AN ECOSYSTEM SERVICES PERSPECTIVE OF LAKE WAIRARAPA:

INSIGHTS FROM THE PAST, PRESENT, AND TOWARD THE FUTURE

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Abstract

Ecosystem services encompass the wide range of intrinsic and extrinsic benefits that humans derive from ecosystems and how such services contribute to community wellbeing. The delivery of effective and efficient provisioning, regulating, and cultural ecosystem services at Lake Wairarapa (a shallow, super-trophic, coastal lake in the lower North Island) has been heavily impacted through current land use. Using a pragmatic epistemology and mixed methods approach, this research sought to understand the past, present, and future delivery of ecosystem services at Lake Wairarapa through three distinct, yet complementary, studies.

Firstly, a palaeo-environmental reconstruction using five proxies was completed to build an understanding of past environmental conditions at Lake Wairarapa. Prior to human arrival, the lake was stable and resilient in response to environmental perturbations. However, alteration of the landscape following human arrival has reduced ecosystem service effectiveness, prompting a transition into an entirely new environmental state at Lake Wairarapa. This chapter highlighted the abrupt removal of mānuka and centennial shift from a forest catchment into one dominated by agriculture so a field trial was conducted to assess the ability of mānuka to reduce nitrogen leaching and *E. coli* contamination. Mānuka can significantly reduce the conversion of ammonium to nitrate compared to pasture, thus regulating nitrate leaching; however, the impact on *E. coli* counts was less conclusive. Finally, cultural services present at Lake Wairarapa and future community aspirations were assessed through seven semi-structured interviews of Wairarapa community members. Place attachment was recognised as the underlying factor that facilitated strong cultural service delivery. Social and environmental restoration was identified as the key vision for the future, underpinned by collaboration within resource management.

From this research, four recommendations were made to enhance ecosystem service delivery at Lake Wairarapa: establishment of ecologically appropriate restoration plans, facilitated collaborative management, further investigation of environmental and economic properties of mānuka, and development of community engagement programmes. This multi-disciplinary and holistic approach outlines a pathway towards a positive and inclusive future for Lake Wairarapa and its communities.

Acknowledgments

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Positionality

Consideration of positionality and administering a self-reflexive approach is increasingly normalised within the social sciences, yet remains uncommon in the physical sciences (Creswell, 2014; Kobayashi, 2003; Sultana, 2007). Here, researchers recognise and consider the societal and physical differences that they may have compared to the subjects with whom they are working (Kobayashi, 2003).

I acknowledge my positionality in all aspects of this research: first and foremost, *ko Wairarapa te roto*. As someone who identifies as both Ngāti Kahungunu ki Wairarapa and Rangitāne o Wairarapa, this research is intimately and inextricably connected to my identity, my whānau (family), and my region. The opportunity to exercise kaitiakitanga (guardianship, stewardship) for my lake has been a driving force behind the research. My position within academia as a young, Māori woman completing a postgraduate qualification in a scientific field is, unfortunately, rare. This was mentioned by a number of the interviewees who sought to encourage me be making suggestions on my future career direction! Whilst I personally knew some of the interviewees, I ensured that interviews were conducted professionally to mitigate any potential biases that my position may have unintentionally induced.

Chapter One: Introducing ecosystem services and Lake Wairarapa

1.1 Introduction

Humans are dependent on the natural environment to support healthy, safe, fulfilling, and prosperous lives. However, continued overexploitation of natural resources and land use intensification globally is pushing the capabilities of ecosystems past critical functioning thresholds and planetary boundaries (Rockström et al., 2009).

In New Zealand, human-induced stresses on the environment are relatively recent (within the past 700-800 years) and noticeable, due to the isolated geographic location of New Zealand and late human settlement comparative to other landmasses (Newnham et al., 1999). Māori arrival and occupation at approximately 1280 CE (Common Era) saw the widespread clearance of indigenous forests, establishment of gardens and crop cultivation (such as bracken fern), and harvesting of faunal species (McGlone & Wilmshurst, 1999). European arrival and settlement in the 1800s saw the introduction of pastoral agriculture and further clearance of native forests and drainage of wetlands (Leathwick et al., 2003; McWethy et al., 2010). More recently, improvements in agricultural technology and the transition to urbanised ways of living continue to add pressure on New Zealand landscapes (Steffen et al., 2015).

Examination of degraded landscapes can be analysed using the ecosystem services framework outlined extensively by the Millennium Ecosystem Assessment (MEA, 2005). Simply put, ecosystem services are the many benefits that humans obtain from ecosystems. Ecosystem services, which include the categories of 'provisioning', 'regulating', 'cultural', and 'supporting' services (see section 1.2.1) , provide valuable and irreplaceable benefits that subsequently enhance human health and wellbeing (MEA, 2005). By accounting for both environmental and social facets of ecosystems, an ecosystem services perspective allows for a holistic and all-encompassing analysis of environmental conditions at particular landscapes.

Intensified anthropogenic land use threatens the provision of healthy, functioning ecosystem services. The impact of human arrival and subsequent land use change is evident at Lake Wairarapa, situated ca. 7 km south of Featherston in the lower Wairarapa Valley (Fig. 1.5). Today, Lake Wairarapa is a shallow (no more than 2.7 m deep), supertrophic freshwater lake. It is the largest in the lower North Island of New Zealand at currently 78 km^2 (Trodahl et al., 2016), but in the past has extended to 240 km^2. Since scientific monitoring of the lake's water quality began 25 years ago, there has been no change or improvement (Perrie & Milne, 2012). Prior to that, there is little known about the effects of land use in past centuries on the lake's current ecological health. Without a clear understanding of the past, it is difficult to provide insights into future management and direction.

This research aims to develop a past, present, and future understanding of ecosystem services for Lake Wairarapa. Three overarching research questions have driven this inquiry, alongside six supplementary questions:

1. How has human use of the environment at Lake Wairarapa altered and changed the distribution of ecosystem services through time?
    a) What was the environment of Lake Wairarapa like prior to human arrival?
    b) How have humans modified the environment and what impact has this had on the Lake Wairarapa ecosystem? Has Lake Wairarapa's current state resulted from a slow and gradual trajectory developed over centuries or a rapid, exponential response similar to the Great Acceleration?

2. How do present mitigation strategies using mānuka in riparian management enhance ecosystem service functionality at Lake Wairarapa?
    c) What is the impact of mānuka on *Escherichia coli* (*E. coli*) counts in a field experiment within a riparian zone at Lake Wairarapa?
    d) How is the distribution of ammonium and nitrate impacted by mānuka in a field experiment within a riparian zone at Lake Wairarapa?

3. How can development of certain ecosystem services at Lake Wairarapa further support and reinforce healthy and prosperous biological and human communities?
    e) In what ways are cultural services provided through Lake Wairarapa and experienced by the community?
    f) What are the aspirations held by community members and how might these shape the future of Lake Wairarapa?

The current environmental status of Lake Wairarapa indicates a landscape and freshwater catchment heavily impacted by human activity – both historically and continuing today. Yet, the lake still holds great environmental, economic, social, and cultural significance to many people in the local and regional community. With this significance in mind, the objectives of this research are threefold and have been addressed in the following three chapters. Firstly, a palaeo-reconstruction using lake sediments has been undertaken to determine past conditions at Lake Wairarapa. Secondly, the potential of mānuka to minimise nitrogen and *E. coli* pollution was tested at a riparian zone at Lake Wairarapa. Finally, key Wairarapa community members were interviewed to understand the motivations, aspirations, and opportunities available at Lake Wairarapa for moving into the future. To answer the research questions and complete the objectives of this study, a pragmatic epistemology and equal status mixed methods research design has been employed.

1.2 Ecosystem services

One mechanism to investigate the relationship between human demands and environmental functioning is through an ecosystem services lens. The concept of ecosystem services first emerged in the 1980s (Abson et al., 2014) and is defined as the natural ecosystem conditions and processes that support and sustain human life, as well as the benefits that humans might obtain from these ecosystems (Daily & Norgaard, 2013; Dempsey & Robertson, 2012). Lake Wairarapa provides innumerable ecosystem services to the people who inhabit the Wairarapa Valley, providing the basis upon which local communities have not only survived but also thrived. This research aims to describe and quantify these ecosystem services at the lake.

While many ecosystem services are intrinsic or difficult to quantify or monetise (i.e. incommensurable), Costanza et al. (1997) attempted to place a monetary value on global biospheric ecosystem services at 33 trillion USD per year in 1995 $US (46 trillion USD per year in 2007 $US, 87 trillion NZD per year in 2019 $NZ). In a subsequent report in 2011, Costanza et al. (2014) valued global ecosystem services between 125-145 trillion USD per year in 2007 $US (235-273 trillion NZD per year in 2019 $NZ). Widespread land use changes were attributed to the large increase in value over this 12-year period, whereby a 4.3-20.2 trillion USD in 2007 $US (8-38 trillion NZD in 2019 $NZ) annual loss in ecosystem services due to degradation meant that the remaining ecosystem services were therefore more valuable (Costanza et al., 2014). These studies show both the extent of degradation over very short time periods, and highlight the rational and fiscal irresponsibility of continued resource exploitation and degradation.

An ecosystem services approach is transdisciplinary (Costanza & Kubiszewski, 2012), with transdisciplinary research key in improving local connections and reducing unhelpful disciplinary speciality (Frost & Jean, 2003). Likewise, the exponential growth in ecosystem service-based research shows interest from science and policy communities alike (Abson et al., 2014). Extensive works produced by the United Nations, such as the Millennium Ecosystem Assessment (MEA) and The Economics of Ecosystems and Biodiversity (TEEB), have also brought ecosystems services to the forefront of global environmental management and planning (Costanza et al., 2014).

Traction for the ecosystem services concept is beginning to appear, albeit slowly, in New Zealand research and policy (Ministry for the Environment & Statistics New Zealand, 2018). Alongside other economic frameworks, the New Zealand Institute of Economic Research suggested the ecosystem services framework as a means to determine physical limitations and accounting of services in water management and planning (Kaye-Blake et al., 2014). Similarly, the Ministry for the Environment & Statistics New Zealand (2018) strongly reference the ecosystem services framework in determining key challenges to land-based resources. Identified challenges include a paucity of comprehensive data regarding land use and land use intensity, waste to landfill, and biological indicators of soils (thus, limited understanding of soil biodiversity and health) (Ministry for the Environment & Statistics New Zealand, 2018).

1.2.1 Millennium Ecosystem Assessment ecosystem services framework

To further understand and implement an ecosystem services approach, the United Nations formed the Millennium Ecosystem Assessment (MEA) in 2001. The MEA involved a wide range of stakeholders tasked with assessing how ecosystem change would affect human wellbeing and determining a scientific foundation for improved conservation and sustainable resource use as well as ecosystem contributions to human wellbeing (MEA, 2005). The resulting conceptual framework represents the different types of ecosystem services and their contribution to human wellbeing and poverty reduction (Fig. 1.1). The framework groups ecosystem services under four categories: provisioning, regulating, cultural, and supporting (MEA, 2005).

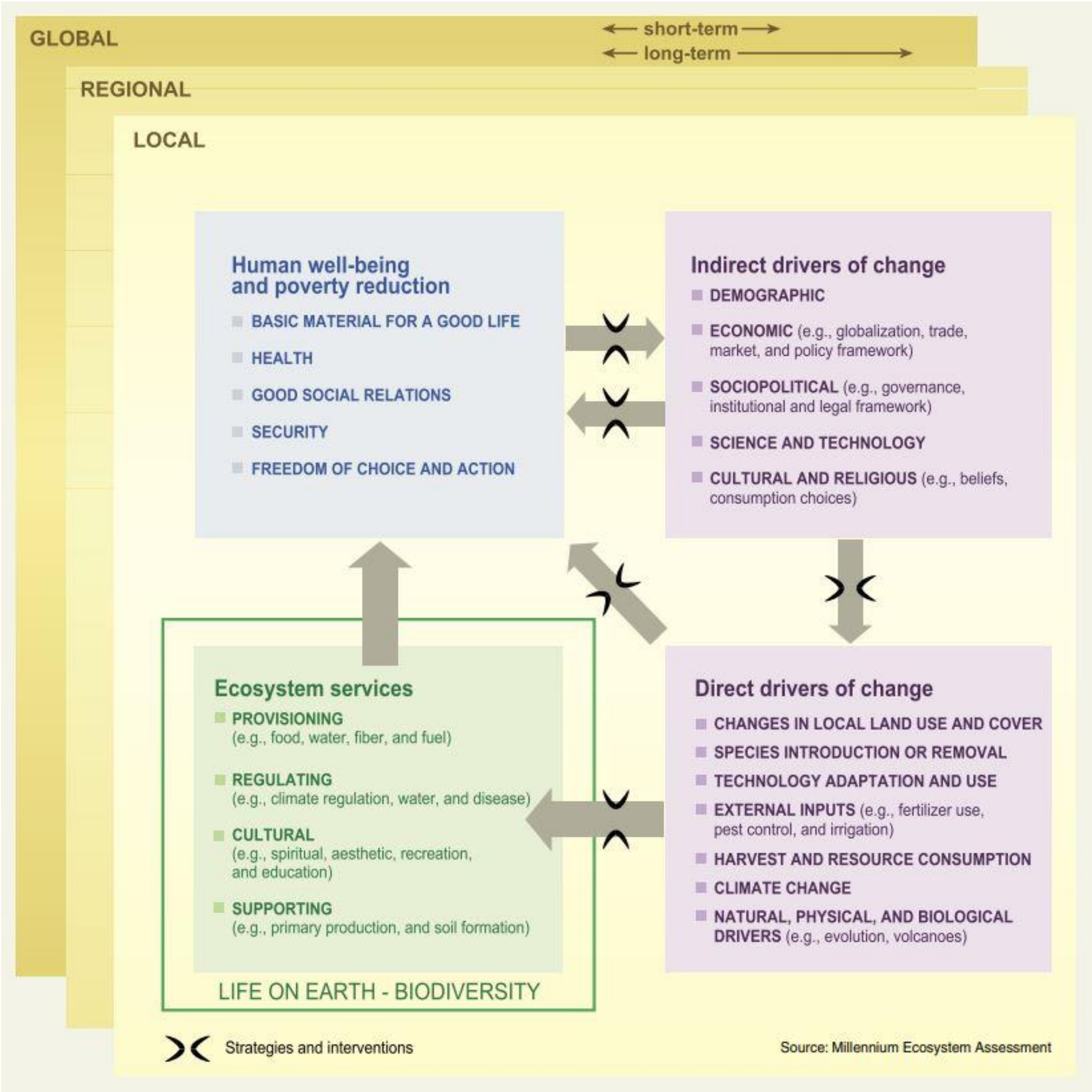


Figure 1.1: The conceptual framework of interactions between ecosystem services, human wellbeing and drivers of change developed by the Millennium Ecosystem Assessment. Ecosystem services have a direct impact on human wellbeing, with human wellbeing influencing indirect drivers of change. Both indirect and direct drivers of change can impact human wellbeing, but only direct changes impact ecosystem services (MEA, 2005).

1.2.2 Provisioning services

Provisioning services are ecosystem goods (or end products) that humans can directly use e.g. freshwater, food, and medicinal resources (MEA, 2005). Demand for provisioning services are primarily regarded for consumption purposes, particularly of water and energy resources (Wolff et al., 2015).

At Lake Wairarapa, provisioning services foster much of the current local economy. In 2015, the largest contributor to South Wairarapa gross domestic product (GDP) was the primary production sector, which includes agriculture, forestry, and food production industries (Stokes & Dixon, 2016). The primary production sector here contributes 90 million NZD to regional GDP and provides 834 full-time employment opportunities (Stokes & Dixon, 2016). More broadly, the provisioning services provided by lakes include sources of drinking water, and fishery and waterfowl resources (Schallenberg et al., 2013). Aquaculture, for example, is one of the top five export earners in New Zealand, annually contributing 200 million NZD. In freshwater systems, eel fisheries dominate aquaculture production. At Lake Wairarapa, restoration of eel populations is desired to support recreational and customary harvests (Ruamāhanga Whaitua Committee, 2018).

1.2.2 Regulating services

Regulating services are considered to be the functions that help regulate and control the ecosystem, including regulation of climate, waste, water flow, floods and storms, water purification, control of pests and disease, and crop pollination (MEA, 2005). Regulating services concern risk reduction; for example, flood regulation contributes to safety and protection of assets, and crop pollination is necessary for the production of food and food-based industries (Wolff et al., 2015).

Natural regulating services concerning flood and water flow regulation and water purification have been heavily compromised at Lake Wairarapa. To further support provisioning services (i.e. pastoral agriculture), the Lower Wairarapa Valley Development Scheme (LWVDS) was completed in 1983 to reduce flood risk and increase arable land availability. Here, the LWVDS diverted the main tributary, the Ruamāhanga River, out of Lake Wairarapa to instead flow farther down the valley, with water releases from the lake now artificially controlled by barrage gates (Trodahl et al., 2016). Likewise, removal of vegetation during early land clearance would have led to reduced soil retention capabilities and thus impacted soil quality, as well as reduced wind and fire protection (Waters et al., 2018).

More generally, lakes also provide many crucial regulating services. The sequestration of nitrogen, phosphorus, carbon, and other nutrients regulates water quality and reduces nitrification and contamination downstream (Schallenberg et al., 2013). Sequestration of carbon, for example, reduces carbon losses by one third – this is critically important in light of climate change (Tranvik et al., 2009). However, this is also determined by abundance and size distribution, with eutrophic lakes more effective at carbon burial than oligotrophic lakes (Downing, 2009).

1.2.3 Cultural services

Cultural services are largely intangible and provide non-material benefits to humans, such as indigenous and spiritual experience, identity formation, recreational capability, cultural heritage, and aesthetic enjoyment (MEA, 2005). Demand for cultural services is expressed as personal preference and values, as well as direct use values (Wolff et al., 2015). Preference values include the high expectation that cultural services (such as protected or heritage areas) are provided; however, exact preferences depend on the educational, social and environmental context, and underlying social values (Wolff et al., 2015). Direct use values refer primarily to the provision of recreation, hunting, fishing, and food gathering (Wolff et al., 2015).

Lake Wairarapa has significant cultural meaning to the people of Wairarapa, particularly tangata whenua of the area: Ngāti Kahungunu ki Wairarapa and Rangitāne o Wairarapa. Identity formation for Māori is inextricably linked to geographical locations. For example, while related to provisioning services, places of mahinga kai (food gathering places) represent a connection to the landscape as well as a source of sustenance. Significant wetland complexes around Lake Wairarapa, and between Lakes Wairarapa and Ōnoke (also known as Lake Ferry), also provide many sources of recreation and contribute to spiritual wellbeing.

1.2.4 Supporting services

Finally, supporting services are responsible for the production, and underpin the success, of the other three ecosystem services. Supporting services are considered to be those that are not able to be used directly by humans. They operate over long time scales, including soil formation, nutrient and water cycling, and photosynthesis (MEA, 2005).

1.2.5 Contribution to human wellbeing

The ecosystem services framework goes beyond purely ecological concerns about environmental capabilities and degradation; an ecosystem services approach is also greatly concerned about the contribution to human health and wellbeing (Fig. 1.1, 1.2) (Fisher et al., 2009). Ecosystem services have a direct impact on human wellbeing and poverty reduction, with indirect and direct drivers of change having impacts (either directly or cumulatively) on both ecosystem services and human wellbeing (MEA, 2005; TEEB, 2010). Similarly, certain ecosystem services have a stronger impact on constituents of wellbeing, as defined by the MEA framework (Fig. 1.2). Here, provisioning and regulating services have strong impacts on human wellbeing but can be mediated by socioeconomic factors (MEA, 2005). Alternatively, cultural services have less direct impact on wellbeing (compared to e.g. sources of food and shelter), yet are difficult to remediate by socioeconomic means (MEA, 2005).

1.2.6 Challenges of an ecosystem services approach

With all conceptual frameworks and models, applications in ‘real world’ settings often encounter challenges. Firstly, ecosystems services are not neatly partitioned as represented in the MEA framework. Given the complexity of interactions and connections between ecosystem services, it is often difficult to manage multiple services across landscapes (Bennett et al., 2009).

Secondly, development and growth of provisioning services (e.g. intensive pastoral agriculture or forestry) can often lead to trade-offs and deterioration in regulating and cultural services, which are already evident at Lake Wairarapa (Raudsepp-Hearne et al., 2010). This can also be a challenge whereby the successful functioning of regulating services is necessary to support further provisioning services (Raudsepp-Hearne et al., 2010). This is examined by Foley et al. (2005) and depicted in a conceptual framework (Fig. 1.3). In a natural ecosystem, provision of wild foods may be limited, while regulating services are strong. And yet, when crop production becomes the primary focus, all other services can be inhibited (Foley et al., 2005). Thus, where ecosystem services have been restored, crop production may be somewhat limited, but good regulating services ensure ecosystem longevity and health (Foley et al., 2005).

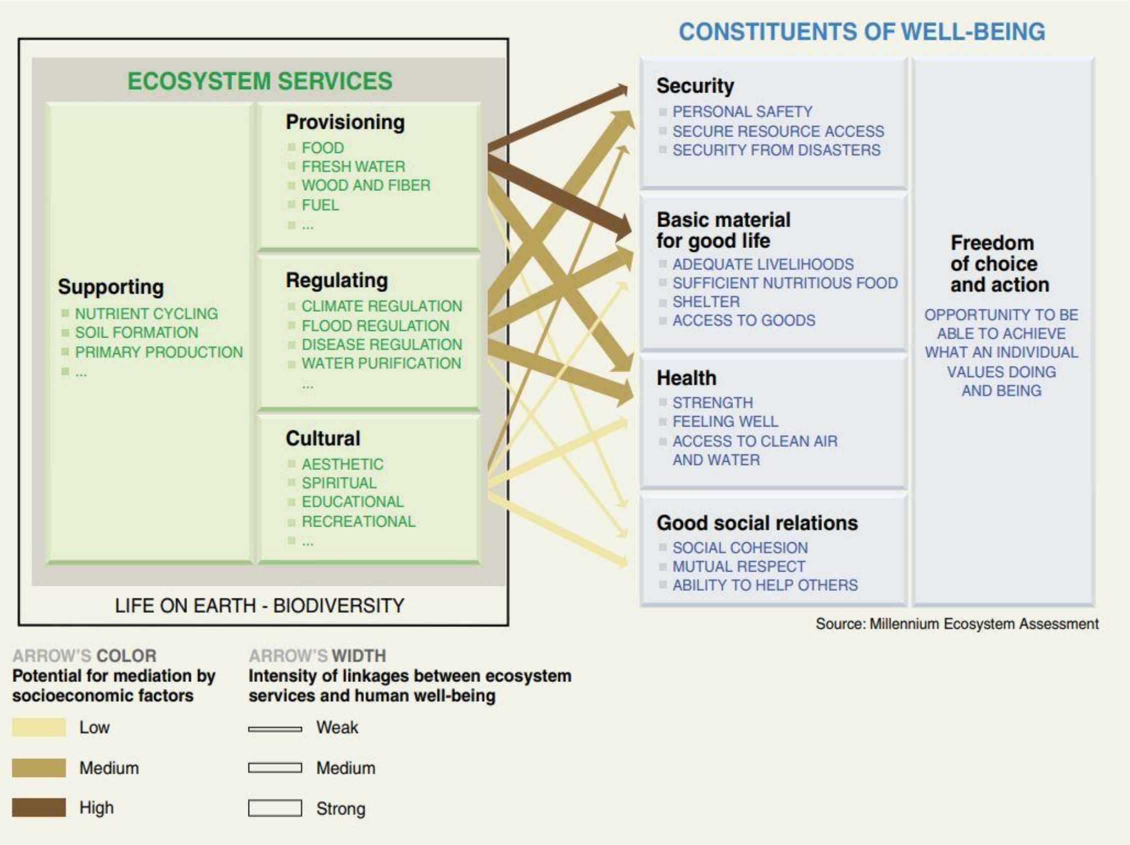


Figure 1.2: Connection between ecosystem services and contribution to constituents of human wellbeing. Provisioning and regulating services have the strongest connections to wellbeing, but can be readily mediated through socioeconomic factors. Cultural services have weaker connection to human wellbeing, but less able to be remedied through socioeconomic factors (MEA, 2005).

