patz et al., 2005). As the climate changes, this service is likely to be affected significantly, leading to new biological control issues for human society (Rands et al., 2010).

4.4.2.3 CLIMATE REGULATION

Climate regulation is the ecosystem service that regulates processes related to atmospheric chemical composition, the greenhouse effect, the ozone layer, precipitation, air quality, and moderation of temperature and weather patterns (including cloud formation), at both global and local scales (Costanza et al., 1997). In terms of

FIGURE 73 EFFECT OF LYME DISEASE ON SKIN (PHOTO BY: CENTERS FOR DISEASE CONTROL AND PREVENTION).

GHG regulation at the global scale, this may include the ability of ecosystems both to emit and absorb chemicals (Forster et al., 2007). At a local scale vegetation lowers temperatures in urban environments and removes pollutants from the air (TEEB, 2011b). Climate change is one of the most important issues humans must consider (IPCC, 2007b, pages 8-22), and great focus is placed upon understanding this service (chapter one). This service is of extreme importance in terms of human health and economic prosperity (Alcamo et al., 2003), but this does not eclipse its significance in terms of its impact on biodiversity and the continuation of ecosystems in general (Gitay et al., 2002).

4.4.2.4 PREVENTION OF DISTURBANCE AND MODERATION OF EXTREMES

Ecosystems provide the valuable service of modification of wind, wave, and water (flood) forces as well as erosion control to prevent disturbance. Vegetative cover and root formations retain soil (figure 74) while coral reefs and mangroves prevent

coastal disturbance (Goreau, 2005). Ecosystems will also modify to an extent the impacts of extremes such as storms, tsunamis, avalanches, floods, landslides and droughts. Intensity of natural fire events is also regulated by ecosystems. Bravo de Guenni et al. (2005) state that:

‘Interactions of modern human activities with ecosystems have contributed to increasing human vulnerability and to the impact of extreme events on human well-being’.

FIGURE 74 SOIL EROSION CAUSED BY DEFORESTATION IN TASMAN, NEW ZEALAND (PHOTO BY: MARTIN WEGMANN).

4.4.2.5 DECOMPOSITION

Decomposition is the process in ecosystems that enables the break down and transformation of nutrients and is a vital part of their continuation (Odum, 1969). It allows the recovery of nutrients for reuse by other elements or organisms in a system and ensures wastes are assimilated, preventing them from becoming pollutants (Daily, 1997).

4.4.2.6 PURIFICATION

Ecosystems allow for the purification or detoxification of air, water and soil through assimilation and transformation of toxic compounds (through the bodies of plants or animals), decomposition, and filtering through abiotic elements (filtering of water through soil or sand). Purification also allows the recovery of mobile nutrients and removal or breakdown of excess or toxic nutrients and compounds (Costanza et al., 1997). While the purification ecosystem service may act to reduce concentrations of substances that are harmful to humans, the capacity of ecosystems to do this is finite, and has been exceeded in many locations (Hinga et al., 2005).

4.4.3 SUPPORTING SERVICES

Supporting services are ones which enable the on-going structure of ecosystems to endure as well as the living elements within them. Such supporting services ensure the continuation of provisioning and regulation services (Daily and Matson, 2008). Supporting services tend to be less tangible to humans than provisioning services or even regulating services, but remain crucially important to the on-going health of ecosystems, and therefore humanity (Daily, 1997).

4.4.3.1 SOIL BUILDING

Soil building refers to the formation and retention of soil (figure 75). It is also associated with ensuring on-going fertility of soil through cycling or storage of nutrients and through the continuation of microbial activity (Alcamo et al., 2003). Soil fertility is essential for the growth of plants and is enhanced by the supply of nutrients and accumulation of organic material provided by well-functioning ecosystems (TEEB, 2011b). Rock weathering also contributes to soil building (Costanza et al., 1997).

This service is significant because it directly supports a viable human agricultural industry and has important links to decomposition, purification and prevention of disturbance services. Soil building could be an important aspect of adaptation to climate change if humans recognise the link between the need to grow food closer to where it is consumed, thus enabling effective cycling of nutrients found in organic 'waste' to support soil fertility. This ecosystem service is difficult to facilitate through the built environment but careful design of systems and infrastructure could contribute to it. Further discussion of soil in relation to ecosystems services can be found in Clothier et al. (2011).

FIGURE 75 SOIL (PHOTO BY SOIL-NET LIBRARY).

4.4.3.2 FIXATION OF SOLAR ENERGY

FIGURE 76 PHOTOSYNTHESIS (SOURCE OF IMAGE: ENCYCLOPEADIA BRITANNICA).

The fixation of solar energy (photosynthesis) forms the basis of the planet's food chain (figure 76). Xiong and Bauer (2002) state:

'The process of photosynthesis is arguably the most important chemical reaction on earth that has led to the development of advanced life forms.'

This fixation of solar energy (primary production) by plants occurs above ground, below ground, in marine environments and in fresh water. Humans currently appropriate 10 to 55% of all of the terrestrial products of photosynthesis and this has a substantial negative effect on ecosystems and biodiversity (Vitousek et al., 1986, Vitousek et al., 1997, Rojstaczer et al., 2001).

4.4.3.3 NUTRIENT CYCLING

Nutrient cycling services include the regulation of biogeochemical cycles (such as those of oxygen, water, potassium, nitrogen, phosphorus, sulphur, and carbon), as well as the retention of nutrients within a system. Provision for storage, internal cycling, processing and acquisition of nutrients are parts of this service (de Groot et al., 2002).

4.4.3.4 HABITAT PROVISION

Habitat provision allows for the shelter and protection of organisms and often provides access to shelter and nutritional needs. Habitat provision also has a nursery function in terms of the protection of young organisms. Habitat provision services are relevant to both permanent as well as transient populations of organisms (de Groot et al., 2002). The provision of habitat is of extreme importance to maintaining biodiversity (Krauss et al., 2010, section 1.4).

4.4.3.5 SPECIES MAINTENANCE

Species maintenance refers to the provision of biodiversity, natural selection, and self-organisation in ecosystems (Daily, 1997). Genetic information enables on-going evolution, and therefore, the potential for adaption to a constantly changing context in which all life exists. Genetic diversity ensures the on-going health of unique biological flora and fauna and plays an important role in maintaining or establishing resiliency (Levin, 1999, page 127). The results of in-breeding or situations where a gene pool becomes too small are well known and include increased risk of disease and malformation (Wright, 1932). The ecosystem service of species maintenance

plays a vital part in ensuring that species needed to produce all ecosystem services continue to exist (Daily, 1997).

4.5 APPLYING ECOSYSTEM SERVICES TO A BUILT ENVIRONMENT CONTEXT

The purpose of this section is twofold. Firstly it tests the usability of the theoretical underpinnings of an understanding of ecosystem functions as generated in the earlier part of this chapter. It does this by taking the ecology information and applying it to the built environment. This process is continued in chapter five. Secondly, this section (and the remainder of this chapter) will demonstrate how the theory could be used as a tool to evaluate the performance of an existing built environment, and how it could reveal places to intervene in the built environment to create a more robust, adaptable and cohesive system in relation to climate change mitigation or adaptation and biodiversity issues.

As discussed earlier, it is known that the built environment has a large negative effect on ecosystem services (Rees, 1999). One way to reduce or to reverse the negative environmental impact of the built environment is to create or re-design such environments so that they provide, integrate with, or support ecosystem services, and therefore reduce pressure on ecosystems. This is important as urban environments continue to grow and as the climate continues to change (Eigenbrod et al., 2011, McKinney, 2002).

Mimicking the functions of ecosystems enables design teams to know what the quantifiable ecological goals should be for a development in a given location and climate if it is to integrate with existing ecosystems and contribute to their health rather than deplete them. This is different from design methods such as industrial, construction, or building ecology (Erkman, 1997, Graham, 2003, Kibert et al., 2002), or process level ecosystem biomimicry (chapter three), because employing an understanding of ecosystems as a metaphor can lead to outcomes that are at or below the sustainability standards of conventional architectural and urban design (Kibert, 2006).

4.5.1 REDEFINING ENVIRONMENTAL PERFORMANCE GOALS IN THE BUILT ENVIRONMENT

Information about the negative environmental impact of the built environment is often relative to other human endeavours. For example, the United Nations Environment Program states that 40% of all global energy and material resources are used to build and operate buildings (UNEP, 2007). Such a figure is useful in setting an agenda for future research and for establishing the urgency of the need to change urban environments and their use, but has no relationship to how much energy is available, what level of use would be sustainable, or what the environmental impact of this use is. A typical goal that fits into this way of thinking related to water consumption for a building might be 'to reduce water use by 10%'. This is based upon human defined goals related to economic, political or convenience factors. It does not give information relative to an example of a successful and sustainable system, nor does it relate to what could be physically possible at a given site. A common reaction to such information is to reduce, remove or stop certain behaviours or ways of constructing the built environment. Regenerative design aims to enable built environments to move beyond that and into the realm of creating health and wellbeing rather than simply reducing damage (Reed, 2007). A goal, again related to water consumption but based on ecosystem services analysis, might be to 'tailor water use within a given site to its annual rainfall budget'. This second kind of target is based upon the physical possibilities the site affords, can be clearly measured, and enables a development to be understood in the wider context of its ecosystem.

4.5.2 KEY PLACES FOR CHANGE IN THE URBAN BUILT ENVIRONMENT

Ecological economists and accountants have sought to place value on ecosystem services in different ways as the concept has been developed to fit into policy frameworks (Turner and Daily, 2008, TEEB, 2011b). This work is still in progress and in many cases the information needed to complete the task does not yet exist (ten Brink et al., 2011). In the past two decades many studies have attempted, with increasing success, to place economic value on ecosystem services (Daily et al., 2000, ten Brink et al., 2011) and The Economics of Ecosystems and Biodiversity

(TEEB) group have collected more than 1100 different economic values for 10 different biomes and 22 different ecosystem services (TEEB Foundations, 2010).

‘Value’ is ultimately still a human subjective measure and attempts to determine value weightings for ecosystem services often attract debate (Carpenter et al., 2009, Rosemond and Anderson, 2003). While all aspects of ecosystem functioning are important to the system as a whole, and it is not perhaps even possible to assign value to discrete parts of an ecosystem, this section investigates which ecosystem services are the most suitable for inclusion in an urban built environment context. This process is important given that twenty-six distinct ecosystem services were initially identified (table 8) and trying to use this long list is likely to be too cumbersome and complicated in a design or evaluation context. It is necessary therefore to determine which ecosystem services appear to be the most appropriate for examination in the context of the built environment. This was assessed using three ranking criteria:

1. The ability of an ecosystem service to be physically mimicked by or integrated with the built environment.
2. The impact of an ecosystem service on the maintenance of overall ecosystem health.
3. The relative negative impact that the urban environment has on the ecosystem service in question and the scale this relates to in terms of a local, regional or global context.

Although the second and third criteria are more important in terms of the regeneration of ecosystem health, the physical constraints of the built environment are an important limiting factor in the context of this research and so this remains the initial ranking criterion. Early attempts were made to define ecosystem services for a built environment context starting with a consideration of ranking criteria two and three, but practically this became difficult for reasons that will be discussed in sections 4.5.2.2 and 4.5.2.3. The results of this ranking investigation are summarised in table 9.

The TEEB group (2011b) provide the following 13 services (not including cultural ones) that are 'relevant to cities': food, raw materials, fresh water, medicinal resources, local climate and air quality regulation, carbon sequestration and storage, moderation of extreme events, erosion prevention and maintenance of soil fertility, pollination, biological control, habitats for species, and maintenance of genetic diversity. The rationale behind this grouping is not discussed.

Bolund and Hunhammar (1999) also attempt to define ecosystem services most applicable to an urban context and state that the services humans directly benefit from in a local context are most appropriate. They provide the following six most significant ecosystem services for an urban context with specific reference to Stockholm, Sweden: air filtering (gas regulation), micro-climate regulation, noise reduction (disturbance regulation), rainwater drainage (water regulation), sewage treatment (waste treatment), and recreational and cultural values. Their methodology for choosing these six services over the others they identified is not described, and it is not clear why supporting services that enable ecosystems to exist should not be included, particularly when it is physically possible for some of them to be part of an urban environment and because they are important for ecological and human health (Carpenter et al., 2009, MEA, 2005b). It is also not clear why ecosystem services that provide benefits that are larger than the urban environment itself, or are able to move past urban boundaries (such as regulation of climate), should not be part of a discussion about urban environments and ecosystem services, given it is well known that the negative environmental impact of urban environments often transcends their physical boundaries (Doughty and Hammond, 2004, McDonald and Patterson, 2004).

The research described in the following sections takes a different approach and is not bound by the direct or localised nature of the ecosystem service in question. It will include a greater range of ecosystem services using the ranking methodology described.

4.5.2.1 RANKING CRITERION ONE:

INTEGRATING ECOSYSTEM SERVICES INTO THE BUILT ENVIRONMENT

Some ecosystem services, for example pollination and regulation of species diversity, cannot easily be integrated or mimicked in a built environment context. Others, such as the provision of energy or fuel are more conducive to integration (Bolund and Hunhammar, 1999). Contribution to or positive integration with some of these ecosystem services could become goals for new developments. Following a methodology similar to that described by Shelton et al. (2002), three levels (low, medium and high) were used to rank the ease of addressing each ecosystem service by the built environment. Criteria used to determine an ecosystem service's applicability to the built environment were: the ease of integrating an ecosystem service into built structure, infrastructure, and its surrounding context; and a consideration of existing technologies or design methods that already support or mimic the service. This allowed services to be prioritised and enabled an initial refinement of the list of ecosystem services suitable for developing regeneration oriented design in the built environment.

Where an ecosystem service is thought to have low suitability for being considered in the context of the built environment, it has been combined with another service as a secondary consideration rather than eliminated altogether, in line with suggestions made by Carpenter et al. (2009). This is illustrated in table 9. For example, the provision of biochemicals (pharmaceuticals or medicines) is not easily met by the built environment, although a small contribution to this service could be made in a similar way to the provision of food service. The latter could entail deliberately growing edible plants in an urban context. Contributing to the service of provision of biochemicals would mean ensuring some of these plants were chosen for their desirable biochemical properties. Bundling the services together encourages designers initially to consider how to provide food in an urban context but to also be aware of the secondary consideration of providing medicines, using the same methods¹⁶⁶. Many of the ecosystem services that cannot be physically provided by

¹⁶⁶ Several architectural projects have been designed to incorporate medicinal plants in the landscaping such as the 1990 Birley Health Centre in Sheffield (Vale, 2012) and the Carolyn Stolman Healing Garden at the Avon Foundation Breast Centre in San Francisco, designed by Topher Delaney to incorporate plants traditionally used

Footnote continued on next page...

an urban environment, such as pollination, provision of genetic material, and species maintenance, can be provided if considered as part of the effort to increase provision of habitat in an urban setting.

The following four ecosystem services are considered to have high applicability to the built environment: provision of fuel / energy, provision of fresh water, purification, and climate regulation (in terms of carbon storage or sequestration). This is because some buildings are already able to perform these functions. For example generating energy within an urban environment or on buildings has already been achieved in built form with established technologies such as photovoltaic panels. Further discussion and case study evaluations of urban and building integrated energy generation is provided by: Bahaj et al. (2007), Bahaj and James (2007), Crawford et al. (2006), Droege (2008), Omer et al. (2003), Storey et al. (2002), Yamaguchi et al. (2007), and Zahedi (2006). It should be noted that several building integrated energy generation systems are not necessarily energy effective when analysed from a life-cycle perspective (Mithraratne, 2009, Omer et al., 2003). This again illustrates the importance of thorough, site specific environmental performance analysis of any building technology before it is integrated into regenerative developments.

In a similar way to generating energy in urban settings, the provision of fresh water in urban environments and buildings, has been the subject of extensive research and testing. References for techniques to enable effective urban rainwater harvesting, water conservation, stormwater pollution mitigation, and stream restoration, along with case studies are indicated in table 9 (section 4.5.2.4). Table 9 also shows similar urban focused research and case studies for the ecosystem services of purification and climate regulation (in terms of carbon sequestration).

Three ecosystem services may have medium applicability to a built environment context: nutrient cycling, provision of habitat, and provision of food (table 9). These may be more difficult to integrate into urban settings than the four services described

to treat cancer (Therapeutic Landscapes Network, 2012). Ismail and Rahman (2001) and Jinghua and Junxin (2007) explore how medicinal plants might be included in urban landscapes. Tamimi (1999) and Therapeutic Landscapes Network (2012) give further case studies and listings of landscapes that incorporate medicinal plants and other aspects of therapeutic landscapes.

earlier. In the case of nutrient cycling and the provision of habitat, while the built environment can contribute to both, the regeneration of ecosystems that are not part of a built environment may be a more effective long term means of restoring these services. For example, if the built environment can contribute to the provision of habitat this may be of benefit to maintaining or restoring local biodiversity health. Many species of both plants and animals need areas of undisturbed and non-fragmented habitat (non-urban or human dominated areas) in order to thrive however. Some plants and, particularly, animal species are not compatible with humans in close quarters, in cities (such as large carnivores or herd animals), or with human pets, particularly cats, dogs, and rats (Wolch et al., 1995). This means efforts to increase the provision of habitat, and thus maintain or increase biodiversity health, will primarily need to focus on non-urban or periurban areas (Clarkson et al., 2007a). Despite this, several researchers argue for increased habitat provision within urban environments and describe numerous benefits (Bradley, 1995, Clarkson et al., 2007a, Duncan et al., 2011, Given and Meurk, 2000, Goddard et al., 2010, Loram et al., 2007, Lundholm, 2006, Mathieu et al., 2007, McPherson et al., 1994), suggesting efforts to increase habitat provision in an urban setting can and should be made.

In terms of nutrient cycling much of this ecosystem service is due to interactions between organisms that enable decomposition, those that use nutrients to grow, and abiotic elements of soil, water and atmosphere. Because the built environment is largely made up of impervious surfaces (Herald, 2003), and because of the way landfills are constructed and managed, altering the capacity for normal decomposition of organic products (Komilis et al., 1999), this natural kind of nutrient cycling is made more difficult.

The built environment holds great stores of materials in its very fabric along with vast amounts of embodied energy and carbon (Alcorn, 2003, Alcorn and Wood, 1998, Alcorn, 2006). Because of the quantity of materials used by the built environment and because of the considerable waste associated with construction and demolition activities (UNEP, 2007), the built environment might contribute to the ecosystem service of nutrient cycling by more carefully considered use and reuse of building materials and the provision of nutrient cycling of organic materials (through facilitating composting). The reuse of waste as building materials or the design of

buildings to enable them to be reused or recycled at the end of their life is not a new idea, but could be more carefully integrated in most urban contexts. Employing such strategies may take pressure off ecosystems to provide more raw materials and may also provide a new source of materials. With a few exceptions buildings are generally demolished rather than deconstructed so that their materials can be reused (Storey et al., 2003, Kibert et al., 2002, page 24). Several authors discuss ideas for changing this and provide case studies (Guy and Shell 2002, Kibert, 2003, Kibert et al., 2000, pages 24-26, Krook et al., 2012, McDonough and Braungart, 2002, pages 92-117). Oliver (1997) provides vernacular examples of building materials reuse or recycling and design for deconstruction. Brown and Jameton (2000), Drechsel and Kunze (2001), Nunan (2000), and Pankhurst et al. (2011) give examples of urban composting. In a built environment context, the ecosystem service of decomposition is most closely linked with how waste is created and treated. Although the built environment itself is not capable of decomposing matter, the way it is built and organised, and the way materials are used within it, can support or hinder this service as part of a wider consideration of nutrient cycling.

The provision of food is considered to be of medium applicability to the urban environment. Although it is vital that urban communities begin to grow some of their own food (Pfeiffer, 2006, Koc et al., 1999, Deelstra and Girardet, 2000), devising urban agricultural systems that can feed large proportions of a city's residents may be difficult (section 5.3.7). Food provision might be developed in concert with periurban areas and agriculturally productive hinterlands (Drechsel and Kunze, 2001). Despite this, and like the earlier provision of habitat example, there is no lack of research advocating the need and benefits of urban and even building integrated agriculture or food growing, with case study examples of how some cities (particularly in 'non-western' countries) already achieve high rates of urban food production (Brown and Jameton, 2000, Funes et al., 2002, Despommier, 2011, Koc et al., 1999, Bakker et al., 2000, Deelstra and Girardet, 2000). In the 1990s Cuba underwent dramatic change due to the crisis brought about by the loss of trade options after the collapse of the socialist bloc in 1989 (Altieri et al., 1999). A large number of urban gardens in Havana (population approximately 2.1 million) and other major cities emerged as a grassroots response to the situation (Altieri et al., 1999). In 1999 a small scale survey of residents of Havana suggested that more than 10%

were eating food from the urban gardens and for those people living in a household with access to an urban garden, an average of 60% of their produce needs were met by these gardens (Moskow, 1999). By 2004 it was reported that approximately 272 100 tonnes of food were produced from urban gardens in Havana (McKibben, 2005). This represents a high proportion of the vegetable needs of inhabitants and a '*more than token*' contribution to the rice and meat parts of the diet (McKibben, 2005, Funes et al., 2002).

Although the provision of habitat, nutrient cycling and the provision of food are possible in urban settings, in order for these three services to become embedded into cities, particularly in industrialised nations, large changes in behaviour and ways of living in urban environments need to take place. This may make the realisation of such ideas more difficult. For this reason, these services are listed as being of medium applicability to a current built environment context. Each ecosystem service is examined in more depth relative to the potential for regeneration in a specific urban context in chapter five.

4.5.2.2 RANKING CRITERION TWO:

A HIERARCHY OF ECOSYSTEM SERVICES RELATIVE TO OVERALL IMPACT

An attempt is made here to examine the importance of each service in terms of an ecosystem service's physical, biological, and chemical contribution to maintaining the functional health of global ecological systems (after the definition of ecological importance found in Costanza and Folke, 1997). As previously noted, any discussion of importance, significance, or value of ecosystem services is relative to the specific goals and perspective of whoever is making the definition. Value in terms of ecological importance is defined as 'intrinsic' because it does not rely on human preferences, while value related to economic or social factors is defined as 'instrumental' because it is inherently anthropocentric in nature (Farber et al., 2002).

Several authors discuss the need for ecological importance factors rather than just economic ones to be taken into account when valuing ecosystem services (Heal,

2005, Patterson, 2002, ten Brink et al., 2011). Despite this, a ranking of ecosystem services based on ecological importance has not been conducted to the author's knowledge. Such a ranking is problematic for a number of reasons. It is difficult because of gaps in knowledge about ecosystems, and also because of the non-linear complexity found in ecosystems and in current ecosystem modelling (Peterson, 2002, pages 128, 137). This, combined with the fact that ecosystems provide both direct and indirect, as well as tangible and more difficult to quantify benefits, over various temporal and spatial scales, makes it hard to predict ecosystem dynamics and assign value to them (Chee, 2004, ten Brink et al., 2011). Furthermore, as demonstrated in figure 63, although different categories of services can be listed, the interlinked and interdependent nature of ecosystem services makes it practically difficult to assign value to them as discrete, independent services (Chee, 2004, Patterson, 2002).

Although there are difficulties in providing rankings of services related to ecological value, Costanza and Folke (1997) examine ways scientists could and do assign value independent of human preferences, such as 'survival value' and 'energy theory of value' based on thermodynamic principles (see also: Patterson, 2002)¹⁶⁷. Chee (2004) also discusses an ecosystem service's contribution to ecosystem 'resilience' as a possible measure of value independent of human concerns.

Another way to gauge importance is to examine how certain ecosystem services are related to others. Figure 63 illustrates that provisioning services are entirely dependent upon regulation and supporting services. The regulation services with the most connections are climate regulation and biological control, while the supporting service with the most connections is provision of habitat. This indicates that design with the increased health of these services in mind may have the most secondary benefits in terms of supporting other ecosystem services. For example a development that successfully regenerates habitat will have positive effects on species maintenance (biodiversity), nutrient cycling and pollination services if designed carefully. Regulation services directly support or enable the most number

¹⁶⁷ Patterson (2002) shows ecosystem services provided by the atmosphere, followed by the ocean, are larger in magnitude than those derived from terrestrial ecosystems.

of provisioning services. This demonstrates that regenerating or maintaining regulation services should be a priority even if provisioning services provide the most tangible, measurable and economically profitable results to humans. Without regulation services all of the provisioning services (with the exception of ornamental resources) are affected.

Shelton et al. (2001) found that all ecosystem services were ranked as having 'high' ecological importance because decline in one would impact on future production capabilities in another. The research presented here follows a similar pattern. The exception is found in some of the provisioning services. These services, while of obvious importance to human wellbeing, tend to be related to human preferences and do not necessarily have high importance in terms of maintaining ecological health. This is why the provisioning service of fuel / energy is listed as being of 'medium' ecological significance in table 9. The provisioning service of fresh water is of great importance to humans but also to all flora and fauna, so has a high rating.

4.5.2.3 RANKING CRITERION THREE:

THE BUILT ENVIRONMENT'S IMPACT ON ECOSYSTEM SERVICES

To determine which ecosystem services might be most appropriate to focus on in the context of the urban built environment, the environmental impact that the built environment has on each ecosystem service was also considered. The underlying rationale was that if the built environment has a large negative effect on a particular service, it would benefit that particular ecosystem service if the built environment could mitigate or reverse this by integrating with or working to restore the service. This provided a further and final set of criteria for ranking the ecosystem services in table 9. The basis of the ranking of the impact of the built environment on particular ecosystem services was drawn from a number of sources (Doughty and Hammond, 2004, McDonald and Patterson, 2004, Graham, 2003, Newman, 2006, Wilby and Perry, 2006, Kibert et al., 2002).

4.5.2.4 RESULTS OF THE RANKING EXERCISE

Through conducting the ranking exercise, seven ecosystem services were identified as most suitable for regenerative design in a built environment context, and are listed in table 9. The following seven services (or bundles of services) presented suggest that in a similar way to the functioning of an ecosystem, an urban environment (and individual buildings as part of it) could be designed with a deliberate focus on generating a system that: provides habitat for species suitable for co-inhabitation with humans in the urban built environment; contributes to soil formation and fertility through careful cycling of bio-degradable wastes and recycling of non-biodegradable wastes; purifies air, water and soil; contributes to regulating climate through mitigating GHG emissions and the heat island effect, and by sequestering carbon; produces renewable energy; collects and distributes fresh water; and produces human food.

The ranking results in table 9 suggest that an initial focus on the three ecosystem services of regulation of climate, purification, and provision of fresh water might be easiest to focus on and have a high number of additional beneficial outcomes for ecosystems and the species within them. The remaining four sets of services can be considered as having an equal ranking. This may change depending on local conditions and whether a design team is more interested in ease of integration with the built environment (when they may choose to focus on provision of fuel or energy, and fresh water), or benefit to ecosystems in general (when the services of climate regulation and nutrient cycling would be preferential).

In the absence of rankings of ecosystem services provided by ecologists, the methods used to create the list in table 9 have produced a more manageable set of ecosystem services for a design context, while still capturing a wide range of ecological considerations. It should be remembered that this is not a ranking of the ecological importance of the ecosystem services alone, but considers if services might be suitable for integration into the built environment. Such a list should be revisited as knowledge gaps are filled in the field of ecology and the understanding of ecosystem services.

TABLE 9 ECOSYSTEM SERVICES FOR THE BUILT ENVIRONMENT

Ecosystem services for the built environment to mimic:					Ranking Criteria:	Climate change / biodiversity implications:	Additional research sources or case studies of built environment design that include an understanding of this service:
Applicability to the Built Environment							
Ecological significance							
Negative environmental impact caused by the built environment							
Supporting Services	1. Habitat provision <i>(including: provision of genetic information; biological control; fixation of solar energy; and species maintenance)</i>	Medium	High	High at a local scale	<ul style="list-style-type: none">Plan for habitat for non-human.Consider reducing fragmentation of habitat.	<ul style="list-style-type: none">Increased / maintained biodiversity may have links to increased ecosystem resilience, and allow for better adaptation to climate change; reduction of the urban heat island effect; sequestration of carbon; increased air, water and soil quality; and more fertile soil meaning greater potential for the growth of biomass and food production and therefore increased human health and resilience.Remediation of some forms of water, air and soil pollution through increased urban vegetation.Possible protection from wind or wave surges; reduced erosion; more adaptable ecosystems as the climate changes; reduction of stormwater peak flows; and cooler urban temperatures (due to increased urban vegetation).	Beckett et al. (1998), Benedict and McMahon (2006), Cavanagh (2006), Kadlec et al. (2000), Lundholm (2006), McPherson et al. (1994), Mitchell and Popham (2007), Pickett et al. (2008), Todd and Todd (1993).
	2. Nutrient cycling <i>(including: decomposition; soil building; and provision of raw materials)</i>	Medium	High	High at a regional / global scale	<ul style="list-style-type: none">Nutrients (materials) should be able to be biodegraded or recycled in closed loops and retained in the system.Development should contribute actively to soil formation and the renewal of fertility. Development should be considered a potential source of future building materials.	<ul style="list-style-type: none">Reduction of waste and ecosystem pollution caused by materials production and transportation.Reduced need for mining / growing / production / transportation of materials and energy leading to reduction in GHG emissions, waste and ecosystem disturbance.Decreased use of energy and therefore GHG emissions.Increased health of ecosystems and humans and reduced biodiversity loss.	Allenby and Cooper (1994), Bogunovich (2002), Desrochers (2001), Erkman (1997), Graedel (1999), Kibert et al. (2002), McDonough and Braungart (2002), Nakajima (2000), Newman (1999), O'Rourke et al. (1996).
Regulating Services	3. Purification	High	High	High at a local / regional scale	<ul style="list-style-type: none">Water, air and soil should be purified on site before return to non-human ecosystems.Water and air should be cleaner leaving the development than when it entered.Surrounding soil should become more fertile over time.	<ul style="list-style-type: none">Increased health of ecosystems and living organisms within them (including humans).Increased terrestrial, riparian and marine productivity.Reduction of air and water pollution.Eutrophication reduction.Remediation of polluted sites.Reduced ozone damaging gas emissions and reduced GHG emissionsReduced biodiversity loss.	Alexander (1994), Beckett et al. (1998), Campbell et al. (2010), Cavanagh (2006), Herald (2003), Kadles et al. (2000), McDonough and Braungart (2002), Todd (2004), Todd and Josephson (1996), Todd and Todd (1993), Salt et al. (1995), Younos (2011)
	4. Climate regulation	High	High	High at a global scale	<ul style="list-style-type: none">Development should contribute to regulating climate by: sequestering carbon; providing protection from decreased ozone; and remediating the heat island effect.	<ul style="list-style-type: none">Mitigation of the causes of climate change.Mitigation of the urban heat island effect.More adaptable communities.Improved health of living organismsImproved ability of ecosystems and the organisms within them to adapt to climate change.	Altomonte (2008), Gill et al. (2007), Hamin and Gurran (2009), Hunt (2004), Hunt and Watkiss (2011), IPCC (2007b), Kirshen et al. (2008), Nottage et al. (2010), Reisenger et al. (2010), Roaf et al. (2005), Steemers (2003).

Provisioning Services	5. Provision of fuel / energy for human consumption	High	Medium	High at a global scale	<ul style="list-style-type: none"> • Development should provide enough fuel or gather energy from renewable sources to provide for its own needs, preferably more so this can be distributed to neighbours. • Design should encourage effective energy use. 	<ul style="list-style-type: none"> • Reduced transport and energy generation related GHG emissions. • More self-reliant and therefore robust urban environments. • Reduction of air, water and soil pollution. • Reduction of fossil fuel mining, drilling and transportation impacts on biodiversity. 	Armstrong (2009), Ewing and Rong (2008), Kay (2002), Leary and Esteban (2009), Mithraratne (2009), Moore et al. (2004).
	6. Provision of fresh water	High	High	High at a regional scale	<ul style="list-style-type: none"> • Development should capture rainwater and conserve water to meet its own needs and preferably more so that excess can be distributed to neighbours. • Design should encourage the conservation of water. 	<ul style="list-style-type: none"> • Reduction of water pollution. • Increased health of riparian systems. • Reduction of the urban heat island effect. • Increased quality of water. • Increased health of living organisms • Reduced wastage of water through pipes. 	Campbell et al. (2010), Gill et al. (2007), Herald (2003), Lee et al. (2012), Mithraratne and Vale (2007), Todd (2004), Winz (2005), Yeomans and Yeomans (2008), Younos (2011).
	7. Provision of food (including: provision of biochemicals)	Medium	Medium	High at a global scale	<ul style="list-style-type: none"> • Development should produce food 	<ul style="list-style-type: none"> • Reduced transport and energy generation food related GHG emissions. • More self-reliant and therefore robust urban environments. • Reduction of air, water and soil pollution. • Reduction of fossil fuels needed to produce the products of large scale agriculture. • Healthier humans. • Reduced land use transformations (i.e. from natural ecosystems to agricultural systems). 	Bakker et al. (2000), Copeman (2008), Despommier (2011), Gerbens-Leenes and Nonhebel (2002), Ghosh et al. (2008), Koc et al. (1999), Mollison and Holmgren (1978), Neff et al. (2007), Vale and Vale (2009).

4.5.3 BEGINNING THE PROCESS OF INCORPORATING AN UNDERSTANDING OF ECOSYSTEM SERVICES INTO BUILT ENVIRONMENT DESIGN

The first step in applying ecosystem services analysis to regenerative design is to determine if there is an adequately healthy existing ecosystem in the locality that can be studied. If not, basing design targets on an ecosystem that existed prior to development on the site could become the focus of study. Measurable rates of ecosystem service provision that exist (or existed) on a site can then be determined. For example, specific figures such as annual rainfall and water retention in a particular place relate to the ecosystem service of provision of fresh water, and can be calculated with accuracy. Although there are knowledge gaps in the field of ecology related to measuring ecosystem services (ten Brink et al., 2011), each ecosystem service has aspects that can be measured and are useful in setting initial design targets for regeneration (see chapter five). These targets can then be used to determine the optimal environmental performance of the built environment that is (or will be) on the same site as the ecosystem studied. For instance, the level of habitat provision in a new (or retrofitted) development should ideally be equal to the level of habitat provision in the original ecosystem. In examining climate regulation, one aspect that could form a design goal would be to determine how much carbon was contained in and sequestered by the original ecosystem. This would set the optimal level as a goal for the new development. Although it may be difficult to determine accurately certain rates or figures related to ecosystem services, an approximate figure is still useful in determining site specific ecological regeneration goals for built environments.

Much like process level ecosystem biomimicry (see chapter three), biomimicry at the function level can become the overall theoretical concept and goal generator for a development, while the specific methods or technologies to achieve the goals can be drawn from a wide range of design techniques and tools. For example, a focus on the ecosystem service of nutrient cycling could draw upon existing knowledge and techniques found in: industrial ecology (Erkman, 1997); 'Cradle-to-Cradle' design (McDonough and Braungart, 2002); design for recycling, reuse and deconstruction (Guy and Shell, 2002); composting and biodegradation techniques and materials

technologies (Vincent, 2010); and landfill mining (Krook et al., 2012). A focus on purification could draw upon: Living Machines (Todd and Todd, 1993); phyto-remediation and bio-remediation techniques (Salt et al., 1995, Alexander, 1994); filtration techniques and materials; green roofs and facades (Lundholm, 2006); green infrastructure concepts (Benedict and McMahon, 2006, Gill et al., 2007); urban forest generation and management strategies (Bradley, 1995); and constructed wetlands (Kadlec et al., 2000).

While there are existing design concepts and technologies that may be worthy of consideration in a regenerative design context, it is of extreme importance that each strategy or technology is studied from a life cycle perspective in the context of each specific project to ascertain if it is suitable to use in that case. This is crucial because some green building technologies that appear to increase one aspect of the environmental performance of the built environment in fact result in negative ecological outcomes over the long term. For example, employing green wall or facade technologies might be appropriate in some locations, but the exact make-up of the systems, the water source and plants used, the distance technologies or systems have to travel, and the climate context, may mean that the overall ecological footprint of a development is increased by their use rather than decreased. Gerhardt and Vale (2010) found that green wall systems used to grow food on building facades are likely to be more resource intensive over a whole life cycle, when considering the environmental impacts caused by the production and transportation of materials to make the green wall systems (stainless steel, aluminium or plastic) than conventional agriculture sourced from within a 500km radius.

New technologies or design methods are not necessarily needed to implement ecosystem based biomimicry at a function level in the built environment, but rather there is need for a reconsideration of the built environment's overall purpose and expectations and evaluation of its performance¹⁶⁸. The fact that many green, sustainable or otherwise environmentally 'better than conventional' design concepts, methodologies, techniques and materials exist, but have not to date made significant

¹⁶⁸ Mitchell (2012) also discusses why advances in technology will not be enough to address the multiple ecological and climate issues that are beginning to impact on humanity.

positive impacts on the environmental performance of the built environment as a whole (or even to individual buildings they may be used on or on as described by Vale and Gerhardt, 2010) is testimony to this¹⁶⁹.

Ecosystem biomimicry at the function level could also define criteria to ensure technologies and systems integrated in a development are appropriate in terms of overall environmental impact on multiple ecosystem services. For example, increasing the provision of metals through mining (increasing the ecosystem service of provision of raw materials) due to their ability to be recycled many times (engaging more effectively with the ecosystem service of nutrient cycling) would be deemed inappropriate, given the negative impacts increased mining could have on the ecosystem services of habitat provision and climate regulation. An important part of an ecosystem biomimicry design methodology, therefore, is to ensure that strategies to address one ecosystem service do not impinge negatively on the health of others. An analysis of associated impacts or benefits of design decisions on ecosystem services is necessary. Figure 63 could be a useful aid for beginning such an endeavour, and figure 66 is an example of how this can be done.

An ecosystem services analysis methodology could be employed by teams of designers and ecologists as well as urban planners, policy makers and ecological economists at local and regional levels. An incremental process that focuses on improving existing ecosystem services in a specific place to an optimal or pre-existing level could be a tangible starting point in the process of regenerating ecosystem services in the urban built environment. The next stage would be to initiate measures to reintroduce ecosystem services that may be absent in urban areas due to past degradation and removal of ecosystems, or because of conventional ways of constructing urban environments. This suggests that a regenerative built environment, if it can exist at all, will need to evolve over time rather than be expected to be fully functional after the initial realisation of a design.

¹⁶⁹ One of the causes of this is the lack of feedback between design intentions and the eventual results experienced by users, or the wider environment after a project is built. Such feedback loops could be enhanced by increased post occupancy evaluations and in use performance monitoring of buildings (Leaman and Bordass, 2001, Leaman et al. 2010).

The built environment varies greatly according to different climatic, economic, political and cultural contexts, and systemic approaches that are appropriate to specific places will also vary (Mang and Reed, 2012). Despite each locality needing to evolve its own unique regenerative built environment system, knowledge of how to create or begin such systems can be transferred. Using ecosystem services in a design context requires design teams to consider which ecosystem services are important or suitable for a particular site before any design of buildings or urban areas begins¹⁷⁰. Although research aimed at establishing this is presented here (section 4.5), discussions with ecologists who have knowledge of local ecosystems may further define the hierarchy of importance of the ecosystem services for a specific site and identify an appropriate ecological focus. This suggests that wider disciplinary inputs into the process would be necessary than those normally found in a traditional design context.

There is a need to determine to what extent a rural hinterland must be considered in tandem with an urban counterpart if regenerative goals are to be achieved across multiple ecosystem services. This implies a need to understand ecosystem services at a larger scale (city, region, or ecosystem boundary) when devising goals and targets for specific individual buildings or small developments. Careful thought in each case needs to be put into whether it is more appropriate to use human-defined urban boundaries, such as city limits or suburb boundaries, or those related to ecosystems themselves, such as habitat type demarcations, or water catchment zones, when employing ecosystem services analysis.

4.6 DESIGN STRATEGIES SIMILAR TO ECOSYSTEM SERVICE BASED BIOMIMICRY

Ecosystem services do not appear to have been explored by researchers examining the concept of biomimicry. The closest example of ecosystem services analysis

¹⁷⁰ TEEB (2011b) present a six step 'stepwise' approach to integrating ecosystem services into city wide management practices (appendix five). Although this is not necessarily instantly applicable to an ecosystem based biomimicry design methodology it could be a starting point for investigation, particularly steps two (identify which ecosystem services are most relevant) and three (determine what information is needed and select assessment methods). Haines-Young and Potschin (2008) also provide information about three different approaches (place based, habitat based and service based) to using ecosystem services analysis at a nation-wide level (in this case England) that may be useful in a design context.

being applied to design may be the proposed Lloyd Crossing Project for Portland, Oregon (section 2.5.3). The design team investigated how the site's original ecosystem functioned before development (in terms of rainfall, carbon balance, solar energy fixation and habitat type and coverage) to determine the ecological performance goals of the project over time (Portland Development Commission, 2004). The project remains un-built, so it cannot be evaluated. The Lloyd Crossing Project design concept differs from that proposed in this thesis because it does not consider wider ecosystem services and therefore, the additional environmental performance benefits that such an approach could bring. Understanding ecosystem services could be an important way to bring a thorough knowledge of ecology into built environment design, because the concept of ecosystem services comes from the study of ecology, rather than designers deciding which aspects of ecological knowledge to integrate into design.

4.7 BENEFITS AND DIFFICULTIES OF USING AN UNDERSTANDING OF ECOSYSTEM SERVICES IN URBAN OR ARCHITECTURAL DESIGN

Aside from the general potential ecological benefits of regenerative design, there are significant social and economic benefits as summarised in appendix six. Elaboration upon these will not be repeated here, but there are several additional advantages when adding ecosystem services analysis to a regenerative design process that will be discussed.

Using ecosystem services analysis to evaluate existing built environments, or to devise design goals, enables the success or failures of developments to be gauged from a perspective of ecological reality. It avoids anthropocentric goals and unhelpful design metaphors that are difficult to quantify, or that ultimately amount to 'greenwash'. Ecosystem services analysis also enables tangible bench marks to be devised over different time periods, and lends itself to long term planning. Using an understanding of ecosystem services is conducive to a regenerative approach, but enables a more specific targeted and measurable design response than simply aiming to 'regenerate ecosystems'. It could provide a practical way to move regenerative design from a theoretical endeavour to the creation of measurable built

examples. Understanding ecosystem services fits well into the philosophy of encouraging people to move beyond the typical 'reduce, recycle, efficiency' sustainability paradigm (Reed, 2007, McDonough and Braungart, 2002), and to grasp the possible potential for increased ecological and human health when adopting a regenerative approach.

A key benefit of mimicking the functions of ecosystems is that through careful urban planning, buildings as part of a larger system that are able to mimic natural processes and functions in their creation, use, and eventual end of life, could have the potential to be more resilient and adapt more readily to climate change (TEEB, 2011b). The Economics of Ecosystems and Biodiversity group (TEEB, 2011b) provide clear reasons why an understanding of ecosystem services should be integrated into urban level decision making. Firstly, when the benefits derived from local ecosystems become apparent and are visible to local residents these are more valued and perhaps therefore preserved. For example, understanding that purer water is a result of nearby forests in a particular city could mean it is easier to convince people of the need to conserve the forest¹⁷¹. This has the potential to contribute to prioritising or preventing certain urban development projects in particular areas, and therefore to long term effective spatial planning, providing the overall values of society change to allow this. Secondly, the impacts of decision making can be understood across multiple interconnected environmental issues, and can therefore be communicated to city residents. This means more accurate planning and budgeting and in some instances could lead in time to a reduction in a city's ecological footprint¹⁷². Other benefits identified by TEEB (2001b) include: increased human health, and increased biodiversity in urban areas.

Although ecosystems are perhaps the best known examples of effective organisation of life on Earth (Vincent, 2010), in some locations the availability of an ecosystem to compare to or mimic may be lacking. In older urban environments, little may be known about the characteristics of ecosystems on a site before development, and

¹⁷¹ For specific case studies of valuing the provision and regulation of water ecosystem services by urban residents in Ulaanbaatar, Mongolia and Moyobamba, Peru see: TEEB (2011b).

¹⁷² Refer to: TEEB (2011b) for case studies.

there may be no similar ecosystems left to study. Uncertainty also exists about what the future effects of climate change will be on ecosystems (Walther et al., 2002). This means that an ecosystem that has evolved in a particular place may cease to be a suitable model for mimicking in the future. In some situations, it may be more appropriate to devise regenerative ecosystem service goals from predictions of future ecosystems and climatic conditions.

4.8 CONCLUSIONS: CHAPTER FOUR

There are several findings in this chapter that can contribute to an understanding of ecosystem services analysis in the context of regenerative design. It may be easier to use an existing or pre-development ecosystem as a model for establishing goals for supporting services than for provisioning services, because provisioning services are closely related to human needs and desires that are independent of the normal functioning of ecosystems. Humans are also able to manipulate ecosystems to provide some of the provision services effectively. The earlier discussion of the green revolution (section 4.4.1.1) is an example of this relating to the provision of food service.

Ecological regeneration goals for developments can be provided by ecosystem services analysis for a particular place. Simultaneously, mimicking the complex interactions between living organisms in ecosystems is a readily available example to draw upon to create built environments that might be able to integrate with the habitats of other species in a mutually beneficial way. Ecosystem services analysis appears to be a promising approach for a longer term response to sustainability issues in general, and to climate change impacts specifically, because it addresses many of the underlying issues in urban environments that need re-evaluation. The analysis presented here provides a starting point for creating regenerative design that is measurable. This is important for the establishment of the credibility of regenerative design.

The application of ecosystem services analysis to regenerative design has significant philosophical implications because it asks design teams to judge their environmental

performance goals against the best an ecosystem could or did do on the same site and in the same climate, rather than on standards defined by humans. Employing ecosystem services analysis in the pursuit of regenerative built environments may, therefore, require a rethinking of key performance indicators. Rather than a 'one size fits all approach', performance levels should be specific to a particular site, locality, or region (TEEB, 2011b). Research is needed to ensure that ecosystem services selected for inclusion in a built environment design context are the correct ones. Failure to assess and amend, if necessary, the ecosystem services to be included could result in misplaced effort and resources. Practically, the use of ecosystem services analysis in design processes will mean working much more closely with ecologists and allowing time for conducting research on site specific ecosystems.

By devising principles for the application of ecosystem biomimicry at a functional level to the built environment, it is anticipated that designers may begin to understand how to utilise ecology knowledge beyond the level of metaphor. The change needed will not necessarily come through new technologies (Mitchell, 2012), but by the adoption of new mind-sets and goals for how built environments can and should function. Ecosystem biomimicry, particularly at the function level could provide such goals, as well as methods grounded in the physical ecological reality of the planet that are proven to be achievable.

New (or retrofitted) developments using an understanding of ecosystem services that become regenerative, even only in part, could act as filters (purifying air and water), providers (of food and fresh water) and generators (of energy) for the rest of the surrounding existing built environment. This is likely to endure for a considerable time, during which it will still be degrading ecosystems and climate. If regenerative developments within existing urban settings could start to perform even small aspects of ecosystem services beyond their own needs or boundaries, the built environment causes of climate change and biodiversity loss may in part be mitigated. At the same time the built environment may become more adaptable to climate change. Whether this is possible is explored in chapter five. Such ideas are discussed by proponents of eco-effectiveness (McDonough and Braungart, 2002) and non-ecosystem based regenerative design (Reed, 2007). The difference with what is proposed here is that measurable targets derived from ecosystem services,

such as emissions levels, carbon storage, water catchment, energy production and resource production, are determined through an understanding of suitable ecosystems or the pre-development ecosystem of the site, and thus are based on ecological reality, rather than human political needs or trends.

5.0 CHAPTER FIVE: APPLYING ECOSYSTEM SERVICES ANALYSIS TO AN URBAN CONTEXT: A CASE STUDY OF WELLINGTON, NEW ZEALAND

When humanity is considered part of nature, cities themselves can be regarded as a global network of ecosystems. If compared with true, natural ecosystems, the man-made ones are however immature due to features like their rapid growth and inefficient use of resources such as energy and water... But there is also a presence of natural ecosystems within the city limits... Natural urban ecosystems contribute to public health and increase the quality-of-life of urban citizens... Most of the problems present in urban areas are locally generated... Often the most effective, and in some cases the only, way to deal with these local problems is through local solutions. In this respect, the urban ecosystems are vital.'

(Bolund and Hunhammar, 1999).

5.1 INTRODUCTION

In chapter four the potential for understanding and then mimicking ecosystem services as a means to address both climate change and biodiversity issues was explored for setting goals for regenerative developments, designing them, and measuring their performance as they evolve. It is not enough just to interpret ecological knowledge and reorganise it so it is useful for designers seeking to mimic ecosystems in an architectural context. A discussion of how to apply the concepts developed in this thesis must be given.

An ecosystem based biomimicry approach to regenerative architectural or urban design is closely related to its physical site, in terms of ecology, climate, and culture. Because of this, a case study of how ecosystem based biomimicry at the function level could be applied to a specific existing urban context will be used. This can

illustrate how the approach can be employed to evaluate built environments and help to devise sustainability or regeneration oriented goals for their re-development.

The process followed in examining Wellington, New Zealand will serve as an illustration of the practical application of the theoretical underpinnings of ecosystem based biomimicry to urban built environments and could be an example for others intending to apply these ideas to different locations. It should be noted that the purpose of this case study is not to provide an exhaustive, in depth evaluation of Wellington itself, but rather is to illustrate (or disprove) the potential usefulness of ecosystem services analysis and further clarify which ecosystem services may be most effective to target in an urban context.

5.1.1 THE CASE STUDY: CHOOSING A LOCATION

The city of Wellington, New Zealand was chosen as the location for the case study for several reasons. It is a suitable subject not only because the author is familiar with it and has access to it, but also because it is small enough to be manageable within the scale of this research, and large enough to be illustrative of potential successes and difficulties in applying ecosystem services analysis to built environments. Due to the relatively young age of the city (approximately 150 years)¹⁷³, information and accounts about the conditions and makeup of the original ecosystem before European settler development were available. This complemented a sizeable amount of existing sustainability focused initiatives and data concerning the city available for analysis (Boffa Miskell, 1998, Croucher, 2005, Milne and Watts, 2008, Mitchell, 2010, Gabites, 1993, Greater Wellington Regional Council, 2005, Greater Wellington Regional Council, 2010b, Greater Wellington Regional Council, 2009, Jollands et al., 2006, NIWA et al., 2011b, Park, 1999, Sorensen, 2010, Waste Not Consulting, 2006, Wellington City Council, 2010a, Wellington City Council, 2010d).

¹⁷³ This refers to the beginning of the larger scale and permanent urban built environment in the region rather than human habitation itself, which began much earlier when successive Māori Tribes settled in the area. (Wellington City Council, 2012b).

An examination of the ecosystems that existed on the site of Wellington before the city was built was conducted to ascertain how a fully functioning and climatically appropriate system probably worked on the site. The results of examining the seven key ecosystem services detailed in chapter four in relation to Wellington will be described. A brief introduction to Wellington follows in section 5.2.

FIGURE 77 WELLINGTON CITY, NEW ZEALAND (PHOTO BY GLUTNIX).

5.1.2 THE EVOLUTION OF THE CASE STUDY: DEAD ENDS, TRUNCATIONS AND OVERLAPS

During the course of the research several different avenues of exploration were examined. Some led to results that are included here while others proved less helpful but instead helped to reshape earlier findings. A brief summary is provided below.

5.1.2.1 ECOSYSTEM PROCESSES VS. ECOSYSTEM FUNCTIONS: A DEAD END

Utilising ecosystem processes in the pursuit of a regenerative built environment was essentially a research 'dead end'. The original intention of this case study was to compare the workings of Wellington City to the processes of ecosystems as described in chapter three and the functions of ecosystems as described in chapter four. After considerable time it became apparent that using ecosystem processes as the basis of design or evaluation of the built environment was extremely difficult and time consuming, and did not result in easily quantifiable environmental performance design goals. Ecosystem processes may be more suitable for informing design metaphors than contributing to measurable outcomes¹⁷⁴.

Focusing on the functions of ecosystems (ecosystem services) rather than the processes of ecosystems shifts the focus from how people design built environments to the outcomes of design. From the point of view of a designer this may be a more promising direction for the research. This is because a focus on ecosystem services is less prescriptive in terms of guidelines for how a built environment should be constructed, and simply provides end goals and a framework to work within. Potentially, any appropriate existing or future design techniques, methodologies, technologies or strategies could be used. This allows synergies between different design methods to be harnessed without disregarding them because they do not mimic or stem from an understanding of biology or ecology. As pointed out in chapter one, it should be remembered that reductions of 80% in carbon emissions associated with the built environment are considered to be possible using current technologies (Lowe, 2000).

¹⁷⁴ Exceptions are found in efforts to mimic single ecosystem processes at small scales. For example, developments utilising industrial ecology concepts employ an understanding of the ecosystem process of cycling of materials (section 3.5.4.6). Case studies of successful industrial ecology projects, such as The Happy Shrimp Farm in the Netherlands, and Denmark's Kalundborg industrial area are given in section 2.6.2.2.

5.1.2.2 TAILORING ECOSYSTEM SERVICES TO THE BUILT ENVIRONMENT: A TRUNCATION

The analysis of ecosystem services in relation to Wellington originally began using all 26 ecosystem services discussed in chapter four (table 8). This quickly ballooned into a cumbersome and overly complex process and led to the decision to determine more precisely which ecosystem services were most appropriate in a built environment context if the concept was to be practically useful. This was the impetus behind the research discussed in section 4.5.2.

5.1.2.3 ECOSYSTEM SERVICES ANALYSIS AND ECOLOGICAL FOOTPRINTING: AN OVERLAP

Some similarities exist between using an understanding of ecosystem services to guide the design of the built environment, and ecological footprint analysis (Wackernagel and Rees, 1996, Venetoulis and Talberth, 2008, Rees and Wackernagel, 1996, Bicknell et al., 1998, McDonald and Patterson, 2004, Smith and McDonald, 2008), particularly when considering the provisioning services. This is because these services are specifically related to human consumption. There are some key differences between the two approaches. Ecological footprinting relates individual, urban population, or national levels of human consumption of natural resources, to the estimated annual regenerative capacity of the biosphere to renew the resources consumed and absorb the waste created (Wackernagel and Rees, 1996). Often land and water productivity levels are used as the basis of these calculations. Ecological footprint analysis normally leads to the approximation of equitable shares of resource use for a given population, and can determine the percentage of 'overshoot' for an individual or population (Venetoulis and Talberth, 2008, and section 1.4.1).

By contrast, the kind of ecosystem services analysis described in this thesis starts from the assumption that an ecosystem that has not been degraded by human activities is likely to be a highly effective example of organisation of life in terms of environmental performance. Such an ecosystem, in a given location and climate, can

therefore provide a model or set of targets for urban areas in the same location and climate. The ecosystem used as the basis for the analysis may exist, or may have been damaged or already removed, implying that analysis must at times be of an ecosystem that existed in the past. Ecosystem services analysis is more site or climate specific than ecological footprinting and relates to an actual ecosystem (which could be terrestrial, riparian, or marine as appropriate) rather than generic land or biosphere capacity factors. The analysis of ecosystem services may be more time consuming initially, because it must be tailored to each specific place, but the potential for accuracy may be increased, particularly when considering the categories of supporting and regulating ecosystem services.

Despite these differences the two approaches are certainly complementary. It may be that ecological footprinting is useful as a way to illustrate the nature of the issues relating to each ecosystem service, and determine design goals for the provisioning services. Ecosystem services analysis may provide possible solutions for specific locations and more focused targets, particularly for the supporting and regulating services.

5.2 WELLINGTON CITY: A BRIEF DESCRIPTION OF CLIMATE AND TOPOGRAPHY

Wellington is New Zealand's capital city, with a population of approximately 197 700 people in 2010 (Statistics New Zealand, 2010b)¹⁷⁵. New Zealand is made up of three main islands that lie between latitudes 35° and 47° South and between longitudes 166° and 178° East (figure 78). Wellington is 41.3° South and 174.8° East.

Wellington is a coastal city nestled into hills surrounding one side of a large harbour at the southern end of the North Island. The urban area hugs the harbour leaving the area to the west of the city (also part of 'Wellington City') mostly unpopulated (figure 78: urban areas are 'artificial' in the key). Wellington is part of the 'Greater Wellington Region' made up of eight territorial authorities besides Wellington City: Lower Hutt

¹⁷⁵ This is approximately 41% of the Greater Wellington Region and 5% of New Zealand's overall population (Wellington City Council, 2012d).

City (population 102 700) and Porirua City (population 52 100); Kapiti Coast District (population 49 400) and Upper Hutt City (population 41 100); and the less populated, predominantly rural agricultural areas of Masterton District (population 23 400), South Wairarapa District (population 9 300), and Carterton District (population 7 500) (Statistics New Zealand, 2010b) (figure 79). For the rest of this chapter ‘Wellington’ will mean ‘Wellington City’ rather than the ‘Greater Wellington Region’. The ‘urban area of Wellington’ refers to the inhabited eastern part of Wellington City.

FIGURE 78 WELLINGTON CITY (SOURCE: JOLLANDS ET AL., 2006).

New Zealand essentially has a temperate climate. There are four distinct seasons in Wellington. On average New Zealand receives 1 400 millimetres of rain per annum. In Wellington the figure is slightly lower at 1 250 millimetres (Ministry for Culture and

Heritage, 2005). Typically it does not snow in Wellington, though snow is occasionally seen on the tops of the hills surrounding the city¹⁷⁶.

FIGURE 79 GREATER WELLINGTON REGION (SOURCE: GREATER WELLINGTON REGIONAL COUNCIL).

The city's harbour faces Cook Strait, the small stretch of ocean separating the North and South Islands of New Zealand. As wind travels in a predominantly westerly direction over New Zealand it hits the spine of mountains running along most of the length of the South Island and is funnelled at higher velocities through Cook Strait and into Wellington. These factors combine to create a situation where Wellington experiences winds for 89% of the time and at speeds of more than 60 kilometres per hour for 173 days per year. Predominant north and westerly winds (61% of all days) are accompanied by cold southerly winds in winter (28% of all days) that sweep cool air from the southern polar region into the mouth of Wellington harbour and directly into the city (Ministry for Culture and Heritage, 2005). Internationally, only New Zealand's Scott Base in Antarctica, and Kaikoura, a small town on the east coast of the South Island, have higher numbers of wind days been recorded.

Wellington has an average temperature of 12.8°C with approximately 2 000 hours of sunshine per annum (Ministry for Culture and Heritage, 2005). The altitude angle of the sun in the sky varies seasonally from approximately 26° to 72° at noon, though

¹⁷⁶ An exception occurred in 2011 when heavy snow fell in the City for days for the first time in at least 50 years (Associated Press in Wellington, 2011).

vast areas of the city experience shadows caused by the surrounding steep hills at different times of the day (Centre for Building Performance Research, 2007).

FIGURE 80 COLLISION OF THE PACIFIC AND AUSTRALIAN TECTONIC PLATES NEAR WELLINGTON (SOURCE: GNS SCIENCE).

Wellington's frequent earthquakes¹⁷⁷ are caused by the collision of the Pacific and Australian tectonic plates to the east of the North Island in an area known as the Hikurangi Trough (figure 80). This causes the predominant south west to north east direction of the ranges of Wellington and surrounding regions. Figure 81 illustrates Wellington's known main active fault lines

¹⁷⁷ The last major earthquake, magnitude of 8.2 on the Richter scale, was in 1855 and caused major uplifts of land changing the shape of the foreshore. Much of the current inner city is built on this uplifted land (Grapes and Downes, 1997).

FIGURE 81 WELLINGTON'S MAIN ACTIVE FAULT LINES (SOURCE: GNS SCIENCE)

5.2.1 A BRIEF ECOLOGICAL HISTORY OF WELLINGTON

'[In the late 1800s Wellington was] a magnificent dense forest – matai, rimu, kahikatea (white pine), miro, totara, maire, kowhai... and a wonderful profusion of creepers, ferns and mosses covering the ground, logs and stumps, and right up the trees and along the limbs, making an entrancing fairyland' (Maxwell, 1937).

Wellington was the first larger scale area settled by European settlers in New Zealand. This began in 1839 and was firmly established by 1865. A small population of European people lived in New Zealand before 1840 made up of whalers, escaped convicts, and sailors who had deserted their ships (Fox, 1851). Before people of

European origin inhabited the region, Wellington was densely forested except for areas Māori (the indigenous people of New Zealand) had cleared, including Mt. Victoria and around the harbour edge¹⁷⁸.

Before 1839 there were four main forest types in the Greater Wellington Region: that of kahikatea, kohekohe, tītoki, and mānuka trees along a strip of the Kapiti coast going right to the sea edge; podocarp (native conifer) broadleaf forest up of rimu, northern rātā and tawa to the west of the region from the southern coast to the Tararua Ranges; valleys and basin forest areas consisting of tōtara and kahikatea; and finally beech (black, silver and red) forests in the Rimutaka ranges and their foothills. In Wellington forest was predominantly a mixture of rimu, tawa, and mataī broadleaf trees with some areas of beech and other podocarp.

‘Trees such as the northern rata, with its bright red flowers, would have been a common sight, along with rimu, matai, kahikatea and totara. These would have been emerging through a solid canopy of tawa, kohekohe, kamahi, titoki, pukatea and kowhai. The forest interior would have been thick with climbers like kiekie and supplejack, and the forest carpeted with ferns’ (Wellington City Council, 2007a).

Descriptions and details of the specific species and locations of ecosystems that existed before the development of Wellington are provided by Boffa Miskell (1998), Gabites (1993), Park (1995), and Park (1999). Appendix eight gives a detailed map of pre-development species locations, and appendix nine lists native plant species in Wellington.

The first European settlers in the region immediately started clearing much of the forests and draining wetlands to create pasture for grazing animals. By 1875 Wellington was described as ‘chiefly pastoral’ (Gabites, 1993). Although some mountainous areas to the north and east were saved from deforestation after the Crown (Government) purchased them in 1870, the loss of the forest, combined with

¹⁷⁸ Holdaway (1989) examines the impact of pre-European human settlement, particularly on the fauna of New Zealand.

the introduction of mammalian predators that were foreign to New Zealand's mostly avian fauna, had a devastating effect on animal life (Clarkson et al., 2007a). The Karori Sanctuary Trust (2010) state that most species once found in the region are now locally extinct or extremely rare. Due to the absence of native birds to carry and disperse the seeds of native trees, the forest remnants were mostly unable to regenerate. The Ministry for Culture and Heritage (2005) state in reference to the Wellington region:

*'The forests once teemed with bird life. This included the huia, North Island takahē and moa (all now extinct), and the still common tūī, fantail and morepork. Ducks and bitterns lived in swamps and waterways. Other wildlife included the lizard-like tuatara, bats, and wētā. Fur seals and sea lions rested on the south coast.'*¹⁷⁹

FIGURE 82 NATIVE BEECH FOREST (PHOTO BY JEAN SPECTOR).

¹⁷⁹ There is a seal colony in Wellington, penguin populations, numerous sea birds, and occasional seasonal marine mammal visitors such as various species of whales, orcas and dolphins.

Reforestation in the city began as early the 1930s (in Te Ahumairangi / Tinakori and Mt. Victoria) though exotic rather than native tree species were commonly planted. By the 1950s many farmers had started to let the poorer farmland pastures surrounding the city regenerate naturally into native bush. This process is on-going (Ministry for Culture and Heritage, 2005). As indicated in figure 78 and appendix seven, large areas of what was once native forest in the largely uninhabited part of Wellington is now 'scrub', which is a mixture of native and non-native species on land regenerating from once pastoral or cleared land.

Key current environmental issues identified by the Wellington City Council include the need to conserve biodiversity through limiting the negative effects of further development in urban areas, and management of pests and weeds (Quality of Life Research Team, 2007). There are 28 sites listed as having ecological heritage value in Wellington City (Quality of Life Research Team, 2007, Wellington City Council, 2010a).

In 2003/4 the Greater Wellington Region's ecological footprint was 777 690 local actual hectares (lha)¹⁸⁰, equating to 9.7% of New Zealand's total ecological footprint. The region exceeds its ecological capacity by 9.1% (65 230 lha). Per capita, Wellingtonians have the fourth smallest ecological footprint of New Zealanders by region of 1.7 lha. In the period from 1997/8 to 2003/4 Wellington's overall ecological footprint increased by 14.8%, while per capita footprint increased by 7.7% (Smith and McDonald, 2008).

5.2.2 THE BUILT ENVIRONMENT OF WELLINGTON

Wellington is an expanding city that is becoming more densely populated (Quality of Life Research Team, 2007). There were 74 000 dwellings in Wellington in 2010 (Wellington City Council, 2010d). The city's population increased in size by 6% between 2001 and 2006, compared to an overall population increase in New

¹⁸⁰ Smith and McDonald (2008, pages 5-7) report that *'regional footprints are recorded in local rather than global hectares due to a severe scarcity of data by land type relating regional land productivities to global equivalents'*. Local actual hectares (lha) are New Zealand calculations rather than adjusted regional ones although differences in land productivity capacities are likely to be large between regions. This is because specific regional figures do not exist currently. New Zealand land is 2.5 times more productive than average global land.

Zealand of 4% in the same period (Statistics New Zealand, 2006a)¹⁸¹. The estimated percentage of population growth for Wellington from 2006 to 2026 is 19.5%, which is slightly lower than a prediction of 21.9% population growth for New Zealand as a whole (Quality of Life Research Team, 2007). Wellington has experienced a period of increased urbanisation in recent years with more apartment dwellers (Statistics New Zealand, 2010a)¹⁸². This is evidenced by an average of 45% of all building consents being issued for apartment buildings between 2003 and 2005, and by an increase from 2% in 2002 to 22.2% in 2006 in the proportion of new tenancy bonds for apartments lodged with the Department of Building and Housing (Quality of Life Research Team, 2007). This suggests the shift to greater proportions of apartment dwellers has occurred over a short period of time. Despite this, Wellingtonians typically live in stand-alone single or double storey detached dwellings (French et al., 2007, Mithraratne and Vale, 2004) set on small parcels of land in suburbs surrounding a small central business district. The average household is made up of 2.6 people (Quality of Life Research Team, 2007). In the Wellington region 67% of households are single family compared to 69% in New Zealand, and 25% are one person dwellings compared to 23% for the entire country (Quality of Life Research Team, 2007).

Many domestic buildings are timber framed structures with weather board or brick veneer cladding (French et al., 2007). This is in response to cultural norms, availability of materials and also because Wellington is very seismically active¹⁸³. The central business district has a small collection of multi-storey buildings, typically constructed out of reinforced concrete (Cousins et al., 2009). The newer buildings are built to strict earthquake codes and older ones are subject to earthquake strengthening programmes (Stevens and Wheeler, 2008).

¹⁸¹ The New Zealand National Census scheduled for 2011 was cancelled due to the major earthquakes in Canterbury so statistics here are currently the ones that are most recently available. The next census is scheduled for 2013.

¹⁸² In New Zealand urban environments occupy approximately 2% of the land mass with 80% of urban areas in the North Island (Statistics New Zealand, 2006b). The proportion of New Zealanders living in urban areas is increasing. In 2006 86% of people in New Zealand lived in settlements with a population of 1 000 or more, making it one of the most urbanised countries in the world. In New Zealand a main urban centre is classified as one with a population of more than 30 000 people (Statistics New Zealand, 2006b) however, which would not be considered to a 'city' in many other countries.

¹⁸³ Timber is an appropriate structural building material because of its ability to flex rather than crack during seismic events (Beattie and Thurston, 2006).

FIGURE 83 WELLINGTON OPEN SPACES (SOURCE: NICHOLSON, 1998).

TABLE 10 OPEN SPACE IN WELLINGTON CITY (ADAPTED FROM: NICHOLSON, 1998).

Total area of Wellington City	28 990 hectares
Total built urban area	4 200 hectares
Total green space	5 620 hectares
Total council owned open space including:	2 800 – 3 600 hectares
Forest / Bush (native, exotic, mixed)	2 500 hectares ¹⁸⁴
General purpose grass areas	200 hectares
Sports turf	100 hectares
Gardens and shrub areas	7 hectares
Annual bedding	0.4 hectares
Maintained tracks	99 kilometres
Street trees	4 000 – 8 000 trees

Wellington City Council manages 2 800 to 3 600 hectares¹⁸⁵ of publicly owned open space (Wellington City Council, 2007a) (figure 83). At least 70% of this is set aside as reserve due to recreational or scenic value (Wellington City Council, 2007a, Nicholson, 1998). This compares to 4 200 hectares of built urban space including roading reserve (Wellington City Council, 2007a) (table 10).

5.2.2.1 TRANSPORT AS AN ASPECT OF THE WELLINGTON BUILT ENVIRONMENT

Wellingtonians own fewer cars on average than all New Zealanders (13.5% own no car compared to 7.5% of all New Zealanders), and make more use of public transport (43% use it two or more times a week compared to 15%) (Statistics New Zealand, 2006a). 45.1% of people use a privately owned vehicle to get to work, compared with 66.7% for all New Zealanders (Quality of Life Research Team, 2007). Public transport within the city is made up of a fleet of electric and diesel buses and an electric rail network bringing people from outer suburbs into the central business district.

¹⁸⁴ This includes 461 hectares of remaining indigenous vegetation that is not formally protected and that is in National Priority One areas (land environments with 20% or less remaining indigenous vegetation) (figure 86 and Ministry for the Environment, 2007).

¹⁸⁵ The number varies between Wellington City Council publications. See for example: Nicholson (1998) and Wellington City Council (2007a).

5.3 ASSESSING WELLINGTON USING THE ECOSYSTEM SERVICES FRAMEWORK

This section will examine how Wellington functions in comparison to a generalised ecosystem. The list of ecosystem services suitable for the basis of analysis in a built environment context generated in chapter four is used to structure the research (see: section 4.5.2 and table 9 for an explanation of the ranking criteria used). The ecosystem services examined in this case study are:

1. The provision of habitat
2. Nutrient cycling
3. Purification
4. Climate regulation
5. Provision of energy
6. Provision of water
7. Provision of food

Explanations of these services can be found in section 4.4. The services listed are not in any order. Sections 5.4 and 5.5 discuss the results of the case study and provide possible rankings.

5.3.1 HABITAT PROVISION

Habitat provision allows for the shelter and nutritional needs of living organisms (de Groot et al., 2002). As discussed in chapter four, many ecosystem services cannot easily be provided by the built environment because their functioning primarily relies on the relationships formed between living plants and animals and their surroundings. The significance of the ecosystem service of habitat provision is that by providing habitat for flora and fauna to exist and thrive, the nexus of a bundle of other services that cannot be physically provided by the built environment itself is formed. These are: regulation of pollination; regulation of biological control; species maintenance; provision of genetic material; and fixation of solar energy. These are examples of services that are not easy to incorporate into the built environment

explicitly, but when combined with the provision of habitat could still be considered by a design team. The methods for supporting or integrating with these services could be largely the same as the provision of habitat. That is, carefully considered conservation, regeneration, or introduction of communities of plants and animals in an urban context. By linking habitat provision with these other ecosystem services, people may see the value of such an exercise more readily than if it is assumed provision of habitat is simply an altruistic, 'feel good', or aesthetic exercise (Ehrenfeld, 2000).

Integrating the provision of habitat with the urban built environment would need careful design collaboration between landscape architects, urban planners, architects, engineers, ecologists, and climatologists (Francis, 2011), taking into account the needs of indigenous biodiversity, present and future predicted climatic conditions, and support for other compatible ecosystem services, to make the process as effective as possible. Such an exercise is likely to be much more complex than simply planting a few native trees (Lipkis, 2004).

The effectiveness of increased habitat provision in terms of addressing climate change impacts will depend on localised climate change impacts and the ability of ecosystems, and therefore their services, to adapt to them. For example, in an area periodically inundated by rising sea water or more frequent storm surges, the provision of more land based habitat may make little difference to effective adaptation to climate change impacts. In an area experiencing less rainfall, however, provision of habitat to form a canopy that shades earth, retains water, and prevents evaporation may make a significant contribution to adaptation (Gill et al., 2007). Depending on the size and type of habitat to be provided, the provision of habitat has the additional potential positive benefits of ameliorating environmental extremes; improving water quality; reducing stormwater runoff; reducing fire hazard; improving air quality; and sequestering carbon (Brown, 2002). These benefits are dependent on the species, life span, and location of what is planted and grown (Nicholson, 1998).

5.3.1.1 THE PROVISION OF HABITAT BEFORE URBAN DEVELOPMENT

Before 1839 the ecosystems growing on the land Wellington occupies provided 100% of habitat for indigenous land based plant and animal species¹⁸⁶. As described in section 5.2.1 Wellington was covered with a mix of forest ecosystems ranging from coastal communities to systems on steep inland terrain. Low land broadleaf podocarp forest (figure 84) covered approximately 20 000 hectares (at least 70%) of Wellington (Wellington City Council, 2007a). Additional detailed and higher resolution pre-development and current habitat cover maps are provided in appendix seven and by Isthmus Group (2009).

FIGURE 84 HISTORICAL AND CURRENT HABITAT COVER OF WELLINGTON CITY (IMAGES BY: TONY STODDARD).

¹⁸⁶ Marine, freshwater and riparian ecosystems are not considered in this case study.

5.3.1.2 THE CURRENT PROVISION OF HABITAT

Due to extensive deforestation in the 19th century (section 5.2.1) only approximately 2% of Wellington's original forest remains (Clarkson et al., 2007b), most of which is contained in remote areas or within Otari-Wilton's Bush and the Wellington Botanic Garden (Gabites, 1993, pg 13, Mitcalfe and Horne, 2005, Wellington City Council, 2007a) (figures 78, 84, and appendix seven). Much of the rich soil was also lost and a high level of fragmentation exists in the remaining forested areas (Gabites, 1993)¹⁸⁷.

Although Wellington's native forest cover has largely been removed there is still a broad diversity of life within the city (Wellington City Council, 2007a). There are almost as many native plants, mostly growing wild, in New Zealand's urban environments (350 to 550 species or 14 to 22% of New Zealand's total flora) as in National Parks¹⁸⁸ (440 to 660 species) (Given and Meurk, 2000).

There are several nationally important biodiversity sanctuary areas in or close to Wellington City including the Karori Sanctuary, or 'Zealandia', an inland fully predator fenced 'ecological island' (figure 85), and Otari-Wilton's Bush. Since 2000 the Karori Sanctuary has reintroduced several species once locally extinct such as: the North Island weka, the little spotted kiwi, the pāteke (brown teal), the pāpango (New Zealand scaup), North Island robins, North Island tomtits, whiteheads, korimako (bellbirds), North Island saddlebacks, hihi (the Stichbird), Maud Island frogs, Cook Strait giant wētā, and North Island kākā and kākāriki (red and yellow crowned parakeets). Tapu Te Ranga Marae / Manawa Karioi Trust are regenerating a large area of vegetation in Island Bay. Several island sanctuaries exist in the region including Matiu Island, Mana Island and Kapiti Island which are predator free homes to rare avian and reptilian fauna. There are two marine reserves in the region. One lies around Taputeranga Island and in Island Bay (in the City) and the other around Kapiti Island.

¹⁸⁷ As discussed in section 1.4, fragmentation impacts negatively on habitat provision (Krauss et al., 2010).

¹⁸⁸ The 14 National Parks are protected habitat areas of New Zealand. These parks, with other conservation areas, account for one third of New Zealand's land mass (Department of Conservation, 2006).

FIGURE 85 'ZEALANDIA'. PRESERVED AND RESTORED FOREST IN KARORI, WELLINGTON (PHOTO BY: JÉRÔME BOUVIER).