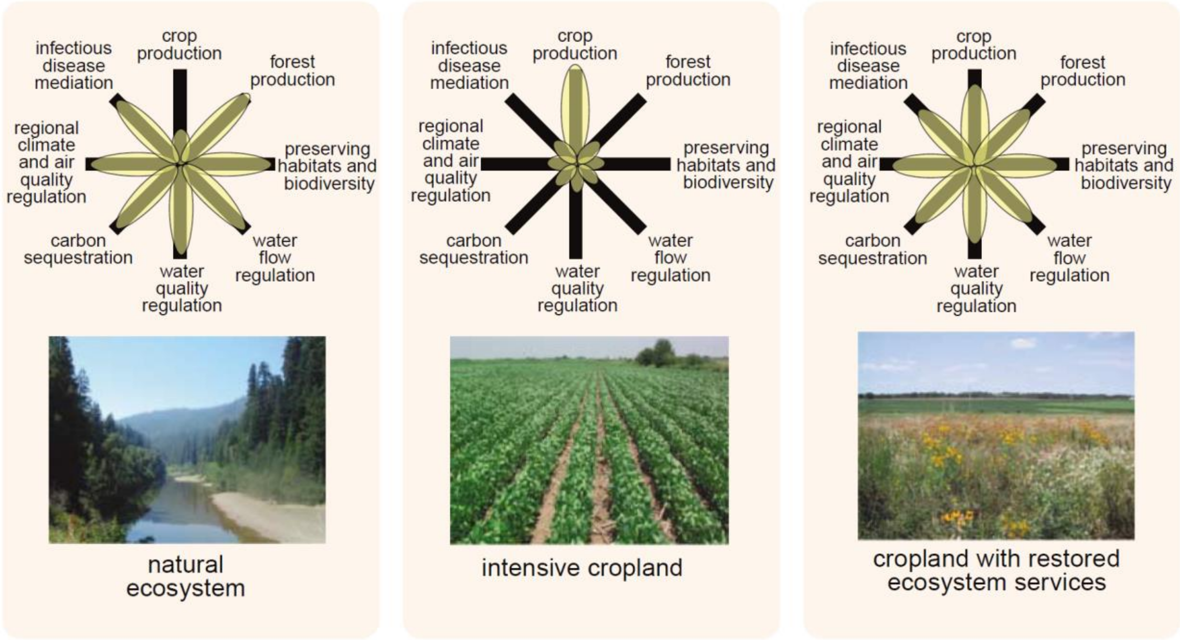


Figure 1.3: Conceptual framework depicting the delivery of provisioning and regulating services and trade-offs under varying land use. The left most image suggests limited provisioning services and strong regulating services in natural ecosystems, whereas under intensive cropping in the middle image, the opposite is true. In restored ecosystems, provisioning and regulating services are more balanced (Foley et al., 2005).

Another challenge of the ecosystem services approach is the lack of relevant information available to implement such a framework at the local scale (Burkhard et al., 2012). As mentioned earlier, monitoring data at Lake Wairarapa only spans the past 25 years; even here, data are intermittent due to not being able to access the lake for routine quarterly monitoring due to weather conditions (Perrie & Milne, 2012). Therefore, the determination of long-term trends and changes in ecosystem services are consequently difficult and likely to be inferential.

Finally, there is a very strong tendency toward economic pricing methodologies within ecosystem service literature. The argument for the inclusion of economic metrics is that estimation and assessment of monetary value allows for the ‘true’ costs and benefits to be considered; that is, environmental effects that are otherwise priced as zero (i.e. market failures and externalities) are accounted for in environmental decision-making (TEEB, 2010). While provisioning services are often able to be adequately priced in the free market, most ecosystem services typically are either open access resources (rival, non-excludable) or public goods and services (non-rival, non-excludable), and thus are more difficult to adequately price (Table 1.1) (Costanza et al., 2014). Burkhard et al. (2012)

also suggest the outcome of monetary approaches to valuing ecosystem services are often unsatisfactory, lacking appropriating pricing mechanisms for many aspects.

Table 1.1: Typology of economic goods and ecosystem services, based on excludability and rivalry (Costanza, 2009).

Ecosystem services classified according to their excludability and rivalness		
	Excludable	Non-excludable
Rival	Market goods and services (most provisioning services)	Open access resources (some provisioning services)
Non-rival	Club goods (some recreation services)	Public goods and services (most regulatory and cultural services)

Despite its limitations, an ecosystem services framework provides a useful approach for considering the physical impacts on environments of different land use changes, as well as a tool for assessing how the provision of different ecosystem services contributes to a healthy community.

1.3 Lake Wairarapa information and site setting

This section provides an overview of Lake Wairarapa and its catchment characteristics. It is not comprehensive, and some areas are covered in further detail in subsequent chapters.

1.3.1 Lake extent and location

At 6,000 cal yr BP (calibrated years based on radiocarbon dating methods), the area that is currently known as Lake Wairarapa was part of a large, shallow, estuarine embayment, which extended from the coast near present-day Lake Ōnoke and as far inland as Papawai (Fig. 1.4) (Hayward et al., 2011). Lake Wairarapa transitioned from an estuarine to a lacustrine lake at around 3,400 cal yr BP due to progradation of the Ruamāhanga River and emergence of the Lake Ōnoke gravel bar (Hayward et al., 2011; Leach & Anderson, 1974). By 3,000 cal yr BP the formation of ancestral versions of Lakes Wairarapa and Ōnoke were beginning to emerge (Hayward et al., 2011).

Today, Lake Wairarapa (41.21° S, 175.24° E) is a shallow (maximum depth of 2.7 m), isothermic lake situated at the bottom of the Wairarapa Valley (Fig. 1.5) (Perrie & Milne, 2012). It is the largest lake in the Greater Wellington region, with a modern surface area of 78 km^2 (Perrie & Milne, 2012). Currently, the lake is 18.2 km long and 6.1 km wide, although it should be noted that this is a significant reduction in size prior to flood control and river diversion interventions (Airey et al., 2000; Trodahl et al., 2016).

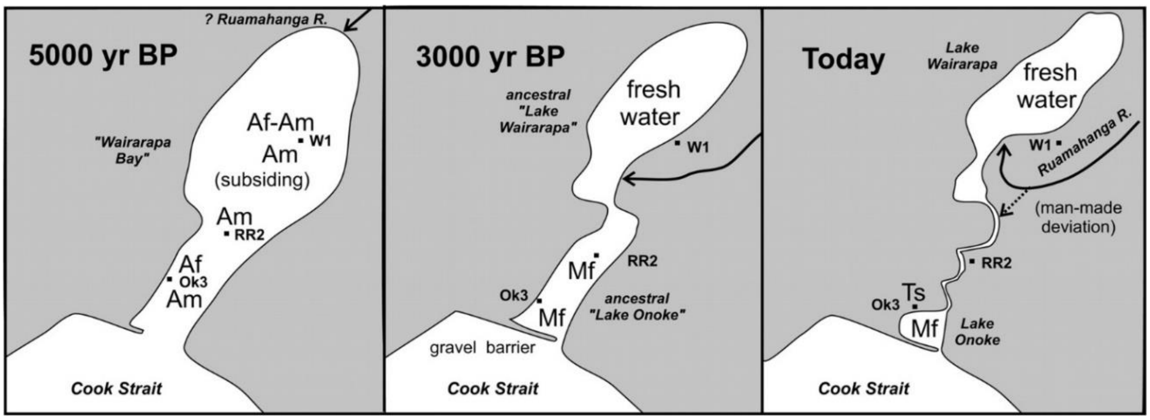


Figure 1.4: Development and emergence of Lakes Ōnoke and Wairarapa over the past 5000 years. This exhibits a slow transition from an oceanic embayment to freshwater lakes (although with persisting marine influences) (Hayward et al., 2011).

1.3.2 Geology

Lake Wairarapa is situated upon alluvial deposits from the surrounding hills and ranges (Trodahl et al., 2016). The ranges to the east of the lake consist of a mosaic of sandstone, mudstone, and limestone that originated during the Cretaceous and Palaeogene periods (Trodahl et al., 2016). The western Remutaka[1] and Tararua Ranges consist of Triassic-Jurassic indurated greywacke, which has been heavily impacted by fault activity (Trodahl et al., 2016). The subducting Pacific Plate lies 30 km below the Wairarapa Valley; a belt of strike-slip faults borders the western margin of the valley, including the Wairarapa Fault, which moves at a rate of 12 mm per year (Cape et al., 1990).

Positioned on the subducting plate, Lake Wairarapa is subsiding under the Indo-Australian Plate (Little et al., 2009). The most recent significant deformation of the Wairarapa Fault occurred in 1855 and is the largest recorded earthquake across New

[1] 'Remutaka' denotes the correct Māori spelling of the mountain ranges, as opposed to the currently used 'Rimutaka'. Remutaka translates to "a place to sit" or "to sit down", describing the journey of a Māori chief, Haunui-a-nanaia, across the Wairarapa region. Rimutaka has no direct translation in Te Reo Māori (Rangitāne Education, 2015).

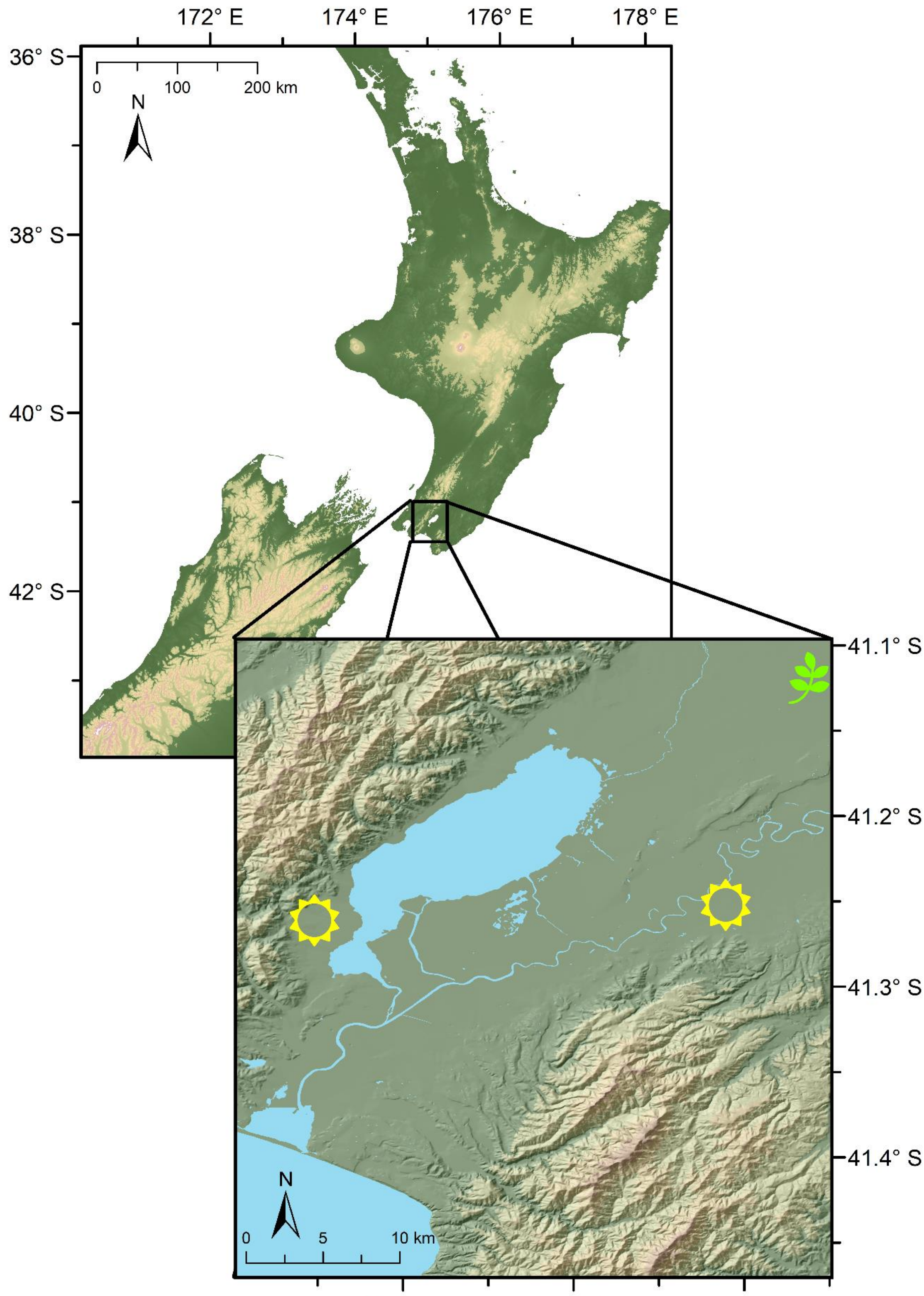


Figure 1.5: Geographical location of Lake Wairarapa in the lower North Island of New Zealand. Sun symbols in the insert show climate stations (eastern symbol being Waiorongomai climate station, and western symbol Martinborough Ews climate station), and leaf symbol the location of fossil pollen records at Bidwill Hill.

Zealand since European arrival, with a magnitude of 8.2 on the Richter scale (Darby & Beanland, 1992; Little et al., 2009). This resulted in a 12-m dextral offset and an average uplift of 1 m (2.7 m uplift at Turakirae Head) (Darby & Beanland, 1992).

1.3.3 Climate

Data from the National Institute of Water and Atmospheric Research (NIWA) Waiorongomai climate station located at the southern end of Lake Wairarapa (Fig. 1.5) between 1970 and 1993 gives an indication on the local climate. Mean annual rainfall at the lake during this 23-year period averaged 1617.47 mm, with summer and winter mean values of 97.73 mm and 173.42 mm, respectively (Fig. 1.6) (NIWA, 2019). The position of Lake Wairarapa (and the Waiorongomai climate station) at the foothills of the Remutaka and Tararua Ranges leads to an orographic effect of rainfall on local climate, with areas east of the lake (e.g. Martinborough) being much drier (Fig. 1.7a) (NIWA, 2012b; Trodahl et al., 2016). Mean air temperature at Waiorongomai station was 12.61°C between 1970 and 1993, with a summer mean of 16.11°C and winter mean of 8.66°C (Fig. 1.6) (NIWA, 2019). Air temperature is much less variable over the valley (Fig. 1.7b) (NIWA, 2012a).

As wind speed and direction was not monitored at the Waiorongomai climate station, data was taken from the Martinborough Ews (Electronic Weather Station) climate station, which is farther from Lake Wairarapa (Fig. 1.5). The wind rose shown in Fig. 1.8 suggests a clear dichotomy in prevalent wind direction. Winds from the north-east to east-north-east direction are the most common, particularly in lower wind speeds between 0-6 m s^{-1} (moving down the Wairarapa Valley). However, higher wind speeds are typically observed from the west-north-west to west direction (over the Remutaka Ranges).

It is important to note that while data from the climate stations can provide a good indicator of local climate, the Waiorongomai data only spans 23 years and Martinborough Ews 18 years (NIWA, 2019). Therefore, data presented here may not account for longer-term changes such as the El Niño Southern Oscillation (ENSO) or Southern Annular Mode (SAM) climate variability patterns or more recent trends in global warming (Jiang et al., 2013; Salinger & Mullan, 1999).

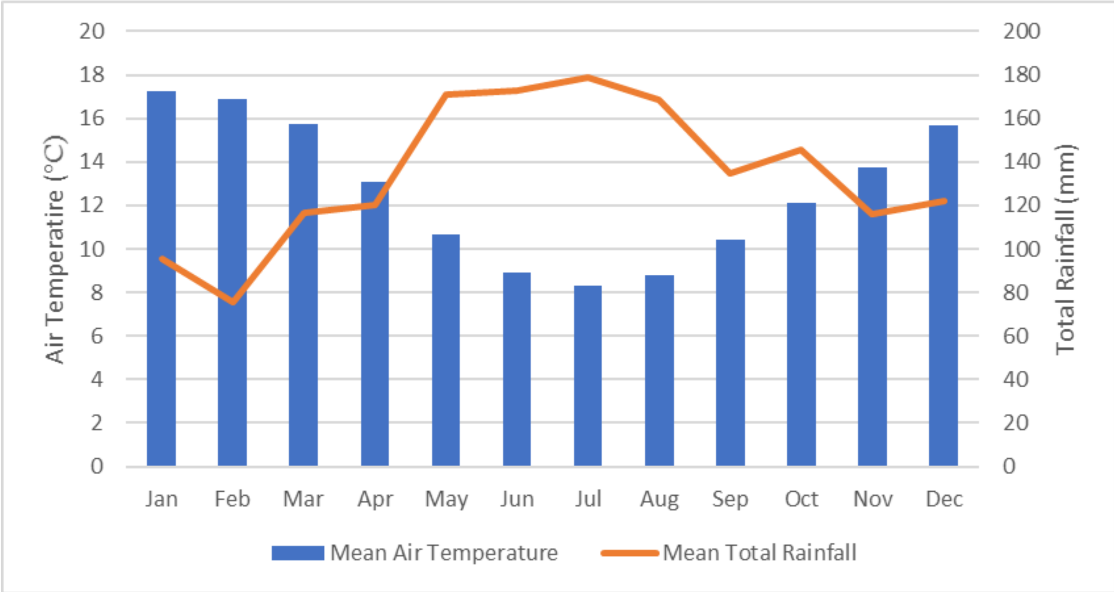


Figure 1.6: Mean air temperature and total rainfall at Waiorongomai climate station between 1970-1993 (NIWA, 2019)

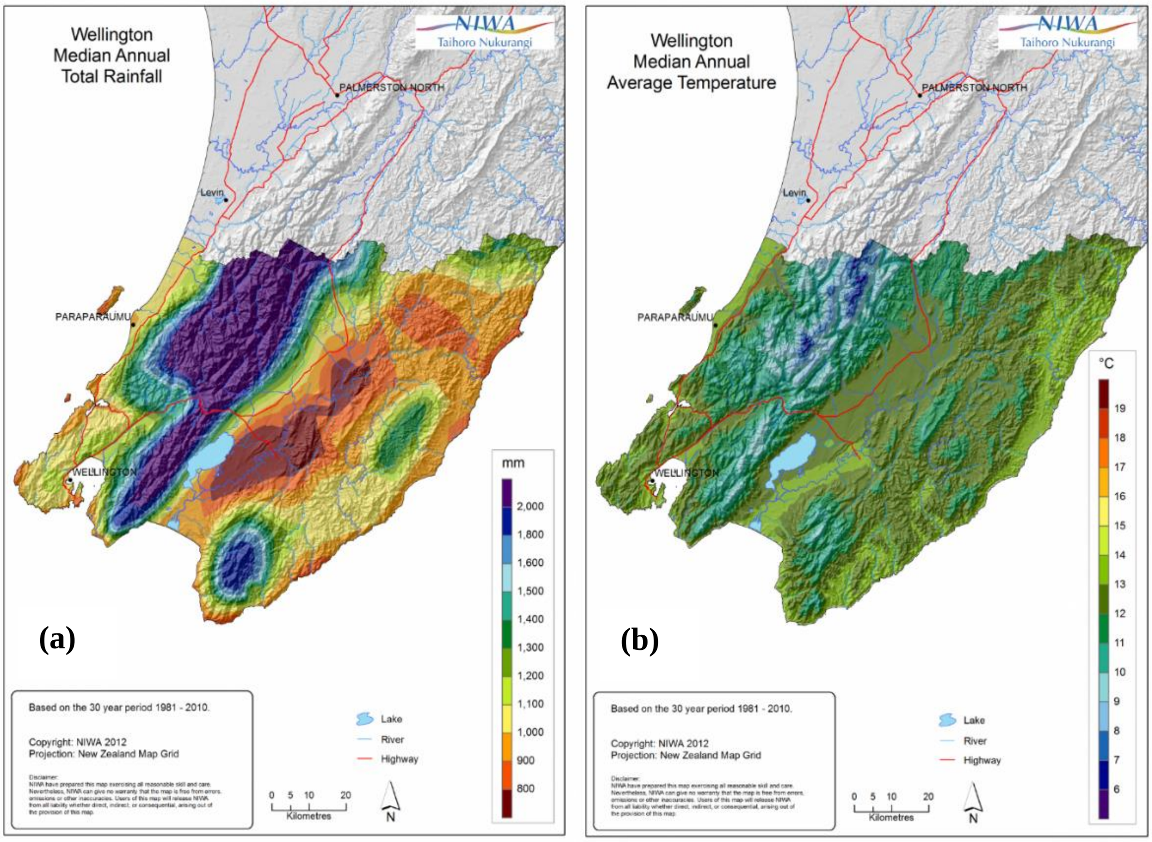


Figure 1.7: (a) Median total rainfall and (b) median annual average temperature for the Greater Wellington Region, from 1981 to 2010 (NIWA, 2012a, 2012b).

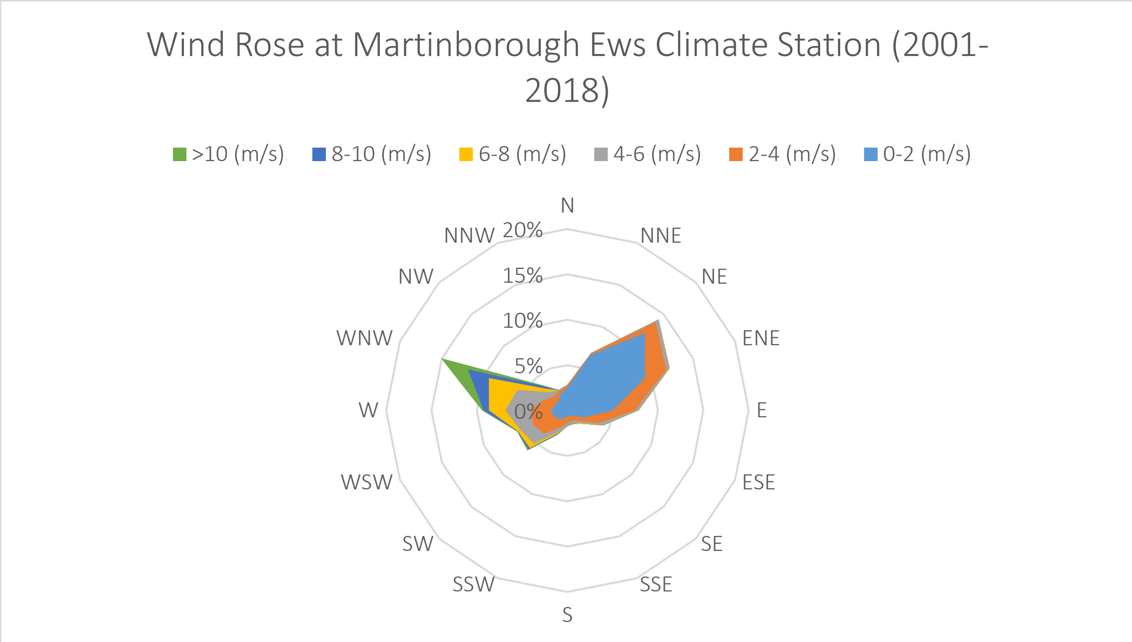


Figure 1.8: Wind speed and direction from daily data at Martinborough Ews (Electronic Weather Station) Climate Station from April 2001 to December 2018 (NIWA, 2019)

1.3.4 Vegetation and land cover

Pollen records near Lake Wairarapa from Bidwill Hill (Fig. 1.5) span from around 100,000 to 80,000 yr BP and covers the early stage of the Last Glacial Period (around 115,000 to 11,700 years ago) (Palmer et al., 1989). This can be considered analogous of modern vegetation communities without human land use alterations, and is characterised as cool but moist (Palmer et al., 1989). The Wairarapa Valley was dominated primarily by *Fuscospora* species (hard, mountain, and black beech species), which accounted for 60% of the record, and *Lophozoni menzeseii* (silver beech) which accounted for a further 8-20% (Palmer et al., 1989). Other trees observed include *Libocedrus* (kawaka), *Prumnopitys taxifolia* (mataī), *Dacrycarpus dacrydioides* (kahikatea), and *Dacrydium cupressinum* (rimu) (Palmer et al., 1989). Further transition into the glacial period is characterised as likely cool and windy. Pollen records show a continued increase in *F. fusca*-type to 83% but marked reduction in most other types of pollen (some prevalence of *Myrsine* (māpou) shrubs), suggesting a valley floor with a paucity of vegetation (Palmer et al., 1989). Once the glacial period was in force, very little pollen was observed beyond hardy shrubs (Palmer et al., 1989).

More recent palynological records from Pohehe Swamp in northern Wairarapa show a similar response to changing climate in the region (McLea, 1990). Warmer conditions support dominance of *F. fusca*-type and silver beech, alongside smaller proportions of rimu, *Prumnopitys ferruginea* (miro), matai, *Podocarpus totara* (tōtara), kahikatea, and *Weinmannia racemosa* (kāmahi) (McLea, 1990). Whereas cooler conditions demonstrated a decline in beech species and growing proportions of Poaceae (grasses), Asteraceae (daisies), and small shrubs such as *Halocarpus*, *Phyllocladus* and *Coprosma* (McLea, 1990).

Warm contemporary climate conditions support continued dominance of beech species along the Remutaka and Tararua Ranges, with indigenous forest accounting for 43.9% of the current Lake Wairarapa catchment (Perrie & Milne, 2012). However, this is primarily constrained to the higher elevation ranges. In the lowlands, the predominant land cover is pastoral agriculture, which accounts for 54.0% of the total catchment area. This includes both high producing (42%) and low producing (12%) agriculture (Perrie & Milne, 2012).