Vinton (2008) examines Wellington's existing native and introduced avian species and their numbers¹⁸⁹. Most current bird populations in Wellington are introduced species, the greatest proportions of which are starlings and sparrows. Vinton (2008) goes on to cite evidence that rare native forest birds have been returning to Wellington and re-establishing local populations alongside the intensive management and species re-introduction programmes of the Karori Sanctuary, Wellington City Council, the Greater Wellington Regional Council and the Department of Conservation.

¹⁸⁹ Before the introduction of species foreign to New Zealand (including humans), many land based ecological niches were occupied by avian species (Daugherty et al., 1993), with forest and wetland birds most dominant. There were only two native mammals (both bats), and many kinds of insects and invertebrates, various lizards, skinks, geckos, frogs and the tuatara (Holdaway, 1989). At least 84% of New Zealand indigenous plant species are endemic. This means that they do not naturally occur anywhere else on the planet (Greater Wellington Regional Council, 2010c). Levels of endemism approach 100% in many groups of native New Zealand fauna (Daugherty et al., 1993).

FIGURE 86 OPEN SPACE CONCEPT PLAN FOR WELLINGTON (SOURCE: NICHOLSON, 1998).

FIGURE 87 THREATENED ENVIRONMENTS OF WELLINGTON (SOURCE: LANDCARE RESEARCH, 2012).

There are several inner green belts or corridors and an outer green belt in the city that provide some habitat as detailed by the Wellington City Council Open Space Strategy (Nicholson 1998). Part of the strategy is a proposed plan for amalgamating the open spaces throughout the city into a considered whole (figure 86). Parks and

green spaces within the urban fabric could be an important additional resource for restoration or reconstruction of depleted ecosystems (Goddard et al., 2010). Figure 87 shows areas of threatened habitat within the city.

The Wellington City Council Open Space Strategy (Nicholson, 1998) notes that aside from the roading network, the city's open spaces are largely a result of spaces left over from building activities rather than active planning relative to high pedestrian numbers or the needs of inner city dwellers. This suggests the provision of habitat for non-human species was also probably not a factor in the planning of Wellington's open spaces. The same observation is also made by researchers investigating other urban environments (Wolch et al. 1995).

The Council acknowledges that there could be a potential conflict between recreational use of open space and the regeneration of native habitat and suggests there should be a balance between these two aims with conflict '*resolved through good design and appropriate management*' (Nicholson 1998). Such issues are examined by Briffett (2001), where factors that can enhance compatibility between provision of habitat and provision of recreational areas are given.

5.3.1.3 DESIGN GOALS FOR THE PROVISION OF HABITAT

Clarkson et al. (2007a) cite a number of studies suggesting that when habitat reserves are less than 10% of an area, a decline in biodiversity and an increase in fragmentation is likely to occur. They state:

'In New Zealand, ecosystem restoration alone is not enough to prevent biodiversity loss from urban environments, with remnant indigenous cover in the urban core too small (and currently too degraded) to support biodiversity long-term... Reconstruction of ecosystems is required to achieve a target of 10% indigenous cover in cities... Future planning that protects indigenous remnants within the periurban zone is critical to the survival of many species within urban areas, mitigating the homogenisation and depletion of indigenous flora and fauna typical of urbanisation'.

This implies that 10% indigenous cover may be an appropriate target. As stated, currently there is only 2% indigenous cover in the urban part of Wellington (Clarkson et al., 2007b) (figure 78)¹⁹⁰. This means the city should aim for an 8% increase (365 hectares) in indigenous habitat just to reach a relatively stable state of habitat needed to maintain biodiversity. If all council owned park, grass areas and roadside planting areas were used for this task an additional 5% of habitat cover could be gained (208 hectares), if there was no compromise on habitat provision from competing recreation or food growing activities. This suggests at least an additional 3% (157 hectares) of indigenous cover would need to come from newly acquired council land, or privately owned green space, roof tops, or other developments within the city. Given the large amount of privately owned land it is reasonable to expect this target could be reached if incentivised (Wellington City Council, 2007a, Ewing, 2008).

Private land owners, including those with small suburban plots may be able to contribute to increasing avian, insect and plant biodiversity within the city through careful choice of plantings¹⁹¹ (Vinton, 2008, Gabites, 1993). The addition of nesting boxes, water sources, high ledges (Goddard et al., 2010), ecologically engineered walls (Francis, 2011), seawalls (Chapman and Blockley, 2009) and other infrastructure, along with assisted dispersal of species, could also be a feature of a built environment working to provide more habitat, even if that habitat is not immediately similar to that existing before development¹⁹² (Lundholm and

¹⁹⁰ Approximately 22% of land cover within a 5km buffer zone around the city is indigenous. 58% is non-indigenous and 20% is water. At 20km from the inner city the figures are 5% indigenous, 4% water and 91% non-indigenous (Clarkson et al., 2007b), due to the farm land surrounding the city. This suggests attention to maintaining and restoring biodiversity could be focused within and near Wellington City and not left to areas far outside it.

¹⁹¹ Vinton (2008) makes a series of recommendations to increase indigenous biodiversity within Wellington city, particularly of avian species. These include diversifying the range of plants in parks and reserves surrounding Wellington to target specific species of animals. She gives the example of planting taller trees to provide habitat for kākā. She also recommends diversification of inner city parks away from large grassed areas, as well as the planting of native species in roof gardens. Gabites (1993, page 108) provides a list of species to plant for regeneration of different habitat types in the Wellington region and discusses the patterns of succession of plant species that would need to be followed to enable regeneration of native forests. The Wellington City Council provide details of suitable native plants for the area that will attract native wildlife on their website: <http://www.wellington.govt.nz/services/environment/biodiversity/biodiversity.html> (accessed April 2012). Extensive and detailed lists of which native plants are appropriate in specific locations in Wellington City and the wider region can also be found in Greater Wellington Regional Council (2010c).

¹⁹² Some researchers (Lundholm and Richardson, 2010, Wolch et al., 1995, Rosenzweig, 2003) point out that because it may be difficult or impossible to recreate habitats that previously existed on certain sites, effort should also be made to provide habitat for native species that may be more analogous to urban environments (walls and

Footnote continued on next page...

Richardson, 2010). Wolch et al. (1995) examine various policy mechanisms, such as zoning, development right transfers, and environmental impact statements that have been used to increase habitat in urban areas with varied levels of success.

Each additional hectare beyond the requisite 157 hectares would contribute to the ecosystem service of habitat provision by beginning a process of restoration. This gives a tangible target for integrating the ecosystem service of habitat provision into the built environment of the city. Given such an analysis, a smaller regenerative development within the city could measure the additional habitat it would provide and, based on the 157 hectare target, could claim to be providing a certain percentage of the extra habitat cover needed for the whole city.

It would take between 100 and 500 years for complete regeneration of some of Wellington's forest areas (Carswell et al., 2008, Karori Sanctuary Trust, 2010). Despite this it is clear from both the Biodiversity Action Plan (Wellington City Council, 2007a) and the Capital Spaces Open Space Strategy (Nicholson 1998) that the council considers regeneration of natural habitats and the *'interweaving of small green spaces, and roof and balcony gardens, into the city centre'* (Wellington City Council, 2007a) as an important outcome of both strategies. It should be noted that the built up parts of Wellington, because of the presence of humans, buildings, and infrastructure, could never be the equivalent of the healthy, functioning pre-development temperate rainforest ecosystem that once existed on the same site. Pursuing such goals would help certain species to continue to exist in the city and would bring other benefits. Nicholson (1998) notes that increasing habitat and trees in the city in particular would: improve air quality; improve energy conservation by ameliorating environmental extremes; improve water quality in streams and the harbour; reduce stormwater runoff and flooding; reduce wind in some locations; and reduce fire hazard around the city.

quarries are like rocky habitats for example). This could be a way to increase the resilience of certain species as global climate change continues. Lundholm and Richardson (2010) point out that *'anthropogenic ecosystems are largely distinct in structure and function from the natural ecosystems they replaced because of alterations to resource availability, stress intensity, disturbance, and changes in the spatial arrangement of ecosystem components'*. More discussion of these ideas can be found in the work of proponents of 'ecosystem analogue' ideas and 'reconciliation ecology' (Rosenzweig, 2003, Lundholm and Richardson, 2010).

In many European landscapes, where human induced exchange of plants has been occurring for a long time, the cultural character of some landscapes is based on non-native flora (Margetts and Haines, 2004). In Tuscany for example, the grape vines, olive trees and cypresses often associated with the people, history and culture of the place are in fact not native, and in many places the boundaries between native and exotic are difficult to distinguish (Margetts and Haines, 2004). The difference in New Zealand is that changes in the makeup of flora and fauna in ecosystems are relatively recent and the classifications between native and exotic are much less ambiguous¹⁹³ (Margetts and Haines, 2004). Since European settlement (approximately from the 1830s) more than 20 000 non-native plant species have been introduced to New Zealand. Approximately 2 000 of these have become naturalised, and tend to have originated from ornamental gardens (Sullivan et al., 2005). This process of naturalisation means there are now almost as many naturalised non-native plant species as there are native species in New Zealand. This process is on-going, so this number will probably increase in the future (Sullivan et al., 2005).

Many naturalised plant species are known to have '*serious, deleterious impacts*' on native flora and fauna in New Zealand and are often associated with problems related to '*weediness*' (Sullivan et al., 2005). This is one of the reasons many experts advocate the planting of native species rather than exotic species, particularly if increasing native biodiversity is the goal, and why native plants are considered better for a New Zealand context than exotic species, particularly near water¹⁹⁴ (Margetts and Haines, 2004, Sullivan et al., 2005), or native forests (Sullivan et al., 2005). In fact, discussion of any benefits of planting exotic species over native ones tends to meet with '*surprisingly strong opposition*' (Margetts and Haines, 2004), except where edible food plant species are concerned.

¹⁹³ The arrival and subsequent wider scale settling of Europeans in New Zealand meant numerous and wide spread change in the plant life occurred due to clearing of forests, draining of wetlands, and introduction of new plant and animal species. Prior to this there had been changes to natural ecosystems including several extinctions (for example the moa) caused by Māori / Polynesian land use and hunting practices. While less in extent than changes brought about by Europeans, these impacts were not insignificant (Daugherty et al., 1993, Holdaway et al., 2001, Holdaway, 1989).

¹⁹⁴ This is because water sources, particularly streams and rivers are very good at transporting plant material to different locations and thus spreading populations of plants far from where they originated (Margetts and Haines, 2004).

Revegetation using native eco-sourced¹⁹⁵ species to promote indigenous flora and fauna biodiversity is recommended by the Wellington City Council and the Greater Wellington Regional Council. Reasons given are that plant species native to an area have particular ecosystem advantages including:

- *‘They are genetically adapted to local conditions and soils and are therefore likely to perform better. They blend ecologically and aesthetically with the local, natural, landscape...’*
- *Their seeds help maintain the integrity of the local gene pool and the sustainability of local ecosystems.*
- *They are more likely to be compatible with local invertebrate populations’* (Greater Wellington Regional Council, 2010c).

Despite these reasons for selecting native plants over exotic ones in a New Zealand context, where improving native biodiversity health is the goal, many exotic species still perform valuable functions in relation to ecosystem services. In urban environments in particular, before any vegetation is removed, there is a need to evaluate which exotic species are problematic in terms of invasiveness or negative impact on native biodiversity, compared to those that provide valuable ecosystem services without harm. A tree for example, even if non-native will still purify air, sequester and store carbon, cycle nutrients, and is likely to provide habitat to some form of life, depending on species, location and age (section 5.3.3.1).

There are examples of exotic species that may benefit native biodiversity in New Zealand, such as the monkey apple tree (*Acmena smithii*). This tree has become established in some native forest remnants and may be partly responsible for an increase in the breeding population of kererū (*Hemiphaga novaeseelandiae*) in parts of Auckland (Margetts and Haines, 2004). The kererū is known to be a keystone species because it is the only dispenser of large native fruit from trees such as miro (*Prumnopitys ferrunginea*) and karaka (*Corynocarpus leavigatus*). When native fruits are not available (typical in urban environments), the kererū will eat exotic fruits such

¹⁹⁵ ‘Eco-sourced’ means that native plants are grown from local seed sources. This means plants are more suited to local conditions, and that natural plant distributions and gene pools are maintained more effectively. See Greater Wellington Regional Council (2010b) for additional benefits of using eco-sourced plants.

as the monkey apple as well as other plants commonly found in suburban gardens such as brush cherry, loquat, guava, and tree privet (Margetts and Haines, 2004). Even gorse (*Ulex europaeus*), one of the most ubiquitous and reviled weeds in New Zealand, has found some reprieve in recent years due to research indicating it is an effective ‘nurse crop’ species for native seedlings (Margetts and Haines, 2004). In fact succession may be more rapid and diverse under gorse than under native kānuka (*Kunzea ericoides*), which would usually provide this function (Margetts and Haines, 2004). Gorse also may provide some protection to certain nesting native birds from introduced mammalian predators, due to its prickly and often impenetrable structure. This does not mean the planting of such exotic species, particularly known weeds, should be actively encouraged, but where they do exist it is possible that it is more beneficial to leave rather than remove them.

Rather than debate the merits of native versus exotic plants for urban environments, an alternative is to consider plant communities as ‘functional units’, based on a systems approach to recognising the processes and functioning of ecosystems (Park, 2000). This may be appropriate in the context of ecosystem services where *‘the nativeness of components does not matter as much as the functioning of the whole ecosystem’* (Margetts and Haines, 2004). Understanding ‘plant functional types’¹⁹⁶ could be an appropriate way to understand existing vegetation in the highly modified context of urban landscapes, and to plan for additional planting (Knapp et al., 2008, Box, 1996). This also indicates that ‘functional units’ (groups of plants and associated fauna communities that provide ecosystem services) can be comprised of mixtures of native and exotic species (Margetts and Haines, 2004). As Professor Ian Spellerberg, director of the Isaac Centre for Nature Conservation at Lincoln University, points out regarding New Zealand however:

‘With so much choice and so many benefits, why would we not use natives as the default position?’ (As quoted in: Smith, 2011).

¹⁹⁶ Plants that perform the same function in ecosystems, based on sets of traits can be grouped into ‘plant functional types’ (Margetts and Haines, 2004).

It is beyond the scope of this thesis to determine exact species that should or should not be used in the urban environment of Wellington to provide the ecosystem service of provision of habitat, or any of the other services, but this issue highlights the importance of working with ecologists that are conversant not only with native and local plants, animals and ecosystems but also with plant functional types and the functions of ecosystems in relation to ecosystem services.

Actions or initiatives already carried out to improve the provision of habitat in Wellington as detailed in Wellington City Council's Biodiversity Action Plan (2007a) include: stream restoration programmes; sand dune restoration; wetland restoration; pest and weed management; including threatened species in roadside plantings plans; Wellington harbour sediment sampling; bird counts and data collection on forest remnants; some protection of ecological links and corridors; provision of eco-sourced plants to community groups¹⁹⁷ along with other support; provision of environmental grants and funding for revegetation projects; and threatened plant conservation. This illustrates the network of council schemes, community groups, and volunteers already working towards the goal of restoring biodiversity within the city that could be harnessed to work towards the regeneration of the ecosystem service of habitat provision.

Aside from established revegetation techniques that are suitable for the Wellington context, as employed by the Karori Sanctuary, Manawa Karioi, the Department of Conservation and other revegetation groups, and careful planting of road sides and open areas, there are built environment focused techniques that exist or have been proposed that could be explored for their suitability to increase habitat in the city. Examples include green roof design (Lundholm, 2006), green infrastructure design (Benedict and McMahon, 2006, Gill et al., 2007), and 'green scaffolding' (Birkeland, 2008, pages 281-282). As noted before (section 4.5.3) all such technologies or systems need to be analysed from a lifecycle perspective and assessed for their suitability to a particular place to avoid using technologies that, while appearing to

¹⁹⁷ Approximately 100 000 eco-sourced trees are planted by the council or provided to volunteers to plant each year. At least 60 volunteer groups with a focus on revegetation exist in Wellington. A list of some of the community revegetation schemes in Wellington can be found on: <http://www.gw.govt.nz/wellington-6/> (accessed February 2011).

have environmental benefits, may be detrimental to ecosystems or climate over the long term. A summary of design goals related to the provision of habitat is given in table 16, page 373. Questions raised with this approach include where to draw boundaries for devising ecosystem service based goals for developments. Although the calculations in this chapter only refer to the Wellington urban environment it would be necessary for any increase in habitat and therefore biodiversity to fit within regional and national programmes of biodiversity restoration. This illustrates that regenerative development cannot exist in isolation from its larger surrounding context.

5.3.2 NUTRIENT CYCLING

Humans are already accomplished at cycling nutrients. Humans take materials from the earth's crust and put them in the atmosphere. They take materials from the ocean and spread them on the land. They take nutrients from one part of the globe and spread them to another. The way that humans cycle nutrients however, is very different from the way these processes occur in ecosystems, and often results in unwanted pollutants, ecosystem degradation, loss of habitat, and depletion of non-renewable resources. The global built environment has been linked with the altering of global biogeochemical cycles, such as the carbon cycle discussed in chapter one, the hydrological cycle (Baik et al., 2001) and changes in concentrations of sulphur and metals in air, land, and water (Vitousek et al., 1997).

In a similar way to the provision of habitat ecosystem services, several other services can be considered under the umbrella of nutrient cycling such as decomposition, soil building, and provision of raw materials. Although these ecosystem services are very different from each other in terms of the functioning of ecosystems, in the context of the built environment they can be grouped together because they are related to waste, recycling and reuse issues. This is important because as noted earlier (section 1.3) 40% of global materials are used in the built environment while 40% of waste is also attributed to construction and demolition activities (UNEP, 2007). These figures suggest that the current use of materials in the built environment is mostly a linear throughput system and that scope exists to

alter this (Rees, 1999, McDonough and Braungart, 2002). 'Nutrients' in the context of this section can be considered as the materials that make up the built environment.

A more thorough understanding and positive integration with this service may enable a more robust and adaptable built environment to evolve that is less dependent on imports and produces less pollution and 'waste'. It may be possible that the built environment could contribute to this service through careful planning to ensure a more cyclic rather than linear system in terms of material use and waste production (Kibert et al., 2002, pages 160-219).

5.3.2.1 THE CYCLING OF NUTRIENTS BEFORE URBAN DEVELOPMENT

In mature forests in New Zealand approximately 80% of nutrients (calcium, magnesium, sulphur, silicon, sodium, phosphorus, potassium and nitrogen) used for plant growth are returned to the soil by way of falling and decomposing leaf litter (Egunjobi, 1969)¹⁹⁸. More nutrients return to the soil annually than those held in trees in forests. Nutrient cycling occurring through root decomposition and root excretion is more difficult to quantify (Egunjobi, 1969). Nutrients (from marine, terrestrial, anthropogenic air pollution, biogenic, or volcanic sources¹⁹⁹) are both added to and leached from ecosystems through rainfall (Attiwill, 1966). The composition of nutrients or chemicals within rainfall is influenced by proximity to the ocean, cities and industrial areas, and by prevailing wind directions (Egunjobi, 1969), suggesting that marine nutrients and those carried on the wind may have been important in Wellington ecosystems. Nutrients in pre-development forests may have been lost due to soil leaching, forest fires and surface run off (Hall and Hollinger, 2000). Nutrients are added to ecosystems through erosion and rock weathering and anthropogenically by the application of chemicals such as fertilisers, or livestock wastes moving through water ways, into naturally occurring ecosystems. Croucher (2005) discusses the measurable effect of nutrients leaching into indigenous forest in Wellington from adjacent areas with different land uses (particularly farms).

¹⁹⁸ The figure refers to a mature stand of beech (*Nothofagus truncate*) (Egunjobi, 1969).

¹⁹⁹ Some inconclusive and controversial research suggests some minerals or substances found in rainfall (Emanuelsson et al., 1954, McCafferty, 2008) and the rocky crust of the earth (University of Toronto, 2009) may be extra-terrestrial in origin (from meteorites).

5.3.2.2 CURRENT CYCLING OF NUTRIENTS

Because the built environment tends to be a '*horizontally disintegrated, throughput system*' (Rees, 1999) nutrient cycles are disrupted. This means that food and other resources from distant places are shipped into urban environments. The 'waste' from this, including nutrients vital to soil fertility, tends to be dumped in places where the nutrients cannot be re-used for further growth, such as landfills or the ocean, where substances dangerous at high concentrations accumulate (McGranahan et al., 2005, page 810). Nutrients are seldom returned to their place of origin. This degrades overall ecosystem fertility. In Canada for example, half of the natural nutrients and organic matter from prairie soils have been lost in over a century of agricultural export (Rees, 1999).

Although information about Wellington City itself was unavailable, Smith and McDonald (2008) detail ecological footprints of the regions of New Zealand for 2003/4. An analysis of the overall flows of embodied land through the Wellington regional economy shows that the Greater Wellington Region is a net consumer rather than producer of ecological capital, with a negative trade balance of 668 270 lha of embodied land²⁰⁰ (figure 88). McDonald and Patterson (2003) say of the Wellington region:

'More than any other region apart from Auckland, the production patterns are oriented to supplying the local regional consumption with relatively light exports to both other regions and overseas'.

This suggests more nutrients are probably imported into the city than lost from it. The way nutrients are lost would be through export of produce, locally made or sourced goods or materials, collected recycling, waste, and compost, and sewage pumped into the ocean (section 5.3.3.5). Figure 89 illustrates the potential complexity of distribution of waste (and therefore nutrients) that is typical of an urban environment in New Zealand.

²⁰⁰ See footnote 180 for details of lha used in the Smith and McDonald (2008) study.

FIGURE 88 BALANCE OF IMPORTS AND EXPORTS (FLOWS OF EMBODIED LAND IN LOCAL ACTUAL HECTARES) THROUGH THE WELLINGTON REGION 307
(DATA FROM: SMITH AND MCDONALD 2008).

FIGURE 89 MODEL OF WASTE DISPOSAL AND DISPERSION INTO THE ENVIRONMENT (SOURCE: MINISTRY FOR THE ENVIRONMENT 1997).

Wellington City Council owns two landfills: the Northern Landfill (closed in 2006) and the Southern Landfill. There are two cleanfills: C&D Landfills Ltd in Carey's Gulley, alongside the Southern Landfill, and T&T Landfill in Happy Valley. In 2005, 242 628 tonnes of waste were disposed of to these landfills (all waste types), or 1.3 tonnes per capita per year. Considering only domestic rubbish, the per capita figure drops to 0.7 tonnes per person (Waste Not Consulting, 2006). It is assumed that waste that goes to Wellington landfills stays there, so although the nutrients contained within the waste stay within the region, they are not likely to be in a useable state or cycled in a similar way to that in a natural ecosystem.

The composition of Wellington domestic rubbish suggests much higher rates of recycling and composting are possible (figure 90)²⁰¹. Possibly only 8 to 30% of materials that are recyclable are collected for recycling at the end of their life (Ministry for the Environment, 1997). In Wellington 60kgs (0.06 tonnes) of recycling waste was collected per capita in 2007 (Quality of Life Research Team, 2007). Information from the National Waste Data Report completed in 1997 suggests most of this is paper, cardboard and glass (Ministry for the Environment, 1997). Exact figures for how much collected recycling was exported out of the city were unavailable, but Zero Waste New Zealand (2001) suggests that recycling of metal in particular is a significant and growing export earner for New Zealand. Wellington City Council has stated they are trying to increase the amount of Wellington waste recycled within New Zealand rather than overseas (Wellington City Council, 2010b), though the majority of New Zealand recycling still occurs offshore (Ministry for the Environment, 1997).

Wellington City Council encourages private domestic composting and states:

'If 50,000 of Wellington's dwellings composted two kilograms of food and/or garden waste per week, up to 5 200 tonnes of waste would be diverted from landfills annually' (Wellington City Council, 2010b).

²⁰¹ In figure 90, 'other' refers to: rubber, timber, rubble, hazardous waste, electrical waste and non-ferrous waste.

FIGURE 90 COMPOSITION OF A TYPICAL DOMESTIC RUBBISH BAG IN WELLINGTON (TOTAL 5.86KG) (ADAPTED FROM: WELLINGTON CITY COUNCIL, 2010).

This would also mean nutrients from the compost would be available for cycling and could contribute to food growing and habitat regeneration activities through supporting the growth of plants and enhancement of soil fertility within the city (McGranahan et al., 2005, page 810).

Wellington City Council manages the Kai to Compost scheme where food waste is collected from supermarkets, cafes, restaurants, and work places in the city. It is sent to the Council's compost facility, mixed with other green waste, and converted into compost. This is sold for use in local gardens, orchards and vineyards (Wellington City Council, 2010b). Estimates obtained from the Council's compost facility are that 6 000m³ of compost are produced each year (Wellington City Council Compost Facility, 2011). It is likely that the nutrients found within food scraps in Wellington have been imported into the city from surrounding regions or other countries because the city grows very little of its own food (section 5.3.7).

Wellington Zoo, principally funded by the City Council, composts 70% of its (mostly animal) waste in their own onsite composting facility (Wellington Zoo, 2008). Some compost is used within the zoo, and some sold to householders by the company ZooDoo, which produces compost sourced from Wellington, Christchurch and Auckland Zoos (Wassilieff, 2009). A composting facility at Carey's Gully (next to the Southern Landfill) operated by Living Earth Ltd. turned sewage sludge and green waste into compost from 1998 to 2008. It processed approximately 130 000 tonnes of dewatered sewage sludge from the Moa Point and Western (South Karori) treatment plants and produced approximately 25 000m³ of compost a year (Wellington City Council, 2007b). The plant was closed for various reasons including: increased costs associated with running the plant; the lack of a viable market for the compost; complaints about odours; and '*new alternative and sustainable ways of dealing with the sludge*' becoming available (Wellington City Council, 2007b). In terms of improving the long term sustainability of Wellington, it is difficult not to see this as a retrograde step.

In summary, although difficult to measure precisely, the only significant loss of nutrients from Wellington would be through the export of recycled waste, through loss of nutrients in sewage to the ocean (section 5.3.3.5), and through the minimal export of food (McDonald and Patterson, 2004). The import of nutrients is likely to be much higher. Nutrients held in landfills are largely unavailable for cycling.

5.3.2.3 DESIGN GOALS FOR NUTRIENT CYCLING

It is unlikely that the built environment could provide all of its own continuing raw material needs in a closed loop of cycling of materials and waste, but if the built environment were perceived as a source of materials, this might lead to fewer raw materials being sourced from distant ecosystems.

If the residents of Wellington, facilitated or aided through the design of the built environment, were able to cycle 80% of nutrients so these remained in a useable state, this would match rates that would have been found in pre-development ecosystems, although the nutrients would be different. Careful consideration of separating nutrient streams into decomposable or recyclable streams (McDonough and Braungart, 2002, page 104) and planning to ensure a suitable eventual destination for decomposable nutrients so they remain available for future use would need to be carefully planned.

Although it is difficult to calculate the amount and type of materials held within the entire built environment of Wellington City with any great level of accuracy to establish goals for reuse or recycling, it would be possible to record accurately what was contained in a single building or larger development if this were done at the design stage. For a retrofit design, this information could be used to plan how the materials contained within the site could become the raw materials for something else once the development reached its end of life. Because many non-domestic projects are built by developers who have an interest in initial profits rather than long term environmental outcomes, this change is unlikely to happen without a different approach to society's current economic and development models. If the design is for a new build project, the construction could be planned to allow for eventual reuse of the materials through deconstruction, adaptable design, or similar ideas (McDonough and Braungart, 2002, Storey et al., 2003, Fernandez, 2004, Thormark, 2006, Kibert et al, 2002, pages 25-26). At the same time materials for the project could be sourced from the built environment, from building materials reuse retailers, or directly from demolition or deconstruction projects. To enable such a concept to be employed on a large scale, changes in both the Building Code and current

standard design, construction and demolition practices would need to occur. Twin (2003) points out that:

‘Locating reused and ‘secondary’ material sources, establishing their provenance, and guaranteeing their performance is currently difficult, requiring significant... resources’.

Design processes would also be affected by the need to design with reused materials or components and planning actively for end of life dismantling of the building so materials are salvageable. Social benefits are likely to arise through such an approach through the creation of employment opportunities (Storey et al., 2003, Zero Waste New Zealand Trust, 2001).

Sourcing building materials locally also has the ecological benefit of minimising GHG emissions from transportation of materials. Although the operational energy of a typical conventional building is approximately 85 to 95% of the total energy use over its lifecycle, this proportion drops as efficient or effective energy measures (either through technologies or behaviour changes) reduce operational energy requirements (Thormark, 2006). This makes the embodied energy component of low energy buildings more important, though the operational energy will probably still be the larger component of overall energy use. An aspect of the embodied energy of materials is the energy used in transportation. Several developments have translated the idea of sourcing materials locally into imposing maximum distances within which a building material can be sourced. The Beddington Zero Energy Development

FIGURE 91 BEDZED HOUSING COMPLEX, WALLINGTON, SOUTH LONDON (PHOTO BY: PEABODYLDN).

(BedZED) (figure 91), a housing development in England designed by Arup Architects and Bill Dunster required that as many of the heavy building materials as possible were sourced from within a 55km radius (Twin, 2003), although it is not clear why this distance was chosen.

TABLE 11 DISTANCE TRAVELLED BY WELLINGTON BOUND BUILDING MATERIALS (ADAPTED FROM: JOHN ET AL., 2009).

Material	Km travelled by truck	Km travelled by ship
Concrete	124	
Steel (NZ)	600	
Steel (Australian)	50	2 500
Glass	600	
Timber	400	
Laminated Veneer Lumber (LVL)	100	
Plywood/Medium Density Fiberboard	400	
Aluminum	400	
Plasterboard	600	
Paint	400	
Glass Insulation	600	
Poly Insulation	600	
Fibre Cement	600	

In a Wellington context boundaries to the south, east and west are defined by the ocean, and to the north either by the political boundary of the Greater Wellington Region, by geographical features such as the Rimutaka ranges, or by climatic boundaries, such as the central mountain plateau region. The latter is used to define insulation requirements in the New Zealand Building Code (Department of Building and Housing, 2012). Average distances that building materials travel to get to Wellington (table 11) suggest that many building materials come to Wellington by truck from New Zealand's largest city, Auckland, which is more than 600km away, and that sourcing common building materials, apart from timber, closer to Wellington may prove difficult. The environmental impact of transport via ship or rail is less than that of road transport, and method of transport is a more important factor for overall ecological impact than distance travelled (Vale and Vale, 2009, page 43). Both of these alternative transport methods are viable options for Auckland to Wellington transportation, so if limiting the distance materials travel is not a practical possibility, limiting the amount of materials used in the Wellington built environment transported by truck could be another way to reduce embodied energy that would fit within an ecosystem service model.

5.3.3 PURIFICATION

Ecosystems allow for the purification of air, water and soil through assimilation and transformation of toxic compounds, decomposition, and filtering (through soil or sand)²⁰². This service is significant because it enables air, soil and water to remain in a state useable for other organisms. The built environment could make a contribution to this service if buildings and the land and infrastructure around them did not pollute air, water and soil, and were designed to purify the air and water (and possibly soil) moving through or near them. Cleaner and more pure ecosystems will thrive more readily and provide the other services humans depend on. Cleaner ecosystems, and cleaner water, air and soil, also have direct positive implications for improved human wellbeing and that of other living organisms (MEA, 2005c).

The rest of this section will focus on the quality of air, water and soil separately in the pre-development ecosystem of Wellington compared to their current state, and will discuss possible design goals arising from the analysis.

5.3.3.1 THE PURIFICATION OF AIR BEFORE URBAN DEVELOPMENT

In the pre-development context of Wellington there would not have been anthropogenic air pollution but it is possible to predict how much air pollution removal the pre-development ecosystem would have provided to enable a goal for rates of air purification for Wellington to be devised.

Trees act as biological filters, removing pollutants from the air (Beckett et al., 1998). Trees also impact on air quality in a number of other ways (Cavanagh and Clemons,

²⁰² Ecosystems (in terms of their abiotic components such as gravel and sand, and biotic components such as plants) are able to filter or purify many pollutants. Depending on the nature of these ecosystems they are able to transform pollutants into substances that are not harmful, stop substances from moving any further in systems or becoming bioavailable (called phytostabilisation), or disperse them, so they are less harmful and concentrated. In some cases ecosystems cannot cope with pollutants either because of their make up or because of their quantity. Examples of this are certain heavy metals in soil and water, and excess GHGs in the atmosphere (Salt et al. 1995). This means that any 'filtering' of pollutants done by ecosystems may require the eventual cleaning or remediation of the filter medium if non-transformable pollutants are trapped and accumulate.

2006)²⁰³. Vegetation, particularly forest canopies, removes more air pollution than water or open areas (Bolund and Hunhammar, 1999). The amount of air purification provided by forests or trees in urban contexts depends on local conditions and species (Cavanagh and Clemons, 2006). It is increased in species with more leaf area and ones which are not deciduous²⁰⁴ (Bolund and Hunhammar, 1999). Furthermore, large, healthy trees remove an estimated 60 to 70 times more pollution than small trees (McPherson et al., 1994). Several studies use modelling to estimate the amount of air pollutants that forests remove (Beckett et al., 1998, Cavanagh, 2006, McPherson et al., 1994, Shelton et al., 2001). Cavanagh et al. (2009) provide details of research examining the potential of urban forest within Christchurch to remediate air pollution, primarily from domestic heating and vehicle emissions. Their results indicate that many different kinds of air pollutants (particularly particles less than 10 microns in diameter (PM₁₀)²⁰⁵) are lower within a forest than outside in an urban context.

Based on the research of Cavanagh and Clemons (2006), the pre-development ecosystem in Wellington would have been capable of removing 7 657 tonnes of particulates, 15 893 tonnes of nitrogen dioxide and 11 543 tonnes of ozone per year. The methodology used to obtain these figures is explained in more detail in the following section (table 12).

²⁰³ *'Various tree configurations can alter wind profiles or create local inversions to trap pollutants such that the localised removal of pollutants is enhanced. Trees can lower air temperatures through transpiration, affecting the photochemistry of ozone and reducing ozone production. Further, trees can reduce building energy use by shading buildings and altering airflows, thereby indirectly reducing pollution emission from power plants. However, trees emit volatile organic compounds (VOCs), which can contribute to air pollution by reacting in the atmosphere to form ozone in the presence of nitrogen oxides (NO and NO₂, collectively NO_x). Whether urban forests enhance air quality is dependent on the net balance of pollutant removal by trees, the relative significance of energy reduction in decreasing air pollution, and the contribution of trees to air pollution'* (Cavanagh and Clemons, 2006). Increased shading of buildings in New Zealand may not have a large impact on reducing building GHG emissions because of the high proportion of renewable electricity (hydro) used (section 5.3.5). Increased shading may lead to increased lighting or heating needs in winter. The assertion that increased vegetation reduces energy use is site and climate specific and not necessarily true in all cases.

²⁰⁴ All but 27 species (c. 5%) of New Zealand native trees are evergreen. Only 10 (c. 2%) can be considered truly deciduous (McGlone et al., 2004). Wellington's forest would have been evergreen.

²⁰⁵ PM₁₀ refers to particles suspended in the air less than 10 microns in diameter. These tend to have a negative effect on human respiratory tissue (Beckett et al., 1998). The main source is the burning of solid fuel for domestic heating (Quality of Life Research Team, 2007). Industrial combustion, sea salt, windblown soil, quarrying, and diesel vehicle emissions are also sources (Mitchell, 2010).

5.3.3.2 CURRENT PURIFICATION OF AIR

Factors from the built environment that impact on air quality include: emissions from domestic home heating; vehicle emissions; industrial emissions; and agricultural and outdoor rubbish burning (Quality of Life Research Team, 2007). Meteorological conditions also play a key role. Primary sources of air pollution in Wellington are from vehicle emissions, domestic home heating, and emissions from industrial processes²⁰⁶ (Mitchell, 2010). There are no active outdoor air purification stations, plants or schemes in Wellington.

Air quality in Wellington is assessed by the Greater Wellington Regional Council by monitoring several key pollutants: particles less than 10 microns in diameter (PM₁₀), carbon monoxide (CO) and nitrogen dioxide (NO₂). Within the Wellington City 'air shed' there are two monitoring sites, one in Karori and one in the central business district (CBD) (Mitchell, 2010). The Quality of Life Research Team (2007) state that:

'New Zealand has relatively good air quality due to a low population density, close proximity to the sea and remoteness from other sources of pollution. However, there are some urban areas where concentrations of air pollution were, at times, quite high'.

Annual mean levels across the two Wellington City monitoring sites of PM₁₀ were 11µgm⁻³ in 2009 with a maximum of 31µgm⁻³. 80% of the time readings were 'good' (5 to 16.5µgm⁻³). The remaining 20% were 'acceptable' (16.5 to 33µgm⁻³) (Mitchell, 2010). The National Environmental Standard (NES) for PM₁₀ allows one daily maximum reading of 50µgm⁻³ per year (Ministry for the Environment, 2004c).

Maximum CO levels recorded over an 8 hour average in Wellington in 2009 were 2.9mg/m³ (CBD) and 1.3mg/m³ (Karori). The NES maximum for CO for an 8 hour average is 10mg/m³. The mean results were: 0.7mg/m³ (CBD) and 0.1mg/m³

²⁰⁶ The majority of CO and NO₂ emissions are from vehicles. PM₁₀ and smaller are made up of vehicle, domestic home heating, industrial, and natural sources but the proportions are unclear (Mitchell, 2010).

(Karori). 80% of the time readings were 'excellent' ($<1\text{mg/m}^3$). The remaining 20% were 'good' (1 to 3.3mg/m^3) (Mitchell, 2010).

Maximum NO_2 readings over a one hour average concentration in Wellington for the year 2009 were $100.1\mu\text{gm}^{-3}$ (CBD) and $47.1\mu\text{gm}^{-3}$ (Karori). The NES for nitrogen dioxide is set at a maximum of $200\mu\text{gm}^{-3}$ for a one hour average concentration with nine exceedances allowed. The mean results were: $27.5\mu\text{gm}^{-3}$ (CBD) and $2.9\mu\text{gm}^{-3}$ (Karori). 40% of the time readings were 'excellent' ($<20\mu\text{gm}^{-3}$). 58% of readings were 'good' (20 to $66\mu\text{gm}^{-3}$). The remaining 2% were 'acceptable' (66 to $132\mu\text{gm}^{-3}$) (Mitchell, 2010).

These figures indicate some air pollution in Wellington City but currently it is not exceeding NES guidelines and annual emissions do not exceed World Health Organisation (WHO) regulations (Mitchell, 2010, WHO, 2006). The quality of air is, however, negatively affected by the built environment in Wellington.

Bolund and Hunhammar (1999) state that 1 hectare of mixed forest can remove 15 tonnes of particulates per year, and could remove up to three times as much depending on local conditions. Different figures, which are substantially lower, are given by McPherson et al. (1994) related to a study on removal of air pollutants by Chicago's forests. Forest may also remove approximately 20% of ozone (O_3) and sulphur dioxide (SO_2) particles (Beckett et al., 1998). Cavanagh and Clemons (2009) point out that:

'The paucity of data and directed science in this area is notable with unresolved controversy surrounding the variables used to determine the amount of air pollutants, such as particulate matter, ozone, and nitrogen and sulphur oxides, that trees can remove or add to the atmosphere... Further, most studies have been conducted in the northern hemisphere and the data is of debatable relevance for New Zealand or Australia – for example there is a greater prevalence of deciduous trees in the northern hemisphere compared to cities in New Zealand and Australia; as such, there may be greater potential for pollutant removal by vegetation in New Zealand and Australian cities.'

FIGURE 92 FOREST IN THE WAITAKERE RANGES, AUCKLAND (PHOTO BY: JOHN ABLE).

In order to find an approximate figure for the amount of air pollution currently removed by vegetation in Wellington per year, and given the lack of available data, this research uses figures provided by Cavanagh and Clemons (2006) for Auckland and converts these into figures for Wellington

City by changing the proportion of pollutant removed relative to the difference in land covered by trees in the two cities (figure 78 shows the relative locations of Wellington and Auckland in New Zealand).

TABLE 12 AMOUNT OF AIR POLLUTION REMOVED BY TREES IN AUCKLAND AND WELLINGTON.

Pollutant	Auckland City Current ²⁰⁷ (tonnes per annum)	Wellington City Pre-development (tonnes per annum)	Wellington City Current (tonnes per annum)	Percentage of pre-development forest that current vegetation in Wellington City provides (%)
Particulates (PM ₁₀)	1 320	7 660	960	12.4
Nitrogen Dioxide (NO ₂)	2 740	15 890	1 990	12.5
Ozone (O ₃)	1 990	11 540	1 440	12.5

Auckland has 3 448 hectares of urban trees (Cavanagh and Clemons, 2006). Wellington currently has 2 500 hectares of managed native exotic and mixed bush and had at least 20 000 hectares of forest before 1839 (Wellington City Council, 2007a). This means that trees within Wellington currently remove approximately 960 tonnes of particulates, 1 990 tonnes of nitrogen dioxide and 1 440 tonnes of ozone

²⁰⁷ Figures taken from: Cavanagh and Clemons (2006).

per year. The figures given in table 12 will not be totally accurate given the differences in climate and tree species between the two cities, but this may be the closest estimate possible relevant to a Wellington context.

5.3.3.3 DESIGN GOALS FOR THE PURIFICATION OF AIR

It is important that air purification initiatives are combined with efforts to reduce the production of pollution first or concurrently²⁰⁸. This is a good strategy for new developments, but as discussed earlier (section 1.9) many buildings that will exist in 80 years' time have already been built (O'Connell and Hargreaves, 2004). This means heating systems (responsible in part for air pollution), or the need to provide heat in these buildings, will be 'locked in' for some time. Some air pollutants remain in the air for long periods after original release²⁰⁹, and air pollutants can travel for long distances²¹⁰. This means efforts to purify air will be required in the future even if all new buildings are designed to emit no air pollution, and all other sources of air pollution in Wellington stop.

Data on background concentrations of air pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x) and PM₁₀ are not available for past or existing native vegetation in Wellington or New Zealand. Levels in existing native forests could be

²⁰⁸ Perhaps the simplest way to improve the air quality of Wellington and cities in general is removing petrol and diesel vehicles. Although changes in personal transport will occur in the future due to changing availability and affordability of petrol and diesel (Atkinson, 2007a), this is unlikely to happen in the short term. The form of the built environment (which may be largely unchanged in the next 80 years) also determines in part how vehicles are used (Steemers, 2003a). Domestic biomass combustion (burning wood for heat) is a major source of air pollution in urban environments, though less so in Wellington (Mitchell, 2010). Cities such as Christchurch have already legislated against the use of inefficient open fires and wood burners as a response to urban air pollution (Baines et al., 2003, Barna and Gimson, 2002).

²⁰⁹ NO_x emissions (including NO₂) may last for a few days or even hours (Beirle et al., 2011). Tropospheric O₃ is formed as a result of NO_x and VOC (volatile organic compound) emissions and lasts for a matter of days or possibly weeks (Freudenrich, 2001). The lifetimes of these two pollutants are less in 'urban plumes' (Beirle et al., 2011). PM₁₀ have different life spans depending on composition. Other gases emitted from vehicles or through activities in the built environment are much longer lived. Nitrous oxide has a life of approximately 114 years, various CFC gases last for hundreds or even thousands of years, and certain perfluorinated compounds last for more than 4 000 years (IPCC 2007d, page 512).

²¹⁰ Distances and dispersal patterns depend on the type of air pollutant, meteorological conditions and terrain (Zoras et al., 2006). Air pollutants from Wellington's nearby cities of Lower Hutt and Porirua may have an impact on Wellington. Ozone pollution may travel for up to 400km (Freudenrich, 2001). PM₁₀ particles can travel for 'long distances' (Ion and Ion, 2009). Barna and Gimson (2002) present results from a study of air pollution distribution in Christchurch. No specific data could be found for Wellington, but considering the high and frequent winds experienced an assumption could be made that air pollutant distribution patterns would be greatly affected by this. Additional research examining the dispersal of various forms of urban air pollution can be found in Bennett et al. (1998) and Karppinen et al. (2000).

measured to provide an indication of what air quality might have been like in Wellington pre-development, and would provide a potential ecosystem service based goal for future air quality for the city. The figures in table 12 could be used in a new development to determine how much air filtration the building or site should provide. For example, a development which makes up 0.001%²¹¹ of the area of Wellington City should, in addition to not emitting any new pollution, filter or remove at least 0.16 tonnes of NO₂ per annum (this is 0.001% of the total amount of NO₂ filtering (15 890 tonnes) that the pre-development ecosystem would have achieved).

Filtering or remediation of air pollutants could be achieved by the addition of vegetation into the urban environment or through mechanical plant added to or incorporated into buildings using current technology, if proven to be ecologically beneficial over the entire lifecycle of the technology. The most effective method for achieving air purification goals should be determined by experts based on calculations of local requirements. Care is needed that such initiatives do not impact negatively on other ecosystem services. For example, running extra air purification plant leading to emission of additional GHGs would impact negatively on the ecosystem service of climate regulation. Adding vegetation for the purpose of air filtration in contrast, could impact positively on the ecosystem service of habitat provision.

Because current levels of air pollution are lower than the amount of pollution the pre-development ecosystem could have removed, new developments, or those that are retrofitted, that reach the goals set by ecosystem service analysis, could become filters for all of the city's air pollution. This would enable goals to be achieved more rapidly than waiting for gradual renewal of the entire built environment to one designed to remove air pollution. Air pollution travels past the boundaries of cities (footnote 210), but many types of urban air pollution tend to be more localised (Fenger, 1999). Further research would need to be conducted to ascertain if additional levels of filtration beyond those needed to address local pollution could address air pollution outside the city boundaries.

²¹¹ This is approximately 1 000m² which is close to the once standard in New Zealand 'quarter acre section'.

5.3.3.4 THE PURIFICATION OF WATER BEFORE URBAN DEVELOPMENT

Information about water quality in a pristine or pre-development ecosystem in the context of Wellington is not available, although ecologists or water experts could reveal ecosystem based bench marks to follow in measuring water quality. For the purposes of this research it is assumed water quality in the pre-development ecosystems of Wellington would typically have been high and without contamination from pollutants.

5.3.3.5 CURRENT PURIFICATION OF WATER

Factors from the urban built environment that impact negatively on water quality include increased areas of impervious materials²¹², human made drainage systems (in terms of piping, straightening, and lining of water channels, increased peak flows, and lower or inconsistent base flows), and entry of contaminants into stormwater systems such as chemicals and heavy metals (Herald, 2003, Greater Wellington Regional Council, 2005). This leads to reduced water quality, reduced local aquatic biodiversity (Herald, 2003), reduced ground water table and recharge capability, loss of wetlands, and greater flood risk (Wolch et al., 1995) (figure 93). Other adverse effects include reduced human health, food gathering opportunities, cultural values, recreational values, amenity values, and 'natural character' (Greater Wellington Regional Council, 2005).

Primary sources of water pollution in Wellington are likely to be from vehicle emissions and wear and tear of tyres and brake pads as particles are rain-washed from roads into water ways, and the degradation of galvanized iron pipes, roofs, fences, roadside fittings, pipes and other metal objects, and the subsequent migration of pollutants into water ways (Herald, 2003) (table 13).

²¹² Herald (2003) points out that: *'expanding imperviousness within the built environment, known as impervious creep, is linked to urban renewal, increased intensification or infilling of housing, and the construction of paved utility areas such as public and private parking...'*

FIGURE 93 IMPACTS OF URBANISATION ON STREAMS (SOURCE: GREATER WELLINGTON REGIONAL COUNCIL, 2005).

24 million litres of sewage are treated in Wellington annually. Sewage includes water from sinks, toilets, laundries, kitchens, and bathrooms. The Wellington City Council operates three sewage purification plants: Moa Point, the Western Treatment Plant in Karori, and the Southern Landfill Sludge Treatment Plant. Sewage from Wellington's northern suburbs is treated in the Porirua Treatment Plant (in Porirua City). As well as three treatment plants, the sewage network consists of: 1 022km of pipes (aged on average 58 years with an estimated lifespan of 80 years), 62 pump stations, and 1 dewatering plant (Wellington City Council, 2012e). Treatment begins with sewage traveling through a series of screens to remove non-organic materials including toilet paper. The output from the screening is washed, mashed and sent to the Southern Landfill. Sedimentation tanks then remove the majority of remaining solids. The resulting sludge is de-watered at the Southern Landfill Sludge Treatment plant. Bioreactors (where bacteria decompose approximately 70% of the effluent), clarifiers and ultraviolet (UV) treatments (to remove any remaining harmful bacteria) are then used. Treated sewage is discharged 1.8km from shore into Cook Strait.

TABLE 13 TYPICAL URBAN RUNOFF CONTAMINANTS AND THEIR SOURCES (ADAPTED FROM: GREATER WELLINGTON REGIONAL COUNCIL, 2005).

Contaminant Source:	Solids	Nutrients	Pathogens	Oxygen Demand	Metals	Oils	Synth-etic Organics
Soil erosion							
Cleared land							
Human waste							
Animal waste							
Fertilizers							
Vehicle fuels/fluid							
Fuel combustion							
Vehicle wear							
Industrial / household chemicals							
Industrial processes							
Paints / preservatives							
Pesticides							

79 million cubic litres per year of stormwater run-off (from roads, driveways, paths, and rooftops) enters streams and Wellington Harbour untreated. The network includes: 650km of pipes (average age of 51 years), 20km of tunnels, 530 stormwater intakes and 12 500 road sumps. Under New Zealand's Resource Management Act (RMA) it is illegal to put anything but rainwater into the stormwater system (Wellington City Council, 2012f). The Greater Wellington Regional Council (2005) acknowledges that current stormwater management system is degrading ecosystems.

The 6 hectare Waitangi Park (figure 94) also treats stormwater before it enters Wellington Harbour. The Wellington City Council Initiative designed by Wraight Athfield Landscape and Architecture was completed in 2006. It is an artificial wetland on the edge of the harbour that partially brings to the surface the Waitangi Stream, which has been in an underground culvert since approximately 1859. A series of pumps and screens combine with a two part wetland system. The first part is a below ground level area of gravel that supports plant roots and microbial activity. Much of the sediments and soluble nutrients are filtered through this layer. This is combined with a UV disinfection system to remove additional pathogens. Along the park's

southern end is a linear wetland that directs most of the water into the Graving Dock Marina wetland. From there water flows into the harbour or is held to be used for irrigation of the park's vegetation and grassed areas (Wellington Waterfront, 2004). The wetland components of the park work much like other constructed wetlands to remove sediments and pollutants, mimicking the processes of a natural wetland to purify water. Approximately 10% of the base flow of the stormwater culvert beneath the park is treated by the park itself (Campbell et al., 2010).

FIGURE 94 WAITANGI PARK, WELLINGTON (PHOTO BY: STEVE SIGLEY).

As discussed earlier, Wellington is a coastal city. 76 coastal beach sites and 23 fresh water sites are monitored for water quality (Quality of Life Research Team, 2007). This is to ensure the health of human residents rather than the health of ecosystems. The results cited here are in reference to the National Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas (Ministry for the Environment, 2003). These contain the recommendation that warning signs should be placed at beaches when bacteria concentrations are greater than 550 E.coli²¹³ for every 100ml in freshwater systems and 280 Enterococci²¹⁴ per 100ml in marine systems for two consecutive samples. Water in both fresh and salt water systems is affected by the quality of a city's stormwater and sewage treatment systems (Quality of Life Research Team, 2007) and is also linked to soil quality (Croucher, 2005).

²¹³ E.Coli are bacteria indicating the presence of faecal matter in fresh water (Quality of Life Research Team, 2007).

²¹⁴ Enterococci are bacteria indicating the presence of faecal matter in salt water (Quality of Life Research Team, 2007).

Before development there would not have been sewage and stormwater pollution sources.

Over the 2003 to 2007 period, 4% of samples exceeded National Microbiological Water Quality Guidelines in Wellington at coastal beach monitoring sites and 8% of freshwater monitoring site samples exceeded guidelines. This follows a national trend where water quality is usually lower in fresh water systems. This may be because there is less dilution of pollutants and less dispersal through wave and tide motion (Quality of Life Research Team, 2007). These results indicate that water quality (and the ecosystems dependent upon it) is negatively affected in Wellington by the built environment and human activities within it (Greater Wellington Regional Council 2005, Milne and Watts 2008).

5.3.3.6 DESIGN GOALS FOR THE PURIFICATION OF WATER

What the data above suggests, is that filtering stormwater (and possibly black and grey water discharges) originating from or moving through the built environment at source, could have a positive impact on fresh water and marine ecosystems, if enough sites were able to do this. The ultimate goal should be for water discharged to streams and the harbour to be free of any contaminants.

Like the discussion of air purification earlier, it is important to ensure that sources of water pollution cease before or at the same time as efforts to remediate water pollution increase. The same argument can be made for the need to purify water even if all new buildings do not pollute at all, due to the on-going damage caused by existing buildings, pollution from vehicles, and certain human activities.

More in-depth research would ascertain if it would be more sensible to have large scale municipal or neighbourhood storm, grey or black water treatment facilities as currently the norm in Wellington. In some new developments it may be possible to incorporate localised facilities that either purify or prevent stormwater run-off into the city's stormwater drainage network. Grey water recycling using conventional or wet-land based techniques is a well-established and readily available (Kadlec et al.,

2000, Todd and Josephson, 1996). Key-lining techniques (Yeomans and Yeomans, 2008); the use of swales or terraces (Mollison, 1988); green roofs (Gerhardt and Vale, 2010); increased porosity of landscaping surfaces (including use of dry wells and trenches) so that impervious surfaces are ideally less than 15% (van Roon and Moore, 2004); stormwater management ponds; natural filtration materials (such as sand and gravel); filtration strips along roads; increased use of rainwater tanks (Younos, 2011, Mithraratne and Vale, 2007) and onsite stormwater storage (Greater Wellington Regional Council, 2005); use of biofilters (Herald, 2003); and increased use of vegetation (60% shrub or tree cover is ideal), particularly near streams (van Roon and Moore, 2004), are ways the built environment can both slow the movement of stormwater runoff from a site as well as purify it if designed correctly. Such methods can be considered part of Water Sensitive Urban Design (WSUD), Low Impact Development (LID) or Low Impact Urban Design and Development (LIUDD) (van Roon and Moore, 2004). Composting sewage systems also exist and could be examined for their suitability for Wellington. Several examples of biomimetic technologies that purify water have already been described, such as the CH2 Building in Melbourne that accesses and purifies sewage water running beneath the site for the building's cooling system (section 2.6.1.1).

In terms of measuring success, overall retention of aquatic ecosystem health and biodiversity in water ways is an important indicator of how well measures to purify water are working (van Roon and Moore, 2004). An additional important measure will be purity of water moving into the city or a specific site compared with purity of water moving out of it. If water is of better quality as it moves out of the system then some success has been achieved. McDonough and Braungart (1998) discuss examples where industrial buildings in combination with water purification methods have achieved this.

5.3.3.7 THE PURIFICATION OF SOIL BEFORE URBAN DEVELOPMENT

'The function of a soil is not only to support plant growth. Soils also store, regulate and filter water and chemicals. These other soil functions have been given a lesser importance in the past, the main focus being on increasing soil

productivity. However, research has shown that all the properties of soils need to be maintained to ensure the most efficient and sustainable use of soils...' (Croucher, 2005).

Soil in Wellington is mainly made up of Brown Soils associated with the Greywacke bedrock (Croucher, 2005, Isthmus Group, 2009). Indicators for soil quality where native vegetation occurs in New Zealand are poorly defined, making it difficult to assess what the quality of soil would have been in pre-development Wellington forests (Croucher, 2005).

Concentrations of heavy metals found in pristine environments are available and could be used to provide ecosystem service based targets for soil quality (table 14). Although further information about soil quality in a pristine or pre-development ecosystem suitable to the context of Wellington is not available, ecologists or soil experts could reveal further ecosystem based bench marks in terms of measuring soil quality.

TABLE 14 BACKGROUND SOIL CONCENTRATION RANGES FOR HEAVY METALS IN PRISTINE SOILS IN WELLINGTON COMPARED TO HUMAN HEALTH GUIDELINES FOR FOOD PRODUCING LAND.

Metal	Pristine Greywacke soil in Wellington (mg/kg) ²¹⁵	Guidelines for protection of human health in soil used to produce food ²¹⁶ (mg/kg)
Boron (soluble)	0.9-2.2	5 200
Arsenic	<2-7	10
Cadmium	<0.1-0.1	0.51
Chromium	6-16	210
Copper	3-25	29 000
Mercury	<0.1-0.2	140
Nickel	4-13	Not defined
Lead	6-79	400
Zinc	24-105	Not defined

²¹⁵ Data sourced from Croucher (2005).

²¹⁶ Values for a number of land uses are given by Ministry for the Environment (2010). Figures used here are the lowest limits given and refer to land where 50% of area is used to produce food. Substantially higher, up to unlimited levels, are given for other land uses such as 'recreation' (Ministry for the Environment 2010).

5.3.3.8 CURRENT PURIFICATION OF SOIL

As is typical in many cities, large areas of urban Wellington are covered with buildings, roads, paving, concrete or other impervious surfaces, meaning soil beneath is often unavailable for nutrient cycling, purification and habitat provision services. The amount of impervious surfaces in the urban part of Wellington could be between 40 to 85% of all surfaces (van Roon and Moore, 2004).

There are 1 900 contaminated or at risk sites registered in Wellington on the Selected Land Use Register (SLUR) (Greater Wellington Regional Council, 2010b). These are sites where one of 53 hazardous activities occur or has occurred in the past (Ministry for the Environment, 2004a). Soil may be contaminated with heavy metals, asbestos, chemicals, solvents, fertilisers, or munitions (Chapman, 2010). Sites registered include current or previous landfills, gasworks, timber treatment sites, munitions sites, and underground hydrocarbon storage facilities. Remediated sites are also registered. Not all of the information in the register is publicly available so the exact location of sites or area covered is unknown. This suggests that at localised sites, significant soil contamination exists in Wellington. Coucher (2005) also states in reference to the Wellington region:

‘Increased leaching of nutrients and pathogens and effluent into aquifers and waterways provide an indication that the function of the soils is being impaired’.

The Greater Wellington Regional Council monitors soil conditions for quality²¹⁷, temperature, and moisture content at 118 sites in the Greater Wellington Region to determine: *‘whether or not... land uses are having any effects on soil health...’* (Sorensen, 2010). Urban sites are not monitored, but regional results indicate that

²¹⁷ ‘Twelve primary soil quality indicators were selected to assess soil quality across the region and a wide range of soil types. The properties have been separated into three distinct groups. The first group are the chemical properties defining the pH of the soil and the concentration of those elements associated with the soil fertility (Total Carbon and Nitrogen, Olsen Phosphate and exchangeable Calcium, Potassium and Magnesium). The second group are the biological properties. Potentially mineralisable Nitrogen concentrations provide an estimate of the nitrogen status of soil organic matter, and [are] a surrogate measure for soil microbial biomass. The third group are the physical properties. These determine the weight, porosity and size of the soil and its particles. The properties measured are bulk density, particle density and water release characteristics, which provide information on total porosity, macroporosity, total available water and readily available water’ (Croucher 2005).

only 43% of the land could meet all soil quality criteria due to soil compaction or excessive phosphates in most cases, implicating animal and crop farming as the primary causes of degradation (Croucher, 2005). These results are similar to those found in other parts of New Zealand. Concentration of cadmium (mostly in dairy farming areas) and copper (in horticultural areas) were found to be increasing in Wellington, but were still within health guidelines (Croucher, 2005)²¹⁸.

5.3.3.9 DESIGN GOALS FOR THE PURIFICATION OF SOIL

Although it is more difficult to purify soil over the lifecycle of a particular site, because it tends not to move through a site, like air or water, but be contained on it, several techniques exist to address this issue. Phytoremediation (the use of plants or micro-organisms to purify soil) (Salt et al., 1995), and conventional soil remediation techniques combined with methods to ensure porosity of landscaping surfaces (Greater Wellington Regional Council, 2005) are existing techniques that could be used to improve the built environment's contribution to soil purification. Some of these techniques are best employed before a building or urban landscape is constructed (at the design stage), but consideration to such issues could be given during retrofitting or upgrading. A focus on soil health in the built environment will also likely have positive impacts on water purification and provision of suitable habitat for plants and soil microbes.

In terms of measuring success, the figures provided in table 14 give designers, developers, or policy makers goals for concentrations of heavy metals in soil that are based on the physical reality of the site before it was exposed to pollutants, rather than the significantly higher levels defined as safe for humans by other agencies.

5.3.4 CLIMATE REGULATION

As discussed in chapter one, the regulation of climate is an important ecosystem service in the context of design and development because of the large contribution

²¹⁸ A discussion of other trends in soil quality is not possible, because to date only one summary of results, (collected only since 2000) has been compiled (Sorensen, 2010).

the built environment can make in reducing the causes of climate change (IPCC, 2007c, page 391), and the large negative impact it has on climate regulation services. This is because of the substantial emission of GHGs (at least 30% internationally and 42% in Wellington) from the large amounts of energy used in the built environment (UNEP, 2007, Sinclair Knight Merz, 2008, Wellington City Council, 2010d).

5.3.4.1 REGULATION OF CLIMATE BEFORE URBAN DEVELOPMENT

Wellington's original forests provided almost 100% of the area's land based climate regulation ecosystem services in terms of storage of carbon (a small amount would also have been provided by wetlands). These forests would have had a significant effect on the humidity, rainfall, temperature, and wind impacts in the area, although it is beyond the scope of this thesis to investigate each of these in depth. The rest of this section will focus on the effects of carbon storage and sequestration in the pre-development ecosystem compared to the current city.

The pre-development forest ecosystem of Wellington would have stored and, to a lesser extent, sequestered carbon and GHGs overall rather than have emitted them. Mature forests store a great amount of carbon within them and the soil beneath but they do not sequester carbon from the atmosphere in any great quantity because the amount of new growth is balanced by decay of dead trees which emit their stored carbon back into the atmosphere. This typically results in a 'neutral equation' (Buchanan, 2005). Carswell et al. (2008) show that carbon stored in lowland broadleaf podocarp forest, which was the dominant forest type in Wellington, is approximately 340 tonnes per hectare²¹⁹. Figures for carbon stored in forest soil applicable to the context of Wellington vary between studies with the lowest estimate from Carswell et al. (2008) of 178.8 tonnes per hectare. This means Wellington's 20 000 hectares of pre-development forest stored at least 6 758 000 tonnes of carbon with an additional 3 576 000 tonnes held in the soil beneath.

²¹⁹ Estimating with great accuracy how much carbon was held in these forests and sequestered is still being determined by ecologists. The difficulty arises from the lack of an inventory of New Zealand's current forest (and past forest) (Beets et al., 2009). There is an inventory of Wellington's forest (Dymond and Shepherd 2004).

5.3.4.2 CURRENT REGULATION OF CLIMATE

As discussed in the provision of habitat section (5.3.1), only 2% of Wellington City's original forest remains (Clarkson et al., 2007b), suggesting that 206 680 tonnes of carbon (including that in the soil) is still stored in Wellington. The Council states that they manage 2 500 hectares²²⁰ of remnant or regenerating native forest (Wellington City Council, 2007a). This would equate to a total of 1 291 750 tonnes of carbon stored (12.5% of that in the original ecosystem) once these forests reach maturity in approximately 500 years (Hall and Hollinger, 2000). It should be noted there is uncertainty about the effects climate change will have on New Zealand's forests in the future, in terms of both carbon sequestration and long term storage (Beets et al., 2009, Buchannan 2005).

Until Wellington's regenerating native forests reach maturity they will be sequestering carbon. Sequestration rates decrease over time because most carbon sequestration occurs when the trees are growing rapidly at the beginning of their life. Beets et al. (2009) give a national mean indigenous forest carbon sequestration rate of 1.4 tonnes of carbon (5 tonnes of CO₂) per hectare per year during the first 100 years of growth. At 300 years, the figures are 0.62 tonnes of carbon (2.3 tonnes of CO₂) per hectare per year. Wellington's forests therefore, are likely to be sequestering carbon at a rate of 1.4 tonnes of carbon per hectare per year because most regeneration of this forest started less than one hundred years ago (Gabites, 1993). A maximum of 35 000 tonnes of carbon (or 128 100 tonnes of CO₂) would be sequestered during the first 100 years of regeneration using figures from Beets et al. (2009).

The Wellington City Council (2010c) give a higher rate of 3 tonnes of carbon sequestered per hectare for native forests, though the time frame this relates to and methodology used are both unclear. They go on to state that 50 000 tonnes of carbon is sequestered by all forests in Wellington in total, including managed exotic pine plantations (at a rate of 34 tonnes of carbon per hectare), 'offsetting' 4% of

²²⁰ This figure is substantially larger than the 2% estimate provided by Clarkson et al. (2007b) because the 2 500 hectare figure relates to forest that is regenerating as well as original forest.

Wellington's annual carbon emissions (Wellington City Council, 2010d). Beets et al. (2009) point out that:

'Although rates of carbon sequestration for indigenous forests are considerably lower than those for exotic forests, indigenous forests can continue to build carbon stocks over a much longer period, while exotic forests generally pass through a series of harvesting/replanting cycles. Depending on location, indigenous forests may deliver larger permanent carbon stocks than exotic forests in the medium to long term (i.e. more than c.100 years).'

This suggests that the benefits in terms of climate regulation of focusing on regeneration of native forests in the medium to long term may outweigh those found in pursuing commercial exotic forestry in Wellington (and possibly in the greater New Zealand context). Additional habitat and biodiversity benefits also accrue with a focus on indigenous rather than exotic forests (Beets et al., 2009).

While more sequestration of carbon probably occurs currently in the city than in pre-development conditions, because of the young age of the forests, considerably larger amounts of GHGs are emitted (Wellington City Council, 2010d) (figure 95). Wellington's total GHG emissions in 2006 were 1 190 000 tonnes of CO₂-^e or 6.2 tonnes of CO₂-^e per person. Buildings and the energy used within them make up 42% of Wellington's GHG emissions (Wellington City Council, 2010d). This equates to 510 200 tonnes of CO₂-^e (13 9145 tonnes of carbon) or 2.6 tonnes CO₂-^e (0.7 tonnes of carbon) per person per year.

The built environment also acts as a store of carbon for the lifetime of the materials containing carbon within it. Timber products are made of approximately 50% carbon²²¹, so using timber materials in the built environment temporarily prevents the carbon within them from being released to the atmosphere (Buchanan, 2005). The pool of carbon stored is not cumulative because when a building is demolished,

²²¹ Other building materials such as those made of plastic and other cellulose products such as straw also contain carbon but are found in smaller amounts than timber in the built environment, making them 'insignificant' (Alcorn, 2003, Buchanan and Levine, 1999).

decays, is consumed by insects, or is burnt, the carbon is released back to the atmosphere (Buchanan, 2005). This means that while the built environment is growing (more buildings are constructed than demolished per year) the pool of carbon stored in the built environment increases, but as a city goes through periods of reduced construction the pool of carbon reaches a more steady state. Wellington is currently an expanding city (Quality of Life Research Team, 2007).

FIGURE 95 WELLINGTON CITY'S GHG EMISSIONS 2006/7 (ADAPTED FROM: WELLINGTON CITY COUNCIL, 2010D).

The storage of carbon in the built environment achieved through greater use of timber or high carbon content products is less important than the reduction in embodied energy achieved, and therefore reduced fossil fuel use and direct GHG emissions, resulting from construction using timber. An increase in the use of timber products of 17% in the building industry would result in a 20% reduction in carbon emissions from the manufacture of all building materials in New Zealand for example (Buchanan and Levine, 1999). Most of the GHG emissions associated with the construction industry in New Zealand come from the fossil fuels used to manufacture building materials²²² (Buchanan, 2005). Storage of carbon in the built environment is not therefore a long term solution to climate change (Buchanan and Levine, 1999) or regenerating the ecosystem service of climate regulation. Despite this, it is possible to estimate (approximately) how much carbon is currently stored in the fabric of Wellington's built environment.

Most of the city's domestic dwellings are made from timber (French et al., 2007) with less than 1% made of concrete (Cousins et al., 2009). The construction of commercial buildings is more varied than residential construction. Cousins et al. (2009) report that medium-rise (4 to 7 storey) and high-rise (8 or more storey) buildings are mostly made of reinforced concrete, while low-rise non-residential buildings may be constructed from reinforced concrete, timber, steel-frame, or even unreinforced masonry (these would date from before 1930 (Thornton, 2010)). Because there are unlikely to be large amounts of timber found in Wellington's non-residential buildings²²³, this calculation uses figures for Wellington's domestic dwellings only. It should be considered a minimum value.

For a typical house in New Zealand 78kg of carbon per m² is released during construction, compared to 34kg of carbon per m² stored²²⁴ (Buchanan and Levine,

²²² Whether emissions attributable to the transportation of building materials have been included in the research of Buchanan (2005) is unclear. John et al. (2009, figure 6.4) show that the transportation component of the lifecycle energy use of common building materials is likely to be significantly less than operational energy and embodied energy of which manufacturing energy would be a component.

²²³ A notable exception found in Wellington is the Old Government Building, designed by William Clayton, completed in 1876, and located on Lambton Quay in the City's CBD. It is the second largest wooden building in the world, and now houses Victoria University of Wellington's Law School. The building is classified as a '*place of special or outstanding historical or cultural heritage significance or value*' by the New Zealand Historic Places Trust (Thornton, 2010).

²²⁴ This assumes that cladding is brick rather than timber weatherboard which is more common in Wellington, so figures may over-estimate carbon released and under-estimate carbon stored.

1999). The average sized house in New Zealand in 2006 was 112m² (Ghosh et al., 2006), so this would store 3.8 tonnes of carbon. There were 74 000 dwellings in Wellington in 2010 (Wellington City Council, 2010d) equating to 281 200 tonnes of carbon stored within Wellington City's built environment²²⁵ or 2.7% of the original amount held in pre-development forests. Figure 96 illustrates carbon (or the equivalent of carbon) emitted and stored by Wellington currently and before development.

FIGURE 96 AMOUNT OF CARBON IN WELLINGTON (IN THOUSANDS OF TONNES).

²²⁵ This figure assumes all dwellings in Wellington are typical New Zealand houses (which could lead to an over-estimate of carbon stored) but does not include carbon storage in commercial or industrial buildings (which would lead to an under-estimate). Maugham and Clough (1986) showed that 39% of timber products used in New Zealand were used for domestic dwellings and 12% for commercial, industrial and other buildings. This is a ratio of 3.25:1, meaning there may be an additional 132 062 tonnes of carbon stored in commercial, industrial and other buildings in Wellington. It is highly likely these figures are no longer current given the research was done 25 years ago. More recent figures were not available.

5.3.4.3 DESIGN GOALS FOR THE REGULATION OF CLIMATE

For the carbon store in the built environment to increase, a significant amount of GHGs would be released in the manufacture of building materials and during the construction process of new buildings (Buchanan, 2005). The resulting buildings would only act as a store for about 50 years (Buchanan, 2005, O'Connell and Hargreaves, 2004). Buchanan and Levine (1999) suggest the amount of carbon released during construction could be 100% more than that stored in the buildings. Carbon in forest and biomass, however, is stored for as long as the forest endures (at least 70% is already protected as reserve in Wellington (Nicholson, 1998)) and results in sequestration of carbon for at least 300 years (Beets et al., 2009). This suggests the greatest contribution the built environment of Wellington can make towards supporting the ecosystem service of regulation of climate might be not to compete with the regeneration of native forest in terms of land use allocations and expanding urban areas. Importantly, the built environment could also enable behaviour change in terms of reducing residents' consumption of carbon-emitting fossil fuels (Brown and Vergragt, 2008, Wood and Newborough, 2003, Owens and Driffill, 2008, Parnell and Larsen, 2005), and could become, at least in part, a renewable energy producer to substitute the use of fossil fuels (section 5.3.5).

It is of note that in New Zealand (and therefore Wellington) the current trend is for GHG emissions to increase annually on a per capita basis (Wellington City Council, 2010d). This is combined with an annual overall increase in human population (Statistics New Zealand, 2006a). The amount of land available for sequestration of carbon through re-forestation is not increasing. These factors suggest that completely regenerating the ecosystem service of climate regulation in terms of carbon storage and sequestration in Wellington without either a large drop in population, or widespread and large-scale behaviour change, would be extremely difficult.

5.3.5 PROVISION OF FUEL / ENERGY

The provision of biomass fuels and the conversion of wind, hydro, and solar energy to electricity and heat is an essential ecosystem service for human society. The following discussion will serve as an example of how the provision of fuel / energy can be analysed for a built environment context to devise ecosystem based design goals.

5.3.5.1 THE PROVISION OF FUEL / ENERGY BEFORE URBAN DEVELOPMENT

Woody biomass in New Zealand produces 8.22MJ (green offcuts) per kilogram (New Zealand Forest Research Institute, 2012) (2 285kWh per tonne). Although this relates to exotic pine plantations, so may be an over estimate, it is possible to work out how much energy potential Wellington's pre-development forests would have had if their annual biomass growth was converted into energy. The author is not suggesting that forest biomass increase should be burned for energy, but understanding the potential inherent in pre-development forests enables ecosystem based goals to be devised for the current and future built environment of Wellington.

Pre-development native forest²²⁶ in Wellington produced 8.4 tonnes per hectare per year of biomass through photosynthesis²²⁷ (Egunjobi, 1969). This means the pre-development ecosystem of Wellington would have produced 168 000 tonnes of biomass per year. This relates to 'as harvested' or wet weight, whereas biomass is normally burnt after drying.

Conversion factors for the amount of energy recoverable from biomass vary depending on how the fuel is used. The efficiency of open fires can be as low as 10% while some wood burners reach 85% efficiency (NZ Wood, 2012). The National Environmental Standards for Air Quality (Ministry for the Environment, 2004b) state

²²⁶ These figures relate to a 110 year old stand of beech forest near Wellington (Egunjobi, 1969).

²²⁷ In comparison pine plantations produce between 20 and 35 tonnes of biomass per hectare per year, with a slightly higher photosynthetic efficiency, while pasture gives 13 tonnes of biomass per hectare per year (Egunjobi, 1969).

that wood burners must have a minimum efficiency of 65%. Using this figure, Wellington's pre-development forest could have produced 250GWh of energy per year if annual biomass increase was converted into energy.

5.3.5.2 THE CURRENT PROVISION OF FUEL / ENERGY

Electricity use for the Greater Wellington Region with a population of 389 700 was 3 144GWh in 2009 (Electricity Authority, 2009, Wellington City Council, 2011). The Wellington City population of 197 700 would have consumed 1 595GWh of electricity therefore if the Greater Wellington Region figure was averaged out on a per capita basis.

TABLE 15 ELECTRICITY GENERATION IN WELLINGTON.

Name of Project	Company	Capacity (MW)	Capacity Factor	GWh per annum	Energy source	% of Wellington's annual electricity use
Westwind	Meridian	143	47% ²²⁸	588.8	wind	36.9
Silverstream (landfill)	Mighty River Power Envirowaste Services	2.7	90% ²²⁹	21.3	biogas	1.3
Southern Landfill	Todd Energy Wellington City Council	1.1	90%	8.7	biogas	0.5
Total Existing		146.8		618.8		38.7

Mill Creek (proposed)	Meridian	71	47%	292.3	wind	18.3
Total Including Proposed		217.8		911.1		57

Currently in Wellington there are three power generating operations²³⁰ and one proposed scheme (table 15). Electricity generation within Wellington is almost

²²⁸ Capacity factor from New Zealand Wind Energy Association (2010).