1.3.5 Tributaries and the Lower Wairarapa Valley Development Scheme

Implementation and completion of the Lower Wairarapa Valley Development Scheme (LWVDS) in 1983 saw great modification to Lake Wairarapa’s catchment for flood protection (Greater Wellington Regional Council, 2014a). The main tributary into the lake prior to the scheme was the Ruamāhanga River, which entered on the eastern side of the lake (Trodahl et al., 2016). The LWVDS subsequently diverted the Ruamāhanga River away from Lake Wairarapa to instead flow to Lake Ōnoke, near the Palliser Bay coast (Greater Wellington Regional Council, 2014a; Perrie, 2005). The outlet of Lake Wairarapa was also modified with barrage gates to maintain the ocean outlet at Lake Ōnoke and to receive excess waters from the Ruamāhanga River in a flood event (Greater Wellington Regional Council, 2014a).

Catchment extent for Lake Wairarapa covered 307,390 ha prior to the diversion, whereas it now covers 57,245 ha; an 80% reduction in total catchment extent (Perrie & Milne, 2012). However, the implementation of the LWVDS is said to have had great economic benefits to the region, with an increase of 19.8 million NZD annually as a result of the scheme (Greater Wellington Regional Council, 2014a). Since the completion of the scheme, the main tributary for Lake Wairarapa is the Tauherenikau River, which enters from the northern end of the lake and drains the Tararua Ranges (Perrie & Milne, 2012).

The LWVDS has consequently led to changes in sediment accumulation and distribution. Total surface area of Lake Wairarapa has decreased, with sediment accumulation along the eastern shore and erosion from the west – a complete reversal of the traditional depositional pattern. Despite this, total volume of the lake has only decreased by 0.01 km^3, indicating a slight deepening overall (Perrie, 2005; Trodahl et al., 2016).

1.3.6 Water quality

Lake Wairarapa is the only lake in the Greater Wellington region to have routinely monitored water quality, with data collected since 1994 (Perrie & Milne, 2012). Currently, the lake has a Trophic Level Index (TLI) value of 5.4, indicating supertrophic (very poor) water quality status. This overall value is heavily governed by hypertrophic values of total phosphorus (mean: 0.106 mg L^{-1}) and Secchi depth (mean: 0.30 m). Total nitrogen and chlorophyll *a* have eutrophic values (0.595 mg L^{-1} and 8.5 mg per m^3, respectively) (Perrie & Milne, 2012). Here, nitrogen is postulated to be the limiting nutrient. Non-volatile suspended solids (NVSS) also exert a strong control on Lake Wairarapa water quality, with all four TLI indicators showing deteriorating trends with increased NVSS values (Perrie & Milne, 2012). Since monitoring began, there has been no significant change in the water quality at Lake Wairarapa between 1994 and 2010 (Perrie & Milne, 2012). As mentioned earlier, the lack of long-term records presents a challenge in determining a baseline for Lake Wairarapa water quality.

1.3.7 Wetlands & Ramsar status

'Wairarapa Moana' (the collective of Lakes Wairarapa and Ōnoke, and the surrounding wetlands) have high ecological values (Greater Wellington Regional Council, 2015). Covering 9,000 ha, Wairarapa Moana possesses high biological diversity and is considered internationally significant due to the number of rare, endangered, nationally threatened, and regionally rare floral and faunal species (Airey et al., 2000; Perrie & Milne, 2012). Submerged turf communities (primarily aquatic herbaceous vascular plants) are the largest in the North Island. The area attracts over 90 bird species, such as the bar-tailed godwit (*Limosa lapponica*), banded and black-fronted dotterels (*Charadrius bicinctus* and *Elseyornis melanops*), pied stilt (*Himantopus leucocephalus*), and Caspian tern (*Hydroprogne caspia*). The lakes provide habitat for ten indigenous fish species, including longfin and shortfin eels (*Anguilla dieffenbachia* and *Anguilla australis*), brown mudfish (*Neochanna apoda*), and giant kōkopu (*Galaxias argenteus*) (Airey et al., 2000).

Wairarapa Moana is currently under consideration by the New Zealand government to be nominated for Ramsar status, due to its habitat values and the important role it plays in preserving ecological and genetic diversity (Airey et al., 2000; Porteous, 2015). The Ramsar Convention on Wetlands is an intergovernmental treaty aimed at promoting wise use and conservation of wetlands (Ramsar Convention Secretariat, 2016). Achieving Ramsar status would likely increase sustainable management emphasis in planning documents, increase international and national social and political pressure to ensure 'wise use', and increase funding and integrated management opportunities (Denyer & Robertson, 2016). This would be an immense step forward for enhancing ecosystem protection and engendering collaborative management in the Wairarapa Moana wetlands.

1.4 Overarching methodology

It is evident that anthropogenic influence at Lake Wairarapa and the wider Wairarapa Moana catchment area have had, and continue to have, an immense impact on the ability of the lake to effectively provide many ecosystem services. This section discusses the overarching research design used to understand and address the research questions. Analysis of ecosystem services requires a transdisciplinary approach. Therefore, a pragmatic epistemology and an equal status mixed methods research approach has been employed.

1.4.1 Epistemology

A pragmatic epistemology was used to guide the research and answer the questions posited in section 1.1. Pragmatism involves clear focus on the problem of the research, as well as the results and consequences that research may lead to (Feilzer, 2010). Pragmatists view the world as consisting of multiple layers, some of which are objective whereas others are subjective, and that relative truth is the result of multiple realities (Baker & Schaltegger, 2015; Creswell, 2014). The use of pragmatism is advantageous in encouraging the collaboration and integration of multiple disciplines and sets of knowledge that arise from the intersection of truth and action (Creswell, 2014). It identifies problems, situations and consequences, and thus aims to deliver mechanisms for problem-solving, prediction for the future, and useable action steps (Creswell, 2014; Fendt & Kaminska-Labbé, 2011; Servillo & Schreurs, 2013).

Ecosystem service research attempts to be transdisciplinary (Costanza & Kubiszewski, 2012), and thus requires an approach where the integration of multiple disciplines is encouraged and considered advantageous. Similarly, in light of national and global concerns around freshwater quality degradation (Foley et al., 2005), an approach that aims to deliver future-focussed research is increasingly pertinent. Water quality and restoration research and outcomes must be grounded in community aspirations and values. For example, the National Policy Statement for Freshwater Management outlines not only guidelines for ecological health, but also stresses the importance of maintaining values that are important to New Zealanders (Ministry for the Environment, 2017). Similarly, utilisation of the Cultural Health Index further highlight the importance of incorporating Māori values within freshwater management (Ministry for the Environment, 2006). Therefore, employment of a pragmatic approach to address water quality and lake restoration work at Lake Wairarapa is necessary.

1.4.2 Mixed methods approach

Given its multidisciplinary approach, pragmatism does not solely rely on a certain methodology to understand an issue; thus, it is conducive to a pluralist research approach and often involves the inclusion of both quantitative and qualitative methods (Feilzer, 2010). Here, ‘engaged pluralism’ refers to the open validation, acceptance and respect of multiple methodological approaches to research and identification of shared goals among researchers (DeLyser & Sui, 2014). Indeed, Barnes (2011) argued that pluralism within the geography discipline is the most important factor when trying to understand a changing world.

The transdisciplinary nature of ecosystem services research, alongside a pragmatic epistemology, lends itself to a mixed methods research approach. In fact, mixed methods research is recommended when conducting pragmatic research (Johnson & Onwuegbuzie, 2004). Mixed methods research involves the inclusion of both qualitative and quantitative forms of research and is able to draw upon the strengths of both approaches as well as minimise the limitations (Creswell, 2014). While still a relatively young approach to research, it is growing rapidly (O'Leary, 2017).

Given the scope of the research questions, a mixed methods approach was taken to comprehensively and holistically address ecosystem services at Lake Wairarapa. An 'Equal Status Mixed Method Design' was employed, whereby both qualitative and quantitative methodologies are equally valued and utilised to contribute to an understanding of ecosystem services at Lake Wairarapa (Tashakkori et al., 1998). While two studies are quantitative and the third qualitative, I argue that this research is equal status mixed methods rather than quantitative dominant mixed methods as overall conclusions could not have be drawn with just a quantitative or qualitative approach (Johnson et al., 2007). The individual methods for each study are outlined in their respective chapters.

1.4.3 Thesis outline

To ground the ecosystem services approach, this thesis undertook a temporal, i.e. past, present, and future, perspective to understand and answer the research questions. Each of the following three chapters contribute in different ways to this. In Chapter 2, a quantitative palaeolimnological study of a 2-m lake sediment core and investigation of five proxies was used to understand the condition of Lake Wairarapa prior to human arrival and the impacts of subsequent anthropogenic land use. Chapter 3 used quantitative soil science methods to investigate the potential antimicrobial properties of mānuka to mitigate bacterial contamination and nitrogenous pollution in a field trial based at Lake Wairarapa. Qualitative interviewing methods were employed in Chapter 4 to better appreciate a range of societal values held for Lake Wairarapa and the aspirations of participants for the lake's future. Chapter 5 synthesises important results and combines findings from the previous three chapters to contribute to a holistic understanding of ecosystem services at Lake Wairarapa over the past and present and toward the future.

Chapter Two: Past. An investigation of lacustrine sediments and ecosystem services at Lake Wairarapa

2.1 Introduction

Lake ecosystems and the surrounding environments provide a multitude of ecosystem services that contribute directly to human health and wellbeing (Schallenberg et al., 2013). Despite this, continued declining trends in national lake water quality and pressure on ecosystems from land use change and intensification highlight the need to develop effective lake resource management plans (Verburg et al., 2010). New Zealand has around 3,820 lakes greater than 1 ha, but of the 119 New Zealand lakes that are currently monitored by regional councils with adequate data, 44% are classed as eutrophic or worse and are those primarily situated in catchments dominated by agriculture (Verburg et al., 2010). The paucity of sufficiently detailed historical information regarding lakes and their ecosystems creates a big challenge in developing robust, evidence-based management and restoration plans.

In the case of Lake Wairarapa, published scientific monitoring data completed by Greater Wellington Regional Council (GWRC) only exists from 1994 to 2010 (although ongoing) (Perrie & Milne, 2012). By 1994, the lake had already been altered by centuries of Māori occupation and subsequent European settlement and land use intensification (Trodahl et al., 2016). Most recently, hydrologic engineering of the Ruamāhanga River in the 1980s has resulted in profound changes in the catchment extent of Lake Wairarapa and reversal of historical zones of sediment accumulation and depletion (Trodahl et al., 2016).

To attain a greater understanding of historical ecosystem services at Lake Wairarapa, a palaeolimnological investigation of lacustrine (lake) sediments has been undertaken. Detailed further in section 2.2, the analysis of multiple proxies such as charcoal, geochemistry, grain size, organic content, and environmental DNA allows the reconstruction of past environmental variability which can provide insight into temporal changes within the lake and its surrounding catchment (Cohen, 2003) . The use of a multi-proxy approach engenders the production of evidence-based solutions to a degraded landscape.

The aim of this study is to contribute to the development of an environmental history of Lake Wairarapa by addressing the following research questions:

1. What was the environment of Lake Wairarapa like prior to human arrival?
2. How have humans modified the environment and what impact has this had on the Lake Wairarapa ecosystem? Has Lake Wairarapa’s current state resulted from a slow and gradual trajectory developing over centuries or a rapid, exponential response similar to the Great Acceleration?

In the absence of long-term records, response to question one will assist in developing a natural reference state in which future land management and restoration work can be grounded. In considering question two, humans have undoubtedly had a significant impact on Lake Wairarapa. Yet, by understanding how different anthropogenic pressures affected the landscape, this can help identify the most severe impacts and inform necessary priorities for remediation. Changing anthropogenic pressures also provide insights into the shifting demands for ecosystem services over time.

2.2 Literature review

In order to understand the current status of Lake Wairarapa and to provide ecological, evidence-based management and restoration recommendations (Chapter 5), it is essential to understand the environmental history of the lake and its surrounding catchment. The arrival of humans in New Zealand and the relationships that different populations have had with the environment is important for fully understanding current relationships and demands for ecosystem services. As discussed in Chapter 1, Lake Wairarapa and the surrounding ecosystem provide a multitude of services that have directly enhanced human health and wellbeing. Examples include the provision of food and fuel resources, regulation of floods and water purification, and recreational opportunities and spiritual wellbeing (Schallenberg et al., 2013).

2.2.1 Lakes as sentinels of environmental change

Lakes are an excellent archive of environmental change (Adrian et al., 2009; Williamson et al., 2009). Variables such as climate, catchment geology, seismicity, volcanism, terrestrial and aquatic flora and fauna, anthropogenic activity, and the interactions between them, all contribute to environmental change (Cohen, 2003). Such variables and interactions result in the production and displacement of organic and inorganic material from autochthonous and allochthonous sources, which are subsequently accumulated and deposited at the bottom of the lake throughout time (Smol, 2008). Palaeolimnology is the study of these materials, providing evidence of the conditions of the lake and wider terrestrial environment at the time of deposition. These layers accumulate in a relatively undisturbed benthic environment, such that lake sediment deposits act as natural archives of environmental history (Cohen, 2003; Smol, 2008).

2.2.2 Using multiple indicators to infer environmental change

The ongoing development and analysis of lacustrine sediments has been critical in addressing many global environmental issues and can inform contemporary anthropogenic concerns. Smol (2008) outlined several vital issues from a palaeolimnological perspective, including acidic deposition (i.e. ‘acid rain’), ozone depletion, climate change, and intensified land use, as well as the cumulative effects of these stressors acting in unison. The lack of long-term modern monitoring data for most New Zealand lakes further increases the need for palaeolimnological reconstructions to inform lake management (Augustinus et al., 2006). For Lake Wairarapa, the Greater Wellington Regional Council (GWRC) has monitored the lake intermittently for the past 25 years (since 1994) (Perrie & Milne, 2012). However, adverse weather conditions often prevent safe access on the lake to complete monitoring, with data collection averaging 2.6 times per year compared to the planned quarterly monitoring programme (Perrie & Milne, 2012).

Geographically isolated and untouched by humans until around 1280 CE (McGlone & Wilmshurst, 1999), New Zealand provides an excellent environmental archive, particularly of anthropogenic-induced environmental change (Newnham et al., 1999). Diversity in sediment types, local and regional climate, anthropogenic variation, as well as the inherent strengths and limitations between individual proxies means a multi-proxy approach to environmental reconstructions is often necessary to improve understanding of a lake and its catchment (Davies et al., 2015).

The following sections (sections 2.2.3 to 2.2.7) outline five key classic and novel analyses that have been used or are under development in New Zealand-based palaeolimnological research, namely: charcoal, sediment geochemistry, grain size, organic content, and environmental DNA.

2.2.3 Charcoal analysis

The analysis of charcoal fragments in sediment cores provides insight into past fire regimes at Lake Wairarapa. Determining the fire history of a landscape can suggest anthropogenic impact on the environment; the linkages between climatic changes, fires, and vegetation; and the contribution of biomass burning to global carbon cycles (Ali et al., 2009). Microscopic charcoal (diameter (ø) < 100 µm) often reflects a regional signal (≤ 100 km radius) (Peters & Higuera, 2007), whereas macroscopic charcoal (ø > 100 µm) primarily indicates local fire history around 1-2 km from the lake edge (Carcaillet et al., 2001). This distinction is generally well established within the literature (Patterson et al., 1987; Whitlock & Larsen, 2001); however, some evidence suggests macroscopic charcoal can originate from a distance of at least 5 km from a fire during a large burn (Tinner et al., 2006), and the impact of secondary charcoal transport and lake mixing may also obscure fire signals (Higuera et al., 2007).

Globally, the drivers of fire regimes are often hard to disentangle. In places such as Australia, where humans have a long history of habitation, the relative contributions of climate versus human activity to fire frequency are difficult to discern (Lynch et al., 2007; Mooney et al., 2011). In New Zealand, however, fire history predominately reflects anthropogenic impact rather than complex relationships between climate and fuel sources (McWethy et al., 2010). While some areas vegetated with drier scrubland or open forest did experience higher rates of natural fire, including parts of Canterbury and Otago (Perry et al., 2014), the majority of New Zealand (70-80%) was covered in native podocarp and beech forests (Perry et al., 2014; Perry et al., 2012). These forests are wet and lack a source of ignition; thus fire was uncommon in most of the pre-human landscape beyond occasional lightning strikes and rare wildfires following large volcanic eruptions (Perry et al., 2014).

Early Māori arrival was detected in lake sediments at approximately 1280 CE, based on a drastically altered landscape (McGlone & Wilmshurst, 1999; Wilmshurst et al., 2008). Deforestation was rapid once anthropogenic fire regimes started, with 40-50% of total forest cover in the South Island lost within 60-155 years following arrival (McWethy et al., 2010). Perry et al. (2012) determined a positive feedback mechanism between individual fire events and increased total flammability of the landscape; that is, once a fire regime was initiated, it was difficult to stop. Except for extremely wet and high elevation sites, the Initial Burning Period (IBP) between 1280-1600 CE following Māori arrival was evident through macroscopic charcoal over most of the South Island (McWethy et al., 2010). These sites primarily followed a three-staged pattern in the development of fire history: intense initial burning for several decades following the IBP, less frequent and severe fires during later Māori occupation (ca. 1600-1840 CE), then increased intensity and frequency again with European settlement (McWethy et al., 2010). Similarly, clear evidence of anthropogenic impact is observed in microscopic charcoal results in North Island studies (Chester & Prior, 2004; Li et al., 2014; Wilmshurst & McGlone, 2005).

As the standard marker for human arrival in New Zealand, charcoal analysis is critical for any study investigating the impact of humans on the environment. Precise human arrival is not known for Lake Wairarapa; thus significant increases in macroscopic charcoal provide indirect evidence of Māori presence in the proximal area. Other changes following a substantial increase in charcoal would likely represent an alteration of ecosystem services to support human demand.

2.2.4 Geochemical X-ray fluorescence analysis

Analysis of sediment geochemistry can provide insight into changes or events within Lake Wairarapa's catchment. X-ray fluorescence (XRF) is a quick, globally established, and non-destructive method (Davies et al., 2015), although it has only recently been applied to New Zealand's natural archives. The technique involves the emission of fluorescent energy and evaluation of the spectra of wavelengths that follow X-radiation pulses (Weltje & Tjallingii, 2008). Elements emit characteristic wavelengths that correlate to their abundance in the sediment (Weltje & Tjallingii, 2008). The applications of this method are rapidly expanding as it can be used to infer catchment events (e.g. floods, landslides), climate variability, and anthropogenic impact (Davies et al., 2015).

Typically, concentrations of lithogenic elements such as aluminium (Al), silicon, (Si), potassium (K), titanium (Ti), iron (Fe), rubidium (Rb) and zirconium (Zr) are used as indicators of detrital (weathered particles from rocks) input, due to their chemical stability and preservation over a long period (Davies et al., 2015). In particular, titanium is associated with silts and often reflects catchment erosion in some depositional environments (Davies et al., 2015).

Despite the use of XRF in the Northern Hemisphere (Brown et al., 2015; El Ouahabi et al., 2018), studies that explore chemical relationships in New Zealand are limited, predominantly focusing on earthquakes. Using XRF, McWethy et al. (2010) found increased concentrations of Ti, K, and calcium (Ca) corresponded to inferred earthquake events and fire events across the South Island. At Lake Taupō, elevated concentrations of Al, sodium (Na), Rb and caesium (Cs) corresponded to pumice deposits associated with detrital input (Koyama et al., 1989). Similarly, micro-XRF (high resolution core scanning) was employed in determining Holocene tephrochronology (volcanic eruption dating through tephra layers) at Lake Pupuke (Zawalna-Geer et al., 2016).

While many studies incorporate organic geochemistry (Augustinus et al., 2006; Howarth et al., 2014) and stable isotope records (Heyng et al., 2012), few published XRF analyses within New Zealand target anthropogenic impacts. Given its widespread use, non-destructive nature, and breadth of data outputs (Davies et al., 2015), XRF is a key technique for understanding Lake Wairarapa's environmental history.

2.2.5 Grain size analysis

Another mechanism for investigating changes in Lake Wairarapa's catchment is clastic sediment grain size analysis. This analysis looks at the abundance of different sized grains within the sedimentary record, distinguishing between clays (ø < 4 µm), silts (ø = 4-63 µm), and sands (ø = 63-2000 µm) (Boggs, 2006; Smol, 2008). Sediment grains on the landscape are mobilised through erosion and weathering processes, then transported to lake systems through surface runoff, and fluvial and aeolian deposition. Grain size distribution can be used to infer catchment-scale events such as climatic variability, land use changes, and singular hazard events such as earthquakes and tsunami (Howarth et al., 2012; Huang et al., 2015; Sun et al., 2002).

Changes in grain size from anthropogenic land use is evident following conversion from forest to dairy farming at Lake Pupuke around the time of European settlement in Auckland (1845) (Augustinus et al., 2006). Land use change likely resulted in a decrease in mean grain size through an increased percentage of very fine silts and clays (ø < 10 µm) and a reduction in sands (ø > 63 µm) (Augustinus et al., 2006). Examples of singular hazard events are evident at Lake Paringa in the Southern Alps. Here, recurring grain size sequences of megaturbidites, turbidite stacks, and interbedded organic silts archive ruptures of the Alpine Fault (Howarth et al., 2012).

Clastic sediment grain size data can also be coupled with modern records to inform decision-making. At Lakes Tutira and Waikopiro, grain size was used to determine erosion rates from storm events (Page et al., 1994). Graded beds were observed in these events, with a sand base that graded into clays. When subsequently combined with a modern 93-year rainfall record, this provided a tool to predict future sediment influx from storms and determined that a rainfall event of > 300 mm was required to produce a noticeable sediment response (Page et al., 1994).

Grain size analysis can inform a wide range of changes in the lake catchment. When coupled with other proxies of catchment activity, like charcoal and geochemical analyses, grain size provides further insight in a weight-of-evidence approach. Therefore, its employment is crucial in building a cohesive catchment narrative about Lake Wairarapa.

2.2.6 Organic content analysis

Organic content in lake sediments can provide insight into changes in lake productivity and catchment changes, such as land use or climatic changes, at Lake Wairarapa. Periods of increased organic content indicate higher levels of autochthonous (e.g. aquatic phytoplankton and macrophytes) and/or allochthonous (e.g. marginal wetland and terrestrial plants) biological productivity (Lowe & Walker, 2015; Woszczyk et al., 2011). Loss on ignition (LOI) analysis is a quick and inexpensive method to determine the organic content of sediment (Heiri et al., 2001; Lowe & Walker, 2015).

At Lake Pupuke, Horrocks et al. (2005) observed the highest values of organic content and total organic carbon (TOC) between the Taupō (1800 cal. yr BP) and Rangitoto tephras (700 cal yr BP). They inferred that increased algal matter in the lake, in conjunction with a higher carbon influx, indicated an environment with consistent lake productivity and a stable catchment. Similarly, the authors confirmed that LOI was significantly correlated to TOC, with an r^2 value of 91.5% (Horrocks et al., 2005). At Lake Chappa'ai in the Southern Alps, organic content was used to distinguish changes in the formation of diamict facies, which the authors suggested reflected climatic variation (Woodward et al., 2018).

Loss on ignition is a good indicator of both autochthonous and allochthonous environmental changes. When coupled with other proxies, it can support an understanding of in-lake processes at Lake Wairarapa (including algal productivity) as well as changes in the terrestrial environment.

2.2.7 Environmental DNA analysis

Analysis of environmental deoxyribonucleic acid (eDNA) is among the most recent and rapidly developing proxies available to palaeoecologists (Thomsen & Willerslev, 2015). eDNA analysis can identify both microbial and macroscopic species to low taxonomic resolution, target a specific species or general community composition, and reflect a local signal of environmental change (Jorgensen et al., 2012; Sjögren et al., 2017; Thomsen & Willerslev, 2015). Preservation of eDNA is higher than pollen and macrofossils due to the vast number of cells within an organism, and the anoxic depositional environment of lake systems reduce degradation (Pedersen et al., 2015; Thomsen & Willerslev, 2015).

Like XRF analysis, eDNA is another proxy that is yet to be thoroughly explored in New Zealand palaeolimnological literature. At Round Lake in the Hawke's Bay, Matisoo-Smith et al. (2008) were able to identify DNA of the common bully (*Gobiomorphus cotidianus*) throughout the sediment record. The authors also targeted human enteric bacteria *Bacteroides* spp. and *Bifidobacterium* spp. to determine human arrival; however, amplification of non-human enteric bacteria confounded the results (Matisoo-Smith et al., 2008). Other New Zealand environmental reconstructions using eDNA have been conducted in rock shelter sediments (Haile et al., 2007), soil cores (Wilmshurst et al., 2014), and cyanobacterial mats (Martineau et al., 2013). However, as Wood et al. (2013) point out, there is still very limited application of eDNA methods by regulatory monitoring agencies, despite technological advancements and thorough methodological validation.