²²⁹ Capacity factors for landfill gas electricity generation could not be found for New Zealand. Eastern Research Group and MGM International Group (2008) provide the capacity figure of 90% used here.

exclusively from Meridian Energy's Westwind project. This is unusual compared to national statistics for energy generation, where wind accounts for only 4% of the nation's total electricity generation (figure 97).

FIGURE 97 ELECTRICITY GENERATION IN NEW ZEALAND 2010 (ADAPTED FROM: MINISTRY OF ECONOMIC DEVELOPMENT, 2011).

5.3.5.3 DESIGN GOALS FOR THE PROVISION OF FUEL / ENERGY

Assuming local power generation schemes supply only local needs (currently they do not) existing power generation schemes within Wellington could cover 39% of Wellington City's current annual electricity demand. Including the proposed scheme takes the percentage to 57% (table 15). This suggests at least 43% of current

²³⁰ 10MW is also produced at Capital and Coast District Health Board's Wellington Hospital in association with Meridian Energy. This power, for hospital use only, is generated by natural gas with a generator for back up and is not included in further calculations (IPENZ 2010).

electricity demand (686GWh) needs to be generated locally in the future, which could be a goal for a rate of electricity generation for the local built environment.

If the 686GWh shortfall were to be met by domestic building integrated systems, each household in Wellington would need to produce 9MWh per annum. This would equate to an 8.5kW photovoltaic system or 60 solar panels per house, occupying an area of 60m² of north facing roof (Vale, 2011). To install such a system would currently be expensive. Mithraratne's (2009) research suggests micro wind turbines on houses or buildings would only contribute up to 30% of domestic power supply in Wellington's urban environment and that large scale centralised wind farms would generate up to 11 times more energy, therefore being more effective. The wind around buildings tends to be more turbulent, erratic and weak. It may be most effective for additional large scale wind powered electricity generating schemes to be installed on the city fringes rather than using building integrated wind energy generators.

Concurrently or before, energy efficiency initiatives (either behaviour or technology based) should be used to lower energy demand. The use of solar hot water panels may be a feasible and effective addition to roof tops in Wellington and if employed on a large scale could lower initial demand for grid sourced electricity. Gillingham (2009) shows that the annual saving for a single family household²³¹ using a typical solar hot water system (likely to be electric in New Zealand)²³² in Wellington is 2 733kWh. This equates to a saving of 202GWh (13% of total electricity usage) for the city per annum if each of Wellington's 74 000 dwellings had a typical solar hot water system installed. This would mean only 484GWh of additional electricity would need to be generated to reach a 100% local electricity generation target. Even if only new

²³¹ Defined as: 'a household containing two or more people usually living together with at least one couple and/or parent-child relationship, with or without other people' (Gillingham 2009).

²³² There is a large variety of kinds and sizes of solar hot water systems available in terms of performance, auxiliary fuel source used (electricity or gas), presence of timers, and cost and subsidy eligibility, meaning results vary considerably between systems (Rouleau and Lloyd, 2008, Crawford and Treloar, 2004). Evacuated tube products may give better results than selective surface collector flat plate thermo-siphon systems in a New Zealand context (Lloyd and Kerr, 2008). The climate the system is located in and the hot water usage patterns of individual households also affect the results, pointing to the importance of behaviour change alongside technology improvements (Crawford and Treloar, 2004). The embodied energy component of various solar hot water systems has been calculated by Crawford and Treloar, 2004. They found it was insignificant in terms of the net energy consumption of such systems over a typical ten year life period. In situ performance testing of solar hot water systems over time may be necessary to verify calculated energy savings and GHG emission results with more accuracy (Lloyd and Kerr, 2008).

dwellings in the Wellington region were required to have a solar hot water system annual savings of 7.5GWh may accrue (Gillingham, 2009).

FIGURE 98 ENERGY AND ELECTRICITY IN WELLINGTON.

Sinclair Knight Merz (2006) identifies additional potential wind (700MW), and hydro (170MW) energy sources in the Greater Wellington Region²³³. If these options²³⁴

²³³ There is currently very little photovoltaic power generation on private or publicly owned buildings in Wellington. Sinclair Knight Merz (2006) state: 'Overall, there is potential for a substantial increase in the uptake of solar thermal use in the Wellington region', but identify that high costs as the main barrier to uptake. The same study estimates a limited potential for energy generated from biomass in the region, but that if wave technology becomes viable 7MW per km² could be generated along 300km of coast line.

²³⁴ A capacity factor of 47% for potential wind energy projects was assumed (table 15). This means 2 882GWh per annum could be generated from additional wind energy. Capacity factors vary widely for hydro power
Footnote continued on next page...

were combined with current power generation and proposed generation schemes for Wellington, this would provide 286% of the current electricity for Wellington City (figure 98).

As part of future planning, investigations need to determine if increased energy production for humans would have a detrimental effect on biodiversity or other ecosystem services long term. Hydro power generation, for example, could have negative impacts for affected river and riparian ecosystems (Sternberg, 2008, Egré and Milewski, 2002, Moog, 1993). This illustrates that because focusing on one ecosystem service alone could impact negatively on others, it is important to consider relationships between ecosystem services (figure 63). What is clear is it is feasible for existing and proposed electricity generation schemes in Wellington, combined with electricity efficiency adjustments made to the built environment, to achieve at least 100% of current electricity from local renewable resources, predominantly wind.

In 2007, the total energy consumption per capita in the Greater Wellington Region was 58.4GJ or 0.02GWh (Landcare Research, 2007, Wellington Regional Strategy Office, 2011). This means total energy use in Wellington City is approximately 3 207GWh per annum. Considering just existing and proposed power generation schemes (figure 98) Wellington could provide for 28% of its total energy use if electricity were substituted for other fuels (gas, coal, and oil) where possible²³⁵. Given the potential for more than 100% of electricity currently used to be generated in Wellington (up to 286%), 140% of total current energy needs could potentially be supplied.

At present Wellington generates 252% of the energy that the pre-development ecosystem could produce on an annual basis. The provision of energy/fuel in Wellington is an example of an ecosystem service where humans could surpass the performance of pre-development ecosystem conditions. This is not surprising given

schemes in New Zealand. Watson (2008) states the average is 52 to 55%. 52% was used in this calculation. This means 774.4GWh per annum could be generated by potential hydro power projects in the region.

²³⁵ This is not currently possible for all fuel types such as aviation fuel. This suggests either technological advancements or behaviour change would be necessary to reach a 100% renewable energy use target.

humanity's current ability to exploit the energy reserves of the planet. A different way of looking at these results would be to aim for a future maximum energy use cap of 246GWh per annum. Although wind generated electricity may not generate GHG emissions, the use of energy can generate other negative impacts on ecosystem health. The high use of energy by humans is also linked to 'over consumption'²³⁶ (Myers, 1997, Princen, 1999) leading to numerous environmental problems such as climate change (Myers, 1997), degradation or destruction of ecosystems (Bormann, 1976), excessive use of non-renewable materials and energy sources (Princen, 1999), and the production of large amounts of waste with associated pollution impacts (Princen, 1999).

Solving environmental problems is not as simple as switching from a fossil fuel energy based economy to a renewable energy one. An examination of how energy is used and for what must also occur to challenge the current positive feedback loop created between use of energy and ecosystem degradation (Bormann, 1976). Use of energy degrades ecosystems in many direct and indirect ways, which leads to more energy use to try to artificially replace ecosystem services lost, which then leads to more ecosystem degradation (Bormann, 1976). Until such issues are solved, ecosystem service derived energy use caps may act to initiate a kind of moratorium on human activities utilising energy that at present often result in ecosystem degradation. It is acknowledged that such a low energy cap (7.6% of the current total energy use or 15.4% of current electricity use), or even a cap of current energy use, would be politically improbable, considering the trend in Wellington, as elsewhere, is for population and per capita consumption of energy to increase. A cap that reduces energy use, even by smaller margins, would entail widespread and probably difficult to accept behaviour change on the part of Wellington's residents.

²³⁶ 'Overconsumption is that level or quality of consumption that undermines a species' own life-support system and for which individuals and collectivities have choices in their consuming patterns... With instances of overconsumption, individual behaviour may be perfectly sensible conforming either to the evolutionary dictates of fitness or to the economically productive dictates of rational decision making. Collective, social behaviour may appear sensible, too, as when increased consumption is needed in an advanced industrial economy to stimulate productive capacity and compete in international markets. But eventually the collective outcome from overconsuming is catastrophe for the population or the species... What is more, for humans it becomes a political problem when the trends are toward collapse and when the distribution of impacts generates conflict' (Princen, 1999).

5.3.6 PROVISION OF FRESH WATER

The hydrological cycle drives the provision of fresh water. Water is stored in lakes, rivers, ice, snow, wetlands, in soil and biomass, and underground in aquifers which are typically recharged by rainfall or snow or glacial melt. Water provision is an important factor in future adaptation to climate change as weather patterns that bring increased or decreased rainfall change (Taptiklis, 2011). Continued potable water supply has been identified as being vulnerable due to climate change in Wellington (NIWA et al., 2011b). Taptiklis (2011) points out that:

‘By 2040 climate change could decrease potentially available water (PAW) by 5% or 12 ML per day on average for January and February, with a corresponding 4.5 litre or 1% increase in average per capita demand (PCD)’²³⁷.

5.3.6.1 THE PROVISION OF WATER BEFORE URBAN DEVELOPMENT

It is assumed that current rainfall is approximately the same as rainfall before urban development in Wellington²³⁸. The average rainfall in Wellington is 1 270mm per year, equating to 368 million m³ in total (Wellington City Council, 2010c). Approximately 58 million m³ of rain falls onto the urban area of the city (4 200 hectares) annually. While major rivers still exist from pre-development times (figure 99), several streams have disappeared, or are now underground in the urban environment (section 5.3.3.5). It has not been possible to find information about the water catchment network of Wellington before development but hydrological flows are expected to have changed significantly from pre-development conditions due to extensive deforestation and the development of urban infrastructure. Catchment areas are likely to be similar to current ones (figure 99).

²³⁷ Climate change decreases potentially available water through changes in precipitation. It could increase average per capita demand due to increased temperatures, leading to more water use (Taptiklis, 2011).

²³⁸ It is possible that the extensive deforestation in Wellington resulted in decreased rainfall (Pielke 2001), but this could not be confirmed.

5.3.6.2 CURRENT PROVISION OF WATER

Water for human use in Wellington comes predominantly from the Waiwhetu Aquifer and the Hutt, Orongorongo and Wainuiomata Rivers (NIWA et al., 2011b). The headwaters of the Hutt River at Kaitoke supply about half of urban Wellington's needs (predominantly the northern suburbs). A combination of Waterloo and the catchment east of Wainuiomata supply water to Wellington's CBD and southern and eastern suburbs. On average, 40% of Wellington's water comes from the aquifer and 60% is sourced from rivers (NIWA et al., 2011b). Greater Wellington Regional Council state the purity of this water is an outcome of the ecosystem service of purification supplied by the surrounding forest (Greater Wellington Regional Council, 2010a).

FIGURE 99 GREATER WELLINGTON REGION WATER SUPPLY NETWORK (SOURCE: GREATER WELLINGTON REGIONAL COUNCIL).

The reticulation network includes: 81 reservoirs and tanks, 1 020km of pipes, 33 pumping stations, and approximately 100 000 fittings, valves and controls (Wellington City Council, 2010c). The two main pipelines (Kaitoke to Karori and Wainuiomata to Wellington) are connected at Nauranga to provide water security for the cities using the water supply (Wellington, Lower Hutt, and Porirua). A new reservoir is being planned by Wellington City Council for the Te Aro / Brooklyn area to provide emergency storage in the event of an earthquake, and to replace and expand existing storage facilities (Wellington City Council, 2010c). The Stuart Macaskill water storage lakes in Te Marua (capacity 3 000ML) provide a few weeks' worth of summer storage. The Waiwhetu Aquifer also acts as a water storage buffer during dry periods (NIWA et al., 2011b).

The Wellington City Council purchases approximately 30 million m³ (30 billion litres) of water per year from the Greater Wellington Regional Council. The city council intends to stabilise consumption at this level (Wellington City Council, 2010c). 7 million m³ is for commercial purposes and is metered (Wellington City Council, 2010c). Per capita daily domestic water use in 2006 was 165 litres in Wellington City (Quality of Life Research Team, 2007)²³⁹, totalling approximately 12 million m³ of water. The remainder of water usage is leakage from both public and private pipes, flushing of hydrants, water for fire-fighting, watering of council owned parks and gardens, street cleaning, burst mains and reservoir overflow, and water removed without permission from hydrants (Wellington City Council, 2010c).

5.3.6.3 DESIGN GOALS FOR THE PROVISION OF WATER

Like previous ecosystem services, a comparison is made between current use and the potential of the pre-development ecosystem to provide this level of ecosystem

²³⁹ Figures vary for domestic water use per capita per day for Wellington City and are somewhat controversial (Cook 2009). The Wellington City Council gives an official published figure of 350 litres per person per day for 'domestic use'. This includes all non-commercial uses not just domestic water use however (Wellington City Council, 2010c). In response to a report on water use in Wellington by Cook (2009) the Council has acknowledged through private correspondence that the figure is likely to be 230 litres per day per person. In addition, The Quality of Life in Twelve of New Zealand's Cities Report (Quality of Life Research Team, 2007) gives 165 litres per day per person for the 2006 period, citing Wellington City Council as their information source. This may reflect domestic use only and is more in line with national averages. This figure will be used in this research.

service as a starting point. In the same manner as previous ecosystem services discussed, demand management through water efficiency technologies (if shown to be appropriate over a whole lifecycle) and through behaviour change measures should be a first priority to reduce the amount of water used (Vale and Ghosh, 2006). There is also New Zealand based research (mostly examining Auckland rather than Wellington) that suggests that in areas served by rainwater tanks rather than reticulated supply systems, per capita water demand is reduced (Mistry et al., 2010, Mithraratne and Vale, 2007). If combined with technological methods to reduce water consumption (such as low flow shower heads) reductions could be in the order of 25% (Mithraratne and Vale, 2007). This means calculations in the following section may underestimate the ability of the built environment in Wellington to meet water demand by up to 25%.

It should be noted that the use of rainwater tanks has potential additional benefits over reticulated water supply such as reduction of GHG emissions²⁴⁰, reduced local ecological impact, reduction of water lost due to leakages and inefficiencies in reticulated systems, potentially better water quality, and more personal control over water source (Mistry et al., 2010). There may be potential benefits in terms of waste and stormwater management (Mithraratne and Vale, 2007, Ghosh and Vale, 2009). Several disadvantages are discussed by Mistry et al. (2010) and rainwater tanks may not always be the most sustainable choice of water provision however (Mithraratne and Vale 2007).

Looking specifically at domestic water use in Wellington and assuming each household is 2.6 people (Statistics New Zealand, 2006c) consuming 165 litres per day (Quality of Life Research Team, 2007), each house would need to capture and store 156 585 litres of rainwater per year (157m³). This assumes suitable water capture surfaces and storage tank installations are available. It also assumes captured and stored rainwater is of a suitable quality for domestic needs. If the average size of the 74 000 dwellings in Wellington City is 112m² ²⁴¹, with a

²⁴⁰ Concrete tanks may be best in this regard over an entire lifecycle (Mithraratne and Vale, 2007).

²⁴¹ Figures taken from Wellington City Council (2010d) and Ghosh et al. (2006). This assumes that most dwellings are single storey (French, 2007) so could be an over-estimate.

corresponding roof area of 123m^2 ²⁴², this suggests each dwelling could capture a maximum of 125m^3 of water per year (80% of the currently required 157m^3)²⁴³. This equates to 9.2 million m^3 per year across all domestic dwellings, or 80% of domestic and 31% of the current total water use.

The effect of 9.2 million m^3 , or roughly 16% of rainfall in the urban environment taken for human use would need to be studied because it could affect ground water recharge, plant growth, and the health of urban aquatic ecosystems. However, rainwater that currently hits roofs typically moves directly into the city stormwater system, and ends up untreated in the ocean (section 5.3.3.5). Collecting more rainwater could decrease stormwater discharge, and reduce some pollution entering the harbour (Quality of Life Research Team, 2007, Greater Wellington Regional Council, 2005).

FIGURE 100 WATER IN WELLINGTON

²⁴² Vale and Ghosh (2006) suggest that roof area is 10 to 20% larger than the floor area of a typical single storey dwelling depending on overhangs. The lower 10% figure has been used here.

²⁴³ A loss of 20% of the rain falling on a roof is due to splashes and evaporation (Younos, 2011).

In summary, the amount of rainwater falling onto Wellington City exceeds the water used by citizens by more than 1 000% (figure 100). In the urban area the total rainfall is almost 200% higher than the water used by residents domestically and commercially. This suggests that harvesting rainwater in the urban environment is plausible, but given calculations of roof size and domestic water use, if rainwater harvested were to meet just the demands of domestic users, a reduction of 20% in water use would be necessary or additional rainwater harvesting, storage, and reticulation would need to occur.

If the built environment were to harvest rainwater even at levels below 100% of current domestic usage, the water in aquifers and rivers may be better able to provide other ecosystem services and support regeneration of habitat and biodiversity, potentially enabling riparian and marine ecosystems to regenerate. Additional benefits could include reduced impact of stormwater runoff, reduced demand for piped potable water, reduced energy use, and contributions to groundwater preservation (Younos, 2011).

Supplying all dwellings in Wellington with rainwater tanks would be a resource expensive undertaking, so it may be better to leave existing reticulated systems in place and stipulate rainwater collection requirements for new or retrofitted buildings (Vale and Ghosh, 2006). If such dwellings in Wellington were required to harvest the maximum amount of rainwater relative to roof size to provide their domestic needs, this would start to move towards the 12 million m³ total required to supply domestic water use. To cover 100% of the city's water needs however, commercial, institutional and industrial sites would need to harvest an additional 21 million m³ of rain per year. An individual development could work out the capacity of its roof and site to harvest and store water and make sure this was at least above its projected water consumption. Excess water could be used to substitute the city supply to older neighbouring developments or apartments that cannot collect sufficient rainwater. Further research is needed to ascertain whether this is plausible in a commercial context, how it could be done, and if there would be any negative ecological impact from such an initiative. Care should also be taken to ensure additional rainwater harvesting infrastructure does not have negative ecological impacts over its lifecycle that would degrade other ecosystem services, and that collection surfaces do not

impact negatively on human health (Lee et al., 2012). The Wellington City Council has already determined a 30 million m³ cap for water use in Wellington (although this is not rainwater), so this is an example of an ecosystem service where humans could potentially stay within the capacity of the local ecosystem to provide the service.

5.3.7 PROVISION OF FOOD

Cities usually draw food resources from distant places rather than from within their boundaries and the provision of food tends to have a large negative impact on the overall ecological footprint of a region (McDonald and Patterson, 2004). This is due in part to the farming methods of food crops or livestock and by what people choose to eat (Vale and Vale, 2009, pages 40-41 and 44-50). Globally, food security issues are becoming increasingly important and urgent (Daily et al., 1998). This is exacerbated by a growing human population, rapid ecological degradation and biodiversity loss (MEA, 2005a), possible scarcity of affordable fossil fuels and phosphorus for transportation and agriculture in the future (Cordell et al., 2009, Neff et al., 2011), and increased urgency for reducing GHG emissions (IPCC, 2007d, pages 3-8, 12-17).

FIGURE 101 NEW ZEALAND'S GHG EMISSIONS FROM 1990 TO 2006 (SOURCE: MINISTRY FOR THE ENVIRONMENT, 2011).

New Zealand's GHG emissions from agriculture are at least as high as from energy use (Ministry for the Environment, 2011) (figure 101). Changes in the climate are and will become a major driver of food insecurity (Brown and Funk, 2008). Every 1°C of warming has been estimated to produce a 10% loss in land suitable for food growing (Despommier, 2011).

5.3.7.1 THE PROVISION OF FOOD BEFORE URBAN DEVELOPMENT

Examining the existing or pre-development ecosystem in terms of provision of food is not relevant for Wellington City because desirable food crops for humans are vastly different from native flora or fauna, which generally are not common food crops²⁴⁴. Conventional methods for producing high yields of food are also radically different from arrangements seen in naturally occurring local ecosystems. There are, however, models of gardening or agriculture based on observing ecosystems such as permaculture (Mollison, 1988) and some indigenous models (Margolin, 2004), indicating there could be mutual benefits between provision of habitat and provision of food in certain urban environments.

5.3.7.2 THE CURRENT PROVISION OF FOOD

It is assumed that people residing in Wellington do not currently grow food in any considerable quantity. This was not the case fifty years ago in New Zealand when 20% of Aucklanders were growing a quarter of their vegetables and the same proportion of Christchurch residents were growing more than 40% of their vegetables (Vale and Vale 2009, page 60), suggesting similar rates may have existed in Wellington. Wellington is not a 'gardener's paradise' however, with difficult soils²⁴⁵, terrain and wind conditions (Jones, 1987). Out of New Zealand's 16 regions Wellington is ranked 10th in terms of land productivity (Smith and McDonald, 2008).

²⁴⁴ Many native plants and animals of New Zealand are edible (Crowe, 1997), but due to the changing cultural, dietary, economic and nutritional needs of a growing population and because many of these species are in decline or protected, most people in Wellington (and New Zealand) currently follow a typical western diet, which includes a variety of cuisines from other cultures.

²⁴⁵ Bradshaw (2003, page 84) states that soils in urban environments often lack nitrogen because organic matter and the micro-organisms in it that convert atmospheric nitrogen into forms usable by plants are not present in subsoil or most building materials. Important minerals such as calcium, potassium, and magnesium are often abundant in urban soils because these are found in many building materials, and presumably transfer to the soil over time.

Within the city there are thirty one community gardens including three fruit orchards. Eight of these are on council land, fourteen in council housing estates, and nine on private land (figure 102) (Wellington City Council 2012c). The amount of land dedicated to these gardens and amount of produce grown in them is currently unknown. Several streets in Mt. Victoria were planted with olive trees in the 1980s by the City Council. In 2002 the Council began to produce extra virgin olive oil called 'Suprema a Situ' from these. This is on a small scale and none is sold to the public. It is mainly given away to visiting dignitaries (Wellington City Council, 2005). There are several Wellington based community groups and academic research projects related to urban food growing:

- The Wellington Chapter of 'Oooby' (Out of our Own Back Yards) that connects local food growers online so they can share their produce.
- The pop-up edible garden initiative driven by researchers at Massey University in response to the Wellington City Council's 'Towards 2040: Smart Capital' strategy²⁴⁶. Wellington City Council's Social Portfolio Leader (2012) Councillor Stephanie Cook said of the project:

'Pop-up gardens are another way to make more socially connected communities... I'm very keen to have a lot more edible planting, especially heritage variety fruit and vegetables. We do have the space in Wellington's urban centre, so I hope we'll be seeing more of these community gardens in the future' (Wellington City Council, 2012a).

At least four other groups or sources of information are targeted at decreasing wastage of food in the city either from food outlets or edible plants growing in Wellington:

- 'Kaibosh Food Rescue' is a group that from April 2011 to March 2012 diverted 29 000kg of edible food from landfill, sourced from retailers unable to sell it. This food is sent to Wellington charities.

²⁴⁶ This strategy can be found at: <http://www.wellington2040.co.nz/> (accessed April 2012). It was published by the Wellington City Council in 2011.

FIGURE 102 COMMUNITY AND SCHOOL GARDENS IN WELLINGTON (SOURCE: WCC GIS TEAM).

- 'Community Fruit Wellington' assigns volunteers to pick fruit from trees of elderly, disabled, or uninterested fruit tree owners. Produce is shared with the owners and/or donated to charities such as Wellington City Mission.
- 'Wild Picnic' is a blog dedicated to encouraging people to forage for food by identifying edible and useful wild plants in Wellington and the Wairarapa.
- 'Edible Wellington - A Gatherer's Guide' is an online map locating fruit trees, vegetables and herbs growing on public land in Wellington.

An examination of food grown in the Greater Wellington Region reveals the primary food crops are grapes for wine production and olives. A minimum of 1 405 hectares are planted in fruit, and 104 hectares are dedicated to growing vegetables (primarily cabbages, cauliflowers and broccoli) and indoor crops (Aitken and Hewett, 2009). These crops are mostly grown to the east of the city in the largely rural South Wairarapa, Carterton and Masterton areas (figure 79).

New Zealand exports much more food than it imports, particularly in the sectors of fresh fruit, wine, and fresh and processed vegetables. Nationally imports are greater in the areas of processed fruit, nuts, and olive oil (Aitken and Hewett, 2009). In terms of embodied hectares within agricultural products, Wellington imports just over 80% of its needs from other regions in New Zealand and exports nothing to other regions (McDonald and Patterson, 2003). Almost all of Wellington's agricultural production is exported to other nations rather than used to feed the local population.

5.3.7.3 DESIGN GOALS FOR THE PROVISION OF FOOD

According to Vale and Vale (2009, page 56) the land required to provide food for the residents of Wellington City²⁴⁷ in a sustainable way is 247 650 hectares (2 477 km²). The area of Wellington City itself is 28 990 hectares (290 km²). This means the land needed is just under ten times larger than the city itself, assuming that Wellingtonians consume a typical Western diet equating to 1.33 global hectares of

²⁴⁷ This calculation uses figures related to 2007.

land use per person²⁴⁸, and that food is grown using conventional agriculture techniques (figure 103). Wellington's population density is low by global standards at 6.4 people per hectare (46.1 in the inner city core) (Slack and Leung-Wai, 2009), so the city may afford some unique urban food growing opportunities. For a denser city the land needed to provide its residents with food can be up to 1 000 times the area of the city (Bolund and Hunhammar, 1999).

FIGURE 103 LAND IN WELLINGTON CITY COMPARED TO LAND REQUIRED FOR THE PROVISION OF FOOD FOR CITY RESIDENTS (ADAPTED FROM: VALE AND VALE 2009, PAGE 59).

Figure 103 suggests that even if all rooftop space, public green space and unused land within the city was converted to food growing (which is highly unlikely) the city could only provide 11.7% of its food needs given the current level of consumption, conventional methods of food production, and dietary choices. If these three conditions were altered, the city could provide a higher proportion of the food needs of the residents. This does not take into account large areas of the city which could not be used for food growing, such as roads and pathways, biological or heritage reserves, and industrial areas. The conversion of damaged or unused publicly owned land, or land used ineffectively (grass playing fields, brown field sites,

²⁴⁸ The figure of 1.33 global hectares comes from a study of the ecological footprint of food conducted for Cardiff City in Wales (Vale and Vale 2009 pages 39-44).

abandoned car parks and buildings, parks, and verges) into more community garden space could be possible. There is currently at least 840 hectares (8.4 km²) of open space in the city managed by the council that is not listed as reserve (Wellington City Council, 2007a, Nicholson, 1998), meaning it is unlikely to be regenerating forest. Utilising this land for food growing would only allow for the production of an additional 0.3% of the city's food requirements.

To ascertain the accuracy of the 11.7% food production in Wellington figure, a different method of calculating food provision potential was used. The average sized house in Wellington in 2006 was 112m² (Ghosh et al., 2006). It has not been possible to find a figure for the average size of residential plots in Wellington City, however an unpublished estimate from Quotable Value (2010)²⁴⁹ (New Zealand's largest valuation and property information company) is that the average residential plot in Wellington is 630m². This compares closely to the average plot size of 627m² for the States of Victoria and New South Wales in Australia in 2003-2004 (Housing Industry Association, 2010) and is slightly higher than 500m² for the 35 year old northern suburb of Grenada Village in Wellington (Zoodle, 2008). Vale and Vale (2009, page 139) suggest that 350m², the average size of residential plots in the United Kingdom is increasingly common in New Zealand and Australia. It is also unlikely in Wellington that an entire property would be suitable for growing food due to the city's steep topography, existing native vegetation, or shading from the dwelling, neighbours or nearby hillsides. 10% of the property is assumed to be used for driveways and paths (Vale and Vale 2009, page 141).

Given the fact that many homes in New Zealand are single storey (French et al., 2007), this means between 203m² (using UK figures of 350m²) and 455m² (using the Quotable Value estimate) would on average be available for food growing in typical suburban plots in Wellington²⁵⁰, if there is no competition with other land uses such as habitat provision. If Wellingtonians were able to use all of the land around their

²⁴⁹ Information, again from Quotable Value New Zealand, gives the average section in New Zealand as 924m², but this includes larger sections in many small towns in New Zealand so is not suitable for a Wellington calculation.

²⁵⁰ There is a trend toward apartment dwelling in inner city Wellington. In 2006 almost 5000 people lived in apartments, presumably with no access to land for food growing, a 300% increase in a ten year period (Statistics New Zealand, 2010a).

dwellings to grow fruit and vegetables²⁵¹, and given that most households in Wellington are single families (67%) of 2.6 people (Statistics New Zealand, 2006c), this results in the provision of 19 to 43% of each person's fruit and vegetable needs. Assuming people follow the New Zealand Ministry of Health recommendation of having fruit or vegetables for 5 out of 14 servings of food a day (Ministry of Health, 2010) this is 7 to 16% of an adult's ideal diet. The mid-point of the ranges provided by this calculation point to an approximate potential for the provision of food within Wellington of only 11.5% which is very close to the original estimate given by Vale and Vale (2009). The availability of land is only one factor that determines if people choose to grow food in an urban setting. The main point, however, is that with a low population density in the city, particularly in the suburbs, and increased nutrient cycling and composting the potential to grow more food within the city exists. Significant behaviour and dietary adjustments would make an even greater contribution to change if addressed first or concurrently²⁵². A wheat based diet requires six times less land than a typical affluent person's diet that includes meat for example (Gerbens-Leenes and Nonhebel, 2002). For the land required for different food types see Vale and Vale (2009, pages 40-41 and 46-47).

While it seems Wellington's urban built environment will not be able to provide for all of the food provisioning of its residents, making an 11% contribution to food provision is worth pursuing given the large discrepancy between the land available within the city and the land required to provide food (figure 103). Utilising some of the urban built environment to contribute to the ecosystem service of food provision could reduce the land needed in the wider region to produce food for Wellingtonians. This could equate to 11% more land being dedicated to providing the other ecosystem

²⁵¹ Vale and Vale (2009, page 307) suggest that 0.1 hectares is necessary to do this per person in the New Zealand climate.

²⁵² The key behavioural and dietary issues to consider are (Vale and Vale 2009, chapter one and pages 29-71):

1. The amount of food consumed: New Zealanders consume 39% in excess of the daily requirements set by the United Nations Food and Agriculture Organisation.
2. The type of food eaten: certain foods require substantially more energy and therefore land to produce such as fish and meat, dairy, and alcohol.
3. How the food is produced: different agriculture methods require different energy inputs.
4. Where the food is consumed: food eaten at home has a reduced footprint compared to food eaten out.
5. Where the food comes from: producing food locally is often cited as making a large contribution to reducing an area's ecological footprint. For Wellington, sourcing agricultural imports from nearby regions to cut back on truck transport would be a positive change to make.

services required for human and non-human health that are better suited to a rural rather than urban setting, such as soil building, fixation of solar energy and decomposition. It is likely, however, given the current economic model operating in New Zealand that sees increased financial profits as a measure of success, combined with the general lack of value for ecosystem services, than any reduction in food sourced from the greater region would translate into more food exports rather than change of land use.

Food growing within the urban fabric is increasing globally (Drescher et al., 2006) and often occurs adjacent to other mostly non-western cities (Deelstra and Girardet, 2000, section 4.4.1.1). Aside from traditional vegetable and fruit tree gardening for house plots (Muller, 2000), there are historic examples: the German 'Schrebergärten' an allotment system that began in the mid-1800s, and the 'Dig for Victory' campaign in Britain and New Zealand, and 'Victory Gardens' in the United States of America during World War Two (Deelstra and Girardet, 2000, Peters, 2010). Contemporary examples include: allotment gardens in the United Kingdom (Leach, 1975); stacked container pyramid gardens in Santiago, Chile; Sri Lankan 'edible air-scapes' used as a rebuilding strategy after the 2004 Boxing Day Tsunami; Latin American 'microgranjas'; and allotment gardens made available to urban poor on private land in Cagayan de Oro in the Philippines (Drescher et al., 2006). Future proposals include urban vertical farming (Despommier, 2011), though without life-cycle analysis the suitability of these is untested.

Employing high yield, low impact systems such as permaculture, organic farming, biodynamic farming or similar techniques may produce similar or higher yields than conventional farming while better maintaining soil fertility, hydrology flows and habitat, as well as impacting positively on human health (Mollison, 1988). Although yield potentials will vary depending on climate and location and will also vary seasonally, it is important to investigate such methods in devising urban food growing systems so that the negative impacts on other ecosystem services inherent in conventional agricultural crop and animal farming are not repeated in an urban food growing context. The impacts of conventional agriculture include: pollution associated with the use of nitrogen and phosphorous; high use of water for irrigation; land use change and associated loss of biodiversity and the ability of ecosystems to

provide ecosystem services; eutrophication of marine and freshwater systems; shifts in food chain structures; increases of 'nuisance' species; high GHG emissions (Tilman, 1999) and high use of fossil fuels (Leach, 1975); ground water depletion; soil erosion; and increased desertification (Swinton et al., 2007).

Additional benefits of urban gardening have been described by Drescher et al. (2006) as: increased food security for the urban poor, particularly in developing countries; conservation of indigenous and heirloom edible and medicinal plants; reduction of waste to landfill; soil building; reduced application of agrochemicals; reduced ground water pollution; soil stabilisation; provision of shade; microclimate modification; reduced urban heat island effect and energy use for cooling; increased variety and nutrient value of diet (particularly vitamins A and D, calcium, and iron); potential additional income for poor households; strengthening of community values; and increased positive social interaction. Deelstra and Girardet (2000) agree with many of these and add the following: improved nutrient cycling; conservation of soils; improved water management; increased biodiversity; increased air quality; an improved O₂ - CO₂ balance; reduced energy for transport and packaging of food; and increased environmental awareness of city inhabitants. Problems that can arise with urban food growing in a typical current urban context include land, air, and water for urban gardening being contaminated by various pollutants including heavy metals and vehicle emissions (Despommier, 2011), and the lack of long term land tenure in some cases (Drescher et al., 2006).

For a summary of design goals determined for all ecosystem services examined in this section please refer to table 16 (page 373).

5.4 RELATIONSHIPS BETWEEN SERVICES

An examination of the relationships between the ecosystem services investigated in this chapter may reveal where effort to integrate with ecosystem services could have most benefit (section 4.3.3). Figure 104 illustrates relationships between ecosystem services analysed in a Wellington context that are potentially mutually beneficial, supportive in one direction, neutral, or potentially antagonistic. Such relationships

may change in different locations. Services like climate regulation, purification and habitat provision are mutually supportive, meaning actions taken to support one service could be the same as actions taken to support another (the planting of certain trees will have a positive effect on the ecosystem services of both habitat provision and climate regulation for example).

FIGURE 104 POTENTIAL RELATIONSHIPS BETWEEN ECOSYSTEM SERVICES IN WELLINGTON.

The following series of figures (105 to 111) show which kind of relationships occur for each ecosystem service separately so that the information is easier to read. The

key given in figure 104 applies to all figures in this section. Each relationship is only described once.

FIGURE 105 HABITAT PROVISION RELATIONSHIPS.

Figure 105 shows the provision of habitat is mutually beneficially to the ecosystem services of nutrient cycling, because increased habitat means increased numbers of nutrient cycling flora or fauna species and increased nutrient cycling supports healthier ecosystems that in turn provide better habitat. It also benefits purification as increased vegetation enables greater purification of air, water and soil and cleaner ecosystems provide better habitat for species (Cavanagh, 2006, Beckett et al., 1998, Kadlec et al., 2000). The provision of habitat benefits climate regulation (section 1.4.1) and the provision of fresh water, due to purification of water creating healthier ecosystems and to the support that natural ecosystems give to normal hydrological flows and interactions with larger hydrological cycles (Postel and Thompson, 2005, Nepstad et al., 1994, Bormann, 1976).

Potentially antagonistic relationships are shown between habitat provision and the provision of food and fuel. With regard to food, there may be conflicts between which species to grow. In a Wellington and wider New Zealand context many terrestrial native flora and fauna species are not suitable human food sources. It is also not possible or advisable from a biodiversity point of view to have large areas where introduced food species are mixed with native flora in New Zealand due to problems with invasive species, though this may be a suitable strategy for suburban gardens or urban areas in different countries (Drescher et al., 2006). The Wellington City Council (2007a) state that:

‘The main weed concern in the urban environment is that of ‘garden escapes’. About 75% of land weeds and 50% of fresh water weeds are garden escapes. On average eight garden plants species each year become established in the wild in New Zealand’.

In a similar way, if energy is generated by degrading aquatic systems by employing large scale hydropower systems, or if space is dedicated to energy generation rather than habitat provision such as growing exotic plants in monocultures for biofuels, then the relationship between habitat provision and the provision of fuel/energy could be conflicting (Sternberg, 2008, Moog, 1993, Tilman, 1999).

Figure 106 illustrates that nutrient cycling has a mutually beneficial relationship with food growing, particularly in an urban context (Deelstra and Girardet, 2000). This is because growing food enables greater cycling of decomposable organic wastes which in turn increases the fertility of soil, and therefore plant growth (Drescher et al., 2006). Because there is a potentially mutually beneficial relationship between nutrient cycling and the provision of habitat, the neutral relationship between provision of energy/fuel and nutrient cycling will be affected depending on how the provision of energy/fuel service impacts on the provision of habitat. Nutrient cycling supports purification particularly in terms of soil quality because it allows for wastes to be transformed into useable substances. Climate regulation supports nutrient cycling through complex relationships between climatic conditions and carbon, nitrogen, and water cycles (Schimel et al., 1996). Nutrient cycling from both terrestrial and marine sources also affects climate (figure 40, section 3.5.5.1,

Charlson et al., 1987, Vitousek and Sanford, 1986). The relationship between nutrient cycling and climate regulation has been altered by certain human activities. Increased climate change caused by methane in the atmosphere from emissions from agricultural livestock is one example (IPCC, 2007d, page 501). Finally, healthy fresh water systems support nutrient cycling (Postel et al., 2005).

FIGURE 106 NUTRIENT CYCLING RELATIONSHIPS.

Figure 107 illustrates that purification supports the growth of food because without clean water or pollutant free fertile soil it is more difficult to grow healthy edible plants, and depending on the system of food growing used, these ecosystem services could be mutually supportive (Mollison, 1988). Many conventional agricultural processes are not supportive of the ecosystem service of purification because they introduce pollutants such as herbicides and pesticides into ecosystems and GHGs into the atmosphere (Tilman, 1999, Leach, 1975). The purification of air contributes to climate regulation, while the purification of water directly underpins the provision of fresh water service (Postel and Thompson, 2005).

FIGURE 107 PURIFICATION RELATIONSHIPS.

Figure 108 illustrates that the ecosystem service of habitat provision contributes to climate regulation, and in turn is enhanced by it (Gitay et al., 2002). Suitable climate conditions underpin the capacity to grow food (Despommier, 2011). Because the provision of food within urban environments requires the growth of edible plants, there are potentially positive links with the regulation of climate due to the ability of any vegetation to sequester and store carbon (Peters, 2010). However, conventional agriculture produces significant GHG emissions (Peters, 2010, Tilman, 1999), particularly in the New Zealand context (figure 101) and so the benefit is recorded as only one way. The provision of energy/fuel from renewable sources can contribute to the regulation of climate if this replaces fossil fuel derived energy and thus prevents additional GHG emissions.

FIGURE 108 CLIMATE REGULATION RELATIONSHIPS.

Further relationships illustrated in figure 109 are the unknown or neutral relationships between the provision of energy/fuel and the other provisioning services of food and fresh water. Depending on how energy is to be generated it could be antagonistic towards the growing of food as is seen in global competition between space to grow food crops and space to grow crops for biofuel production (Rosegrant, 2008, Peters, 2010). In the context of Wellington however, the generation of energy from wind farms does not appear to either negatively or positively impact on food growing so this relationship is illustrated here as being neutral. In a similar way, the provision of fresh water to some ecosystems and some people could be negatively impacted upon by hydropower projects (Sternberg, 2008). Although Sinclair Knight Merz (2006) states there is further potential for hydro power in the Wellington region, no hydropower schemes currently exist or are actually proposed in Wellington.

FIGURE 109 PROVISION OF FUEL / ENERGY RELATIONSHIPS.

The relationship between the provision of food and the provision of fresh water is depicted as one potentially in conflict in figures 110 and 111 because extra food growing in an urban context might require additional watering, meaning increased pressure on the provision of fresh water ecosystem service (Syme et al., 2004). Several researchers point out that increased green areas and gardens in cities can help with water management and regulate stormwater flow (Deelstra and Girardet, 2000). Urban food gardens may, depending on their design, use less water per kilogram of food produced than conventional large scale agriculture systems and result in less water consumption overall (Peters, 2010). These issues indicate that the effect on water consumption caused by urban food growing should be carefully considered (Molden, 2007, Smit and Nasr, 1992).

FIGURE 110 PROVISION OF FRESH WATER RELATIONSHIPS.

What the series of figures in this section illustrate is that the provision of habitat seems to have the most mutually beneficial relationships (indicated by the most dark green lines. See: figure 105). This means that a focus on habitat regeneration may have the most secondary benefits in terms of supporting other ecosystem services. Care should be taken however that a scenario is avoided where non-human species flourish in urban areas at the expense of the provision of services also vital to human survival, such as food growing. This points to the need to consider each ecosystem in relationship to others in specific locations. Figure 107 illustrates by way of light green lines that the ecosystem service of purification supports all but one ecosystem service (the provision of energy/fuel) so this would appear to be the next most beneficial ecosystem service to consider. Because there are potentially antagonistic relationships associated with the provision of food and the provision of fuel, increasing these ecosystem services should be done with thorough ecological life cycle analysis so that negative impacts on other ecosystem services do not occur.

FIGURE 111 PROVISION OF FOOD RELATIONSHIPS.

In terms of solving some of the apparent conflicts between ecosystem services it might be beneficial to employ mapping techniques to establish which parts of the city are most suited to providing which ecosystem service(s). An attempt to do this relating to the potential conflict between food growing and providing habitat has been made (figure 112). Such a map illustrates how these two services could co-exist within a given area without directly competing for space.

A series of maps (figures 78, 86, and 102, appendix seven, and maps from Isthmus Group, 2009) were overlaid to determine existing habitat areas, existing food growing areas, and other land types. The red line on figure 112 indicates the eastern and northern boundaries of Wellington's urban area. Habitat areas in figure 112 include: areas of existing native forest; areas of native scrub (assumed to be regenerating forest); riparian areas; Department of Conservation (DOC) protected private land; DOC indigenous threatened environments; DOC coastal landscapes

and seascapes of significance; Greater Wellington Regional Council coastal sites of regional significance; and Wellington City Council significant landscapes (ridges and hilltops).

FIGURE 112 AREAS FOR HABITAT AND AREAS FOR FOOD GROWING IN WELLINGTON.

Outside of the urban area food growing areas are existing pastoral land. Within the urban area this zone was determined as: areas not designated as habitat areas; not recorded as containing non-native scrub; and areas not included as part of the proposed extended inner or outer green belts in the Wellington City Council Open Space Strategy (Nicholson, 1998) (figure 86). Areas that could potentially be either habitat or food growing areas were determined by: areas not categorised as habitat,

but part of the Open Space Strategy proposed green belts; areas of non-native scrub (this is probably land cleared for pasture that has been left to regenerate); and boundaries areas between habitat and food growing areas. Depending on the specific location, some areas of existing exotic forest were included in habitat zones and some in the purple food or habitat zones (exotic forest is harvested in relatively short rotation periods, so it may not be exotic forest in the future). Where habitat could be linked through small areas of proposed green belt or areas of non-native scrub these were included in the habitat zone because of the significant negative impacts on biodiversity that fragmentation of habitat has (Brook et al., 2008, Hanski, 2005, Krauss et al., 2010) (section 1.4). Within the urban area, approximate areas suggested by figure 112 are: 3 950 hectares for habitat, 2 100 hectares for food growing and 950 hectares of land that could be used for either ecosystem service. Outside of the urban boundary approximate areas suggested by figure 112 are: 14 500 hectares for habitat, 3 700 hectares for food growing, and 3 900 hectares of land for either food growing or the provision of habitat. The initial map devised that records all land uses investigated can be found in appendix nine. It should be noted that the zoning illustrated in figure 112 and appendix nine should be used as an example of how to proceed with resolving conflicts between ecosystem services, rather than as a map to be used practically in a Wellington context without review from qualified experts. Marking of the sites that are unsuitable for either habitat provision or the growing of food such as the airport, industrial areas, and other similar areas would provide a further level of detail to figure 112.

5.5 SUMMARY OF THE ECOSYSTEM SERVICES ANALYSIS OF WELLINGTON

'For most general ecosystem services, the share generated by ecosystems within the urban area is expected to be limited compared to the total service. However, even if the generation of the services can often be made at a distance from the city, there are reasons why part of the services should be produced locally. It can be advantageous to generate ecosystem services locally for pure efficiency reasons, but also on ethical and educational grounds... As cities are expected to grow at a rapid rate in the coming

decades, it is important that the ecosystem services in urban areas and the ecosystems that provide them are understood and valued by city planners and political decision-makers' (Bolund and Hunhammar, 1999).

The aim of this chapter was to ascertain what proportion of ecosystem services used by Wellington are, and could be provided by local ecosystems, infrastructure, or buildings. If the built environment can provide some of its own services, pressure is potentially decreased on local and distant ecosystems. This means these may be able to become healthier, or regenerate if they are currently degraded, and therefore be able to support more species. Healthier ecosystems more readily provide ecosystem services to humans that cannot be provided by the built environment (section 4.5.2) and therefore enable humans to be better able to adapt to the impending impacts of climate change (MEA, 2005b). Table 16 collates the results of the pre-development, current, and potential future ecosystem services analysis for Wellington²⁵³. These results are represented graphically in figures 113 to 115.

Figure 113 indicates the current percentage of ecosystem services that come from the local area in Wellington in relation to benchmarks devised from analysis of the pre-development ecosystem. This was done to determine the potential inherent in the local area to provide these services. It should be noted that these figures relate to current demand for these services, so there may be scope for lowering overall demand through efficiency mechanisms and behaviour change strategies. As Bolund and Hunhammar (1999) point out:

'Urban ecosystem services contribute to the quality of urban life even if urban citizens are still dependent on global ecosystem services for their survival. The quality of life for urban citizens is improved by locally generated services... It should however be remembered that it is only the effects of these problems that are decreased, not the cause of the problem that is solved. It is necessary to work to both ends'.

²⁵³ A selection of additional behaviour or technology changes that could reduce initial demand for ecosystem services in Wellington and therefore reduce the amount of services required to meet regenerative development goals are included in table 16. This is not an exhaustive list. Where percentages for savings were able to be calculated for the Wellington context these are included. Levine et al. (2007) provide details of additional technology changes that could contribute to reducing GHG emissions from the built environment.

TABLE 16 ECOSYSTEM SERVICES ANALYSIS OF WELLINGTON

Ecosystem service	Percent of service supplied by pre-development ecosystem	Percent of service supplied by current urban environment	Ecosystem services provided in a potential future Wellington			
			Ecosystem based regenerative development goal <i>(Exceeding these goals could be considered 'regenerative')</i>	Percent of service supplied in a potential future	Behaviour / technology changes assumed in calculation of potential future	A selection of additional behaviour / technology changes to increase future potential urban supplied ecosystem services <i>(Percent of savings supplied where possible. Detailed lifecycle analysis should be undertaken for each technology and location)</i>
Habitat provision	100	2	157 hectares of additional habitat.	10	<ul style="list-style-type: none"> • Revegetation of council owned green space to provide habitat. • Habitat provision on privately owned land or on buildings. • Provision of measures to counter fragmentation of habitat. 	<ul style="list-style-type: none"> • Further habitat provision on private land or buildings. • Ecological engineering strategies.
Nutrient cycling	80	~0	80% recycling, reuse or safe decomposition of waste.	80	<ul style="list-style-type: none"> • Separation of waste streams (recyclable and biodegradable). • Changes in building design and demolition practices. • Increased use of local or nearby materials. 	<ul style="list-style-type: none"> • Reduction or cessation of the creation of pollution and non-recyclable / non-reusable / non-biodegradable wastes. • Cessation of landfilling. • Cessation of emission of sewage to ocean.
Purification	100	13	Air: 7 660 tonnes PM ₁₀ , 15 840 tonnes NO ₂ , 1 990 tonnes O ₃ filtered per annum. Water: 15%	100	<ul style="list-style-type: none"> • Increased urban vegetation. • Suitable mechanical plant (air purification). 	<ul style="list-style-type: none"> • No pollution of water ways or harbour • No air pollution • No soil pollution

			impervious surfaces. Higher quality water leaving the urban environment. See table 12. Soil: See table 14.			<ul style="list-style-type: none"> • Water sensitive urban design practices. • Phytoremediation. • Increased porosity of surfaces (decreased imperviousness).
Climate regulation (carbon storage)	100	5	10 334 000 tonnes of carbon stored.	15	<ul style="list-style-type: none"> • Regeneration of forest. • Reduced use of fossil fuels. 	<ul style="list-style-type: none"> • Further reduction / cessation of GHG emissions. • Carbon sequestration.
Provision of fuel/energy	100	19	686GWh (electricity only), 2 588GWh (total energy use) extra renewable energy generation.	286 (electricity only) 140 (total energy)	<ul style="list-style-type: none"> • Additional renewable electricity generation. • Substitution of fossil fuel sources by renewable ones. 	<ul style="list-style-type: none"> • Solar hot water heaters (potentially 8% (202GWh) reduction in total additional energy required).
Provision of fresh water	100	~0	30 million m ³ rainwater harvested per annum. (52% of total rainfall on Wellington urban area).	80 (domestic water use) 31 (total water use)	<ul style="list-style-type: none"> • Rain water harvesting from domestic dwellings. 	<ul style="list-style-type: none"> • Reduced water use per capita. • Use of water efficient technologies. • Rain water tank rather than reticulated water supply (potentially 25% (3 million m³) less water use domestically).
Provision of food	100	~0	100% of food production for urban population.	11	<ul style="list-style-type: none"> • Urban food growing around domestic dwellings. 	<ul style="list-style-type: none"> • Plant based diets. • Reduced food consumption per capita. • Food growing on council owned and non-domestic sites. • Increased yield food growing techniques. • Roof top / façade / interior / vertical food growing. • Reduced export of food.

FIGURE 113 CURRENT ECOSYSTEM SERVICES SITUATION IN WELLINGTON

FIGURE 114 POTENTIAL OF WELLINGTON TO PROVIDE ECOSYSTEM SERVICES PRE-DEVELOPMENT

FIGURE 115 POTENTIAL SHIFTS IN PERCENTAGES OF PRE-DEVELOPMENT ECOSYSTEM SERVICE PROVISION THAT THE CURRENT BUILT ENVIRONMENT OF WELLINGTON COULD PROVIDE FOR ITSELF

In figure 113 each ecosystem service has a green and a red part. The green part indicates where the built environment provides its own services or utilises ecosystem services provided by the local remaining ecosystem. The proportion is represented by a positive percentage figure. Green areas exist due to ecosystem services still operating in the areas after development (from remnant patches, or regenerating forest). An example of this is the ecosystem service of air and water purification that is due in part to vegetation found in the Wellington area (van Roon and Moore, 2004). The other possibility is that green areas are present because the built environment is able to use other means to generate the service (such as the provision of energy from wind in Wellington). It is important that any analysis takes into account whether these other methods to supply certain ecosystem services in the built environment are beneficial or detrimental to ecosystems over their entire lifecycle, so that methods that increase one ecosystem service do not inadvertently reduce another.

Red areas in figure 113 (represented by a negative percentage figure) indicate where Wellington sources a particular service from outside the region, such as in the cases of provision of water and food. The proportions of red and green for the service of purification use calculations relating to air quality because these provided the most accurate measurements. Although no green areas are recorded for the services of nutrient cycling, provision of water, and provision of food, it is likely, as described in section 5.3, that minimal amounts of these services are provided within Wellington. It was not possible to deduce exact figures and these proportions are assumed to be close to zero.

The built environment not only uses ecosystem services from other areas but also contributes to degrading ecosystems both locally and remotely (Rees, 2003), leading to less overall availability of ecosystem services. This is exacerbated by increasing demand from an expanding population and by rising per capita demand (Turner, 2008) as discussed earlier. For example, the built environment in Wellington not only prevents the levels of pre-development carbon storage and sequestration from occurring, but also emits GHGs that cause climate change through the actions of people living within it (Dodman, 2009). In a similar way, the built environment not only prevents the ecosystem service of purification from occurring but pollutes

ecosystems through stormwater run-off, dumping of waste, and vehicle emissions (Herald, 2003, Steemers, 2003a, Komilis et al., 1999). This additional degradation is represented by the red arrows in figure 113. Although effort has been made to determine the size of this negative ecological impact, insufficient information was available to determine exact additional ecosystem degradation percentages or proportions for each service in the context of the Wellington built environment. Red arrows are, therefore, indicative only and should not be read as exact measures, particularly in the case of the ecosystem services of nutrient cycling and purification.

Red arrows were determined as follows: habitat provision is degraded by the built environment due to pollution, fragmentation and land use changes driven by demands such as provision of food and provision of raw materials (growing exotic timber plantations for example) (section 1.4). Exact degradation proportions are unknown. The degradation of the purification service occurs through built environment driven pollution of ecosystems (Herald, 2003, Mitchell, 2010, Greater Wellington Regional Council, 2010b) or the actual removal of ecosystems caused by similar factors to the provision of habitat service described above. Exact percentages are unknown. The degradation of the nutrient cycling service is caused by increasing imperviousness of land in the built environment and current manufacturing, construction, and landfilling practices (materials cannot be easily reused or recycling) (Herald, 2003, Komilis et al., 1999). The climate regulation red arrow is due to increasing annual GHG emissions from the city. It should be noted that calculations in section 5.3.4 refer only to carbon storage and sequestration and that including other aspects of climate regulation could increase the red arrow related to this service. The provision of water red arrow is set at approximately 8% because that is the percentage of rainfall on Wellington that, instead of being utilised, is being provided by river and aquifer water from adjacent areas. The current reticulated water system in Wellington creates loss of aquatic ecosystem health and uses non-renewable aquifer water (NIWA et al., 2011a). The provision of food red arrow is determined by the fact that approximately ten times more land is required to provide the current food needs of Wellington residents than the land area of the entire city (including both urban and non-urban areas) (figure 103).

Results of the ecosystem service analysis of Wellington represented in figure 113 are that in relation to the potential devised by calculations of pre-development ecosystem services in the Wellington, almost all ecosystem services are provided from outside the area. Wellington does best in terms of the provision of renewable fuel/energy with 39% of the service being provided (potentially) within Wellington. The service that is most out of proportion with the ability of the local area to supply it appears to be the provision of food.

Figure 113 shows where the built environment may cause the most stress on ecosystem services and where the most potential for intervention may lie in the context of Wellington. In an ideal situation all ecosystem services would be at the same green proportion illustrated in figure 114, meaning that according to calculations, the service could be provided by the built environment or through local regeneration of ecosystems. The research indicates that for some services, such as the provision of habitat, the regulation of climate, and the provision of food, it is likely to be very difficult to meet such goals without a radically different way of creating and living in the built environment, at least in the context of Wellington, and probably any modern city.

Figure 114 illustrates the pre-development potential of Wellington to provide its own ecosystem services. The red area in the nutrient cycling service indicates that 20% of nutrients were probably not cycled within the pre-development system (Egunjobi, 1969). It is possible that the ecosystem would have contributed to cycling nutrients lost from other non-local ecosystems as they moved into the forest however. This is represented by the green arrow.

Figure 115 illustrates potential shifts in percentages of pre-development ecosystem service provision that the current built environment of Wellington could provide. These shifts could be made by changing aspects of the built environment using behaviour change methods and/or current technologies or design methods as described for each ecosystem service in section 5.3. Given currently available options for changing behaviour and existing technologies (such as photovoltaic solar panels, solar hot water heaters, and water efficiency equipment) (Newton and Tucker 2010) it may be possible to remove the additional degradation element (the

red arrows in figure 113) from the supporting services of habitat provision and purification and the regulation service of nutrient cycling. The rationale for this is described in section 5.3.

Green and red areas in figure 115 were determined as follows: in the case of the provision of habitat ecosystem service, the 10% green figure is based on the amount of indigenous forest required in Wellington to begin a process of regeneration rather than perpetuate on-going degradation (Clarkson et al., 2007b). This target seems reasonable given current green space available in Wellington and land surrounding residential homes in suburbs. Such a target may vary considerably in different locations with different types of indigenous ecosystems.

The amount of purification that could be provided in the built environment is uncertain. Because capacities for purification in the pre-existing ecosystem are significantly higher than pollution levels that exist locally, because purification would increase with the addition of habitat and food growing in the city, and because current technologies or methods exist that could be used to remove and treat pollution effectively, it is conceivable that 100% of the ecosystem service of purification could be provided locally.

Nutrient cycling is one of the ecosystem services that proved to be the most difficult to quantify. The green and red areas in figure 113 are based on the potential inherent in the pre-development system and represent a goal. Additional research by lifecycle analysts, urban metabolism experts, and ecologists would be needed to determine the potential of the current built environment to contribute to nutrient cycling with more accuracy.

While there are some successful examples of carbon neutral developments (Lazarus, 2003, Society of Building Science Educators, 2012), the difficulty in achieving the complete cessation of GHG emissions, particularly in existing rather than newly constructed built environments, means it is unlikely that the red arrow related to climate regulation, representing damage done by the built environment to the climate, will disappear in the near future. In fact emissions are growing in New Zealand and globally (Ministry for the Environment, 2012, IPCC, 2007c, page 97,

WWF New Zealand, 2012), so this arrow increases in size from figure 113 to figure 115. If the provision of habitat and the provision of food increase in Wellington it is possible that the potential to sequester extra carbon will increase, depending on how food is grown and urban trees are maintained (Nowak and Crane, 2002). This is represented by the green arrow attached to the climate regulation part of the graph.

The provision of fresh water calculations are based upon the addition of simple rainwater harvesting systems to domestic buildings. Any water that continues to be provided from outside Wellington using conventional methods is likely to continue to degrade ecosystems. This is represented by the red arrow attached to the provision of water part of the graph. It may be plausible, with significant investment in additional infrastructure and given the amount of rainwater that falls on the urban area that 100% of water supply could be provided locally, if combined with significant demand management strategies (section 5.3.6). This is represented by the green arrow on figure 115.

In the case of the provision of food, calculations relate to what is physically possible based on current food consumption in Wellington, conventional agriculture practices and land available. The green arrow indicates, however, that according to some research and evidence from case studies (Despommier, 2011, Koc et al., 1999, Drescher et al., 2006) with significant changes in diet and amount of food consumed, combined with utilisation of urban food growing techniques on a large scale, provision of economic incentives, and societal change, proportions higher than 11% of food provision may be possible. Again, utilisation of new kinds of food growing technology (such as green facades, hydroponic systems, or vertical farming) would need to be assessed on a life-cycle basis to determine if such technologies impact negatively on other ecosystem services (Gerhardt and Vale, 2010).

If the urban built environment can provide 100% of its needs for a particular ecosystem service (green bar), anything above that 100% (green arrow) could be termed 'regenerative'. The provision of energy/fuel appears to be the only ecosystem service that can be provided locally and could exceed the pre-development ecosystem potential by up to 249%.

Practically, the roof tops of buildings should collect energy, harvest rainwater, and provide habitat, or preferably a combination of at least two of these. Open space, including land around dwellings and other buildings should be vegetated, with plant selection tailored to habitat provision, food growing, or if possible both (figure 112).

Although it will be difficult for the built environment to match the potential of the pre-development ecosystem in terms of providing ecosystem services, the changes possible as illustrated in figure 115 are not insignificant and if implemented, could contribute numerous positive benefits for humans, ecosystems, and the climate system. Because of the mutually reinforcing relationships between certain ecosystem services (section 5.4) and the nature of ecosystems with their complex thresholds of ecosystem service provision, it is possible that improvement in the provision of services would not be a simple linear process, just as impacts on ecosystem services caused by degradation of ecosystems are not simple to predict (MEA, 2005b). It is possible that slight improvement in the provision of one service (like habitat provision) may result in significant improvements in another (such as purification).

5.6 CONCLUSIONS: CHAPTER FIVE

McGranahan et al. (2005, page 817) point out that:

‘A city may represent as little as 0.1% of the area of the host ecosystems that sustain it. Such fractions emphasise that even in a stable world, no city or urban region as presently configured could be sustainable on its own. Moreover, the combined requirements of urban systems are increasingly unsustainable in the long run; in a politically unstable world, dependence on extensive and often distant ecosystems raises issues of shorter-term sustainability’.

The case study of Wellington appears to reinforce this observation and illustrates that the Wellington built environment does not function like a natural ecosystem, and is unlikely to do so without large scale change in both its physical makeup and

behaviour of its inhabitants. Areas of stress on ecosystem services have been exposed and areas where quantifiable improvements may be made demonstrated. This shows where changes could be made (the provision of fuel/energy and provision of water) and where extra focus on solving the ecosystem services equation for Wellington is needed (the provision of food, provision of habitat and the regulation of climate).

During the course of this research it became apparent that the techniques for evaluating the impact of an existing or future built environment, and the use of this evaluation to determine design goals or places to intervene in an existing system for provisioning services, are different from those that can be used for regulating or supporting services. This is because provisioning services are based on human defined needs and wants. The basis for the required quantities of these services is not physical reality, but the cultural and societal perceived realities that are largely determined by human consumption and behaviour patterns. Regulation and supporting services occur regardless of human needs and desires and relate to ecological reality independent of humans, so can be measured based on pre-development or existing ecosystems and goals can then be determined from such an exercise.

In the analysis of provisioning services, it is more logical (illustrated by the provision of food research in section 5.3.7) to use ecological footprint methodologies to determine the potential for such services to be provided locally. Ecosystem services analysis may be useful in understanding where limits could be devised in the provisioning services. A fuel/energy provision limit below current consumption has already been discussed in section 5.3.5.3. In the case of the provision of fresh water the current capacity of domestic roofs to capture rainwater is only 16% of the rain that falls on the urban part of Wellington. While a cap of 30 million m³ of water use for the city has been set by the Wellington City Council²⁵⁴ (Wellington City Council, 2010c), this does not seem to be based on local ecological factors. Ecologists would need to determine what would be an appropriate percentage of harvested rainfall in

²⁵⁴ The 30 million m³ of water the council currently sources is not harvested rainwater as described in section 5.3.6.2.

order to set a cap based on ecological reality. 30 million m³ of rainwater (approximately 52%), even if it could be collected in the future, may prove to be too great a proportion of overall rainfall if appropriating more than half of all rainwater for human use would be detrimental to the wider local ecosystem. The next stage of any research utilising ecosystem services analysis for proposing goals for change in the built environment to support certain ecosystem services would be to ascertain that the changes suggested do not impact negatively on other ecosystem services. The services of ecological footprint experts, lifecycle analysts, and ecologists with local knowledge would aid in this endeavour.

This research has examined a whole city, but the methodology employed could also be used for a single building site. Exploring how the ecosystem services analysis methodology could be applied at smaller scales would extend the research undertaken in this chapter. By looking at a context larger than a localised site initially, a smaller development's contribution to larger regenerative goals can be evaluated and elaborated upon. Another way to extend the research begun in this chapter would be to investigate cities situated in different climates and ecological systems as well as those of a developing rather than industrialised nature. Results could be compared and conclusions drawn about how different cities could cooperate to provide ecosystem services. Wellington may be able to provide energy to a neighbouring urban area in exchange for food if that ecosystem service is more easily provided by that place for example. This would be a different way of accounting for trade between cities or regions by using ecosystem services as a basis rather than typical current economic systems.

The most important conclusion of this chapter is that while the idea of regenerative urban environments relating to ecological performance is philosophically appealing, making this a reality in terms of built and measured urban environments is likely to be very difficult in Wellington in the near future. This does not mean such goals should not be adopted in order to improve the relationship between urban environments and the ecosystems on which they rely and are part. Having the knowledge of goals to aim for in terms of urban ecological performance and the provision of ecosystem services, may be a helpful initial step in working out how to practically achieve such goals.

6.0 CHAPTER SIX: A WIDER CONTEXT, REFLECTION AND EVOLUTION

Given that the research in this thesis examines ecosystems as a basis for contributing to regenerative architectural and urban design, it may be appropriate to use the analogy of an ecosystem to conclude the research, examine its major findings, point out possible extensions, predict possible change over time, and understand its holistic implications. The particular ecosystem used as a metaphor to structure this chapter is one which experiences a natural disaster, a period of upheaval and a succession of species, and then begins a long process of regeneration, mutating and evolving in the face of new conditions, thus following the adaptive cycle of resilience theory (Holling, 1973). The following sections use this ecosystem analogy to place the research within the wider context of current society and understand how the research may or may not influence change.

6.1 A LARGE SCALE NATURAL DISASTER (FUTURE CHANGES IN THE CONTEXT OF URBAN ENVIRONMENTS)

As discussed in chapter one, it is increasingly recognised that the built environment is responsible for many of the drivers of global environmental degradation (UNEP, 2007, Newman, 2006) and it is becoming clear that substantial changes must be made to its creation and use to limit, and if possible reverse, damage to climate and ecosystems (McGranahan et al., 2005, pages 797, 806). It remains to be seen if future societies will hold the built environment accountable for its contribution to damaging the very ecosystems that support human life. Currently this is not the case. The conventions that created the cities that have caused in part these ecological problems (Dodman, 2009, Newman, 2006), and the conventions that keep these urban environments operating (primarily due to the behaviour of people within them) remain mostly unchallenged at a large scale. This is evidenced by the rising of emissions of GHGs attributed to the built environment despite various local, national, and international initiatives (IPCC, 2007c, page 391), and by the fact that the built environment causes of global biodiversity decline continue and in some cases are accelerating (MEA, 2005b).

The interlinked issues of climate change and loss of biodiversity are disasters of the greatest magnitude. Each amplifies the impacts of the other and will lead to changes in the ability of many species to exist (Rockstrom et al., 2009). These changes will be felt by all species (human and non-human), everywhere on the planet. As Parmesan (2006) points out, the impacts of climate change have already affected a wide range of species types and whole terrestrial, fresh water and marine ecosystems in all continents and oceans. Climate change and the loss of biodiversity are disasters that humans have understood were coming for relatively long time periods. The same luxury is not given before much less globally serious natural disaster events (in terms of magnitude and time scale) such as earthquakes, tsunamis, tornados, and hurricanes. This affords an important opportunity for humans to prepare for the impacts of climate change and biodiversity health decline and possibly dampen the effects of some of the worst impacts.

Humans have been given notice of potential global temperature increases as a result of the emission of carbon dioxide since 1896 through the work of Swedish Chemist Svante Arrhenius (1896). He calculated a doubling of atmospheric concentrations of carbon dioxide (based on 1890 levels) due to industrial emissions would result in average global temperature increases of 5°C (Hamblyn, 2009). Numerous other researchers and scientists have since added to and refined these conclusions²⁵⁵. Various ‘canaries in the coal mine’²⁵⁶ have also ceased to sing indicating that something is wrong with climate and biodiversity. For example: rapid declines in amphibian numbers were reported in the late 1980s and frogs became an early symbol of the impacts of climate change on biodiversity (Kerby et al., 2010); declines in polar bear numbers elevated them in the 1990s to a widely recognised emblem of the effects of climate change (Slocum, 2004); while disappearances and changes in Arctic and Antarctic ice are often used as a warning of global changes in climate.

In a similar way to climate change, the understanding that global biodiversity health is in decline is not new. Although early works such as Norman Meyer’s ‘Sinking Arc’

²⁵⁵ For a summary of the history of climate change science see: Hamblyn, (2009) and Le Treut et al. (2007).

²⁵⁶ The ‘canary in the coal mine’ metaphor represents ‘*individualised instances of warning signs or wake-up calls, that alert [people] to the presence of wider perils, analogous to the caged birds that were taken into British coal pits until the closures of the mid-1980s*’ (Hamblyn, 2009).

(1979) were criticised for being based on controversial research methodologies (Mann, 1991), warnings of a global biodiversity crisis have been given by scientists for more than forty years (McNeely 1992).

Notice of the converging crises of climate change and the decline of biodiversity does not seem to have spurred humans into action to prevent them. In fact Hamilton (2009) points out that:

‘The world’s top climate scientists are now ringing the alarm bell at a deafening volume because the time to act has virtually passed, yet it is as if the frequency of the chime is beyond the threshold of human hearing’.

If such warnings are ever to cause rapid and wide-spread change in the behaviour that causes global environmental problems, perhaps change must first occur in humanity’s psychological environment. Mind-sets and value systems may need to become aware of humanity’s complete dependence on ecosystems for survival, understand the worth of ecosystems and the relationships between the organisms that create them, and be more sympathetic towards the plight of other species that inhabit the Earth.

6.2 A SYSTEM NEAR COLLAPSE AND RAPID CHANGE (WHY THE SITUATION MUST CHANGE AND HOW TO GO ABOUT IT)

This thesis is not about why people and the institutions of society do not act to address environmental issues that threaten humanity (see: Hamilton 2010a, 2010b, 2009, Hulme 2009). Nor it is about the causes of this behaviour that seem to be the antithesis of one of the main drivers of ecosystem processes, which is that living entities usually work to stay alive (section 3.5.1.2). However, one of the main conclusions reached in this research is that the social context that causes many of the environmental issues humans are facing (i.e. the domination of the economic theory of capitalism that requires infinitely increasing economic growth fuelled by increased resource and energy use) is also a barrier to changes being made to address the negative environmental and social outcomes of that same system

(Jamieson, 1992, Balakrishnan et al., 2003, Wilkinson and Reed, 2007). This is because decisions based on ethical imperatives, even if in the best interest of humans as a species, are often not rewarded financially, and so in this system are discriminated against (Balakrishnan et al., 2003). The current financial system is also biased towards short term decision making to maximise profits (Hope, 2011) and so is often incompatible with long term goals of maintaining ecological health. Balakrishnan et al. (2003) state:

'Unlike the current system, where the emphasis on capital... allows for a short term and narrow focus on quarterly balance sheets and fluctuating stock prices, the impact of decisions made in terms of human and ecological interests cannot be appreciated or evaluated in the short term. Such decision-making militates against ecological sustainability because life... cannot be analysed in terms of quarterly reports'.

Capitalism in its current form does not take account of the value of ecosystem services (particularly supporting and regulating services (TEEB, 2011b, 2011a, TEEB Foundations, 2010, TEEB in Business, 2011, TEEB in Local Policy, 2011) or the value of species that make up ecosystems beyond their ability to provide resources for human endeavours (Hawken et al., 1999). Nor can it respond adequately to problems such as climate change through typical market adjustment mechanisms because climate change is global in scale, and is driven not by an individual that can be punished through market mechanisms, but by the collective behaviour of humans, predominantly in affluent countries (Jamieson, 1992, Hawken et al. 1999, Wolch et al. 1995).

The current system of industrialised trade and economic institutions based on the theory of capitalism may not be in a healthy state globally. This is evidenced by the 2007/8 global 'financial crisis' and its on-going repercussions (Crotty, 2009, Morgan et al., 2011), by citizen dissent regarding growing social and economic inequality and environmental degradation (Dube and Kaplan, 2012, Hawken, 2007, Rogoff, 2011), by increasing global scarcity of some resources (Heinberg, 2007, Aguilar-Millan et al., 2010), by the impacts of the system that are increasingly intolerable to people

and other species on the planet including climate change (Clark and York, 2005), and the on-going loss of biodiversity (Brockington and Duffy, 2011).

Hope (2011) points out that various problems with the current system are *'not apparent to finance sector participants or their acolytes, because they inhabit a world in which calculable risks obscure future uncertainties'*. Not all researchers agree that capitalism may change substantially in the near future, though many are highly critical of it in its current form (Barton 2011). Barton (2011, page 1) asserts that many business and government leaders *'share the belief that capitalism has been and can continue to be the greatest engine of prosperity ever devised'*, but that it must change fundamentally to a new kind of 'long term' capitalism. Morgan et al. (2011) observe that the 'financial crisis' of 2007/8 seems to have become several crises of individual state budgets bought about in part by large private sector bail out packages that *'once again [raise financial markets] to the status of omniscient and implacable forces of inevitable... economic logics'*, and that the impacts of problems with state government budgets are felt most profoundly by poorer people. Rogoff (2011) discusses that the only viable replacements for the current dominant 'Anglo-American' form of capitalism are other forms of capitalism and believes the problems of the system can be overcome. Meltzer (2012) defends capitalism, asserting it is *'the only system that achieves both economic growth and individual freedom, and it adapts to the many diverse cultures in the world'*. Aside from ecological sustainability issues caused by capitalism (Clark and York, 2005), a critique of the problems inherent in infinitely increasing economic growth and profit (Turner, 2008, Clark and York, 2005), the marginalisation of the majority of humans who are not wealthy, and the negative impacts of globalisation in the current economic system on various cultures (Hope, 2011, Morgan et al., 2011) does not seem to have occurred and the capitalist optimists still exist.

What emerges from the debate is that climate change and loss of biodiversity are not technical problems that can easily be solved by tinkering with established industrialised trade practices (Clark and York, 2005). Rather they require a re-examination of the underlying values of that system (Jamieson, 1992). The necessary change will not occur through experimenting with new technologies within this same system (Mitchell, 2012, Hamilton, 2010b, Rogoff, 2011, Clark and York,

2005) or even by rebuilding the entire built environment. It is unlikely that there is the time, ability of the biosphere to absorb the impacts, or the physical resources (including affordable and easily accessible energy) to rebuild the built environment before the impacts of climate change become more frequent and extreme. The problems this will cause for humans will be compounded by the continued decline in global biodiversity, changes in the global financial situation, and an expanding and more energy and resource demanding human population (Turner 2008, George 2010, Gills 2010a, Gills 2010b).

Despite a rapid increase since the late 1990s in the number of 'high performance green' building projects²⁵⁷ (Kibert, 2004, Yudelson, 2008) such buildings still are the minority among new construction projects, and as Kibert (2007) points out regarding increasing the sustainability of buildings, *'progress has been made but the difficult problems remain unsolved'*. The United States is considered to be a leader in 'green' building due to the success of the United States Green Building Council which continues to record exponential growth in national LEED certified²⁵⁸ projects (Yudelson, 2008). However, the value of this rating tool in really changing the system is questionable, since LEED is market driven (Cole 2000). Additionally, the 32 246 certified projects by April 2012 since the inception of the US Green Building Council in 1993 (U.S. Green Building Council, 2012) still only accounts for approximately 0.02% of all buildings in the United States and approximately 1.6% of the number of new buildings constructed per year (United States Census Bureau, 2011, United States Environmental Protection Authority 2009). Transformation of the building industry does not appear to be happening fast enough (Kibert, 2007).

²⁵⁷ The increase in high performance green building has occurred according to Kibert (2004) because of the beneficial economic outcomes and increased health of users of green buildings compared to conventional ones, and because green buildings *'are the ethical response to both global and local environmental and resource issues [and are] the 'right' way to approach construction'*. This last point is debatable given that even high performance green buildings still typically result in damage to ecosystems and climate, even if at reduced rates (Reed, 2007). The rise in world green building activity is commonly attributed in part to the global Green Building Council movement and use of various building rating tools such as the US Green Building Council's LEED, The UK's BREEAM, Green Star in Australia and New Zealand, and CASBEE in Japan (Yudelson, 2008, Cole, 2005). The merits of such tools have attracted critique and debate (Kibert 2007, Cole 2005 and Haapio and Viitaniemi 2008).