Analysis of prokaryotic community composition can provide insight into in-lake variations through time. Although a largely overlooked component of the ecosystem, prokaryotic organisms are particularly diverse and occupy a vast range of habitats (Torsvik et al., 2002). Understanding of prokaryotic characteristics and ecological niches can subsequently inform the environmental conditions that existed at the time of deposition (Nealson, 1997). In particular, the development of molecular biology methods in 16s ribosomal ribonucleic acid (16s rRNA) sequencing over the past 20 years has allowed for microbes to be identified rapidly to high taxonomic resolution (Nealson, 1997).

Using eDNA as a proxy for microbial community composition provides a good mechanism to understand in-lake productivity and ecosystem response to perturbation at Lake Wairarapa, complementing the catchment-scale proxies. Analysis of prokaryotic community composition at Lake Wairarapa also provides an opportunity to contribute to this growing body of literature in palaeolimnological studies.

2.2.8 Previous Lake Wairarapa research

Despite significant ecological and cultural value, little published lake sediment research has been conducted in the Greater Wellington region (Fig. 2.1). Trodahl et al. (2016) analysed historical changes in sedimentation rates at Lake Wairarapa. They identified a transition from an estuarine to lacustrine environment following a large disturbance at 2,500 cal yr BP. This event was hypothesised to be the rupturing of the Wairarapa Fault (2,740-2,290 cal yr BP) or potentially the meandering of the Ruamāhanga River into Lake Wairarapa (3,500-3,100 cal yr BP), which significantly altered its depositional setting. Similarly, the study showcased the large impact anthropogenic land use has had on sediment distribution at Lake Wairarapa (Trodahl et al., 2016). While not directly discernible, the changes in land use from European settlement, the 1855 earthquake, as well as the implementation of the Lower Wairarapa Valley Development Scheme were all likely contributing factors to the lake's current ecological condition (Trodahl et al., 2016).

Waters et al. (2018) advanced the work of Trodahl et al. (2016) through investigation of a separate 2-m sediment core from Lake Wairarapa. They used a multi-proxy approach, which incorporated LOI, clastic sediment grain size, XRF, pollen, microscopic charcoal, plant macrofossil, and diatom analyses. The authors distinguished three key land use phases archived by the Lake Wairarapa sediment core: pre-human (> 700 cal yr BP), early Māori settlement and occupation (700-95 cal yr BP), and European settlement and land use intensification (< 95 cal yr BP). In the contemporary environment, Waters et al. (2018) suggested that there is low nutrient cycling between lake sediment and the water column, with high non-bioavailable phosphorus sorbed to suspended sediments. Therefore, an emphasis on increased catchment management was recommended (Waters et al., 2018). Further information on modern and past conditions can be found in Chapter 1.

Building upon the pre-existing literature at Lake Wairarapa, the first aim of this study is to increase temporal resolution of previously analysed proxies including geochemistry, grain size, and organic content covered in Waters et al. (2018). The second aim of this study is to introduce alternative and novel proxies, namely macroscopic charcoal and eDNA, to further understand in-lake and catchment scale changes. The combination of these datasets allows for an improved reconstruction of the environmental history of Lake Wairarapa through time.

2.3 Methodology

Developing a comprehensive and detailed reference state for Lake Wairarapa and understanding anthropogenic impacts requires a number of proxies sampled at relatively high resolution. This study roughly doubled the sample resolution from the existing Lake Wairarapa core analysed in Waters et al. (2018), by adding 24 new data points to the existing 36 point dataset (60 data points in total). Where possible, methods for grain size, organic content, and geochemistry were replicated from those used by Waters et al. (2018) to maintain continuity. Two additional proxies were analysed, namely macroscopic charcoal and microbial eDNA, which were not part of the study by Waters et al. (2018).

2.3.1 Core collection and sampling strategy

A 2-m sediment core was extracted in June 2017, using a Livingston piston corer and 65-mm PVC barrel. The sediment core was transported within five hours to GNS Science (Wellington) and stored at 4°C before further analysis (Waters et al., 2018). Waters et al. (2018) analysed 36 samples using a 2-cm resolution in the top 20 cm of the core, 5-cm resolution between 20 and 100 cm, and 10-cm resolution from the remaining 1 m of core

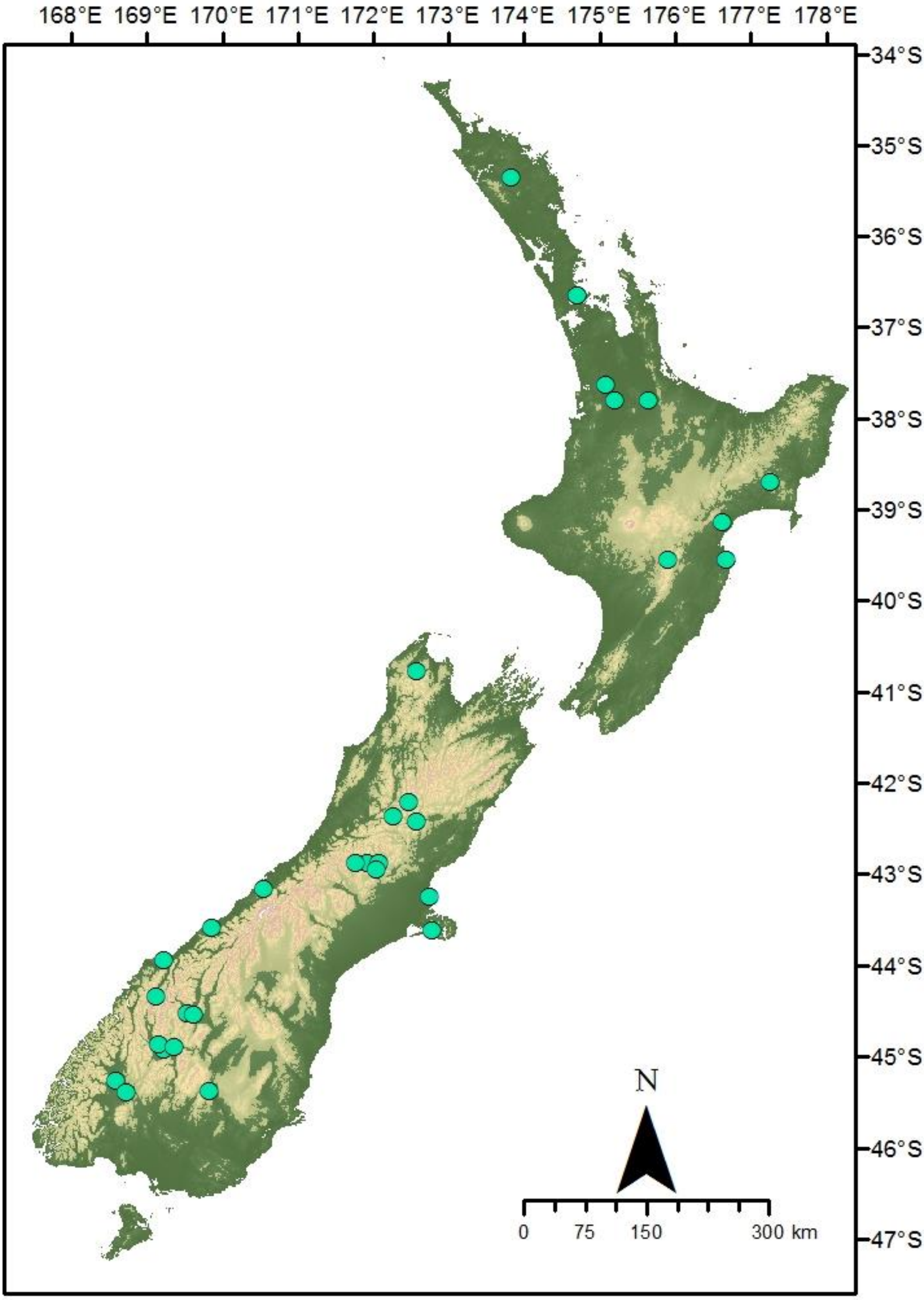

168°E 169°E 170°E 171°E 172°E 173°E 174°E 175°E 176°E 177°E 178°E
34°S
35°S
36°S
37°S
38°S
39°S
40°S
41°S
42°S
43°S
44°S
45°S
46°S
47°S
N
0 75 150 300 km

Figure 2.1: New Zealand-based literature of lacustrine sediment studies (overleaf). Study sites include Lake Tauanui, Northland (Elliot et al., 1998); Lake Pupuke, Auckland (Augustinus et al., 2006; Heyng et al., 2012; Newnham et al., 2018); Lakes Rotokauri, Okoroire, and Rotomanuka, Waikato (Newnham et al., 1989); Tinoroto Lakes, Gisborne (Li et al., 2014); Lake Tutira (Eden & Page, 1998) and Round Lake (Chester & Prior, 2004), Hawkes Bay; Lake Colenso, Manawatu (MacDonald-Creevey, 2011); Adelaide Tarn, Nelson (Jara et al., 2015); Travis Swamp (McWethy et al., 2010) and Lake Forsyth (Woodward & Shulmeister, 2005), Canterbury; and Pomahaka, Otago (McWethy et al., 2010)

Extensive work has been completed in the Southern Alps, including Lake Chappa'ai (Woodward et al., 2018), Lake Mapourika (Howarth et al., 2014), Lake Paringa (Howarth et al., 2012), and Lake Ellery (Howarth et al., 2016). A meta-analysis completed by McWethy et al. (2010) studied 14 Southern Alp lakes including:Lewis Pass, Horseshoe Lake, Lake Sarah, Lake Letitia, Lagoon Saddle, Blackwater Lake, Dingle Burn, Diamond Lake, Glendhu Lagoon, Duke's Tarn, Lake Johnson, Lake Kirkpatrick, Lake Te Aroha, and Lake Thomas. This list is not exhaustive but rather illustrates the spatial bias and lack of published data in the Wairarapa Valley.

length. A further 24 data points were analysed as part of this research beginning at 24.5 cm, increasing resolution to 2.5-cm between 20 and 100 cm down the core, and 5-cm resolution between 100 and 200 cm (Fig. 2.2). Subsampling was conducted in October 2018 at the Micropalaeontology Lab at GNS Science.

2.3.2 Charcoal

Analysis of macroscopic charcoal was completed using methods from Carcaillet et al. (2001) and Whitlock and Anderson (2003) in the Palynology Laboratory at Victoria University of Wellington (VUW). Here, 2 cm^3 of bulk sediment was immersed in 20 ml of 10% KOH for approximately four weeks on average to deflocculate the sediment. Samples were washed with distilled water through nested 125-µm and 250-µm mesh sieves. As microscopic charcoal analysis had already been completed (25-50, 50-100 and >100 µm) by Waters et al. (2018), smaller sieves were deemed unnecessary. Samples were rinsed into gridded petri-dishes and counted using a dissecting microscope at 40x magnification. Charcoal morphotypes originating from grasses or wood species were differentiated, using characteristics outlined in Jensen et al. (2007) and Umbanhowar Jr and Mcgrath (1998).

2.3.3 Loss on ignition

LOI analysis followed well established methods (Dean, 1974; Sjögren et al., 2017; Waters et al., 2018) and was conducted in the Soils Laboratory at VUW. Approximately 3 g of bulk sediment was dried for 12 hours at 105°C (to determine dry mass), ashed in a muffle furnace at 550°C for four hours (ashed mass), allowed to cool to room temperature in a desiccator following each treatment, and weighed. The percentage of organic matter was calculated using the following formula adapted from Heiri et al. (2001) and Sjögren et al. (2017):

$$\frac{dry\ mass - ashed\ mass}{dry\ mass - crucible\ mass}\ x\ 100$$

2.3.4 X-ray fluorescence

Following LOI analysis, the inorganic sediment was ground into a fine powder using a mortar and pestle in preparation for analysis of elemental composition and concentrations by XRF at VUW's X-ray facilities. Samples were analysed using the Olympus Vanta M series Handheld XRF Analyser set on 'Geochem' mode. This involves irradiation of samples using two energy pulsations; detection of heavy elements involved irradiation at 40 kV for 30 seconds and lighter elements at 10 kV for 90 seconds.

2.3.5 Grain Size

For grain size analysis, this study deviated from the methods outlined in Waters et al. (2018). Instead methods from the VUW's Sedimentology Laboratory manual were used, due to time restraints and expertise availability. This included freeze-drying of bulk sediment for 24 hr, mechanical disaggregation using physical pressure, and split using a riffle splitter to ensure even distribution of the sample. About 0.5 g of sediment was digested in 8 ml of 27% H_2O_2 for 72 hr to remove organic materials, then 30 ml of H_2O was added. Samples were then heated to 65°C in a hot water bath for 6 hr, rinsed three times with reverse osmosis (RO) filtered water to remove remaining acid, and left overnight. Next, 2.5 ml of 32% HCl was added to remove carbonates, with the reaction left for 2 hr. Samples were rinsed three times with RO filtered water and then disaggregated using 5% Calgon ($Na_6O_{18}P_6$) and sonicated for at least 30 min before analysis using the Beckman Coulter LS 13 320 Laser Diffraction Particle Size Analyser on 'quartz setting'.

2.3.6 Environmental DNA

Samples to analyse prokaryotic eDNA were taken immediately following core collection and were processed by Dr. Susie Wood at the Cawthron Institute in Nelson. Extraction of 16s rRNA was completed using the DNeasy Power Soil Kit (produced by Qiagen, USA) and amplified using Polymerase Chain Reaction (PCR). High throughput sequencing of samples was then completed, followed by bioinformatics analyses (Caporaso et al., 2011; Glöckner et al., 2017; McMurdie & Holmes, 2013).

2.3.7 Data analysis

Following completion of individual analyses for this study, results were aggregated with those produced by Waters et al. (2018) to create a combined dataset for XRF, grain size, and LOI. As macroscopic charcoal was not completed in Waters et al. (2018), this variable remained separate. The combined dataset for XRF, grain size and LOI and the individual charcoal record was standardised in *R Studio* to provide equal weighting to drastically different variables prior to principal component analysis (PCA), which was completed using the factoextra package (Kassambara & Mundt, 2017). PCA is a widely used technique for comparing and correlating standardised variables within large datasets (Jolliffe, 2011). PCA biplot A used the combined dataset from this study and Waters et al. (2018), which was limited to XRF, grain size, and LOI. As macroscopic charcoal was absent from Waters et al. (2018), a separate PCA was required. PCA biplot B used only the samples from this study comprising macroscopic charcoal, XRF, grain size, and LOI.

eDNA results following bioinformatics processing were analysed independently by Dr. Susie Wood (Cawthron Institute). Results produced included cumulative abundance of prokaryotic bacterial communities and a cluster analysis showing similarity between prokaryotic eDNA samples.

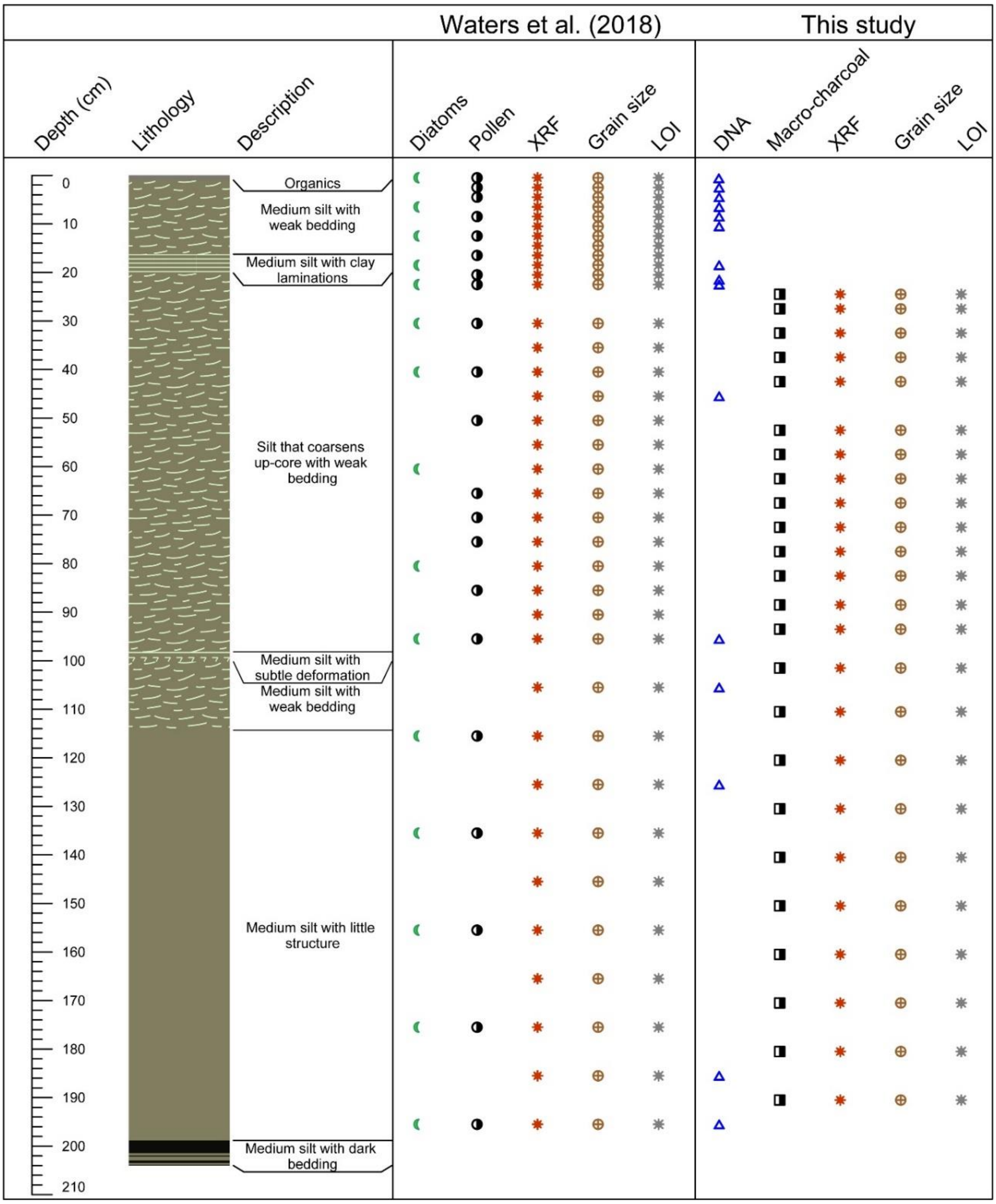


Figure 2.2: Contribution of proxy data points from this study and Waters et al. (2018) compared with core depth. Each symbol represents an individual sample that has been analysed. The left-most image provides a description of core stratigraphy, completed prior to core sampling by Dr. Andrew Rees, Victoria University of Wellington.

2.4 Results

2.4.1 Coring and chronology

Age-depth modelling and establishing an independent chronology is typically a fundamental component within palaeolimnological studies. However, such modelling has proven difficult at Lake Wairarapa due to a lack of dateable macrofossil material found throughout the core. Radiocarbon dating of a kākahi shell provided a provisional age-depth model in Waters et al. (2018); however, the model should be treated with caution due to incorporation of radioactively inert carbon in the kākahi shell, potentially creating a reservoir effect. No further dateable material was found in this study to improve the current age-depth model. Broadly, Waters et al. (2018) suggest pre-human conditions correspond to 200 to 65 cm (c. 2,300 to 1,300 cal yr BP), Māori arrival and occupation to 65 to 15 cm (1,300 to 95 cal yr BP), and European settlement and intensification from 15 to 0 cm (95 cal yr BP to the present).

2.4.2 Proxy results

Results from the analysed proxies, alongside some key proxies from Waters et al. (2018) are presented in Figs. 2.3 and 2.4. Macroscopic charcoal (Fig. 2.3a) is negligible throughout the core, before a large increase at around 67.5 cm, dominated by herbaceous particles. Organic content (Fig. 2.3c) is relatively constant throughout the record with a mean of 3.43% and maximum of 6.33% at 57.5 cm.

Results of geochemical analyses are shown in Figs. 2.3b, d and 2.4a-d. Concentrations of Ti (Fig. 2.3b) are relatively elevated between the lower 80-200 cm of the core, then decrease below the mean before a sharp increase at 16.5 cm and 14.5 cm. Similar trends are observed in the K/Al ratio (Fig. 2.4c). Ratios of Zr/Rb and Zr/Ti (Figs. 2.3d and 2.4d) show the inverse trend: relatively low levels in the lower portion of the core, increased levels from around 80 cm, then punctuated by a large decrease at around 16.5 cm. Concentrations of P and Mn (Figs. 2.4a, b) display relative consistency through the core, before a substantial increase at 0.5 cm.

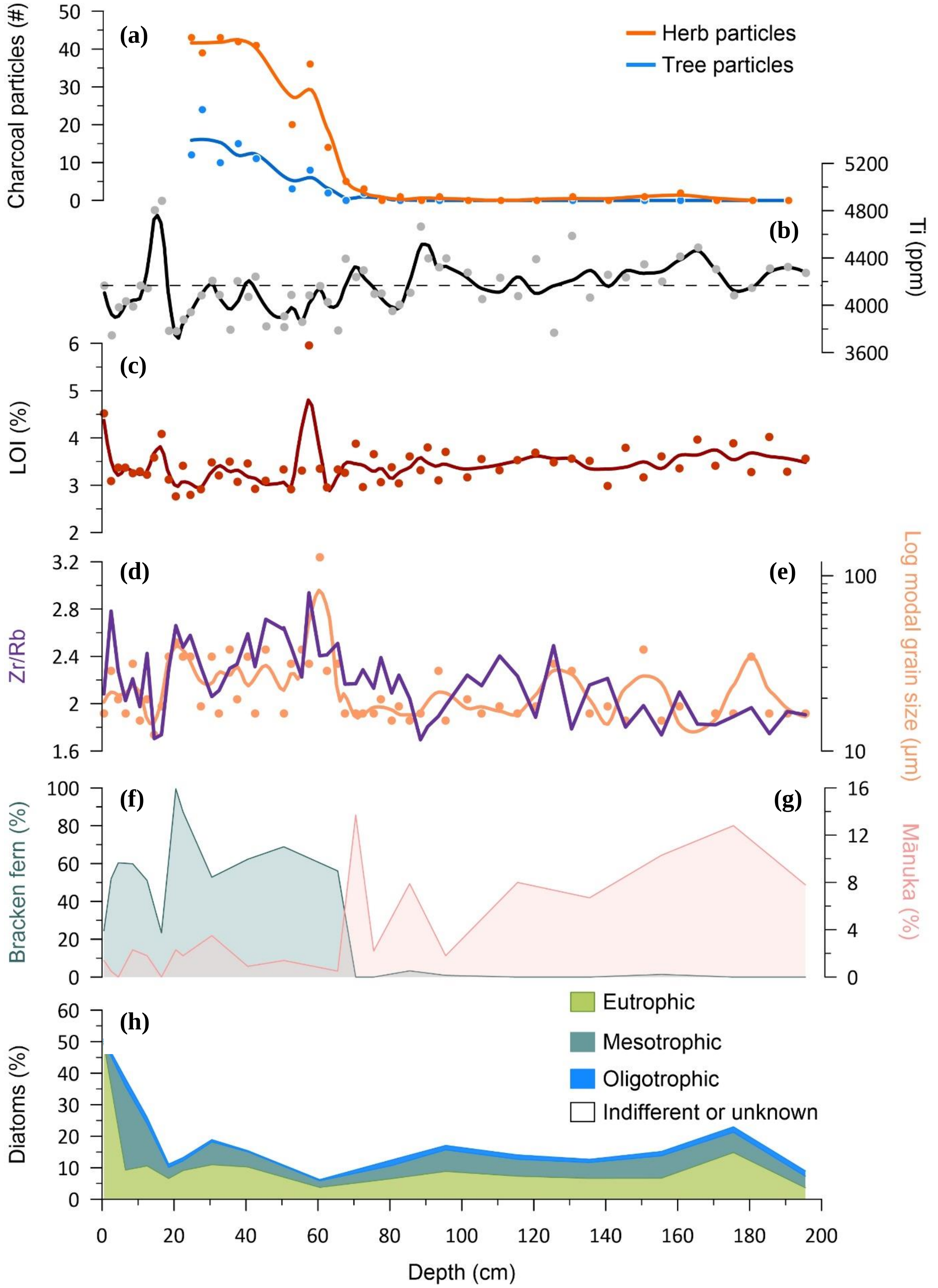
Modal grain size (Fig. 2.3e) shows a similar response to Zr/Rb ratios. Grain size is relatively depressed in the upper portion of the core, then punctuated by a large increase of 127.6 µm at 60.5 cm. Grain size then remains elevated until a large decrease around 16.5 cm. Selected pollen species from Waters et al. (2018) show a decline in mānuka at around 62.5 cm corresponding to an increase in bracken fern (Figs 2.3f, g). Likewise, diatom analyses show a proportional increase in eutrophic species in the upper 5 cm of the core (Fig. 2.3h).