²⁵⁸ LEED stands for: Leadership in Energy and Environmental Design, see the US Green Building Council Website: www.usgbc.org.

Change may need to be initiated through the adoption of new mind-sets and goals for how built environments could be adapted to function in a way more conducive to the regeneration of ecosystems. This is because humans are dependent upon the continuation of ecosystems for the provision of ecosystem services and in fact for survival (MEA, 2005b). More healthy ecosystems may also lead to more resilience in the face of negative impacts of climate change and therefore lessen its impact on humans (Chapin et al., 2000, Rands et al., 2010). Coupled with this, a re-evaluation of typical lifestyles in industrialised nations, consumption patterns (Rees, 2003, Vale and Vale, 2009), and the framework for assigning value to ecosystems and the life within them (TEEB Foundations, 2010), needs to lead to tangible and large scale behaviour change among individuals, governments, corporations, and economic institutions.

The problem with urban environments is not that humans lack an understanding of the negative ecological impact of current collective societal behaviour, or an understanding of how they must change, or that technology to enable humans to live in cities that mimic the regenerative capacity of ecosystems is not already developed. The fact is that humans continue to damage the very thing that sustains them: ecosystems. As Baskin (1998, page 233) points out:

'It's time to complement our sense of obligation as stewards of the earth with a somewhat humbler sense of self preservation, to acknowledge that despite our increasing estrangement from nature, even urban societies are profoundly dependent on it. Self-preservation is no substitute for ethics, but it's a strong companion...'

Rather than another new green design methodology, what may be needed is a way to enable people to see the relationship between themselves and the other species on the planet differently (Mathews, 2011). Such a change in relationship might enable people to value and understand ecosystems (Wolch et al., 1995) and ultimately to act to regenerate them. The basis of this research is that the regenerative design approach is useful in this regard because while aiming to return ecosystem health to levels where ecosystems thrive and are self-managing, it also challenges traditional human – nature relationships because of its dual focus on

human (physical, societal and cultural) health as an aspect of ecosystem health (Reed, 2007, Mang and Reed, 2012b, du Plessis, 2012, Cole et al., 2012, Cole, 2012b, Busby et al., 2011). Ecosystem based biomimicry may also have the ability to challenge human - nature relationships. This is because trying to understand ecosystems as an exemplar of effective organisation of life, rather than how to best extract resources from them for human needs and desires, requires that people reassess the value and status of ecosystems within a human framework of perception (Mathews, 2011).

Ecosystem based biomimicry has been examined here for its potential in determining practical regenerative environmental performance goals for existing urban environments, based on quantifiable metrics defined by the physical reality of a specific place using the reference point of an actual ecosystem, rather than other human activities or political compromises. If investigated in the same way as an ecosystem, an urban environment and the buildings within it could be designed or altered to produce, to some extent: energy, water, and food; to cycle nutrients (materials); to clean air, water, and soil; to store and sequester carbon; and to provide habitat. The initial assumption made in this research was that an urban environment that is part of a larger system and is able to function like an ecosystem in its creation, use and eventual end of life, could potentially move towards becoming regenerative (Van der Ryn, 2005; Reed, 2007).

Rather than advocating sets of new and untested technologies or construction methods, regenerative design that incorporates an understanding of ecosystems, allows for a re-organisation of existing design methods and technologies and a reorientation of performance goals (chapters three and four).

6.3 SIGNS OF REGENERATION. A SINGLE SEED (THE CONTRIBUTION TO KNOWLEDGE)

The negative impacts of a degraded biosphere faced by humanity because of its own actions are huge (Schneider, 2009). The task of understanding how best to alter what is left is challenging and complex. The effort required to change physical and

psychological infrastructure within the time frame left is immense (Hamilton, 2010b). The results will be uncertain. It is possible that there is not much of great consequence that can be done at this late hour without a global revolution of thinking and control (Hamilton, 2009). Nevertheless these difficulties pale into insignificance when facing the consequences of continuing on a 'business as usual' pathway for humans living on this planet (Stern, 2006), and in the context of this research, in urban environments. Voluntary change is difficult but change will be even more painful and devastating without any preparation (IPCC, 2007b, page 360) in the face of famine, drought, storm damage, scarcity of resources, and disease, all of which will challenge the ability of the structures of society to continue, and could be caused by climate change, decline in biodiversity health and other converging global environmental issues (Gills, 2010).

This research is based on the optimistic and as yet unproven assumption there is time, ability, and will to make the necessary changes to ameliorate some of the worst impacts of climate change and loss of biodiversity. It offers a different way of perceiving the built environment, of measuring its performance and of relating to ecosystems around and within it. It is only the beginning of exploration into such ideas. It builds upon the works of other researchers and sits alongside parallel investigations seeking a different way forward in response to environmental issues discussed throughout the thesis. The research presented here is not designed to provide comprehensive solutions to all issues discussed but, more humbly, is intended to plant a seed that may enable a transformation in human psychology to occur in the context of urban and architectural design. It may prove to be an inconsequential attempt given the scale of change that is needed, but this thesis has answered the research questions it set out to investigate in each chapter and has resulted in some key findings that could be built upon in the future. Table 17 summarises the findings of the research relative to the initial questions posed (chapter one). More detailed conclusions for each part of the research are found in the concluding sections of each chapter. Findings listed in table 17 are expanded upon and argued, and broader conclusions and observations resulting from the research as a whole are discussed below.

TABLE 17 SUMMARY OF RESEARCH QUESTIONS AND FINDINGS

Research questions	Findings
Chapter One	
What are the potential impacts of climate change and the decline of biodiversity health on urban built environments, and how does the built environment contribute to these issues?	<ul style="list-style-type: none"> The impacts of climate change are summarised in table 1 (direct impacts) and table 2 (indirect impacts) (section 1.3.1, pages 17 and 23). The impacts of the decline of biodiversity health are summarised in table 3 (section 1.4.1, page 42). The built environment contributes substantially to both climate change and the decline in biodiversity health through construction and demolition practices, through buildings being high energy users, through its form in terms of vehicle use, land transformation, habitat fragmentation, and pollution (sections 1.3 and 1.4, pages 14 to 50).
What are the possible responses to these issues using the medium of the built environment as an agent of positive change?	<ul style="list-style-type: none"> Typical responses to climate change in the built environment are either to mitigate the causes or adapt to the impacts. It is important to understand the relationship between mitigation and adaptation strategies to ensure that they do not conflict (section 1.3.2, pages 30 to 38). Typical responses to the decline of biodiversity in the urban environment are: to conserve remnant ecosystems or species; to provide connections between remnant habitats to reduce fragmentation; to restore degraded ecosystems; and to manage urban vegetation and/or structure to increase biodiversity (section 1.4.2, pages 45 to 50). It is important to ensure that responses to climate change and to the loss of biodiversity health are compatible because there is a positive feedback loop between climate change and the decline of biodiversity (section 1.5 and 1.6, pages 51 to 55). Regenerative design (in terms of ecosystem health) may be one strategy that utilises synergies between responding to climate change and responding to biodiversity issues (section 1.6.1, page 55). Mimicking the living could contribute to regenerative design strategies, but needs to be investigated further (section 1.6.2, page 61).
Chapter Two	
Is mimicking the living world a potentially useful strategy to employ in increasing the regenerative potential of the built environment as a response to climate change and loss of biodiversity? If so, in what way?	<ul style="list-style-type: none"> It appears most biomimicry is used to develop innovative technologies that do not produce better environmental outcomes as a way to increase financial profits. Some biomimicry is devised to increase environmental sustainability outcomes. Confusion between these two main kinds of biomimicry can lead to accusations of 'green-washing' (sections: 2.2.2, page 76 and 2.2.4, page 85). There are some drawbacks to using biomimicry in a design context (section 2.3, page 91). Biomimicry is in general poorly defined for practical application in a built environment design context. A framework for understanding different types of biomimicry was developed and illustrates that there are three levels of biomimicry: organism, behaviour and ecosystem (table 4 and section 2.5, pages 104 to 108). Several examples of biomimetic concepts, strategies or technologies that address the mitigation of the causes of climate change or work to adapt to its impacts, and work to restore ecosystem health exist (section 2.6, pages 109 to 119). Ecosystem based biomimicry may have the most beneficial outcomes in terms of improving environmental performance over the long term, particularly if the processes or functions of ecosystems are mimicked.
Chapter Three	
How can generalised ecosystem processes be understood and presented so they are relevant for a built environment context?	<ul style="list-style-type: none"> Ecology literature typically does not offer sets of generalised principles of how ecosystems work but tends to explore the complexities of certain aspects of ecosystems. Descriptions of the processes of ecosystems that exist are varied in their format (sections: 3.3 and 3.4, pages 148 to 170, and appendix 2, page 409). A comparative analysis was conducted (section 3.4.1, page 150) and a set of ecosystem processes devised (table 5, page 151). Descriptions of each ecosystem service are given in section 3.5, pages 171 to 210.
What relationships exist between each ecosystem process and how does understanding these aid in the employment of relating ecosystem processes to the built environment?	<ul style="list-style-type: none"> Typical sets of ecosystem processes are represented in a list format, however examining the relationships between processes proved to be an ordering mechanism for them, and for understanding how to use knowledge of ecosystem processes in a design context (sections 3.4.2 and 3.4.3, pages 152 to 171). An ecosystem processes relationship matrix in a nested hierarchical format was devised (figure 34, page 159). Features of ecosystems that make them resilient and adaptable could be useful in the context of adapting to climate change. These are illustrated in figure 59, page 211. Aspects of the processes of ecosystems that could add to strategies to mitigate the causes of climate change and address loss of biodiversity relate to the fact that ecosystems enhance the capacity of the biosphere to support life, and functioning and processes in ecosystems and within organisms tend to be benign. Processes that contribute to this are represented in figure 60, page 212. Figures 59 and 60 illustrate how an understanding of the relationships between ecosystem processes can be used in a design context. Strategies for applying ecosystem process to a built environment context are summarised in table 7, page 214.

Chapter Four	
How can generalised ecosystem functions / services be understood and presented so they are relevant for a built environment context?	<ul style="list-style-type: none"> The services of ecosystems are less controversial than the processes of ecosystems (section 4.2, page 221). Ecosystem services are easier to understand and organise than the processes of ecosystems. Ecosystem services could be used as the basis of ecosystem based biomimicry at the function level in relation to a built environment context (section 4.3, page 226). A list and a relationship matrix diagram of ecosystem services were devised (section 4.3, table 8, page 228 and figure 63, page 232). Understanding the relationships between ecosystem services can illustrate where related bundles of services can be provided by single interventions. Descriptions of each ecosystem service are given in section 4.4, pages 236 to 251.
Where are the key places to intervene in the built environment in terms of ecosystem services for maximum benefit when working with development goals that seek to regenerate ecosystems and address the causes and impacts of climate change and biodiversity loss?	<ul style="list-style-type: none"> Key places to intervene in a built environment context were examined in section 4.5.2, pages 252 to 264. The initially defined 26 ecosystem services (table 8, page 228) were refined through a three tiered ranking exercise into 7 sets of key ecosystems services that may be most suitable for use in a built environment context. These are: provision of habitat; climate regulation; purification; nutrient cycling; provision of fresh water; provision of fuel/energy; and provision of food. The results of the ranking exercise are summarised in table 9, page 263 along with potential implications for responding to climate change and a loss of biodiversity. Potential starting points for beginning a process of ecosystem service based design are summarised in section 4.5.3, pages 265 to 268. Various benefits and difficulties exist to utilising the concept of ecosystem services in a design context (section 4.7, pages 269 to 271).
Chapter Five	
In what way are the theoretical underpinnings of an ecosystem based strategy for built environment design as devised in chapters three and four useful as a practical evaluation and design goal setting tool in existing urban environments?	<ul style="list-style-type: none"> Using an understanding of ecosystem services in relation to regenerative design may be more beneficial than employing an understanding of ecosystem processes because the focus is shifted from how to design to the outcomes of design. This means measurable goals can be devised for the built environment that are based in ecological reality rather than design metaphors (section 5.1, pages 274 to 279). Being able to measure aspects of regenerative design may also be useful in enabling the concept to have more scientific credibility. Care should be taken not to neglect the holistic and more qualitative aspects of regenerative design. A case study of an existing built environment (Wellington in New Zealand) was conducted to test the concepts generated earlier in the thesis (section: 5.3, pages 290 to 360). A summary of the findings from this case study including ecosystem services analysis devised goals for the future relative to the current situation is found in section 5.5, pages 371 to 382, and figures 113, 114, and 115 (pages 375 to 377). The case study illustrates that while the idea of regenerative urban environments relating to ecological performance is appealing, making this a reality is likely to be very difficult in the near future in Wellington and generally. Adopting regenerative ecosystem service analysis devised goals could improve the relationship between urban environments and ecosystems and have beneficial ecological outcomes. Determining goals based on the ecological reality of a specific place using an understanding of how a functioning ecosystem works or worked in the same location may be a helpful step in working out how to achieve such goals.
In what way does analysing relationships between ecosystem services relevant to a built environment context aid in employing such a strategy?	<ul style="list-style-type: none"> An analysis of relationships between each ecosystem service in the context of the case study reveals that some services are mutually supporting, some are supportive of other services on one direction and others have potentially antagonistic relationships (figure 104, page 361). This indicates that one ecosystem service should not be considered in isolation if unintentional damage to other services is to be avoided. Understanding the relationships between the services illustrated where additional benefits may arise from focusing on certain services. The provision of habitat and the service of purification appear to have the most mutually beneficial or supportive relationships to other services. The provisioning services seem to have the most potential for conflict. Geographic mapping techniques may be useful to resolve conflicts and illustrate how certain services may be able co-exist without competing (figure 112, page 370).

While the philosophical basis of regenerative design would appear to be a logical goal for development as set out in chapter one, the fact remains that it is difficult to find successful built examples or guidance about how to begin and work through a regenerative design process. A potential starting point for regenerative design in terms of increasing ecological health is needed and with this aim an investigation of whether mimicking organisms or ecosystems (biomimicry) could be useful was conducted. This is because organisms solve many of the same design problems that humans face in ways that are often (but not always) more effective than human solutions and in many cases outperform what humans are currently able to do (Pawlyn, 2011, page 114, Vincent et al., 2006). Ecosystems remain the best example of effective organisation of life on the planet and so would logically be a good model for reorganising how people live, particularly in urban environments (Cohen, 2003).

To examine biomimicry's potential effectiveness or failure as a suitable response to climate change, loss of biodiversity and general improvement of environmental performance in the built environment, it was first necessary to define biomimicry and determine the different kinds that exist and their potential to contribute to regenerative outcomes in an urban context. The results of this exercise as detailed in chapter two show that biomimicry is typically exemplified by products that mimic part of a single organism and very different motivations behind the process of biomimicry exist, leading to different environmental performance incomes. The majority of biomimicry seems to be for technical innovation rather than to increase the environmental performance of products, technologies or the built environment. Although some notable exceptions exist, as evidenced in the series of case studies of biomimetic technologies that mimic single organisms and contribute to mitigating or adapting to climate and biodiversity changes (section 2.6), the kind of biomimicry with the most potential to contribute to regenerative built environments was found to be the mimicry of ecosystems, particularly at the function level. Adapting the concept of ecosystem services to a design context proved to be a useful way to begin the research process.

As determined in chapter three, the mimicry of the processes of ecosystems is the most common manifestation of trying to mimic ecosystems found in the literature.

Defining the processes of ecosystems in more detail, specifically for a built environment context, and then using this as a basis for quantitative measures of environmental performance proved to be a complex and cumbersome exercise, and would probably result in design based on the metaphor of an ecosystem rather than the reality of what ecosystems do.

The research has defined and provided a practical example of what regenerative development could mean in terms of ecosystem health, and how it could be applied to an urban setting. Chapters four and five demonstrate how the concept of ecosystem services can be applied to a built environment context so that an understanding of ecosystems goes beyond simple analogies and determines quantifiable and tangible performance goals. Seven key ecosystem services (provision of food, provision of fuel/energy, provision of water, purification, climate regulation, nutrient cycling and the provision of habitat) may be most suitable for a built environment context, and the provision of habitat has the most mutually supportive relationships with other ecosystem services. It would be useful in the course of future research to determine if this list of services remains the same in different climatic or cultural contexts, and how to order such a list for specific sites in terms of services that are the easiest to mimic in the built environment and those that have the most beneficial ecological and/or climatic outcomes.

In attempting to examine if urban environments could address the causes and impacts of climate change and biodiversity loss concurrently, this research took a unique approach in that it examined relationships between environmental problems (specifically climate change and negative changes in global biodiversity), the drivers of these problems (focusing on the medium of the built environment), solutions to these problems (to harness synergistic relationships and avoid antagonistic ones) and, more specifically, ecosystem processes and then ecosystem services. This relationship analysis led to some important practical understandings about how to apply ecosystem services to an urban context. In chapters three, four and five, analysing the relationships between ecosystem processes and services added to an understanding of how knowledge of ecosystems can be employed in design processes, so solutions contribute to solving multiple environmental issues rather

than reducing the drivers of one kind of negative environmental change by adding to the causes of another.

The case study of Wellington New Zealand, attempted to apply the concept of ecosystem based biomimicry at the function level to a real world situation. It indicated that for Wellington the concept of regenerative design does have some merit, but addressing the issues of climate regulation, provision of habitat, and provision of food will be extremely difficult in typical urban contexts. This suggests that regenerative development is worth pursuing though because tangible results, particularly in terms of the provision of water and fuel/energy and, to a lesser extent, in purification and nutrient cycling may be possible, given current consumption patterns and the physical make-up of the city. Although there appears to be regenerative capability for the urban environment to produce more than 100% of the original ecosystem's service capacity only in the ecosystem service of provision of fuel/energy in Wellington, increases in the capacity of urban environments to provide some of their own services or to source these from local ecosystems would mean more distant ecosystems may be under less pressure to provide these ecosystem services. This could shrink an urban area's ecological footprint and lead to increased ecosystem health outside the urban boundary.

6.4 MUTATIONS

(COMPLICATIONS, CONTROVERSIES, AND LIMITS OF THE FINDINGS)

The findings of the case study in chapter five point to the fact the ideal of completely regenerative built environments does not seem to be at present physically possible. without tremendous change for the people living within urban environments across many aspects of lifestyle. Even with substantial changes in consumption patterns and behaviour, transforming an existing urban environment into a truly regenerative one seems to be a very difficult, if not impossible goal to achieve. Similar conclusions about the seemingly impossible task of cities in their current form becoming 'sustainable', without reliance on rural hinterlands, has been reached by other researchers using different methods (Rees and Wackernagel, 1996, McGranahan et al., 2005). A re-imagining of diet, transportation, energy use,

materials use in the built environment, how materials (including green waste) are disposed of, how water is cleaned and transported, how and which chemicals are used, and how space is utilised and shared within a city, would need to occur in the short term for cities to become even close to being regenerative. Many of the decisions about living in an urban environment sustainably will in the future be determined by physical environmental or resource constraints, or by political means (legislation, taxation, or war). Until then most changes may have to be voluntary and rely on a changing governmental, corporate and public moral compass (Kibert, 2007, Lützkendorf and Lorenz, 2007). As discussed, the current dominant economic system means this is likely to be an impossible task (Hope, 2011). Without changes in regulations or policies that govern decision making processes that affect ecosystem services, tangible progress towards improving ecosystem health may be difficult to achieve (Kibert, 2007).

Unless clear targets to improve ecosystem health are set, the highly economically competitive nature of built environment development and design (Hunt, 2004), may mean actions to regenerate ecosystems in this context remain voluntary and dependent upon the 'goodwill' of designers and developers²⁵⁹. This reliance on goodwill, combined with the fact it is difficult to understand the complexity of ecosystems and the nature of their public good (Costanza et al., 1997), and the failure of capitalism to value these public goods (Rogoff, 2011), means it is currently difficult to achieve a level of protection of ecosystem services that would enable them to function at an optimal level. Regenerative developments may, therefore, remain uncommon and not be truly effective beyond isolated cases at small scales within current society. Until such wider issues are addressed restoration of degraded ecosystems to either a level of basic operation or improved health through design interventions is to be encouraged.

²⁵⁹ The idea of 'goodwill', or doing something for ethical purposes (such as building a regenerative development) is selected against in the capitalist model if it leads to extra financial cost or any loss in profits (Wilkinson and Reed, 2007). This means for successful developers under a capitalist model, examples of the practical application of 'goodwill' may be difficult to find (Wolch et al., 1995, Lützkendorf and Lorenz, 2007, Wilkinson and Reed, 2007).

6.5 SUCCESSION, FEEDBACK LOOPS AND MATURATION (IMPLICATIONS OF THE RESEARCH ON ARCHITECTURAL AND URBAN DESIGN)

If ecosystems rather than industrial processes and machines became the philosophical design metaphor and practical metric for architectural and urban design, the built environment would be considered less as a collection of distinct buildings that behave like objects in an arbitrary landscape, but rather as nodes in a complex, cyclic system where they become producers and distributors of energy, nutrients (materials), food, and water, or filters and remediators of past pollution. This is in direct contrast to the current status of the built environment as a heavy consumer and polluter (Newman, 2006).

Such an approach would ultimately be rooted in the design team having a deep understanding of the climatic and cultural context of the site, as well as the local ecology and concept of ecosystem services. Increased collaboration between fields that seldom work together, such as architectural and urban design and ecology, would be required (Wahl, 2006). Even with increased collaboration, achieving success in such an approach may be dependent on design professionals understanding basic concepts of ecology and ecologists understanding basic design. Only then perhaps will designs based on ecosystem principles transcend the level of metaphor and incorporate a 'deeper' form of biomimicry (Mathews, 2011), able to imbue urban environments with the ability to become a functioning part of ecosystems.

The creation of regenerative built environments must be considered as a process continually evolving over time. This lends itself to the phasing of targets for the regeneration of ecosystem services, allowing planners, designers, and decision makers to focus first on the 'low hanging fruit' (ecosystem services that are most easy to address) and, in the process, learn about the use of ecosystem services analysis to the greatest effect. Examining in more depth how ecosystem services analysis fits in with the wider aspirations of regenerative design would ensure

potential synergies could be harnessed between the ecological benefits and social benefits of such an approach.

6.6 EVOLUTION (EXTENDING THE RESEARCH)

During the final stages of this research the author become aware of the work of Professor Janis Birkeland (Birkeland, 2008, Birkeland, 2009) who advocates design for 'eco-services' (ecosystem goods and services) as the basis for 'positive development' (meaning the ecological base of a place is larger and more resilient after construction than before). Birkeland is careful to distinguish this concept from 'regenerative design' claiming that regenerative design means any slight improvement of ecosystem health (Birkeland, 2009), rather than the full return of ecosystems to a pre-development state, so they are self-sustaining, thriving, becoming more healthy, and generating increased capacity for life to exist without human intervention. This latter definition of ecosystem health is more aligned to the group of researchers exploring regenerative design that authored a special issue of the Building Research and Information Journal in January of 2012 (Volume 40, issue 1). The concept of positive development appears to have overlaps with concepts presented in this thesis. Birkeland relates the addition of individual building technologies to achieving better environmental performance outcomes such as: Todd's Living Machines to purify sewage and water ways (Todd et al., 2003); green roofs to purify air; 'algaetecture' to produce oxygen and biofuels (Pike, 2008, Birkeland, 2009); and 'green scaffolding' to clean air, increase length of building life and contribute to other ecosystem services such as provision of food and fuel (Birkeland, 2009). Her research shares with this thesis a call for a shift in thinking about the built environment (Birkeland, 2008, page xi). This body of research may be an additional source for designers wanting to take the ideas described in this thesis forward in practice therefore.

While this thesis provides an argument for why an understanding of ecosystems is useful in creating or retrofitting urban built environments so they can move towards becoming regenerative, a series of theoretical case studies illustrating how the

ecosystem based concepts described in this thesis can be applied to urban contexts in different climates and social contexts would strengthen the initial findings. These additional urban analyses would serve to define with more certainty the ecosystem services that could be applied to a built environment and the order in which they should be attempted. This would enable research that builds upon the idea of ecological performance goals for specific urban locations indicated in this thesis, to determine how to practically implement regenerative design based on these goals. A focus on lifecycle considerations will be of great importance so that overall ecological outcomes are positive over the long term. Determining practical regenerative design guidelines, benchmarks, and processes would be aided by an increase in regenerative development and design examples. Creating new or finding additional existing demonstration examples of regenerative design would be useful in this regard.

One of the findings of chapter five was that some ecosystem services appear to be in competition with others in an urban context in terms of available space. The provision of food and the provision of habitat are the obvious examples of this. While a simple spatial analysis to resolve the conflict for space between the two services was attempted (section 5.4.1), further examination of and experimentation with ecosystem and urban spatial analysis tools and methodologies would be useful. These could reveal how to determine where ecosystem services could or should occur in a given location and where their provision could overlap spatially and where separations must be made. This may be the next step in the process of determining how to go about creating regenerative urban environments that use an understanding of ecosystem services as their basis for environmental performance goals.

Finally, it should be remembered that although this thesis has primarily focused on the non-human ecological health side of regenerative development, a whole-systems regenerative approach to built environment design acknowledges that human developments and humans are not separate from the living. This research could be extended, therefore, by a complementary examination of how to determine tangible (possibly qualitative rather than quantitative) community regeneration goals. An analysis of the relationships between goals for ecosystem regeneration and

community regeneration may reveal many of these goals are either similar, or can be achieved by similar methods. This is because humans are a part of ecosystems, influence them profoundly, and are entirely dependent upon them. Synergies revealed between the goals of regenerating community and ecological health would help to articulate more clearly how to begin a holistic process of regenerative development and determine if it has been successful, so that methodologies and outcomes can be improved over time.

6.7 REFLECTION, RECONFIGURATION, REINCARNATION (CONCLUSION)

Although there are draw backs to a regenerative adaptation of the built environment and such a concept may not be able to address all urban environmental issues, it appears to be a suitable solution for a longer term response to climate change impacts and loss of biodiversity, because it starts to address many of the underlying issues with current urban environments that are in need of re-evaluation (Grimm et al., 2008, Wahl and Baxter, 2008a). The difference can be likened to the long term treatment of the underlying cause of an illness, rather than the short term treatment of symptoms which may aggravate the underlying condition. In the context of this research, the underlying condition is the fact that the majority of urban settlements are dependent on fossil fuels to heat, feed, and transport people in a linear system which creates pollution, leading to climate change and the decline of biodiversity health. This system also causes the degradation of water ways, air, soil, and human health while using non-renewable resources in wasteful ways such that they cannot be used again (Rees, 1999, McDonough and Braungart, 2002, page 18).

Ecological regeneration goals for developments can be provided by ecosystem services analysis of a particular place. Simultaneously, mimicking the complex interactions between living organisms comprising ecosystems may be a readily available example to learn from and draw upon to create built environments that could integrate with the habitats of other species in a mutually beneficial way. The creation of regenerative architecture challenges human habitats to give back to rather than just take from ecosystems they are part of. In addressing humanity's

negative environmental impact, it may be possible with such an approach, to create a more liveable and healthy habitat for people, even if truly regenerative urban environments may not be currently possible. Perhaps more importantly, it has the potential to be part of a survival strategy, given the impending and inevitable impacts of global climate change and the on-going decline of the health of planetary biodiversity.

APPENDICES:

APPENDIX ONE: MAIN FEATURES OF NEW ZEALAND CLIMATE CHANGE PROJECTIONS FOR 2040 AND 2090

TABLE 18 CLIMATE CHANGE IMPACTS ON NEW ZEALAND (ADAPTED FROM: MULLAN ET AL., 2008, PAGE 13).

Climate variable	Direction of change	Magnitude of change	Spatial and seasonal variation
Mean temperature	Increase (****)	All-scenario average 0.9°C by 2040, 2.1°C by 2090 (**)	Least warming in spring season (*)
Daily temperature extremes (frosts, hot days)	Fewer cold temperatures and frosts (****), more high temperature episodes (****)	Whole frequency distribution moves right	See: section 2.2.3 of Ministry for the Environment (2008a) for detailed information.
Mean rainfall	Varies around country, and with season. Increases in annual mean expected for Tasman, West Coast, Otago, Southland and Chatham Islands; decreases in annual mean in Northland, Auckland, Gisborne and Hawke's Bay (**)	Substantial variation around the country and with season	Tendency to increase in south and west in the winter and spring (**); to decrease in the western North Island, and increase in Gisborne and Hawke's Bay, in summer and autumn (*)
Extreme rainfall	Heavier and/or more frequent extreme rainfalls (**), especially where mean rainfall increase predicted (***)	No change or up to halving of heavy rainfall return period by 2040; no change or up to fourfold reduction in return period by 2090 (**)	Increases in heavy rainfall most likely in areas where mean rainfall is projected to increase (***)
Snow	Shortened duration of seasonal snow lie (***), rise in snowline (**), decrease in snowfall events (*)		
Wind (average)	Increase in the annual mean westerly component of windflow (**)	About a 10% increase in annual mean westerly component of flow by 2040 and beyond (*)	By 2090, increased mean westerly in winter (>50%) and spring (20%), and decreased westerly in summer and autumn (20%) (*)
Strong winds	Increase in severe wind risk possible (**)	Up to a 10% increase in the strong winds (>10m/s, top 1 percentile) by 2090 (*)	

Storms	More storminess possible		
Sea level	Increase (****)	At least 18–59 cm average rise between 1990 and 2100 (****)	Refer to: Ministry for the Environment (2008b) for more information.
Waves	Increased frequency of heavy swells in regions exposed to prevailing westerlies (**)	Refer to: Ministry for the Environment (2008b) for detailed information.	
Storm surge	Assume storm tide elevation will rise at the same rate as mean sea-level rise (**)	Refer to: Ministry for the Environment (2008b) for detailed information.	
Ocean currents	Various changes plausible, but little research or modelling done	See 2.2.9 of the source report	
Ocean temperature	Increase (****)	Similar to increases in mean air temperature	Patterns close to the coast will be affected by winds, upwelling, and ocean current changes (**)

The degree of confidence placed by Mullan et al. (2008) in the projections is indicated by the number of stars in brackets:

**** **Very confident**, at least 9 out of 10 chance of being correct, meaning it is considered very unlikely that these estimates will be substantially revised as scientific knowledge progresses.

*** **Confident**.

** **Moderate confidence**, meaning it is more likely than not to be correct in terms of indicated direction and approximate magnitude of change.

* **Low confidence**, but the best estimate possible at present, although estimates could be revised in the future.

APPENDIX TWO: ECOSYSTEM PROCESSES COMPARISON

TABLE 19 LISTS OF ECOSYSTEM PRINCIPLES¹

Reap (2005)	Korhonen (2001)	Kibert et al. (2002, page 7)	Kelly (1994)
Life's Characteristics in Relation to Engineering. Conditions Conducive to Life. <ol style="list-style-type: none"> 1. Life Builds from the bottom up 2. Life fits form to function 3. Life depends on water 4. Life is cyclic (processes and recycles materials resources) 5. Life is locally attuned and resourceful 6. Life adapts and evolves 7. Life coexists within a cooperative framework 	Ecosystem Principles. <ol style="list-style-type: none"> 1. Roundput <ul style="list-style-type: none"> -Recycling of Matter -Cascading of energy 2. Diversity <ul style="list-style-type: none"> -Biodiversity -Diversity in species, organisms -Diversity in interdependency and co-operation 3. Locality <ul style="list-style-type: none"> -Utilising local resources -Respecting the local natural limiting factors -Local interdependency, co-operation 4. Gradual Change <ul style="list-style-type: none"> -Evolution using solar energy -Evolution through reproduction -Cyclical time, seasonal time -Slow rates in the development of system diversity 	Natural process are: <ol style="list-style-type: none"> 1. Predominantly cyclic rather than linear 2. Operate by solar flux and organic storages 3. Promote resilience within each range of scales by diversifying the execution of functions into arrays of narrow niches 4. Maintain resilience across all scales by operating functions redundantly over different ranges of scale 5. Promote efficient use of materials by developing cooperative webs of interactions between members of complex communities 6. Sustain sufficient diversity of information and function to adapt and evolve in response to changes in their external environment. 	<ol style="list-style-type: none"> 1. Distribute Being 2. Control from the bottom up 3. Cultivate increasing returns 4. Grow by chunking 5. Maximize the fringes 6. Honour your errors 7. Pursue no optima; have multiple goals 8. Seek persistent disequilibrium 9. Change changes itself
Hoeller (2006)	Hoagland, Dodson, and Hauck (2001)	Hastrich (2006)	Faludi (2005)
Patterns in Nature <ol style="list-style-type: none"> 1. Stable Growth 2. Closed Loop 3. Resilience 4. Feedback 5. Redundancy and diversity 6. Effective no Efficient 7. Something for Nothing 8. Built in Buffers 9. Hierarchical Systems 	Patterns: An Overview of the Basic Concepts of Biology <ol style="list-style-type: none"> 1. Life builds from the bottom up 2. Life assembles itself into chains 3. Life needs an inside and an outside 4. Life uses a few themes to generate many variations 5. Life organizes with information 6. Life encourages variety by recombining information 7. Life creates with mistakes 	Life's Principles <ol style="list-style-type: none"> 1. Is the design Modular / segmented? 2. Is it built to shape? 3. Does it use self-assembly? 4. Is shape designed to minimize material? 5. Is it optimized rather than maximized? 6. What role does water play? 7. Is the design cyclic, does it adapt to cycles? 8. Does it use recycled materials? 9. Is it recyclable? 	<ol style="list-style-type: none"> 1. Waste is food 2. Self-assemble from the ground up 3. Evolve solutions, don't plan them 4. Relentlessly adjust to the here and now 5. Cooperate and compete, not just one or the other 6. Diversify to fill every niche 7. Gather energy and materials efficiently 8. Optimise system rather than maximising components

¹ Not all sources used discrete lists of strategies or principles.

Hoeller (2006) cont...	Hoagland, Dodson, and Hauck (2001) cont...	Hastrich (2006) cont...	Faludi (2005) cont...
10. Distributed Systems 11. Imbedded Information 12. Do more with Less 13. Surface Folding 14. Smart Materials 15. Symbiosis 16. Cascade of messages 17. Adaptation	8. Life occurs in water 9. Life runs on sugar 10. Life works in cycles 11. Life recycles everything it uses 12. Life maintains itself by turnover 13. Life tends to optimize rather than maximize 14. Life is opportunistic 15. Life competes within a cooperative framework 16. Life is interconnected and interdependent	10. Is the design locally attuned? 11. Does its manufacture use free energy? Abundant materials? 12. Can the design detect feedback? Can it adapt? Evolve? 13. Does the design promote appropriate behaviour by users? 14. Is there cross pollination? 15. Does the design embrace diversity and redundancy? 16. Does it use life friendly materials? 17. Is the manufacturing benign? 18. Does the design enhance the biosphere? 19. How does the design coexist? 20. Does the design 'create conditions conducive to life'?	9. The whole is greater than the sum of its parts, design for the swarm (community) 10. Use minimal energy and materials 11. Don't foul the nest 12. Organise fractally 13. Chemical reactions and processes are life friendly
Benyus (1997) 1	Benyus (1997) 2	Dinur (2005)	Berkebile and McLennan (2004)
Nature's Laws, Strategies and Principles 1. Nature runs on sunlight 2. Nature uses only the energy it needs 3. Nature fits form to function 4. Nature recycles everything 5. Nature rewards cooperation 6. Nature banks on diversity 7. Nature depends on local expertise 8. Nature curbs excesses from within 9. Nature taps the power of limits	Ten Commandments of the Redwood Clan 1. Use waste as a resource (Nature recycles everything) 2. Diversify and cooperate to fully use the habitat (nature rewards cooperation) 3. Gather and use energy efficiently (nature uses only the energy it needs) 4. Optimize rather than maximize 5. Use materials sparingly (nature fits form to function) 6. Don't foul your nest 7. Don't draw down resources 8. Remain in balance with the biosphere (nature curbs excesses from within) 9. Run on information 10. Shop locally (Nature demands local expertise)	How Living Systems Function and Develop 1. Emergence 2. Fluctuations 3. Symmetry breaking 4. Dissipation 5. Instability 6. Criticality 7. Interdependence 8. Redundancy 9. Adaptation 10. Complexity 11. Hierarchy The Organisation of Living Systems 1. Fluctuations 2. Stratifications 3. Interdependency	The living building will: 1. Harvest its own energy needs on site 2. Be adapted specifically to site, and climate and built primarily with local materials 3. Operate pollution free and generate no wastes that aren't useful for some other process in the building or immediate environment 4. Promote the health and wellbeing of all inhabitants – consistent with being an ecosystem 5. Be comprised of integrated systems that maximise efficiency and comfort 6. Be beautiful and inspire us to dream

Copeman (2008)	Biomimicry Guild (2007a)	Biomimicry Guild (2007)	Vogel (1998)
Principles of Permaculture <ol style="list-style-type: none"> 1. Relative location 2. Each element performs multiple functions 3. Each function is supported by many elements 4. Energy efficient planning 5. Using biological resources 6. Energy cycling 7. Small-scale intensive systems 8. Natural plant succession and stacking 9. Polyculture and diversity of species 10. Increasing "edge" within a system 11. Observe and replicate natural patterns 12. Pay attention to scale 13. Attitude 	Life's operating parameters: <ul style="list-style-type: none"> • Water based world • Dynamic non-equilibrium • Subject to limits and boundaries <ol style="list-style-type: none"> 1. Life creates conditions conducive to life <ol style="list-style-type: none"> a. Optimising rather than maximising <ol style="list-style-type: none"> i. Using multi-functional design ii. Fitting form to function b. Leveraging interdependence <ol style="list-style-type: none"> i. Recycling all materials ii. Fostering cooperative relationships iii. Self-organising c. Using benign manufacturing <ol style="list-style-type: none"> i. Using life-friendly materials ii. Using water based chemistry iii. Using self-assembly 2. Life adapts and evolves <ol style="list-style-type: none"> a. Resourceful and opportunistic <ol style="list-style-type: none"> i. Shape rather than material ii. Builds from the bottom up iii. Simple building blocks iv. Free energy b. Feedback loops <ol style="list-style-type: none"> i. Antenna, signal and response ii. Learns and imitates c. Integrates cyclic processes <ol style="list-style-type: none"> i. Feedback loops ii. Cross-pollination and mutation d. Resilient <ol style="list-style-type: none"> i. Diverse ii. Decentralised and distributed iii. Redundant 	Successful principles of nature <ol style="list-style-type: none"> 1. Life builds from the bottom-up <ul style="list-style-type: none"> - modular - built to shape (no waste) - self-assembly (natural affinities) 2. Life fits form to function <ul style="list-style-type: none"> - shape is cheaper than material - optimizes rather than maximizes - multi-functionality 3. Life is cyclic (processes) and recycles (material resources) 4. Life is locally attuned and resourceful <ul style="list-style-type: none"> - uses free energy (e.g. sunlight) - abundant materials - detects feedback 5. Life adapts and evolves <ul style="list-style-type: none"> - appropriate behaviour (learning, imitation) - cross-pollinates and mutates - embraces diversity and redundancy 6. Life creates conditions conducive to life <ul style="list-style-type: none"> - life-friendly materials - benign manufacturing - water as solvent - bio-sphere enhancing 7. Life coexists with a cooperative framework <ul style="list-style-type: none"> - interconnected and interdependent <p>Nature works with small feedback loops, constantly learning, adapting and evolving.</p> <p>Evolve designs in repeated steps of observation and development.</p>	Specific technical examples <ul style="list-style-type: none"> • Nature uses fewer flat and more curved surfaces than we do • Ours is a far more rectilinear world while nature shows little bias in favour of right angles • Corners in our technology are abrupt; nature's are often rounded. • Numerous mechanically separate but individual homogenous components make up our devices; nature uses fewer components whose properties vary internally. • Nature's designs take advantage of diffusion, surface tension. And laminar flow; gravity thermal conductivity, and turbulence matter more for ours. • We most often design to a criterion of adequate stiffness, while nature seems more commonly concerned with ample strength. • Partly as a consequence, our artefacts tend to be more brittle while nature's are tougher. • As another consequence, our things move on sliding contacts between stiff objects whereas nature's objects bend, twist, or stretch at predetermined places. • As an additional result, we minimize drag with streamlined bodies of fixed shape, but nature often does so with non-rigid bodies that reconfigure in flows. • Human technology makes enormous use of metals, while metallic materials (as opposed to materials containing metal atoms) are totally absent in nature. • As a result, we use the ductility of metals to prevent crack propagation; nature does as well, but with foams and composites instead. • We more commonly load materials in compression while nature more often loads in tension. • Concomitantly, we make greater use of shear preventatives such as nails and mortar to keep stacked objects aligned. • Structures with tensile sheaths outside and pressurised fluid inside are both more common and diverse in natural designs than in ours. • For such hydrostatic and aerostatic systems, nature's predominant fluid is water while our structures mostly contain air or some other gas. • We make profuse and diverse use of rolling devices based on the wheel and axle; but things rarely roll in nature, and only one true wheel and axle is known.