2.4.3 Principal Component Analyses

Results from PCA biplot A show samples are broadly grouped into three key groups (Fig. 2.5). Group 1, on the right side of the biplot, encompasses younger samples 2 to 35, corresponding to 2.5 to 82.5 cm. Group 2, on the left side of the plot, generally spans older samples 36 to 60, which correspond to 85.5 to 195.5 cm. Finally, a sub-zone of the younger group only contains sample 1 – the youngest at 0.5 cm.

PCA biplot B (Fig. 2.6) corroborates the broad groupings from PCA biplot A. Older samples 37 to 58 (88.5 to 190.5 cm) appear on the right of the plot and correspond to Group 1, whereas younger samples 13 to 35 (24.5 to 82.5 cm) appear on the left and correspond to Group 2. Since samples from this study only start from 24.5 cm, there is no sub-zone limited to 0.5 cm in the younger group.

These three broad groups likely represent the three main phases of land use and occupation at Lake Wairarapa: Pre-human Phase (85.5 to 195.5 cm), Human Settlement and Occupation Phase (2.5 to 82.5 cm), and Modern Intensification Phase (0.5 cm).



Charcoal particles (#)
(a)
Herb particles
Tree particles
(b)
Ti (ppm)
(c)
LOI (%)
(d)
(e)
Zr/Rb
Log modal grain size (µm)
(f)
(g)
Bracken fern (%)
Mānuka (%)
(h)
Diatoms (%)
Eutrophic
Mesotrophic
Oligotrophic
Indifferent or unknown
Depth (cm)

Figure 2.3: Proxy results summary figure one (overleaf): (a) macroscopic charcoal, (b) titanium (ppm), (c) organic content (%), (d) ratio of zirconium to rubidium, (e) modal grain size (log scale), (f) bracken fern pollen abundance (Waters et al., 2018), (g) mānuka pollen abundance (Waters et al., 2018), and (h) cumulative diatom abundance categorised by nutrient preference (Waters et al., 2018)

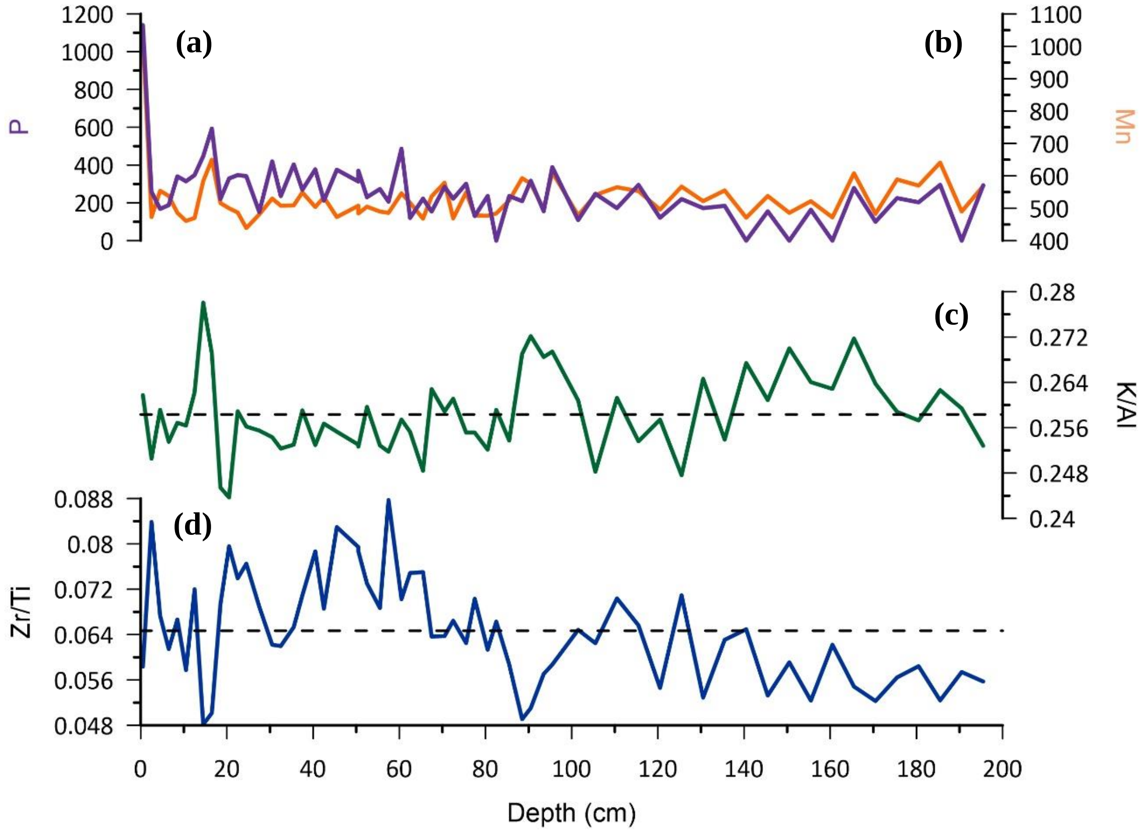


Figure 2.4: Proxy results summary figure two: (a) phosphorus concentrations (ppm), (b) manganese concentrations (ppm), (c) ratio of potassium to aluminium, and (d) ratio of zirconium to titanium

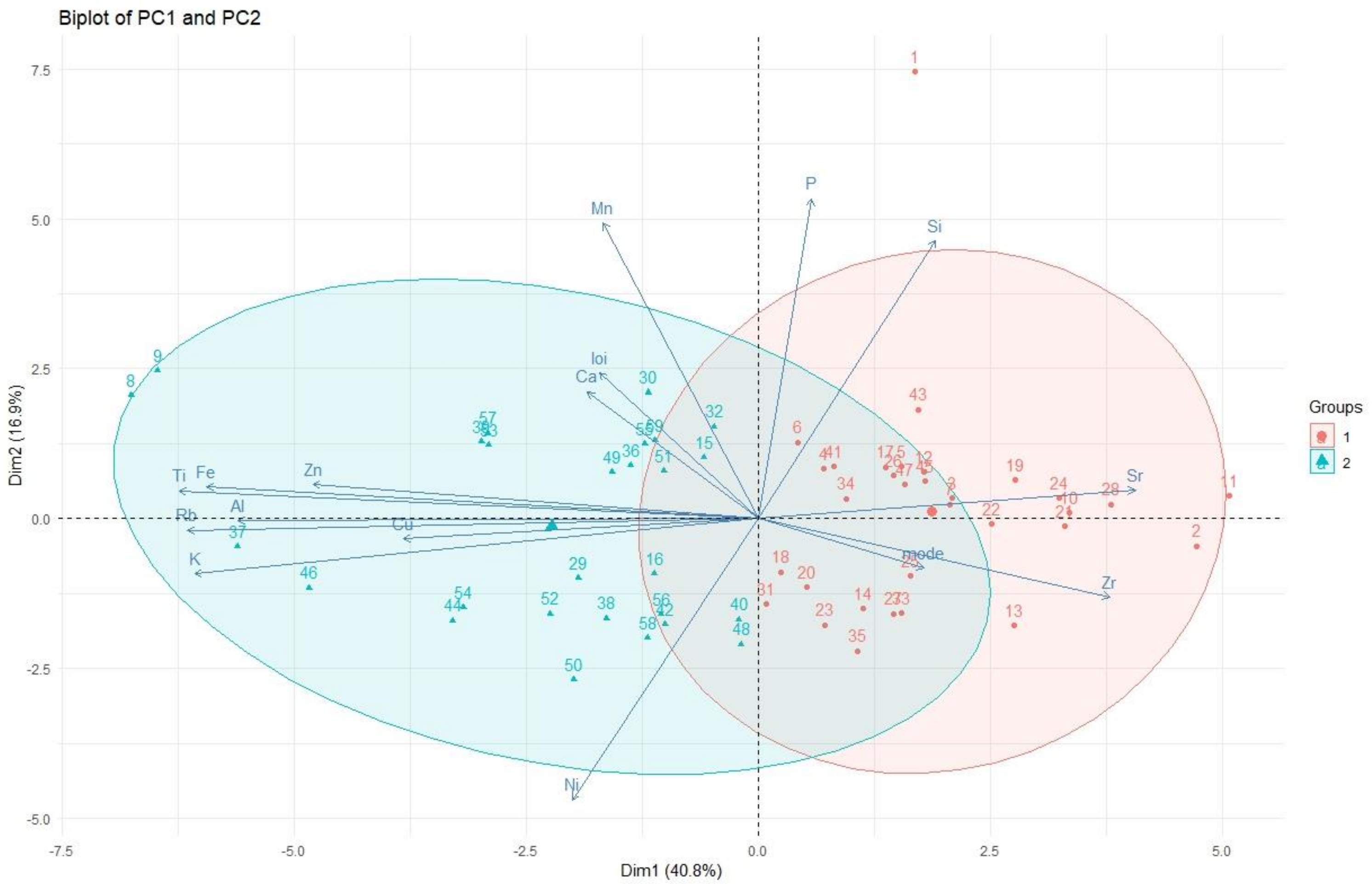


Figure 2.5: Principle Component Analysis biplot A, depicting the combined dataset of this study and Waters et al. (2018). Numbers in the biplot correspond to sample depths, with ascending numbers associated with increasing depth (e.g. sample 1 corresponds to 0.5 cm depth, sample 8 to 14.5 cm depth, sample 26 to 60.5 cm, etc.). Samples are broadly clustered into two groups based on sample characteristics and relation to proxies.

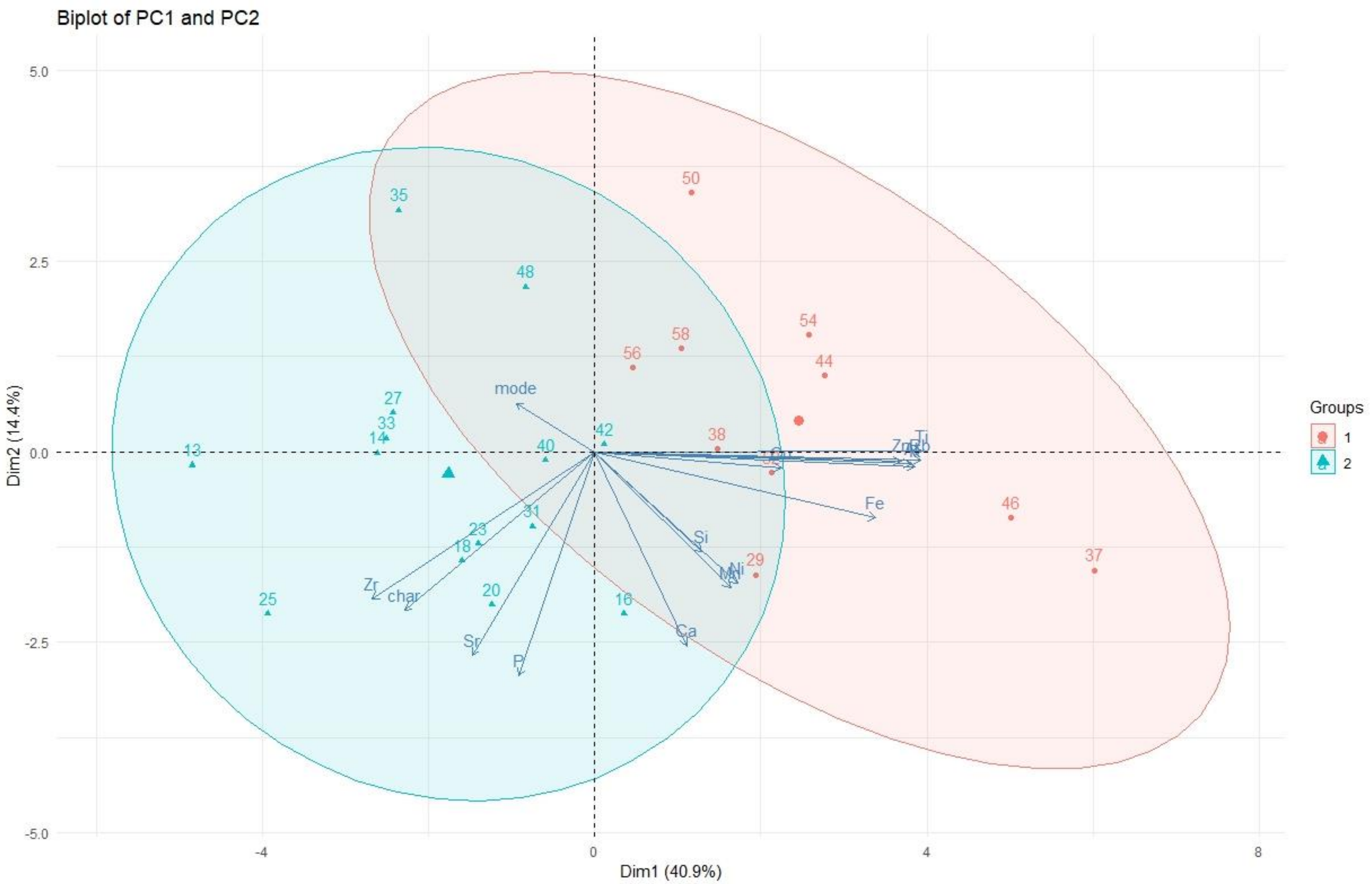


Figure 2.6: Principle Component Analysis biplot B, depicting the dataset from this study, including charcoal data. Numbers in the biplot correspond to sample depths, with ascending numbers associated with increasing depth. Samples are broadly clustered into two groups based on sample characteristics and relation to proxies.

2.4.4 Pre-human Phase: 85.5 to 195.5 cm

Within the PCA biplot A (Fig. 2.5), the Pre-human Phase is dominated by elevated levels of detrital elements Ti, Rb, K, Al, and Fe. Vectors produced from these elements demonstrate strong loading on PC1 (horizontal axis) and are positively correlated. PC1 accounts for 40.8% of the variance in the dataset. Spread along the second axis, which accounts for 16.9% of the variance in the data, is driven by P, Mn, Zn, Cu, and to a lesser extent LOI.

While DNA results were not included in the PCAs, proportional abundance of bacterial community structure from the depths included in the Pre-human Phase show *Crenarchaeota*, *Euryarchaeota*, *Calditrichaeota*, and *Elusimicrobia* are the most dominant taxa (Fig. 2.7). Samples within the Pre-human Phase also form a distinct cluster, with 30-40% similarity between samples (Fig. 2.8).

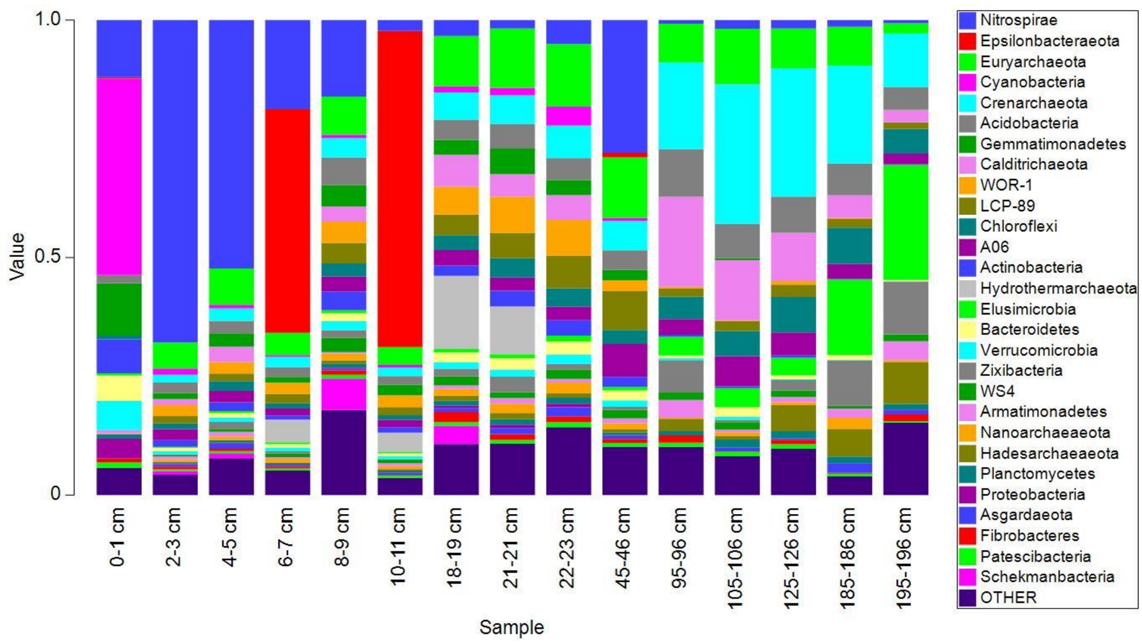


Figure 2.7: Cumulative abundance of prokaryotic bacterial community structure, produced by Dr. Susie Wood, Cawthron Institute (unpublished). Dominant taxa are named in the key on the right of the image, and their abundance within each sample represented in the stacked bar chart.

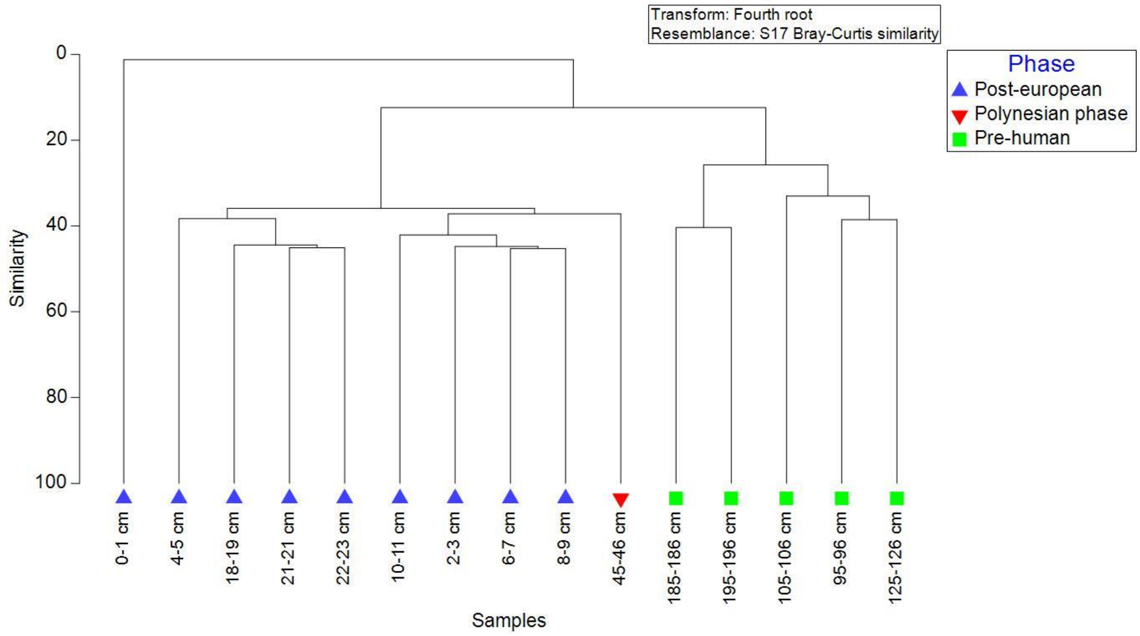


Figure 2.8: Cluster Diagram of similarity between prokaryotic eDNA samples, produced by Dr. Susie Wood, Cawthron Institute (unpublished). Samples had been grouped based on land use phases outlined in Waters et al. (2018). The majority of samples fall within two main clusters, these being a pre-human cluster and a human occupation cluster. The 0-1 cm sample shows no similarity with either of these main clusters.

2.4.5 Human Settlement and Occupation Phase: 2.5 to 82.5 cm

For the majority of the Human Settlement and Occupation Phase, modal grain size, Zr and Sr concentrations have the strongest loading on PC1 in biplot A, with negative affinities to the detrital elements (Fig. 2.5). Grain size increases in the Human Settlement and Occupation Phase, with modal grain size ranging between 127.64 and 12.40 µm. However, grain size values here are primarily impacted by an anomalous peak at 60.5 cm, with a modal grain size of 127.64 µm.

Increased prevalence of charcoal fragments becomes evident in the Human Settlement and Occupation Phase, with moderate loading on PC1 biplot B (Fig. 2.6). Charcoal abundance continues to be negligible until 72.5 cm where it appears at a low abundance (5 fragments at 72.5 cm and 67.5 cm) (Fig. 2.3a). Total charcoal sharply increases from 67.5 cm to a peak of 63 fragments at 27.5 cm. One anomalous drop is observed at 52.5 cm but returns immediately to previously high values. Rates of tree-generated charcoal are less abundant than herbaceous fragments.

Results from eDNA analysis show an increase in *Nitrospirae* at 45.5 cm and the continued presence of *Euryarchaeota*, which is prevalent between 45.5 cm and 18.5 cm (Fig. 2.7). Younger samples in the Human Settlement and Occupation Phase at 10.5 cm and 6.5 cm show dominance of *Epsilonbacteraeota*, accounting for > 50% of the total species abundance. *Nitrospirae* returns at 8.5 cm and is dominant at 4.5 cm and 2.5 cm. eDNA samples from the Human Settlement and Occupation Phase exhibit 35-45% similarity between samples, as well as 15% similarity with samples in the Pre-Human group (Fig. 2.8). Unfortunately, due to file corruption during bioinformatics processing, there are limited eDNA results available between 23 cm and 95 cm.

2.4.6 Modern Intensification Phase: 0.5 cm

The Modern Intensification Phase only consists of the most recent sample in the sediment core at 0.5 cm. It is completely dissimilar to all other samples, strongly affected by elements loaded on PC2 (2.7), namely P and Mn.

Results from eDNA show the first presence of Cyanobacteria, which is the most dominant taxon alongside *Nitrospirae* and gemmatimonadetes (Fig. 2.7). This sample exhibits zero similarity to all other samples in the record (Fig. 2.8).

2.5 Discussion

2.5.1 Natural reference state of Lake Wairarapa

In considering the first research question, results from the Pre-Human Phase provide insight into the natural environmental conditions at Lake Wairarapa. Prior to human arrival, the lake and surrounding environment showed a paucity of natural fires, relatively high concentrations of detrital elements, low organic content, invariant grain size inputs, and a persisting marine influence in prokaryotic lake communities show through presence of *Crenarchaeota*, *Euryarchaeota*, *Calditrichaeota*, and *Elusimicrobia* (Figs. 2.3-2.8).

The scarcity of macroscopic charcoal implies an absence of anthropogenic presence at Lake Wairarapa and on the surrounding landscape. Microscopic charcoal (ø = 25-50 µm and ø = 50-100 µm) from Waters et al. (2018) suggests some distal fires were evident within the catchment; however, such results are subject to the confounding effects of wind-dispersal, catchment size, and soil reworking that may bias microscopic charcoal results (Peters & Higuera, 2007; Tinner et al., 2006). Pollen records from Waters et al. (2018) and past climate-vegetation relationships covered by Palmer et al. (1989) and McLea (1990) show prevalence of beech and podocarp forests. As discussed in Perry et al. (2014), these indigenous forests are wet and not prone to ignition. Pollen records also indicate the widespread prevalence of mānuka on the lake edge. Mānuka exhibits fire-mediated serotiny (seeds released post-fire events), is well-adapted to fire, and relatively easy to ignite (Perry et al., 2014). The lack of fire, despite an easy ignition source, reinforces the conclusion that a localised fire regime in the proximal vicinity of Lake Wairarapa is unlikely.

Thus, in the absence of human presence and low fire frequency, the Lake Wairarapa catchment shows relative stability. Relatively depressed modal grain sizes likely result from a well-vegetated and stable catchment, whereby the prevalence of mānuka and tree ferns, which likely occupied the margins and tributaries of Lake Wairarapa, likely intercepted some finer catchment-generated sediments from reaching the lake (Waters et al., 2018). Vegetation, particularly in riparian zones, reduces flow velocity in moderately high run-off flows and entraps sediment particles from reaching further downhill (Tabacchi et al., 2000). Similarly, the lack of larger silt and sand particles suggests high-energy transport mechanisms were limited over this period, indicative of a generally stable climate. The natural diversion of the Ruamāhanga River into Lake Wairarapa at ca. 3500-3100 cal. yr BP (which occurred prior to what is observed in this study) (Trodahl et al., 2016) probably provided a constant, abundant source of fine sediment inputs. Transport of sediment in fluvial channels, such as the Ruamāhanga River, preferentially entrains finer sediments (Powell, 1998), with exponential decreases in grain size corresponding to increasing distance downstream (Knighton, 1980). The underlying geology of the Wairarapa Valley may also contribute to sediment input rates. Menting et al. (2015) described that sediment abrasion rates can be controlled by lithology. In the Wairarapa, sedimentary sandstones, mudstones and limestones in the eastern ranges (Trodahl et al., 2016) are potentially a greater contributor of sedimentary inputs, due to their characteristic ease of erosion (Basher, 2013; Hancox & Wright, 2005). By contrast, the greywacke underlying the Remutaka and Tararua Ranges may contribute less sediment as it is less easy to erode (McFadgen, 2003).