			Vogel (1998) cont...
			<ul style="list-style-type: none"> • Our prime movers – engines – are based on rotation or expansion; most of nature's are based on sliding or contracting. • Many of our engines extract mechanical energy from temperature differences, whereas all natural engines are isothermal. • Levers in human technology most often amplify force at the expense of distance, while nature's commonest levers amplify distance at the expense of force. • Our devices store mechanical work as electrical, kinetic, gravitational, or elastic energy; nature mainly uses the last two and most often the last one. • Our fluid transport devices often interchange pressure drop and volume flow, but equivalent transformers are rare in nature. • Surface ships have long played an important role in human technology, but nature overwhelmingly prefers submarines. • Our factories dwarf the items they produce; nature's factories make products far larger than themselves. • We judge our devices best when they need only minimal maintenance, but nature's devices get continuously rebuilt. • Our technology is as dry as nature's is wet.

TABLE 20 RE-ORGANISATION OF ECOSYSTEM PROCESSES MATRIX

Combined list (see table 5)	(Biomimicry Institute, 2007)	(Biomimicry Guild, 2007a)	(Hastrich, 2006)	(Copeman, 2008)	(Hoeller, 2006)	(Dinur, 2005)	(Faludi, 2005)	(Reap et al., 2005)	(Berkebile and McLennan, 2004)	(McDonough and Braungart, 2002)	(Kibert et al., 2002)	(Vincent et al., 2006) (Vincent, 2002)	(Hoagland et al., 2001)	(Korhonen, 2001)	(Vogel, 1998)	(Benyus, 1997) 1	(Benyus, 1997) 2	(Kelly, 1994)	(Thompson, 1942)
Ecosystems adapt and evolve within limits at different levels and at different rates.	Life adapts and evolves	Subject to limits and boundaries Life adapts and evolves	Can it adapt? Evolve?	Creatively use and respond to change Design from patterns to details		Adaptation	Relentlessly adjust to the here and now	Life adapts and evolves			Adapt and evolve in response to changes in their external environment		Life maintains itself by turnover					Change changes itself Seek persistent disequilibrium	Discuss adaptation and evolution
Ecosystems enhance the capacity of the biosphere to support life and functioning and processes in ecosystems and within organisms tend to be benign	Life creates conditions conducive to life life-friendly materials Benign manufacturing bio-sphere enhancing	Using life friendly materials Using benign manufacturing Life creates conditions conducive to life.	Does the design 'create conditions conducive to life'? Does it use life friendly materials? Is the manufacturing benign? Does the design enhance the biosphere?				Chemical reactions and processes are life friendly Don't foul the nest		Operate pollution free and generate no wastes that aren't useful Promote the health and wellbeing of all inhabitants		Ecosystems consume life's by-products (waste)							Don't foul your nest Remain in balance with the biosphere Don't draw down resources	
Ecosystems are resilient. They can persist through time even as components within them change.					Resilience						Ecosystems remain resilient in the face of change Maintain resilience across all scales	Autonomy and independence leads to adaptability and versatility (2006)							

Combined list (see table 5)	(Biomimicry Institute, 2007)	(Biomimicry Guild, 2007a)	(Hastrich, 2006)	(Copeman, 2008)	(Hoeller, 2006)	(Dinur, 2005)	(Faludi, 2005)	(Reap et al., 2005)	(Berkebile and McLennan, 2004)	(McDonough and Braungart, 2002)	(Kibert et al., 2002)	(Vincent et al., 2006) (Vincent, 2002)	(Hoagland et al. 2001)	(Korhonen, 2001)	(Vogel, 1998)	(Benyus, 1997) 1	(Benyus, 1997) 2	(Kelly, 1994)	(Thompson, 1942)
Ecosystems are diverse in species, relationships and information.	Embrace diversity and redundancy		Does the design embrace diversity and redundancy?	Use and value diversity Use edges and value the marginal	Redundancy and diversity		Diversify to fill every niche			Respect diversity	High biodiversity of species			Diversity in species, organisms		Nature banks on diversity	Diversify and cooperate to fully use the habitat	Maximise the fringes	
Ecosystems are self-organising, decentralised and distributed.					Distributed systems						Self-organising processes, not top down control.	Decentralized feedback (2006)						Distribute being Control from the bottom up	
Ecosystems function through the use of complex feedback loops or cascades of information.			Can the design detect feedback?	Observe and Interact Apply self-regulation and accept feedback	Embedded Information Cascade of messages Feedback								Life organises with information			Nature curbs excesses from within	Run on information	Honour your errors	
Organisms within ecosystems operate in an interdependent framework.	Life coexists with a cooperative framework Interconnected and interdependent	Life is interconnected and interdependent Fostering cooperative relationships Leveraging interdependence	How does the design co-exist?	Cooperative and supportive Integrate don't segregate	Symbiosis	Interdependency	Cooperate and compete	Life coexists within a cooperative framework		Interdependence with other living systems	Each individual in a species acts independently yet its activity patterns cooperatively mesh with the patterns of other species. Complex webs of relationships.	Competition leads to optimization (2002)	Life is interconnected and interdependent Life competes within a cooperative framework	Diversity in interdependency and cooperation		Nature rewards cooperation	Diversify and cooperate to fully use the habitat		

Combined list (see table 5)	(Biomimicry Institute, 2007)	(Biomimicry Guild, 2007a)	(Hastrich, 2006)	(Copeman, 2008)	(Hoeller, 2006)	(Dinur, 2005)	(Faludi, 2005)	(Reap et al., 2005)	(Berkebile and McLennan, 2004)	(McDonough and Braungart, 2002)	(Kibert et al., 2002)	(Vincent et al., 2006) (Vincent, 2002)	(Hoagland et al. 2001)	(Korhonen, 2001)	(Vogel, 1998)	(Benyus, 1997) 1	(Benyus, 1997) 2	(Kelly, 1994)	(Thompson, 1942)
Ecosystems and the organisms within them optimise the whole system rather than maximise components.	Optimise rather than maximises		Is it optimised rather than maximised?				Optimise system rather than maximising components						Life tends to optimise rather than maximise				Optimise rather than maximise	Pursue no optima; have multiple goals	
Ecosystems and organisms are dependent upon and responsive to local conditions.	Life is locally attuned and resourceful		Is the design locally attuned?	Relative location				Life is locally attuned and resourceful	Harvests all its own water and energy needs on site		Concentrated toxic materials are generated and used locally			Utilising local resources Respecting the local natural limiting factors		Nature demands local expertise.	Shop locally		
Living organisms within ecosystems are resourceful and opportunistic. Abundances or excesses are used as a resource.	Life is locally attuned and resourceful Uses free energy Abundant materials	Free energy Resourceful and opportunistic	Does its manufacture use free energy? Abundant materials?	Catch and store energy Obtain a yield	Something for nothing					Runs on sunlight	The sole source of power for ecosystems is solar energy. Operate on solar flux and organic storages		Life is opportunistic	Evolution using solar energy		Nature runs on sunlight.		Cultivate increasing returns	
Ecosystems and the organisms within them have the capacity to learn from and respond to information and self-assemble	self-assembly appropriate behaviour Life builds from the bottom-up	Using self-assembly Builds from the bottom up Learns and imitates	Does it use self-assembly?				Self-assembly from the ground up	Life builds from the bottom up					Life builds from the bottom up					Grow by chunking	

Combined list (see table 5)	(Biomimicry Institute, 2007)	(Biomimicry Guild, 2007a)	(Hastrich, 2006)	(Copeman, 2008)	(Hoeller, 2006)	(Dinur, 2005)	(Faludi, 2005)	(Reap et al., 2005)	(Berkebile and McLennan, 2004)	(McDonough and Braungart, 2002)	(Kibert et al., 2002)	(Vincent et al., 2006) (Vincent, 2002)	(Hoagland et al. 2001)	(Korhonen, 2001)	(Vogel, 1998)	(Benyus, 1997) 1	(Benyus, 1997) 2	(Kelly, 1994)	(Thompson, 1942)
Ecosystems and the organisms with them have the capacity to heal within limits.																Nature taps the power of limits			
Ecosystems often have in-built redundancies.			Does the design embrace diversity and redundancy?		Redundancy and diversity Built in buffers														
Variety can occur through emergent effects (rapid change).							The whole is greater than the sum of its parts					Emergent effects (2006)							
Variety can occur by recombination of information and mutation (gradual change).	Cross-pollinate and mutates	Cross pollination and mutation	Is there cross pollination?	Use small and slow solutions	Stable Growth							Four billion years' worth of 'R&D' (2002)	Life encourages variety by recombining information Life creates with mistakes Life uses a few themes to generate many variation	Gradual Change Slow rates in the development of system diversity Evolution through reproduction					

Combined list (see table 5)	(Biomimicry Institute, 2007)	(Biomimicry Guild, 2007a)	(Hastrich, 2006)	(Copeman, 2008)	(Hoeller, 2006)	(Dinur, 2005)	(Faludi, 2005)	(Reap et al., 2005)	(Berkebile and McLennan, 2004)	(McDonough and Braungart, 2002)	(Kibert et al., 2002)	(Vincent et al., 2006) (Vincent, 2002)	(Hoagland et al. 2001)	(Korhonen, 2001)	(Vogel, 1998)	(Benyus, 1997) 1	(Benyus, 1997) 2	(Kelly, 1994)	(Thompson, 1942)
Ecosystems are organised in different hierarchies and scales.			Is the design modular or segmented?		Hierarchical systems Importance of scale emphasised		Organis e fractally	Discuss es scale and the potential of holistic biomimicry to affect multiple scales.			Operatin g function s over different ranges of scale.	Typically complex and hierarchical Hierarchical level defines the context of the system (2006)	Life assembl es itself into chains		Importan ce of scale emphasised				Importan ce of scale and time emphasised
Ecosystems and organisms use cyclic processes in the utilisation of materials.	Life is cyclic (processes) and recycles (material resources)		Does it use recycled materials? Is it recyclable? Is the design cyclic, does it adapt to cycles?	Use and value renewable resources and services Produce no waste	Closed Loop		Waste is food		Generat es no wastes that aren't useful	Waste equals food Cradle to cradle	Predomi nantly cyclic rather than linear		Life works in cycles Life recycles everything it uses.	Round-put Recyclin g of Matter		Nature recycles everything.	Use waste as a resource		
Parts of ecosystems and organisms are often multifunctional.	Multi-functionality				Do more with less		Use minimal energy and materials										Use materials sparingly		
The form of ecosystems and organisms is often a result of functional need.	Life fits form to function shape is cheaper than material modular built to shape (no waste)		Is it built to shape? Is shape designed to minimise material ?		Smart materials			Life fits form to function								Nature fits form to function			

Combined list (see table 5)	(Biomimicry Institute, 2007)	(Biomimicry Guild, 2007a)	(Hastrich, 2006)	(Copeman, 2008)	(Hoeller, 2006)	(Dinur, 2005)	(Faludi, 2005)	(Reap et al., 2005)	(Berkebile and McLennan, 2004)	(McDonough and Braungart, 2002)	(Kibert et al., 2002)	(Vincent et al., 2006) (Vincent, 2002)	(Hoagland et al. 2001)	(Korhonen, 2001)	(Vogel, 1998)	(Benyus, 1997) 1	(Benyus, 1997) 2	(Kelly, 1994)	(Thompson, 1942)
Living organisms that make up ecosystems are typically made from commonly occurring elements.	Water as solvent	Simple common building blocks. Water based world	What role does water play?					Life depends on water					Life runs on sugar Life occurs in water						
Ecosystems and the organisms within them gather, use and distribute and energy effectively.				Catch and store energy	Effective not efficient		Gather energy and materials efficiently Use minimal energy and materials		Be comprised of integrated systems that maximize efficiency and comfort.	Aim for energy effectiveness				Cascading of energy		Nature uses only the energy it needs	Gather and use energy efficiently		
Local energy / resources become spatial and temporal organisational devices			Is the design cyclic, does it adapt to cycles?						Adapted specifically to site, and climate	Use the sun				Cyclical time, seasonal time					

APPENDIX THREE: BIOMIMICRY GUILD / GROUP 'LIFE'S PRINCIPLES' DIAGRAMS 2007, 2009, 2011

FIGURE 116 LIFE'S PRINCIPLES, 2011 (SOURCE OF IMAGE: BIOMIMICRY GROUP, 2011).

FIGURE 117 LIFE'S PRINCIPLES, 2009 (SOURCE OF IMAGE: BIOMIMICRY GUILD, 2009).

LIFE'S PRINCIPLES

FIGURE 118 LIFE'S PRINCIPLES, 2007 (SOURCE OF IMAGE: BIOMIMICRY GUILD, 2007B).

APPENDIX FOUR: ECOSYSTEM SERVICES COMPARISON

TABLE 21 LISTS OF ECOSYSTEM SERVICES¹

SCHLÄPFER (2007)	KELLERT (2005)	ALCAMO ET AL. (2003)	DE GROOT ET AL. (2002)
<p>Process</p> <ul style="list-style-type: none"> • Biodiversity • Stability • Resilience • Adaptability <p>Service</p> <ul style="list-style-type: none"> • Water catchment / regulation of run off / groundwater recharge • Storage and cycling of nutrients and organic matter • Fixation of solar energy (production) • Regulation of local climate • Accumulation and recycling of interacting organismic populations including pests 	<ul style="list-style-type: none"> • Waste decomposition • Soil formation • Remediation of chemical and biological pollution • Control of injurious organisms • Plant pollination and seed dispersal • Hydrological regulation and control • Water supply and purification • Nutrient retention and cycling • Oxygen production • Products from wild animals (e.g. honey, shellfish) • Products from wild plants (wood, paper, lubricants) • Pharmaceuticals and other medicinal materials • Crop and livestock production 	<p>Provisioning Services</p> <ul style="list-style-type: none"> • Food • Fresh water • Fuel wood • Fibre • Biochemicals • Genetic resources • Ornamental resources <p>Regulating services</p> <ul style="list-style-type: none"> • Climate regulation • Disease regulation • Water regulation • Water purification • Pollination <p>Cultural services</p> <ul style="list-style-type: none"> • Spiritual / religious • Recreation / ecotourism • Aesthetic • Inspirational • educational • sense of place • Cultural heritage <p>Supporting Services</p> <ul style="list-style-type: none"> • Soil formation • Nutrient cycling • Primary production • Production of oxygen • Water cycling • Provision of habitat 	<p>Regulation functions</p> <ul style="list-style-type: none"> • Gas regulation • Climate regulation • Disturbance prevention • Water regulation • Water supply • Soil retention • Soil formation • Nutrient regulation • Waste treatment • Pollination • Biological control <p>Habitat functions</p> <ul style="list-style-type: none"> • Refugium function • Nursery function <p>Production functions</p> <ul style="list-style-type: none"> • Food • Raw materials • Genetic resources • Medicinal resources • Ornamental resources <p>Information functions</p> <ul style="list-style-type: none"> • Aesthetic information • Recreation • Cultural and artistic information • Spiritual and historic information • Science and education

¹ Not all sources cited here used discrete lists.

DAILY ET AL. (2000)	SCHWARTZ ET AL. (2000)	NORBERG (1999)	NAEEM (1999)
<ul style="list-style-type: none"> • Seafood • Timber • Life support services: • Pollination • Purification • Life fulfilling conditions: • Beauty • Serenity • Conservation of options • Genetic resources 	<ul style="list-style-type: none"> • Productivity • Root biomass • Above ground productivity • Nutrient cycling • Field water capacity • Biomass • Exergy • Nitrogen retention • Respiration • Plant shoot biomass • Above ground biomass • Nitrogen use • Decomposition • Invasion susceptibility • CO₂ flux • Nitrogen, potassium, phosphorus retention • Transmittance • Potassium retention • Percent cover • Extractable nitrogen • Resisting change 	<p>Production: maintenance level</p> <ul style="list-style-type: none"> • Water • Timber • Food • Clothing • Stone, minerals • Fuel pharmaceuticals • Genetic information • Ornamental objects <p>Regulatory Services</p> <ul style="list-style-type: none"> • Pollination (fruit development) • Provision of structure (habitat) • Biological control (preventing pests) • Resistance against invasion (foreign species) • UV protection by ozone • Climate regulation by gases • Mitigation of floods and droughts • Preventing erosion • Denitrification • Detoxification • Decomposition and recycling (prevention of waste) • Nutrient regeneration • Moderation of extremes <p>Support services</p> <ul style="list-style-type: none"> • Species maintenance and regeneration (self-regulation) • Natural selection and genetic variability (evolution) • Selective processes and variability (organisation) <p>Information Services</p> <ul style="list-style-type: none"> • Conspicuous patterns, spectacular behaviour (benefit is aesthetic appreciation) • Complexity beyond our understanding (benefit is religious inspiration) • Dramatic landscapes (benefit is cultural inspiration) 	<p>Goods / products (market value possible)</p> <ul style="list-style-type: none"> • Food • Medicine • Industrial products • Genetic resources (crop breeding) • Natural pest control <p>Services</p> <ul style="list-style-type: none"> • GHG regulation • Water treatment • Erosion control • Soil quality / control • Plant growth / production <p>Non marketable goods / products / services</p> <ul style="list-style-type: none"> • Knowledge • Aesthetic value • Existence (of other species) <p>Cultural benefits</p> <ul style="list-style-type: none"> • religious • aesthetic • recreational • inspirational

DAILY (1997)	VITOUSEK ET AL. (1997)	COSTANZA ET AL. (1997)	NAEEM ET AL. (1994)
Goods <ul style="list-style-type: none"> • Seafood • Forage • Timber • Biomass fuels • Natural fibre • Pharmaceuticals • Industrial products Services <ul style="list-style-type: none"> • Purification of air / water • Mitigation of flood / drought • Detoxification and decomposition of waste • Generation of soil / renewal of soil fertility • Pollination • Pest control • Dispersal of seeds (translocation) • Cycling of nutrients • Biodiversity • Protection from UV • Stabilization of climate • Moderation of temperature • Modification of force of wind / wave • Support of diverse human cultures • Aesthetic beauty • Intellectual stimulation • Spirit lifting 	Regulation of biogeochemical cycles <ul style="list-style-type: none"> • Carbon • Water • Nitrogen • Sulphur • Phosphorus • Others 	<ul style="list-style-type: none"> • Gas regulation • Climate regulation • Disturbance regulation • Water regulation • Water supply • Erosion control and sediment retention • Soil formation • Nutrient cycling • Waste treatment • Pollination • Biological control • Refugia • Food production • Raw materials • Genetic resources • Recreation • Cultural 	<ul style="list-style-type: none"> • Community respiration • Decomposition • Nutrient retention (available nitrogen, phosphorus, potassium) • Plant productivity • Water retention • Percent vegetative cover • 'Energetic ecosystem functions'

TABLE 22 RE-ORGANISATION OF ECOSYSTEM SERVICES MATRIX

Combined list (see table 8)	de Groot et al. (2002)	Alcamo et al. (2003)	Norberg (1999)	Naeem (1999)	Naeem et al. (1994)	Schwartz et al. (2000)	Costanza et al. (1997)	Daily et al. (2000)	Daily (1997)	Vitousek et al. (1997)	Schläpfer (2007)	Kellert (2005)
Provisioning Services	Production Functions	Provisioning Services	Production: maintenance level	Goods / products				Goods	Goods			
Food -human (land / marine -forage	Food	Food	Food	Food			Food production	Seafood	Seafood			Crop and livestock production
									Forage			
Biochemicals -medicines -other		Biochemicals	Pharmaceuticals						Pharmaceuticals			
	Medicinal resources			Medicine								Pharmaceuticals and other medicinal materials
Raw materials -timber -fibre -stone -minerals	Raw materials			Industrial products			Raw materials		Industrial products			Products from wild plants (wood, paper, lubricants) Products from wild animals (honey, shellfish)
			Timber					Timber	Timber			
		Fibre	Clothing						Natural fibre			
			Stone, minerals									
Fuel -biomass -mineral -other		Fuel wood	Fuel						Biomass fuels			
Fresh water -consumption -irrigation -industrial processes	Water supply	Fresh water	Water			Field water capacity	Water supply					Water supply and purification Hydrological regulation and control
Ornamental resources	Ornamental resources	Ornamental resources	Ornamental objects									
Genetic information	Genetic resources	Genetic resources	Genetic information	Genetic resources (crop breeding)				Conservation of options Genetic resources				.

Combined list	de Groot et al. (2002)	Alcamo et al. (2003)	Norberg (1999)	Naeem (1999)	Naeem et al. (1994)	Schwartz et al. (2000)	Costanza et al. (1997)	Daily et al. (2000)	Daily (1997)	Vitousek et al. (1997)	Schläpfer (2007)	Kellert (2005)
Regulating services	Regulation functions	Regulating services	Regulatory Services	Non marketable goods / products / services					Services		Service Process	
Pollination and seed dispersal	Pollination	Pollination	Pollination (fruit development)				Pollination	Pollination	Pollination			Plant pollination and seed dispersal
									Dispersal of seeds (translocation)			
Biological control -pest regulation -invasive species resistance -disease regulation	Biological control		Biological control (preventing pests)	Natural pest control			Biological control		Pest control		Accumulation and recycling of interacting organismic populations including pests	Control of injurious organisms
		Disease regulation	Resistance against invasion (foreign species)			Invasion susceptibility						
Climate regulation -GHG regulation -UV protection -moderation of temperature	Climate regulation	Climate regulation	Climate regulation by gases				Climate regulation		Stabilization of climate and moderation of temperature		Regulation of local climate	
			UV protection by ozone						Protection from UV			
	Gas regulation			GHG regulation	Community respiration	Respiration CO ₂ flux	Gas regulation					
Prevention of disturbance and moderation of extremes -wind / wave force modification -mitigation of flood / drought -Erosion control	Disturbance prevention		Moderation of extremes	Erosion control		Resisting change	Disturbance regulation				Resilience Stability	
			Mitigation of floods and droughts						Mitigation of flood / drought			
			Preventing erosion				Erosion control and sediment retention		Modification of force of wind / wave			
Decomposition -waste removal -purification (water / air / soil)			Decomposition and recycling		Decomposition	Decomposition			Detoxification & decomposition of waste			Waste decomposition
	Waste treatment		Detoxification				Waste treatment	Purification	Purification of air / water			Remediation of chemical and biological pollution
		Water purification		Water treatment								Water supply and purification

Combined list	de Groot et al. (2002)	Alcamo et al. (2003)	Norberg (1999)	Naeem (1999)	Naeem et al. (1994)	Schwartz et al. (2000)	Costanza et al. (1997)	Daily et al. (2000)	Daily (1997)	Vitousek et al. (1997)	Schläpfer (2007)	Kellert (2005)
Life fulfilling conditions:	Information functions	Cultural services	Information Services	Cultural benefits				Life fulfilling conditions				
Artistic inspiration	Cultural and artistic information	Inspirational		Inspirational								
Aesthetic Value	Aesthetic information	Aesthetic	Conspicuous patterns, spectacular behaviour (benefit is aesthetic appreciation)	Aesthetic value				Beauty	Aesthetic beauty			
Education and Knowledge	Science and education	Educational		Knowledge					Intellectual stimulation			
Cultural Diversity and history	Cultural and artistic information Spiritual and historic information	Cultural heritage	Dramatic landscapes (benefit is cultural inspiration)				Cultural		Support of diverse human cultures			
Recreation and tourism	Recreation	Recreation / ecotourism		Recreational			Recreation					
Spiritual and religious inspiration	Spiritual and historic information	Spiritual / religious	Complexity beyond our understanding (benefit is religious inspiration)	Religious					Spirit lifting			
Creation of a sense of place		Sense of place										
Relaxation and psychological wellbeing (biophilia)								Serenity				
Supporting Services		Supporting Services	Support services					Life support services				
Soil -formation -retention -renewal of fertility -quality control	Soil formation Soil retention	Soil formation		Soil quality / control			Soil formation		Generation of soil / renewal of soil fertility			Soil formation

Combined list	de Groot et al. (2002)	Alcamo et al. (2003)	Norberg (1999)	Naeem (1999)	Naeem et al. (1994)	Schwartz et al. (2000)	Costanza et al. (1997)	Daily et al. (2000)	Daily (1997)	Vitousek et al. (1997)	Schläpfer (2007)	Kellert (2005)
Fixation of solar energy -primary production / plant growth (above ground, below ground, marine, fresh water)		Primary production		Plant growth / production	Plant productivity	Productivity: -Above ground productivity Biomass: -Plant shoot biomass -Above ground biomass -Root biomass					Fixation of solar energy (production)	
Nutrient cycling -Regulation of biogeochemical cycles (oxygen, water, potassium, nitrogen, phosphorus, sulphur, carbon) -Retention of nutrients	Nutrient regulation	Nutrient cycling	Nutrient regeneration			Nutrient cycling	Nutrient cycling		Cycling of nutrients	Regulation of biogeochemical cycles	Storage and cycling of nutrients and organic matter	Nutrient retention and cycling
		Production of oxygen										Oxygen production
										Carbon		
	Water regulation	Water regulation Water cycling			Water retention		Water regulation			Water	Water catchment / regulation of run off / groundwater recharge	
					Nutrient retention (available nitrogen, phosphorus, potassium)	Nitrogen, potassium, phosphorus retention				Phosphorus Sulphur Others		
			Denitrification			Extractable nitrogen Nitrogen use Nitrogen retention				Nitrogen		
Habitat provision -refugium -nursery function	Habitat functions	Provision of habitat	Provision of structure (habitat)				Refugia					
	Refugium function											
	Nursery function											

Combined list	de Groot et al. (2002)	Alcamo et al. (2003)	Norberg (1999)	Naeem (1999)	Naeem et al. (1994)	Schwartz et al. (2000)	Costanza et al. (1997)	Daily et al. (2000)	Daily (1997)	Vitousek et al. (1997)	Schläpfer (2007)	Kellert (2005)
Species maintenance -biodiversity -natural selection -self organisation			Species maintenance and regeneration (self-regulation)	Existence (of other species)					Biodiversity		Biodiversity	
			Natural selection and genetic variability (evolution)								Adaptability	
			Selective processes and variability (organisation)									
Others					'Energetic ecosystem functions'	Transmittance						
					Percent vegetative cover	Percent cover						
					Pin encounters	Exergy						

APPENDIX FIVE: THE TEEB STEPWISE APPROACH

(HOW TO INCLUDE ECOSYSTEM SERVICES IN DECISION MAKING AND POLICY IN AN URBAN CONTEXT)

FIGURE 119 TEEB STEPWISE APPROACH (SOURCE: TEEB 2011B).

APPENDIX SIX: POTENTIAL BENEFITS OF REGENERATIVE DESIGN

TABLE 23 POTENTIAL BENEFITS OF REGENERATIVE DESIGN (ADAPTED FROM: PEDERSEN ZARI AND JENKIN, 2009).

Potential ecological, economic, social and cultural benefits of regenerative design	References and additional information and/or case studies
1. Reduced and potentially positive environmental impact. Increased biodiversity and ecosystem health	Balmford et al. (2002), Cole, (2012b), Cole et al. (2012), du Plessis (2012), Haggard et al. (2006), McDonough and Braungart (2002), Plaut et al. (2012), Reed (2007),
2. Increased human physical health	Cole et al. (2012), Fullbrook et al. (2006), Haggard et al. (2006), Hoxie et al. (2012), Ryan and Deci (2001), Thomas et al (2002).
3. Increased productivity of people	Fullbrook et al. (2006), Hoxie et al. (2012), Leaman and Bordass (2001).
4. Improves effectiveness of lifecycle resource use	Cole et al. (2012), Fullbrook et al. (2006).
5. Increased economic value of project / generation of local wealth	Cole et al. (2012), Couchman (2007), Fullbrook et al. (2006).
6. Increased psychological wellbeing	Cole et al. (2012), Fullbrook et al. (2006), Haggard et al. (2006), Hoxie et al. (2012), Kellert (2005), Leaman and Bordass (2001), Walsh (1992).
7. Increased robustness and resilience in the face of environmental change in a local context.	Cole et al. (2012), Fullbrook et al. (2006), Haggard et al. (2006).
8. Building / development becomes a potential source of income.	McDonough and Braungart (2002).
9. Facilitates a shift in thinking regarding the relationship between people and nature	Cole (2012a, 2012b), Cole et al. (2012), Fullbrook et al. (2006), Haggard (2001), Haggard et al. (2006), Hoxie et al. (2012), Kellert (2005), McIndoe et al. (2005), Plaut et al. (2012), Reed (2007), Svec et al. (2012).
10. Increased flexibility and adaptability.	Couchman (2007), McIndoe et al. (2005), Reed (2007) Svec et al. (2012).
11. Creates stronger, more equitable communities	Couchman (2007), Haggard (2001), Haggard et al. (2006), Hoxie et al. (2012), Kellert (2005), McIndoe et al. (2005), Plaut et al. (2012), Reed (2007).
12. Emphasis on creation of relationships and user participation / education and adjustments and monitoring beyond the traditional end of the design process can have economic and social benefits.	Cole et al. (2012), du Plessis (2012), Fowles (2003), Grinde (2002), Hoxie et al. (2012), Mang and Reed (2012), McIndoe et al. (2005), Plaut et al. (2012), Reed (2007), Voyle and Simmons (1999).

13. Generates opportunities for cultural expression, restoration or evolution through creating a sense of place.	Cole (2012a), Cole et al. (2012), Hoxie et al. (2012), Mang and Reed (2012).
14. Creates more capacity for peaceful human communities. Can act as a positive catalyst beyond development boundaries	Cole et al. (2012), Hoxie et al. (2012), Loomis (2000), Plaut et al. (2012), Reed (2007), Thomas et al. (2002).

The field of literature on regenerative design is small and because of this, information from related areas of research has been used in gathering evidence of the benefits described. Each of the benefits listed in this table depends on the specific project in question and should be understood to be potential rather than definite positive outcomes arising from regenerative design processes or projects. Regenerative developments evolve over time so benefits may vary depending on the stage of the project.

APPENDIX SEVEN: PRE-DEVELOPMENT AND EXISTING VEGETATION COVER IN WELLINGTON (CITY)

FIGURE 120 EXISTING VEGETATION IN WELLINGTON (ADAPTED FROM: LANDCARE RESEARCH, 2011A).

FIGURE 121 PRE-DEVELOPMENT VEGETATION IN WELLINGTON (ADAPTED FROM: LANDCARE RESEARCH, 2011B).

APPENDIX EIGHT: INDIGENOUS TREE SPECIES OCCURRING ON PERMANENT FOREST PLOTS OF WELLINGTON

TABLE 24 BROAD-LEAVED TREES COMMONLY OCCURRING IN PERMANENT FOREST PLOTS OF THE WELLINGTON REGION (ADAPTED FROM: DYMOND AND SHEPHERD, 2004).

Maori name	Scientific name	English name
Pate	<i>Schefflera digitata</i>	Seven finger
Whauwhaupaku	<i>Pseudopanax arboreus</i>	Five finger
Kawakawa	<i>Macropiper excelsum</i>	Kawakawa
Rata	<i>Metrosideros robusta</i>	Northern rata
Kamahi	<i>Weinmannia racemosa</i>	Kamahi
Pukatea	<i>Laurelia novae-zelandiae</i>	Pukatea
Makomako	<i>Aristotelia serrata</i>	Wineberry
Porokaiwhiri	<i>Hedycarya arborea</i>	Pigeonwood
Kohekohe	<i>Dysoxylum spectabile</i>	Kohekohe
Kaikomako	<i>Pennantia corymbosa</i>	Kaikomako
Houhere	<i>Hoheria populnea</i>	Lacebark
Horoeka	<i>Pseudopanax crassifolius</i>	Lancewood
Rewarewa	<i>Knightia excelsa</i>	New Zealand Honeysuckle
Mahoe	<i>Melicytus ramiflorus</i>	Whiteywood
Hinau	<i>Elaeocarpus dentatus</i>	Hinau
Titoki	<i>Alectryon excelsus</i>	Titoki
Putaputaweta	<i>Carpodetus serratus</i>	Putaputaweta
Kanuka	<i>Kunzea ericoides</i>	White tea tree
Manuka	<i>Leptospermum scoparium</i>	Tea tree
Mapou	<i>Myrsine australis</i>	Red matipo
Papauma	<i>Griselinea littoralis</i>	Broadleaf
Rangiora	<i>Brachyglottis repanda</i>	Rangiora
Kotukutuku	<i>Fuchsia excorticata</i>	Tree fuchsia
Tawa	<i>Beilschmiedia tawa</i>	Tawa

TABLE 25 INDIGENOUS CONIFER TREES FOUND IN PERMANENT FOREST PLOTS OF THE WELLINGTON REGION (ADAPTED FROM: DYMOND AND SHEPHERD, 2004).

Maori name	Scientific name	English name
Rimu	<i>Dacrydium cupressinum</i>	Red pine
Kahikatea	<i>Dacrycarpus dacrydioides</i>	White pine
Miro	<i>Prumnopitys ferruginea</i>	Brown pine
Matai	<i>Prumnopitys taxifolia</i>	Black pine
Totara	<i>Podocarpus totara</i>	Totara
–	<i>Podocarpus hallii</i>	Hall's totara
–	<i>Phyllocladus alpinus</i>	Mountain toatoa

TABLE 26 INDIGENOUS BEECH TREES FOUND IN PERMANENT FOREST PLOTS OF THE WELLINGTON REGION (ADAPTED FROM: DYMOND AND SHEPHERD, 2004).

Maori name	Scientific name	English name
Tawhai	<i>Nothofagus manziesii</i>	Silver beech
Tawhairaunui	<i>Nothofagus truncata</i>	Hard beech
Tawhairaunui	<i>Nothofagus fusca</i>	Red beech
Tawhairauriki	<i>Nothofagus solandri</i>	Black beech

APPENDIX NINE: DETERMINING AREAS OF THE PROVISION OF FOOD AND THE PROVISION OF HABITAT

This map is the original map that was devised to determine the potential food and habitat zones shown in figure 112 (chapter five).

FIGURE 122 LAND USES AND LAND DESIGNATIONS OF WELLINGTON.

Landcare Research maps in appendix seven were used to determine existing native shrub, existing non-native scrub, existing pasture, existing native forest, existing exotic forest, and the urban area of Wellington. The proposed green belt area was taken from the Wellington City Council Open Space Strategy (Nicholson, 1998).

Existing community gardens were determined using the Wellington City Council (2012c) map. Areas noted as protected or reserve areas are illustrated in maps in the Wellington Regional Landscape Atlas (Isthmus Group, 2009). Where overlaps occurred, layers were organised in the following order from top to bottom: existing native forest, existing food growing areas, existing exotic forest, protected or reserve areas, proposed green belt, existing pasture, existing native scrub, existing non-native scrub, and urban areas.

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