Elemental geochemistry from sediments suggests another narrative, indicating elevated catchment erosion. For example, detrital elements, namely Ti and Zr, are typically used as erosion indicators because they are conservative elements with slow mobility during weathering and erosion processes (Davies et al., 2015). Detrital elements tend to concentrate in coarser grained sediments; therefore, elevated concentrations over this period suggest a more active landscape with higher energy potential to transport larger grain sizes (Davies et al., 2015), contradicting the grain size evidence. Trends in detrital elements are unusually anti-phased to Zr, which typically reflects signals seen in other detrital elements (Koinig et al., 2003). This disparity between grain size and elemental geochemistry is further explored in section 2.5.2.

In contrast to the other XRF data, low values of Zr/Rb align with evidence for a stable catchment. Zr is typically enriched in larger silt particles, whereas Rb typically sorbs to clays (Kylander et al., 2011). Ratios of Zr/Rb therefore should complement grain size, as the ratio does here, with finer sediments represented by lower values, and coarser sediments characterised by higher values. High K/Al ratios during the majority of the Pre-Human Phase indicate less chemical weathering (although with a slight increase over time). Ratios of K/Al can be used to infer dominance of chemical weathering mechanisms versus physical weathering mechanisms (Burnett et al., 2011). Here, low K/Al ratios suggest increased kaolinite inputs (reflective of chemical weathering processes), whereas high values suggest increased illite inputs (inferring physical weathering) (Burnett et al., 2011; Yarincik et al., 2000).

Organic content varies little throughout the entire record. This suggests a dominance of allochthonous minerogenic material deposited in the lake basin, which is unsurprising for a lake with such a large catchment (Rowan et al., 1992). Further, windiness and the large fetch of Lake Wairarapa also supports the breakdown of organic matter through resuspension and water column oxidation prior before deposition (Meyers & Ishiwatari, 1993).

Within Lake Wairarapa, microbial community abundance suggests persisting marine influence during the Pre-Human Phase. *Crenarchaeota* and *Euryarchaeota* are typically absent from freshwater prokaryote communities; however, these taxa are common in marine environments and sediments (Fig. 2.7) (Madigan et al., 2015). Similarly, *Calditrichaeota* and *Elusimicrobia* also both exhibit strong affiliation to the marine environment (Brune, 2014; Marshall et al., 2017). An early marine phase is corroborated by Waters et al. (2018), who found diatoms that favour brackish environments during the same timeframe. Despite the transition from an estuarine to lacustrine environment at ca. 4000-3500 yr BP (much earlier than this study), formation of the Ōnoke gravel bar and alluvial plain between Lakes Wairarapa and Ōnoke and intermittent breaching of the

Ōnoke gravel bar may have allowed such taxa to persist (Hayward et al., 2011; Leach & Anderson, 1974).

The catchment stability over this period suggests little environmental perturbation. Trodahl et al. (2016) suggested a major shift in the depositional environmental at Lake Wairarapa at c. 2,500 cal yr BP, either through the meandering of the Ruamāhanga River into Lake Wairarapa or a large rupture of the Wairarapa Fault. The absence of such perturbation in this study suggests the record does not extend that far back in time (which corroborates the age-depth model suggested in Waters et al. (2018)), or that higher resolution work is needed in the lower portion of the core.

2.5.2 Māori arrival and occupation

The arrival of humans at Lake Wairarapa is evidenced by a significant increase in fire frequency, and changes in catchment and lake stability. Māori presence is inferred through a large increase in macroscopic charcoal at around 72.5 cm. In the absence of large rearrangements of New Zealand's climate during this period, increases in charcoal primarily reflect Māori settlement in the area (McWethy et al., 2010). While Māori may have arrived earlier than this time, their presence on the landscape is undetectable through palaeolimnological methods and other archaeological archives (McFadgen, 2003). Pollen records from Lake Wairarapa also exhibit pronounced reductions in mānuka and tree ferns as well as an opening of the canopy in the more densely forested area; this is accompanied alongside an concomitant increase in bracken fern (Waters et al., 2018). Differentiation between wood and herbaceous charcoal fragments suggest greater burning of herb species, likely in the maintenance of cultivated areas. Tall tree abundance remains relatively constant, although the prevalence of kāmahi (*Weinmannia racemosa*), *Pseudopanax* spp. and *Coprosma* spp. suggest movement toward a more open canopy (Waters et al., 2018).

Mānuka likely provided a good initial source of fuel for Māori settlers, as well as use for rongoā (traditional Māori medicine) purposes due to its anti-microbial properties (Williams, 1996). However, once a fire regime began, this potentially made the Lake Wairarapa environment more susceptible to future fire events (Perry et al., 2014). Likewise, the cultivation of bracken fern – a primary source of carbohydrates in traditional Māori diets – also likely enhanced fire susceptibility in the area, as dry, dead fronds are an easy source of fuel for ignition (McGlone et al., 2005; McWethy et al., 2010).

Removal of riparian vegetation and generalised land clearance likely facilitated changes in catchment erosion processes, as inferred by increases in clastic sediment flux. While still within the silt range, increases in grain size suggest reduced barriers to hill slope erosion and entrainment through fluvial processes (Page et al., 1994). Although not directly comparable, similar changes in grain size are observed by Trodahl et al. (2016). Here, median grain size increases and grain sorting moves from ‘very poorly sorted’ to ‘poorly sorted’ following Māori arrival.

Clastic sediment flux is punctuated by a large peak at 60.5 cm, exhibiting the largest values in modal grain size seen in the record (by an order of magnitude) and deposition of fine sands. The anomalous peak in organic content of 5.95% also occurs at approximately the same time at 57.5 cm. As discussed in Shuman (2003), variations in organic content of less than 2-5% suggest insignificant changes in the environment, therefore this peak is likely to be inconsequential. The significant increase in charcoal precedes these two events. This series of peaks could reflect a large and rapid pulse of landscape destabilisation following widespread vegetation clearance and changing land use. However, as these events are anomalous and only represented by a single sample in both cases, this interpretation should be treated with caution.

Again, sedimentary geochemistry does not align with the results found in terms of clastic sediment grain size. During the time of Māori occupancy, the Zr/Rb ratio correlates with grain size whereas the Ti profile (alongside other detrital elements) decreases relative to the pre-human period, suggesting less catchment erosion (Davies et al., 2015; Kylander et al., 2011). Similarly, the increase in the K/Al ratios over this period suggests increased chemical weathering (Burnett et al., 2011), perhaps due to greater exposure of the landscape following land clearance. Although inferential, anti-phased increases in Sr over this period could potentially suggest increased carbonate weathering and in-lake $SrCO_3$ precipitation (Kylander et al., 2011).

One possible explanation for the contrast found between grain size and sediment geochemistry is the exposure of the Kawakawa/Oruanui tephra (KOT). As discussed in Waters et al. (2018), volcanic glass shards were found throughout the core which could suggest remobilisation of the KOT; however, shard abundance was insufficient to determine the source. The KOT, which is relatively depleted in Ti, is a product of the super-eruption of Taupō at approximately 25,360 (± 160) yr. BP, and resulted in 20 to 40 cm of deposited material covering the lower Wairarapa Valley (Vandergoes et al., 2013). Pedogenesis of more recent soils following the eruption likely buried the majority of the tephra, although the ash would have been mixed through lower soil horizons. With the arrival of Māori and subsequent land clearance, topsoils may have been removed and remnants of more weathered horizons relatively rich in KOT eroded into Lake Wairarapa (Boygle, 1999). Similarly, the peak in organic content could reflect this large in-wash of organic-rich topsoils (Meyers & Ishiwatari, 1993). However, without identification of volcanic shard source or other supporting data, this is a speculative explanation.

Understanding of in-lake processes is limited during this period as there is only one viable DNA sample, due to file corruption and data loss. *Nitrospirae*, a known nitrogen fixer, facilitates nitrite oxidation to nitrate and is the most dominant in this sample (Madigan et al., 2015). Presence of this taxon could suggest greater in-lake productivity or greater sources of nitrogen due to potentially increased catchment erosion. *Euryarchaeota* and *Crenarchaeota* are also still present but in lesser abundance, suggesting brackish conditions at Lake Wairarapa.

2.5.3 European settlement and intensification

The European Phase in the most recent sediments (spanning from around 20.5 to 2.5 cm) is a period of large perturbations, rapid change, and increasing catchment destabilisation. The start of this phase coincides with a large peak in detrital elements, a small peak in organic content, and depressions in the Zr/Rb ratio and modal grain size over 16.5 to 14.5 cm. Corroboration with the microscopic charcoal data from Waters et al. (2018) could further imply the impact of European settlers at Lake Wairarapa.

The leading potential cause of the disturbance seen over 16.5 to 14.5 cm is the 8.2 magnitude rupturing of the Wairarapa Fault in 1855, which has potentially the largest dextral offset documented globally of 12-m (Little et al., 2009; Rodgers & Little, 2006). The fallout from the earthquake included landslides, tsunami and regional uplift (Rodgers & Little, 2006). This event likely led to the destabilisation of Lake Wairarapa's catchment in the successive years, demonstrated by somewhat elevated organic content and depressed modal grain size and Zr/Rb for the remainder of the European Phase. Likewise, sustained elevation of macroscopic charcoal indicates continued burning of the landscape for clearance and cultivation of crops. Microscopic charcoal from Waters et al. (2018)

suggests the arrival of Europeans near Lake Wairarapa at around 24.5 cm. Continued reductions in indigenous vegetation cover on the valley floor to establish farming likely facilitated further catchment erosion. However, modal grain size over this time suggests a return to similar catchment erosion rates seen prior to human arrival.

The decrease in marine microbial taxa and dominance of *Nitrospirae*, *Epsilonbacteraeota*, and *Hydrothermarchaeota* suggest reduced tidal influence at Lake Wairarapa following the proposed 1855 earthquake event. The presence of these taxa found in this study support the work of Leach and Anderson (1974), who suggested the 1855 earthquake was the likely cause for the transition from an estuarine to lacustrine environment.

2.5.4 The 'Great Acceleration'

The youngest sediment sample from the Lake Wairarapa sediment core provides the strongest evidence of anthropogenic impact and suggests a shift to a wholly distinct and novel environment. However, this conclusion is provisional given only the youngest sample reflects such abrupt changes.

Strong loading of P in biplot A (Fig. 2.5) is likely linked to increased agricultural productivity (Corella et al., 2012), with such land use accounting for 54% of the modern catchment (Perrie & Milne, 2012). Phosphorus loading is also reflected in monitoring data, whereby Lake Wairarapa has hypertrophic P values (Perrie & Milne, 2012; Ruamāhanga Whaitua Committee, 2018). Likewise, a noteable increase in Mn suggests a substantial increase in recent lake productivity, with Mn often used as an indicator of biological productivity in lakes (Kylander et al., 2011).

Cyanobacteria appear for the first time and dominate the community in the most recent sediment sample. Cyanobacteria thrive in environments with increased nutrient levels, with certain cyanobacterial species producing neurotoxins and hepatotoxins, posing risk to animal and human health (Madigan et al., 2015; Sivonen & Jones, 1999). The presence of cyanobacteria corroborates with diatom data from Waters et al. (2018), whereby the proportion of eurotrophic diatoms dramatically increases at the top of the core, supporting an enhanced nutrient load at Lake Wairarapa.

These changes potentially indicate signs of the 'Great Acceleration' at Lake Wairarapa. Humans have had an increasingly noticeable impact on the environment following the industrial revolution (i.e. the so-called Anthropocene) (Crutzen, 2006). From the latter half of the 20th Century, changes have accelerated in a wide variety of areas corresponding to intensification in land use and increasing demand from humans including increasing global population, lower morality rates and longer life expectancy, among many other factors (Fig. 2.9) (Steffen et al., 2015; Steffen et al., 2005).

In answering the second research question for this study, human modification of the Lake Wairarapa environment has had a great impact on critical ecosystem functions such as flood regulation, erosion control, and water purification processes. Clearance of the landscape (including drainage of the vast wetland system surrounding Lake Wairarapa) has reduced the capability of the ecosystem to filter nutrients, intercept sediments, and facilitated changes in microbial communities. Since the arrival of humans at Lake Wairarapa, anthropogenic and environmental perturbations have continued to change the ecosystem, with little evidence of a new equilibrium emerging in contrast to the pre-human stability.

The impacts from Māori arrival and occupation, European settlement and intensification, and the modern findings support the narrative of the Great Acceleration. Although the onset of rapid landscape modifications coincides with Māori occupation, cyanobacterial blooms and magnitude increases of P only appear in the youngest sample. The impact of the suggested 1855 earthquake obscures this trajectory somewhat, but small increasing trends following the earthquake support further intensification from European settlement. The most modern findings most clearly support the Great Acceleration narrative, where rapid changes are observed in almost all proxies.

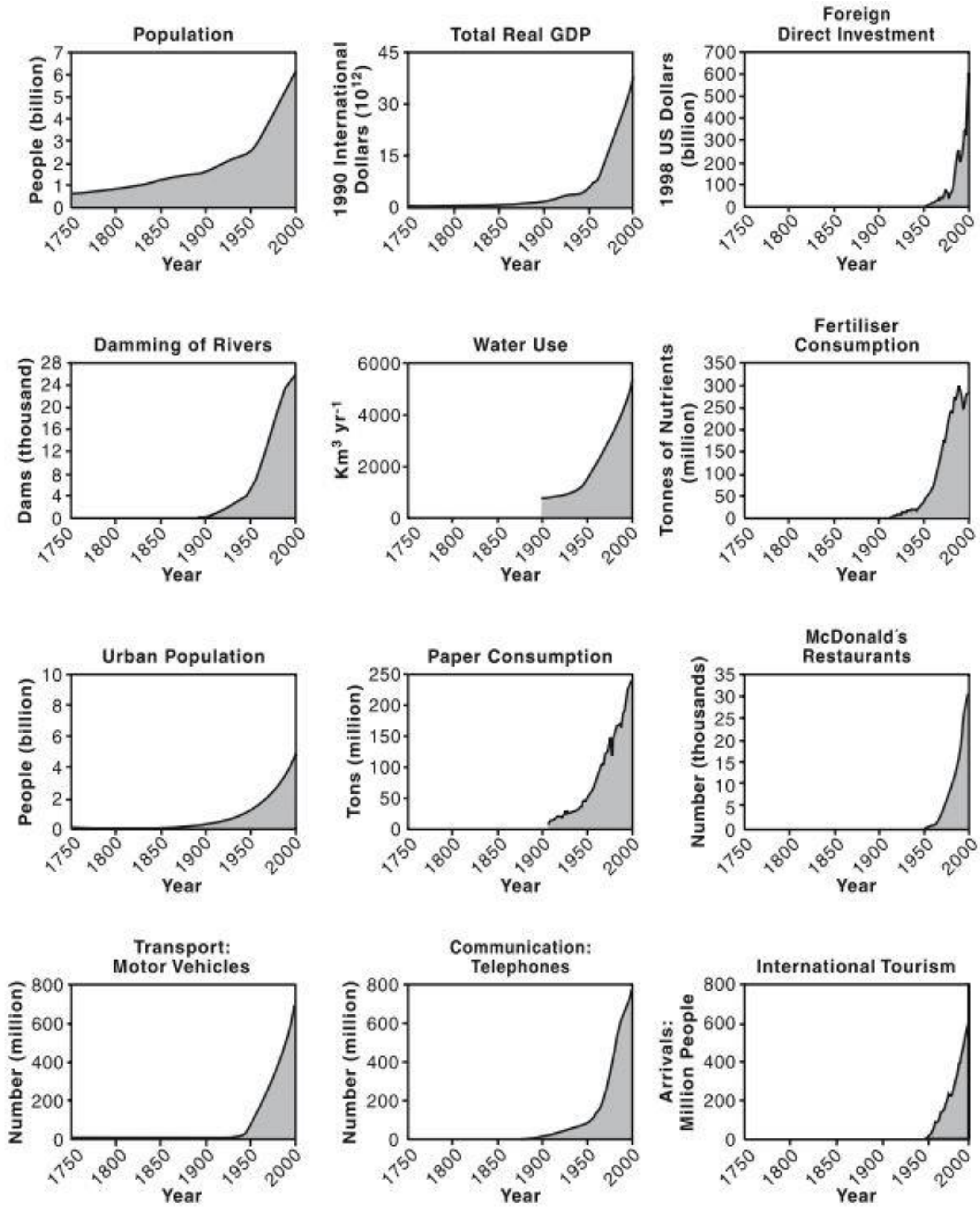


Figure 2.9: The 'Great Acceleration' observed in global data from human activities following the Industrial Revolution (Steffen et al., 2005)

2.6 Conclusion

Understanding contemporary lake conditions in New Zealand is often constrained due to a lack of longitudinal environmental data (Perrie & Milne, 2012). Therefore, palaeolimnological investigations of lake sediments through a multi-proxy approach can provide a wealth of information regarding changes in lake and catchment conditions through time (Cohen, 2003). The results of which can be used to support and direct future lake management and restoration.

The evidence provided from analysis of Lake Wairarapa sediments produce knowledge about the natural environmental conditions in the lake's immediate catchment as well as the changes and impacts that may be attributed to human arrival and occupation. From the proxies analysed in this study, namely macroscopic charcoal, grain size, organic content, geochemistry, and environmental DNA, the results support the narrative of a Great Acceleration at Lake Wairarapa.

The pre-human landscape was relatively stable, demonstrated through few natural fires, fine sediment inputs, and a well-vegetated catchment. The arrival of Māori, inferred through the sharp increase in charcoal, resulted in a more active catchment, with erosion likely exposing the KOT. Furthermore, subsequent European settlement (although difficult to disentangle from large environmental disruptions of the 1855 earthquake) equally demonstrates a period of rapid change and enhanced destabilisation. Finally, the most recent record indicates the Great Acceleration, whereby a heavily modified catchment has accelerated in terms of biological productivity, nutrient loading and cyanobacterial presence.

The impacts of anthropogenic land use practices are evident at Lake Wairarapa. Thus, future management directions must recognise the impacts and pressures that continued intensification is having on the lake's health, wellbeing, and ecosystem services. If restoration work seeks to re-establish conditions similar to those recorded in during the Pre-Human Phase at Lake Wairarapa. Then scientists, tangata whenua and other members of the Wairarapa community will need to consider what social trade-offs are necessary to achieve this.

One remedial step could involve the restoration of mānuka on riparian margins to buffer the lake. This not only links to the pre-existing natural reference state of Lake Wairarapa, but similarly may offer additional benefits in reducing current agricultural pollution.

Chapter Three: Present. The potential of mitigating agricultural pollution using mānuka

3.1 Introduction

Widespread pastoral agriculture in New Zealand provides many ecosystem services to New Zealand citizens, being a key export and employment opportunity for regions such as the Wairarapa (Stokes & Dixon, 2016). However, current agricultural practices have large, pervasive impacts on all facets of the local environment (Parliamentary Commissioner for the Environment, 2015). Indeed, shallow lakes tend to be supertrophic or worse when situated in agricultural catchments (Drake et al., 2011). In particular, excrement from ruminant stock can be a large contributor to diffuse agricultural pollution, contributing large volumes of nitrogen and microbial pollutants to pastoral environments (Di & Cameron, 2016; Moriarty et al., 2008).

One method increasingly employed to mitigate such effects is the restoration or protection of riparian zones (Parkyn et al., 2003). Development of riparian zones have demonstrated the ability to mitigate agricultural pollutants through biological and physical means, including excessive nutrient runoff, microbial contamination, and sedimentation (McKergow et al., 2016). Though not a silver bullet, it is a well-supported strategy and incentivised to landowners through the Greater Wellington Regional Council (River Ecosystems Group of Greater Wellington, 2003).

Utilisation of native plants are increasingly popular in riparian restoration projects (Franklin et al., 2015), with mānuka (*Leptospermum scoparium*) and kānuka (*Kunzea ericoides*) identified as having additional antimicrobial properties. In laboratory settings, these species have demonstrated the ability to reduce microbial contamination of *Escherichia coli* (Prosser et al., 2014; Prosser et al., 2016) and minimise nitrogen leaching through enzyme inhibition of the nitrification process (Esperschuetz et al., 2017a; Esperschuetz et al., 2017b). Additionally, recent proliferation of the mānuka honey and essential oil industries provide an added incentive to landowners through alternative income streams (Nickless et al., 2017).

However, it is unclear to what extent these antimicrobial properties of mānuka operate outside controlled laboratory conditions in the actual environment. Thus, there is a clear opportunity for research into the efficacy of mānuka in reducing agricultural pollution at Lake Wairarapa.

To contribute to this line of inquiry, the following research questions are posed:

1. What is the impact of mānuka on *E. coli* counts in a field experiment within a riparian zone at Lake Wairarapa?
2. How is the distribution of ammonium and nitrate impacted by mānuka in a field experiment within a riparian zone at Lake Wairarapa?

Regarding question one, the literature suggests that mānuka can greatly influence the survival rates of *E. coli* in laboratory settings (Prosser et al., 2014; Prosser et al., 2016); these properties need to be tested under conditions with more complex interactions. As a key indicator of faecal contamination that may pose a potential risk to human health and recreational capabilities, minimisation of *E. coli* from agricultural areas can greatly improve ecosystem services. Regarding the second question, nitrogen has been postulated as the limiting nutrient at Lake Wairarapa (Perrie & Milne, 2012), thus interception of nitrogen is crucial for effective management at the lake. Esperschuetz et al. (2017b) suggested that nitrogen cycling can be inhibited under mānuka, which could foster further regulating services at Lake Wairarapa.

3.2 Literature Review

3.2.1 Agricultural intensification in New Zealand

In New Zealand, pastoral agriculture accounts for almost 40% of total land cover (Ministry for the Environment & Statistics New Zealand, 2018). Recently, sectoral shifts have reflected increased market preferences for dairy products (Ministry for the Environment & Statistics New Zealand, 2018). For example, total land cover of dry stock farming reduced by 151,700 ha whereas dairy expanded by 157,900 ha between 2008 and 2012 (Parliamentary Commissioner for the Environment, 2015). Similarly, stocking intensity in dairy herds rose 147% between 1990 and 2012, and milk solid production increased 40% per cow between 1993 and 2012 (Foote et al., 2015).

Agriculture provides many social and economic benefits to New Zealanders (e.g. export earnings of 35.4 billion NZD in 2016); however, these benefits come at the expense of environmental resources such as freshwater (Ministry for the Environment & Statistics New Zealand, 2018). In a meta-analysis of 45 shallow coastal lakes (similar to Lake Wairarapa), Drake et al. (2011) found that the seven supertrophic or hypertrophic lakes were situated in catchments supporting intensive agriculture.

3.2.2 Agricultural pollutants and environmental impacts

From intensification in the pastoral agriculture sector, three key pressures emerge on waterways: nutrient loading, pathogen contamination, and sedimentation (Parliamentary Commissioner for the Environment, 2015). Increased nitrogen (N) and phosphorus (P) loading emerge primarily from excessive fertiliser input, animal excreta and decomposition, and erosion of soils (Parfitt et al., 2006). High N concentrations in pastures, resulting from excessive nitrogenous fertiliser use, far exceed animal nutritional requirements (Cameron et al., 2013; Oenema et al., 1997). Typically, pastoral stock only use 5-20% of total N available; therefore, the remaining 80-95% of N is excreted (Di & Cameron, 2016; Oenema et al., 1997). Here, total concentration of excreted N is 20-80 g N m^{-2} and 20-200 g N m^{-2} for urine and faeces, respectively (Oenema et al., 1997). Cows urinate between 13 and 73 times per day (total volume of 5.8-54.7 L per day), with such urination events contributing a N load of 0.8-14.1 g N L^{-1} (Betteridge et al., 2013). Nitrogen in urine is primarily in the form of urea, accounting for 69% and 83% in cows and sheep, respectively (Bristow et al., 1992).

Excessive nitrogen inputs can contribute to ammonia volatilisation, nitrate leaching, denitrification, and nitrous oxide (N_2O) emissions (Di & Cameron, 2016; Oenema et al., 1997). Within soils, nitrogen in the form of ammonium (NH_4^+) is oxidised rapidly to nitrate (NO_3^-), a more mobile form of N (Di & Cameron, 2016). As predominately negatively charged soil colloids cannot bind to nitrate, the compound is easily lost through water (i.e. leaching) (Di & Cameron, 2016). Denitrification of nitrate to nitrous oxide also contributes to total greenhouse gas emissions from agriculture (Di & Cameron, 2016).

Similarly, diffuse inputs of phosphorus from agricultural areas is considered the greatest risk to phosphorus loading in waterbodies (Li et al., 2015). Abell et al. (2010) concluded that New Zealand lakes tend to be phosphorus-limited, despite generally low total nitrogen to total phosphorus ratios. Here, low nitrogen values were due to an abundance of phosphorus inputs rather than nitrogen deficiency; thus, measures to reduce phosphorus were recommended in highly productive lakes (Abell et al., 2010). Although, for Lake Wairarapa, nitrogen is postulated to be the limiting nutrient (Waters et al., 2018).

Pathogen transmission from animal faeces also poses a risk to human health and decreases opportunities for contact recreation. Significant bacterial inputs such as *E. coli*, enterococci, and *Campylobacter* are observed in fresh bovine faeces, and parasitic inputs such as *Cryptosporidium* and *Giardia* are also present in some cases (Moriarty et al., 2008). Faecal contaminants enter waterways directly from stock access to waterbodies, or indirectly from hill country runoff, dairy shed effluent, artificial subsurface drains, or percolation to groundwater reservoirs (Collins et al., 2007). Likewise, irrigation of pastures further exacerbates risk of microbial contamination (particularly *E. coli*) through transport to surface water and groundwater (Weaver et al., 2016).

Finally, in-stream sedimentation from land erosion and cattle degradation of stream banks has many impacts, including reduced aesthetic appeal and dissolved oxygen, and increased phosphorus and heavy metal concentration (Ballantine & Davies-Colley, 2013; Bilotta & Brazier, 2008; Grove et al., 2015). Congruently, compaction of soils from animals and heavy machinery on pastures reduces porosity and negatively influences effective production of crops (Drewry & Paton, 2000; Ministry for the Environment & Statistics New Zealand, 2015). Among many others, these impacts curtail the effectiveness and efficiency of ecosystem services in agricultural areas (Foote et al., 2015; Meurk & Swaffield, 2000).

3.2.3 Mitigation through riparian management

A method commonly employed to mitigate the effects of diffuse agricultural pollution in New Zealand is the restoration or protection of vegetated riparian margins (Parkyn et al., 2003). Riparian zones refer to the "interface between terrestrial and aquatic ecosystems" (Gregory et al., 1991, p. 540) and can attenuate diffuse pollution through both physical and biological mechanisms (Fennessy & Cronk, 1997). While interest in maintaining and developing vegetated riparian margins has grown in New Zealand since the 1990s, margins are typically less than 5 m wide, are primarily planted with exotic species, and contain poor plant diversity (McKergow et al., 2016).

New Zealand-based literature has demonstrated reduced runoff of nutrients and sediments, microbial retention, and erosion in small streams that are protected by riparian planting (McKergow et al., 2016). For example, Smith (1989) concluded that dissolved nitrogen runoff was reduced by 67% in retired riparian zones compared to those that were still grazed. Similarly, Parkyn (2004) determined that subsurface nitrate concentrations were reduced by greater than 90% when flow passed through riparian areas. Cooper (1990) also noted the importance of soil type on nitrate depletion in riparian areas, where 56-100% of nitrate depletion occurred within organic soils (compared to mineral soils), yet organic soils only comprised 12% of total soil type.

Microbial contaminants in surface runoff that encounter riparian margins are reduced in magnitude and momentum, with microbes often trapped or infiltrated in riparian zones (Collins et al., 2007). This is also controlled by flow rate, with margin widths greater than 5 m needed to reduce microbes during a large runoff event (Collins et al., 2004). Parkyn et al. (2003) demonstrated that *E. coli* can be substantially decreased in riparian zones, but that riparian fencing alone is not sufficient and must be coupled with planting regimes. Likewise, mitigation of bacterial inputs on land is most beneficial, as microbes stored in stream sediments can be released in flood events (Nagels et al., 2002).

However, riparian margins are no panacea for instantaneous improvements in water quality. Hughes (2016) argued that riparian restoration projects would likely yield results over decadal timescales. Likewise, improvements in water quality are difficult if upstream areas are not well managed (or managed at all) (Collins et al., 2013; Parkyn et al., 2003). Therefore, any riparian management programmes ought to be coupled with other measures to reduce agricultural impacts (Maseyk et al., 2017).

3.2.4 Greater Wellington Regional Council riparian management approach

National trends showing increased uptake of riparian management strategies are also observed within the Greater Wellington Regional Council (GWRC). The 2003 Riparian Management Strategy outlines the importance of riparian management in the region, stating that 90% of nutrient loading and four-fold increases of faecal contaminants are observed in the Ruamāhanga River during elevated flows (River Ecosystems Group of Greater Wellington, 2003).

The GWRC takes a non-regulatory approach to riparian management and offers incentives to fence and plant riparian areas (River Ecosystems Group of Greater Wellington, 2003). Incentives range from stream fenced and no planting ($23.70/m) to stream fenced (10 m width) and native species ($68.46/m). Given these costs, the council prioritises areas where land use is threatening otherwise healthy aquatic systems, those that may provide natural biodiversity corridors to Lake Wairarapa or the sea, and areas that are of high cultural significance to Māori (River Ecosystems Group of Greater Wellington, 2003).

Pilot rehabilitation studies investigating the effectiveness of riparian management were conducted by the GWRC at three streams following release of the strategy document (Perrie, 2008). The study noted varying improvements in vegetation cover and stream shading, bank stability, aquatic habitat and macroinvertebrate communities, fish communities, and aesthetic quality. Likewise, reduced water temperature, instream plants, and nutrient and sediment input were also observed (Perrie, 2008). The study corroborated other literature and concluded that whilst riparian rehabilitation was able to mitigate some impacts of land use on stream health, improved upstream land management was also required (Perrie, 2008).

3.2.5 Native riparian restoration

While riparian restoration from planting many species can inhibit excess nutrients and microbial contaminants from reaching surface waters (Franklin et al., 2015; Mander et al., 2005; Zhang et al., 2010), recent experiments in laboratory settings have shown that regulating services can be further enhanced by species in the Myrtaceae family, namely mānuka (*Leptospermum scoparium*) and kānuka (*Kunzea ericoides*). For example, Prosser et al. (2014) found that mānuka leaf, oil, and root extracts all either significantly reduced or inhibited growth of five bacterial species (both gram-positive and gram-negative strains), whereas ryegrass supported bacterial growth in all but one species. In a subsequent study, Prosser et al. (2016) observed significant *E. coli* reductions in pots containing kānuka and mānuka, where 90% reductions were observed after five and eight days, respectively. In contrast, *E. coli* counts under ryegrass would have taken 93 days to reach a 90% reduction (Prosser et al., 2016). Contrastingly, greenhouse experiments completed by Mishra (2018) demonstrated that root networks of mānuka and kānuka created preferential flow pathways and increased *E. coli* leaching compared to pasture under high irrigation or dairy shed effluent application regimes.

In a laboratory study, Downward (2013) demonstrated that mānuka and kānuka extracts inhibited the activity of nitrifying bacteria *Nitrosospira* cultures, compared to pasture or other tree species, therefore reducing nitrate leaching. Furthermore, in a greenhouse lysimeter study, Esperschuetz et al. (2017b) found mānuka and kānuka significantly reduced nitrate leaching (both 2 kg ha^{-1}) compared to pine (53 kg ha^{-1}) following successive urea application. Higher concentrations of ammonium in mānuka and kānuka treatments suggest inhibition of nitrification enzymes thus reducing conversion from ammonium to nitrate (Esperschuetz et al., 2017b). Similarly, higher cumulative nitrous oxide emissions from pine treatment compared to mānuka and kānuka suggest enzyme inhibition of the denitrification process as well (Esperschuetz et al., 2017b). However, there were no significant differences in nitrogen leaching between mānuka, kānuka, and pine following the application of biosolids, potentially due to the composition of nitrogen species in biosolids (Esperschuetz et al., 2017a). Similarly, large losses in biosolids through ammonia volatilisation may have contributed to overall reduced nitrogen leaching (Robinson & Röper, 2003). These recent studies indicate the potential of mānuka and kānuka to mitigate bacterial and nitrogen pollutants in laboratory settings. However, a large gap exists within the literature as to how these interactions operate within a natural environment.

3.2.6 Benefits of mānuka

While both mānuka and kānuka potentially offer similar environmental benefits, this apparent gap in the literature is examined with mānuka in riparian management – this is for several key reasons. One reason is that mānuka honey production offers many potential economic benefits. Mānuka honey exports in the 2015/16 season earned between 12-148 NZD per kg, and a 35% in total honey exports from 233 million NZD (2015) to 315 million NZD (2016) has been largely attributed to the growth of the mānuka honey industry (Ministry for Primary Industries, 2016). As mānuka also thrives in marginal land and disturbed environments (Stephens et al., 2005), some farmers with marginal land have been incentivised to convert from agriculture to the more economically beneficial honey production (Nickless et al., 2017). Mānuka in riparian zones may therefore mitigate the lost opportunity costs and incentivise farmers to retire riparian areas to generate alternative income sources. Mānuka is also important in New Zealand forest succession as well as added environmental benefits through carbon sequestration (Allen, 1988).

Mānuka is also culturally important to Māori as a rongoā species (traditional medicinal resource). The antimicrobial properties of mānuka were realised by Māori and utilised in traditional Māori medicine (Williams, 1996). In contemporary medicinal practice, mānuka honey has been utilised in the treatment of bacterial infection and wound dressings (Old, 2013).

Through the survey of the literature, it is suggested that mānuka does have the ability to affect *E. coli* survival and the distribution of nitrogen species. However, to date, these experiments have been constrained to lab and greenhouse-based studies that allow for controlled measurement and reduced effects from multiple confounding variables. Such luxuries do not exist in the natural world. Therefore, if the use of mānuka is presented as a viable option to farmers and landowners to mitigate diffuse agricultural pollution, testing needs to be conducted in the field.

3.3 Methods

In order to answer the research questions concerning how mānuka would affect *E. coli* counts and nitrogen cycling in 'real-world' conditions, a small-scale field trial was conducted in a fenced riparian zone comparing mānuka and ryegrass. Here, designed 'excrement patches' of urea and *E. coli* from dairy shed effluent were applied to mānuka and ryegrass treatments to simulate the effect of an animal excretion event, and responses were measured over a three-week period.

3.3.1 <u>Site description & experimental design</u>

The field trial was conducted in a riparian zone situated on the western side of Lake Wairarapa (-41.183182°, 175.254344°). As part of a larger experimental project between the Institute of Environmental Science and Research (ESR), GWRC, and Ngāti Kahungunu ki Wairarapa, two areas were planted in August 2017 with mānuka at 1-m spacing and a middle section left unplanted as a control (Fig. 3.1). Flax and cabbage trees were also planted along the edges of the mānuka stand to provide shelter. The riparian area had been fenced for approximately six months, and then retired from grazing and sprayed with herbicides about two months prior to planting. The area is relatively flat and slopes gently to the edge of the lake. The riparian area margins a sheep and beef farm that primarily uses sulphur, phosphate, and nitrogen fertilisers. Soils along the western edge of Lake Wairarapa are predominantly Recent Gley and Orthic Brown, with Orthic Brown underlying the area of this study (Landcare Research, 2018). Further environmental information is outlined earlier in Chapter 1.

The field experiment was carried out between October and November 2018, by which point the mānuka plants had been growing for around 14 months and were approximately 1 m tall. Mānuka were considered as one treatment and the control area (henceforth, ‘stock exclusion’) as the second treatment (Fig. 3.2, 3.3). For each treatment, fifteen areas with a radius of 15 cm (approximately 707 cm^2) were randomly selected and marked out using rope (Fig. 3.4a-d).

3.3.2 Nitrogen simulation

For the application of nitrogen, a urine patch was simulated using urea (CH_4N_2O). Although average urination events from cows are 2.1 L (Betteridge et al., 2013), a 700 mL urination event was created to avoid saturation and movement of nutrients out of the sampling areas. The average urine concentration of 0.95 g N 100 mL^{-1} found by Betteridge et al. (2013) was used equating to 6.65 g N 700 mL^{-1}. This resulted in a 95 g N m^{-2} ‘urination’ event, which approximates values from existing literature of 20-120 g N m^{-2} nitrogen loading from cow urine (Selbie et al., 2015). The urination event was simulated using urea, where 6.65 g N 700 mL^{-1} equated to 14.15 g urea 700 mL^{-1}. Here, 424 g urea was added to 21 L of distilled water, with the total solution divided into 700 mL aliquots for each of the 30 treatment sites

Figure 3.1: Planting strategy of the overall field trial (produced by GRWC)

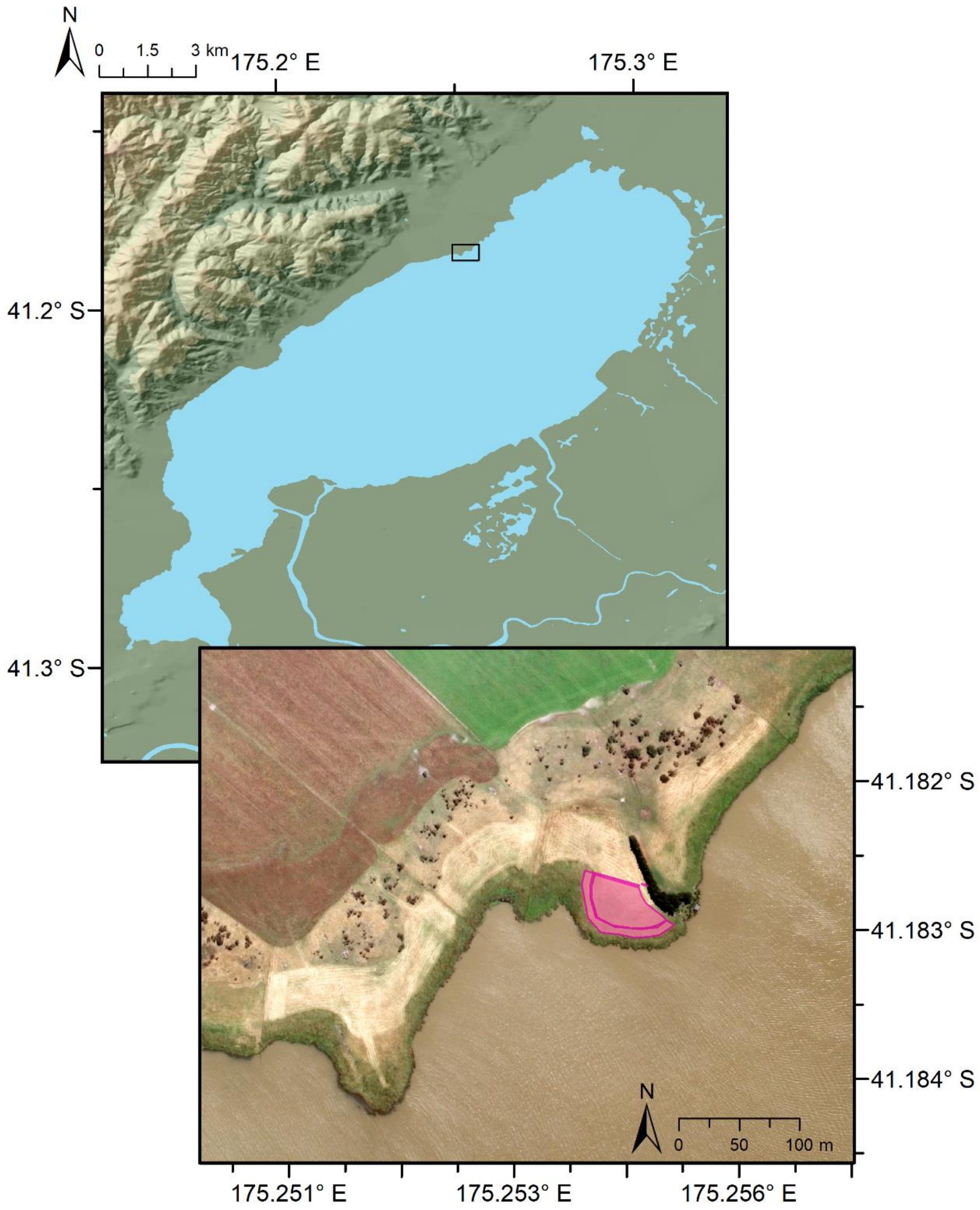


Figure 3.2: Map of the study site used in this experiment. Mānuka was planted in the pink area, with the stock exclusion site in the riparian area immediately west of the mānuka site. The upper map shows the site location in relation to the wider Lake Wairarapa landscape.

Figure 3.3: Photo of mānuka plot with 1-m spaced saplings (October 2018)

.

Figure 3.4: Example sites of mānuka and stock exclusion treatments following sampling: (a) mānuka prior to sampling, (b) stock exclusion prior to sampling, (c) mānuka after sampling, and (d) stock exclusion after sampling.

3.3.3 *E. coli* simulation

An excrement event was simulated using *E. coli* isolated from dairy shed effluent, which was stored at ESR in a -80°C freezer. One loopful was taken from the glycerol stock and added to 5 mL of Luria broth and replicated three times. *E. coli* was incubated at 180 RPM for 24 hr at 34°C. The three replicates were then combined and centrifuged for 1 hr at 2,500 RPM. Following this, the supernatant was removed, and the remaining culture was re-suspended in 3 mL of Ringer's solution. This was centrifuged again for 20 min at 4,000 RPM, after which the supernatant was removed, and the culture was re-suspended in 3 mL of Ringer's solution, and stored at 4°C. This process was repeated six times to ensure enough *E. coli* colonies for the experiment.

The six bacteria stocks were enumerated following resuscitation. A 10-fold serial dilution (10^{-1} to 10^{-10}) was performed, whereby 100 µL of resuscitated stock was added to 900 µL of Ringer's solution. From each dilution, three 10 µL aliquots were transferred to Lysogeny broth agar plates and incubated at 34°C for 24 hr. Colony forming units (cfu) were counted from the dilution containing between 10-30 colonies per aliquot, with the result from all three colonies of that dilution averaged. This process was repeated for all six stocks.

Colony forming units in stock (cfu/mL) was calculated using the following formula:

$$= average\ no.colonies\ \times 100\ \times serial\ dilution\ value$$

From the six resuscitated stocks, the four stocks with the highest cfu counts were identified, being 5.3 x 10^9 cfu mL^{-1}, 7.3 x 10^9 cfu mL^{-1}, 1.8 x 10^{10} cfu mL^{-1}, and 2.3 x 10^{10} cfu mL^{-1}. Each of the 3 mL stocks were then combined (12 mL in total), with an average count of 1.8 x 10^{10} cfu mL^{-1}. The 12 mL combined bacterial stock was initially added to 1188 mL of Ringers solution (10^{-2} dilution) and shaken well to distribute and homogenise *E. coli*. This solution was then added to a further 10.8 L of Ringers solution (10^{-3} dilution) and homogenised again. The total 12 L solution was divided into 400 mL aliquots for each of the 30 treatment sites, with the final concentration approximately 7.2 x 10^9 cfu per aliquot. When applied to the sampling areas, this equated to 1.02 x 10^7 cfu per cm^2. Although slightly elevated, this corresponds to values observed by Himathongkham et al. (1999), whereby cattle shed *E. coli* 0157:H7 at levels around 10^2 and 10^5 cfu g^{-1}. However, the *E. coli* calculated for this experiment correspond well to *E. coli* counts of around 10^6 and 10^9 cfu mL^{-1} observed in dairy shed effluent (Mishra, 2018).

3.3.4 Application of excrement patches and soil sampling

Prior to application to the excrement patches, baseline soil sampling was conducted. Samples from the mānuka and stock exclusion treatments were taken at 0-10 cm, 10-20 cm, and 20-30 cm. These samples were taken across four transects, moving from the fence-line towards the edge of the lake.

As mentioned earlier, sample plots were marked out with a rope on application day. Excessive grass growth around mānuka trees was cut back and grass in the stock exclusion treatment was trimmed to approximately 2 cm to allow solutions to reach root networks. Then, a staged approach was taken for the application of solutions. Firstly, approximately 350 mL of the urea solution was applied, left for 30 min to percolate into soil, then the remaining 350 mL applied. After a further 30 min, the *E. coli* solution was applied. Both solutions were applied using a watering can to allow for more even distribution onto sample plots

Soil samples were collected at five different time points after the application event: 1 day, 3 days, 7 days, 14 days and 21 days. At each of these sampling points, three sites from each treatment (i.e. three mānuka and three stock exclusion) were randomly selected across the experiment area and soil samples taken. At the sites, five soil samples were taken at 0-10 cm, 10-20 cm, and 20-30 cm from each sample plot to observe changes down the profile. This was conducted using a soil probe, with samples from the same depth homogenised and subsequently treated as one. The soil probe was washed and sterilised with 80% ethanol between sampling to avoid cross contamination. Following sample collection, soils were transferred on ice to the Soils Laboratory at ESR within two hours.

3.3.5 Laboratory methods

Once at the ESR Soils laboratory, all soils were immediately sieved using 2-mm meshes and stored at 4°C before completion of *E. coli* enumeration, nitrogen extractions and soil moisture analyses. *E. coli* and soil moisture analyses were performed on fresh soil within 24 hr from soil collection, and remaining soils frozen. Nitrogen extractions were completed near the end of the experiment, where soils were thawed, and all extractions were completed in three batches.

3.3.6 Soil moisture

Soil moisture was calculated to determine dry mass of soil for subsequent calculations. A glass universal tube was weighed (universal), then approximately 10 g of fresh soil added and weighed again (wet mass). Soil was then dried for 24 hr at 104°C, then weighed a final time (dry mass).

Soil moisture percentage was calculated using the following formula:

$$= \frac{(\,wet\ mass - dry\ mass\,) \times 100}{wet\ mass - universal}$$

3.3.7 MPN method for enumerating *E. coli*

E. coli in soil samples were enumerated using a five-tube most probable number (MPN) estimation method. Here, 10 g of fresh soil was weighed out, added to 90 mL of Ringer's solution then shaken for 60 min at 200 RPM and 22°C. Serial dilutions were then performed: 1 mL of extracted solution was inoculated into 9 mL of Ringer's solution, shaken and repeated, until a 10^{-5} dilution was achieved. Afterwards, 1 mL from 10^{-1} to 10^{-5} dilutions were inoculated into five laurel tryptose (LT) broth tubes with an inverted glass (Durham) tube and incubated at 35°C for 24 hr. LT broth tubes that exhibited gas production (gas bubble in Durham tube) were recorded as positive for coliform bacteria. Then, 10 µL from positive LT broth tubes were inoculated into *E. coli* medium with 4-methylumbelliferyl-β-D-glucuronide (EC+MUG) tubes and incubated at 44°C for 24 hr. Negative LT broth tubes after 24 hr were incubated for a further 24 hr at 35°C and also transferred into EC+MUG if positive. LT broth tubes that were negative after 48 hr were recorded as containing no coliform bacteria. Following 24 hr of incubation at 44°C, EC+MUG tubes were viewed under UV light (366 nm). Tubes that fluoresced under UV light were recorded as positive for *E. coli*. MPN results were then calculated using standard MPN tables.

MPN g^{-1} of dry soil was calculated using the following formula:

$$= MPN\ per\ g\ (wet\ soil)\ \times\ 1000\ /\ (\ 10\ \times (\ 100 - soil\ moisture\ \%))/\ 100\ )$$

3.3.8 Potassium chloride extractions for ammonium and nitrate

Ammonium and nitrate were extracted from soil samples using the 2 M potassium chloride (KCl) extraction method (Blakemore et al., 1987; Franklin et al., 2015). Approximately 4.5 g of fresh soil was added to 45 mL of 2 M KCl solution and shaken for 1 hr at 200 RPM. Samples were then centrifuged for 10 min at 2,000 RPM. Supernatant liquid was filtered through Whatman 41 filter paper and stored at -20°C until analysis. For each sampling day, reagent blanks were also completed. Frozen samples were analysed for ammonium and nitrate by Flow Injection Analyser (Quikchem 8500) at the Environmental Chemistry Laboratory at Manaaki Whenua/Landcare Research (Palmerston North).

Results were calculated using the following formulae:

Ammonium (mg/kg dry soil) $= \frac{(a \times 45 \times 100)}{(b \times (100 - SM\%)}$ Nitrate (mg/kg dry soil) $= \frac{(c \times 45 \times 100)}{(b \times (100 - SM\%)}$	Where– a = NH_4^+-N (mg/L) b = initial soil weight c = NO_3^--N (mg/L)

3.3.9 Data analysis

Following completion of *E. coli*, ammonium and nitrate analyses, results were explored using Analysis of Covariance (ANCOVA). This was completed with Microsoft Excel using the XLSTAT statistical analysis data add-in (Addinsoft, 2017). ANCOVA testing allows the user to assess multiple categorical and continuous independent variables (covariates) thought to affect the experimental dependent variable (Rutherford, 2011). In this study, the independent variables included treatment type (categorical), date of collection (continuous), and soil depth (continuous). An ANCOVA test was performed for each dependent variable: *E. coli*, ammonium and nitrate. Data was log-transformed for *E. coli* and nitrate analyses, while ammonium was left untransformed. Transformations were completed for *E. coli* and nitrate to produce normally distributed residuals, satisfying the assumptions of ANCOVA. However, due to the nature of incorporating time series data (date of collection) may have led to inflation of p values.

3.4 Results

3.4.1 Climate and soil moisture

Results for climatic variables over the course of the experiment (Fig. 3.5) were taken from the Martinborough Ews climate station managed through the National Institute of Water and Atmospheric Research (NIWA, 2019). Maximum daily temperatures ranged from 24.9°C and 13.1°C (mean = 19.6°C), and minimum daily temperatures ranged from 18.0°C to 3.9°C (mean = 9.6°C). Precipitation data shows varying rainfall prior to onset of the experiment until just after Day 3 (3 Nov 2018). Rainfall was then negligible until the final four days of the experiment.

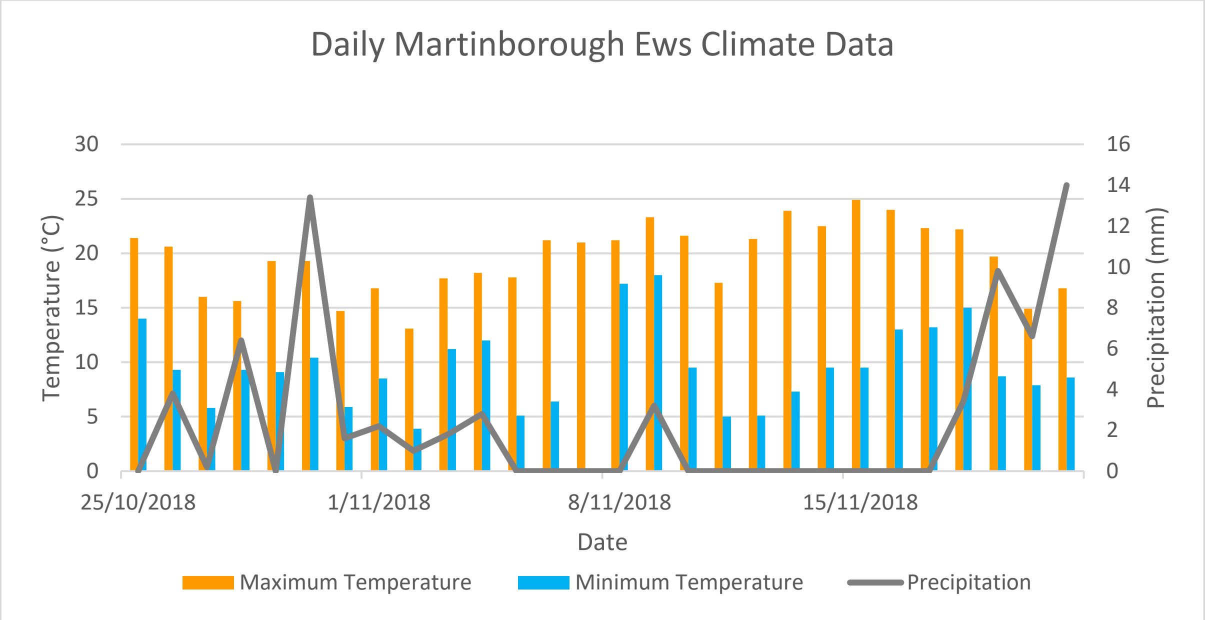


Figure 3.5: Daily maximum and minimum temperature (°C) and precipitation (mm) data from 25 Oct 2018 to 21 Nov 2018, collected from the Martinborough EWS (Electronic Weather Station) climate station (NIWA, 2019).

Averaged soil moisture results from this study (Fig. 3.6) show general declining in soil moisture farther down the soil horizon. The highest soil moisture percentage is observed at Day 1 of the experiment across all three depths, with a slight increase toward Day 21.

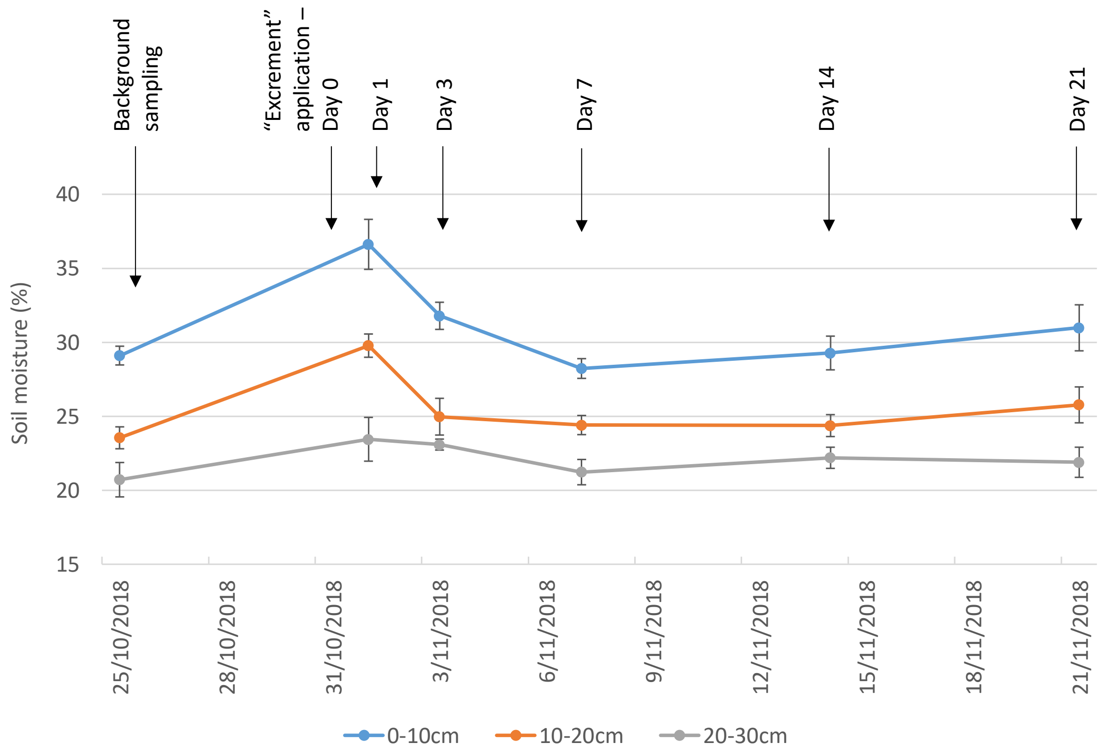


Figure 3.6 Average soil moisture percentages of both treatments by soil depth across the experiment.

3.4.2 *E. coli*

Mean results of *E. coli* counts from soil samples following the application of 7.2 x 10^9 cfu per sampling area are shown in Figs. 3.7a-c. *E. coli* counts are similar between mānuka and stock exclusion in the 0-10 cm and 10-20 cm horizons, at around 2.3 x 10^3 MPN g^{-1} at Day 1 and Day 3, then slowly decreasing over the remainder of the experiment. In both soil depths and both mānuka and stock exclusion treatments, a 90% reduction (one log reduction) in *E. coli* is observed around 10-11 days following the application of simulated excrement. The 20-30 cm horizons showed a similar response to *E. coli* application in both treatments, with a 90% reduction after 10-11 days. Stock exclusion exhibits around 10 times fewer *E. coli* counts throughout the duration of the experiment than mānuka treatment.

The results of the ANCOVA (Table 3.1) indicate that the independent variables explain 57.6% of the variance in *E. coli* numbers. All variables are significant, with date of collection having the most significant impact. Fig. 3.8 indicates that the majority of data points (aside from two) fit between the model's confidence intervals.

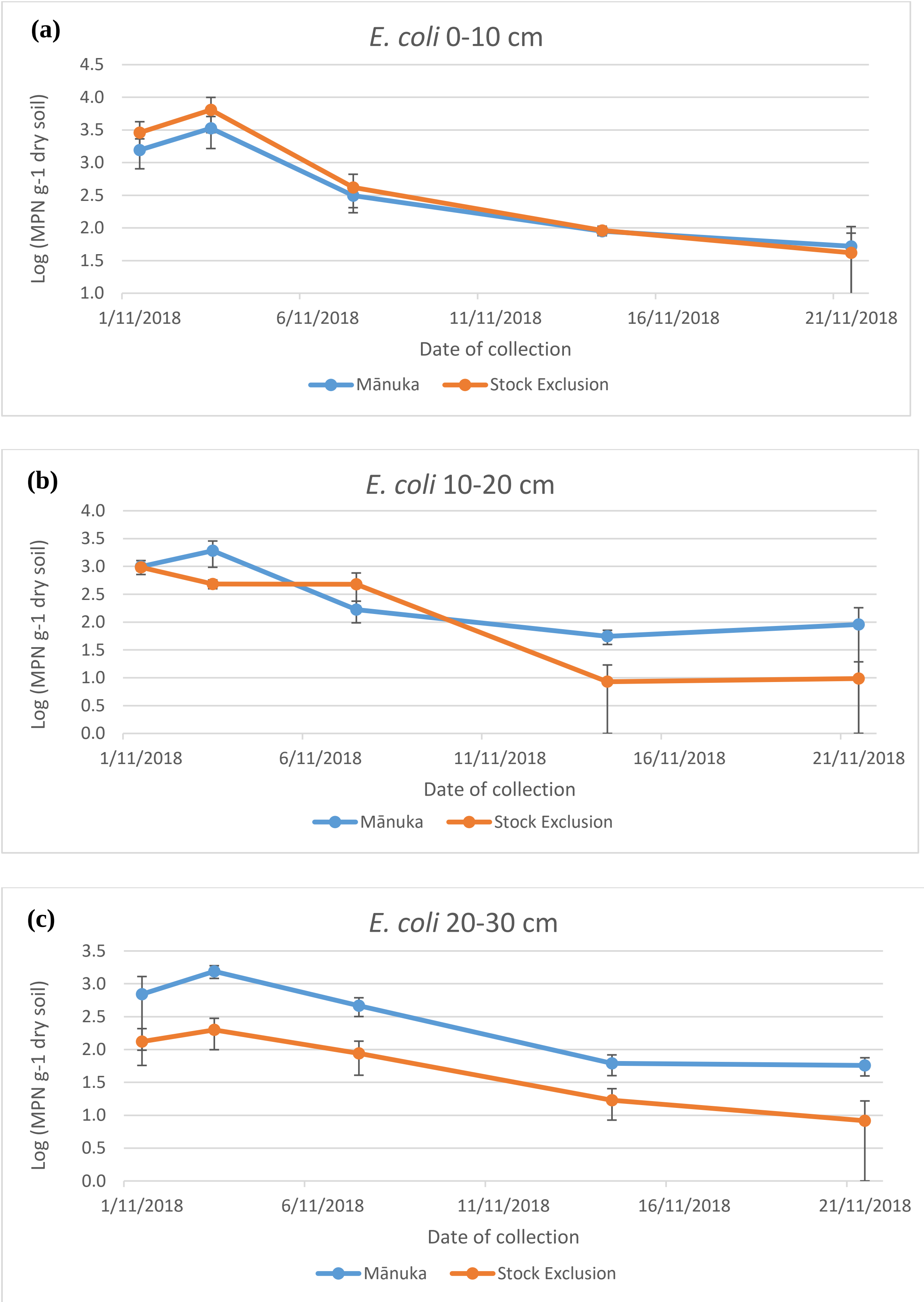


Figure 3.7: Results of MPN g^{-1} (dry soil) for both mānuka and stock exclusion treatments with standard errors from (a) 0-10 cm, (b) 10-20 cm, and (c) 20-30 cm horizons. Y-axis values are logarithmic.

Table 3.1: ANCOVA results from E. coli counts

Goodness of fit statistics						
Adjusted R^2	0.576					
RMSE	0.724					
Correlation matrix:						
	Depth (cm)	*Date of Collection*	*Treatment-Mānuka*	*Treatment-Stock Excl.*	*MPN/g*	
Depth (cm)	**1**	0.000	0.000	0.000	-0.205	
Date of Collection	0.000	**1**	0.000	0.000	-0.717	
Treatment-Mānuka	0.000	0.000	**1**	-1.000	0.186	
Treatment-Stock Excl.	0.000	0.000	-1.000	**1**	-0.186	
MPN/g	-0.205	-0.717	0.186	-0.186	**1**	
Analysis of variance						
Source	*DF*	*Sum of squares*	*Mean squares*	*F*	*Pr > F*	
Model	3	64.9583374	21.6527791	41.3586136	< **0.0001**	
Model parameters						
Source	*Value*	*Standard error*	*t*	*Pr > |t|*	*Lower bound (95%)*	*Upper bound (95%)*
Intercept	3.245	0.201	16.165	< **0.0001**	2.846	3.644
Depth (cm)	-0.028	0.009	-2.978	**0.004**	-0.046	-0.009
Date of Collection	-0.107	0.010	-10.390	< **0.0001**	-0.128	-0.087
Treatment-Mānuka	0.411	0.153	2.696	**0.008**	0.108	0.714
Treatment-Stock Excl.	0.000	0.000				

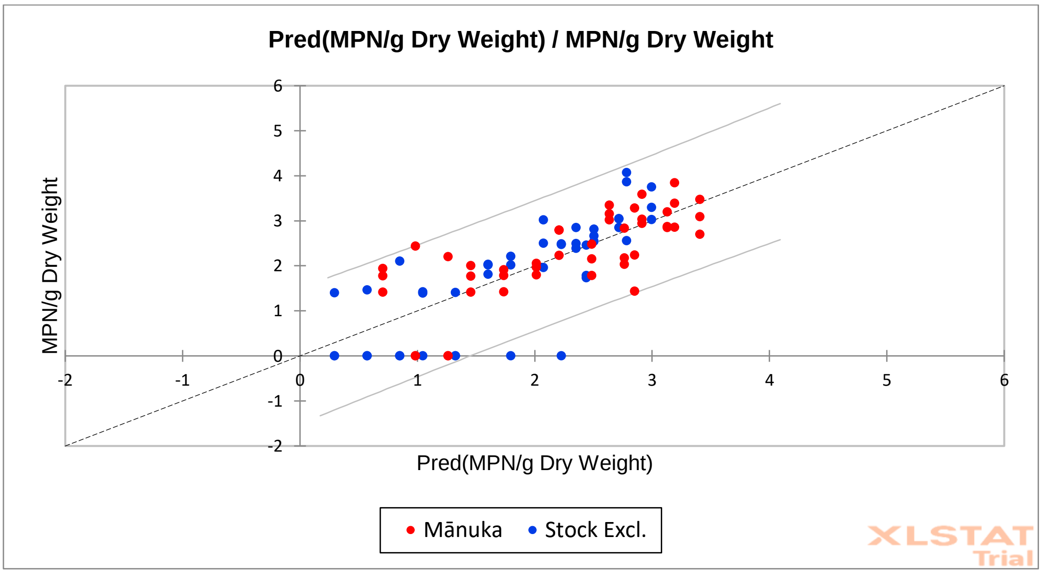


Figure 3.8: Plot of predicted E. coli values compared to observed values. X- and y-axes values are logarithmic.

3.4.3 Ammonium

Mean results of ammonium (Figs. 3.9a-c) show a general decline in concentration over the course of the experiment for 0-10 cm and 10-20 cm. The highest concentrations are observed in the 0-10 cm horizon, where concentrations of ammonium in the stock exclusion treatment of 552 mg kg^{-1} and 599 mg kg^{-1} are observed at Days 1 and 3, respectively. Comparatively at the same depth, mānuka shows mean concentrations of 387 mg kg^{-1} and 263 mg kg^{-1} at Days 1 and 3, respectively, before following a decline similar to stock exclusion for the remainder of the experiment.

General trends for stock exclusion and mānuka at 10-20 cm and 20-30 cm are similar. The 10-20 cm horizon exhibits higher concentrations at Day 1 of 285 mg kg^{-1} and 274 mg kg^{-1} for stock exclusion and mānuka respectively, declining to 115 mg kg^{-1} and 94 mg kg^{-1} for stock exclusion and mānuka treatments by Day 21. Here, concentrations reduce at Day 3, are relatively constant until Day 7, and decline over Days 14 to 21. At 20-30 cm, ammonium concentrations are relatively constant for both treatments, with a peak on Day 3 for mānuka and Day 7 for stock exclusion.

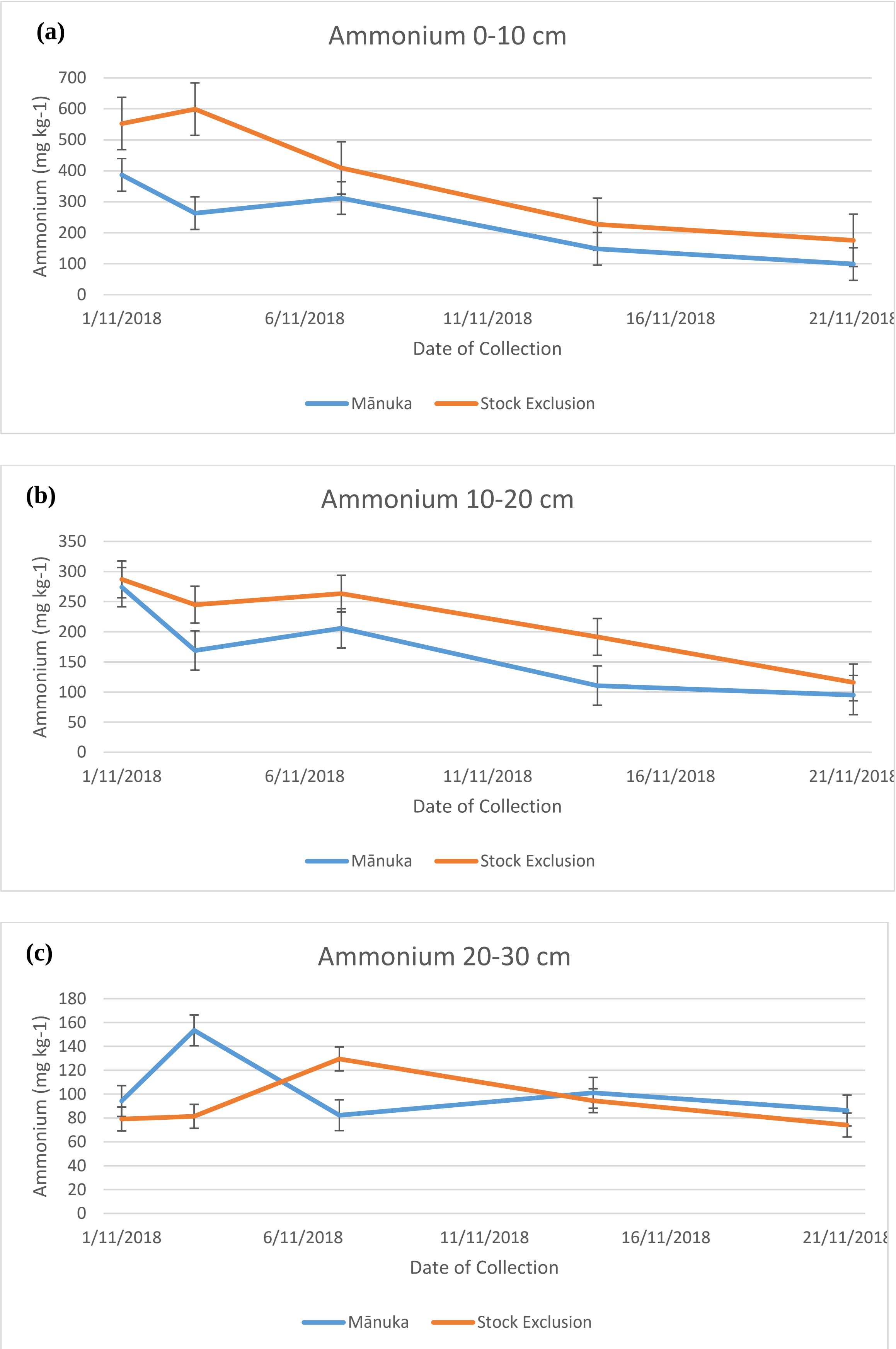


Figure 3.9: Ammonium concentrations (mg kg^{-1}) for mānuka and stock exclusion treatments with standard errors for the (a) 0-10 cm, (b) 10-20 cm, and (c) 20-30 cm horizons.

Table 3.2: ANCOVA results from ammonium concentrations

Goodness of fit statistics						
Adjusted R^2	0.601					
RMSE	93.171					
Correlation matrix:						
	Depth (cm)	*Date of Collection*	*Treatment-Mānuka*	*Treatment-Stock Excl.*	*Ammonia-N (mg/kg)*	
Depth (cm)	**1**	0.000	0.000	0.000	-0.611	
Date of Collection	0.000	**1**	0.000	0.000	-0.442	
Treatment-Mānuka	0.000	0.000	**1**	-1.000	-0.215	
Treatment-Stock Excl.	0.000	0.000	-1.000	**1**	0.215	
Ammonia-N (mg/kg)	-0.611	-0.442	-0.215	0.215	**1**	
Analysis of variance						
Source	*DF*	*Sum of squares*	*Mean squares*	*F*	*Pr > F*	
Model	3	1192020.06	397340.02	45.7716331	< **0.0001**	
Model parameters						
Source	*Value*	*Standard error*	*t*	*Pr > |t|*	*Lower bound (95%)*	*Upper bound (95%)*
Intercept	480.597	25.847	18.594	< **0.0001**	429.215	531.980
Depth (cm)	-10.986	1.203	-9.134	< **0.0001**	-13.377	-8.595
Date of Collection	-8.781	1.330	-6.604	< **0.0001**	-11.424	-6.138
Treatment-Mānuka	-62.966	19.642	-3.206	**0.002**	-102.013	-23.918
Treatment-Stock Excl.	0.000	0.000				

ANCOVA results for ammonium (Table 3.2) reveal that the independent variables explain 60.1% of the variance in ammonium concentrations. All variables are statistically significant, with the correlation matrix indicating that depth has the most significant impact. Fig. 3.10 suggests that the majority of data points fit within the model's confidence intervals.

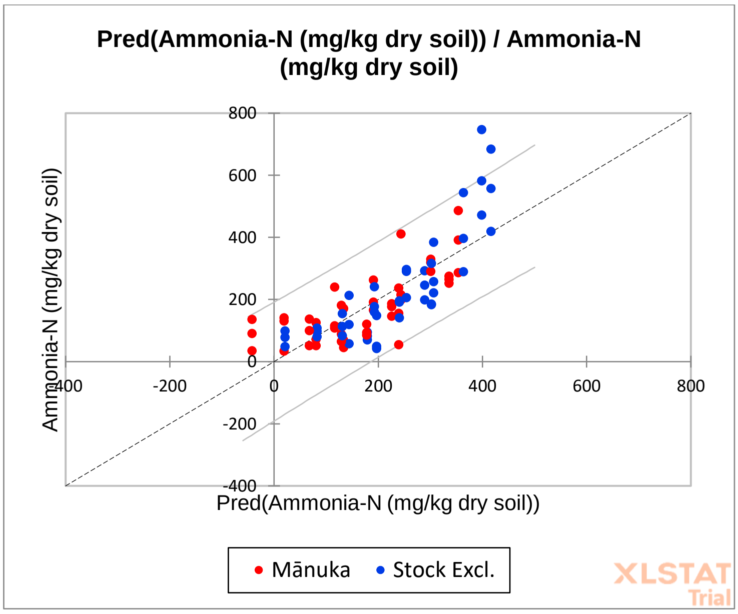


Figure 3.10: Plot of predicted ammonium values compared to observed values

3.4.4 Nitrate

Mean concentrations of nitrate are presented in Figs. 3.11a-c. Trends are similar between the stock exclusion and mānuka treatments, beginning at very low concentrations and increasing through time, although values generally change at a higher rate for stock exclusion. Stock exclusion at the 0-10 cm horizon exhibits the greatest increase in concentrations, with mean results of 19 mg kg^{-1} at Day 1, 72 mg kg^{-1} by Day 7, and 206 mg kg^{-1} by Day 21. Comparatively, mean results for mānuka at depth 0-10 cm are 14 mg kg^{-1} at Day 1, 58 mg kg^{-1} at Day 7, and 109 mg kg^{-1} by Day 21.

Trends in treatments are more distinct in the 10-20 cm and 20-30 cm horizons. Stock exclusion at 10-20 cm and 20-30 cm show a similar, gradually increasing trend. Here, an increase from 11 mg kg^{-1} to 139 mg kg^{-1} and 3 mg kg^{-1} to 51 mg kg^{-1} between Days 1 and 21 is observed for 10-20 cm and 20-30 cm, respectively. Similarly, mānuka at 10-20 cm and 20-30 cm show comparable trends, although with negligible increases between Days 1 and 14 (9 mg kg^{-1} to 22 mg kg^{-1} for 10-20 cm, and 2 mg kg^{-1} to 7 mg kg^{-1} for 20-30 cm). Nitrate then increases between Days 14 and 21, with concentrations at Day 21 of 88 mg kg^{-1} and 63 mg kg^{-1} for 10-20 cm and 20-30 cm, respectively.

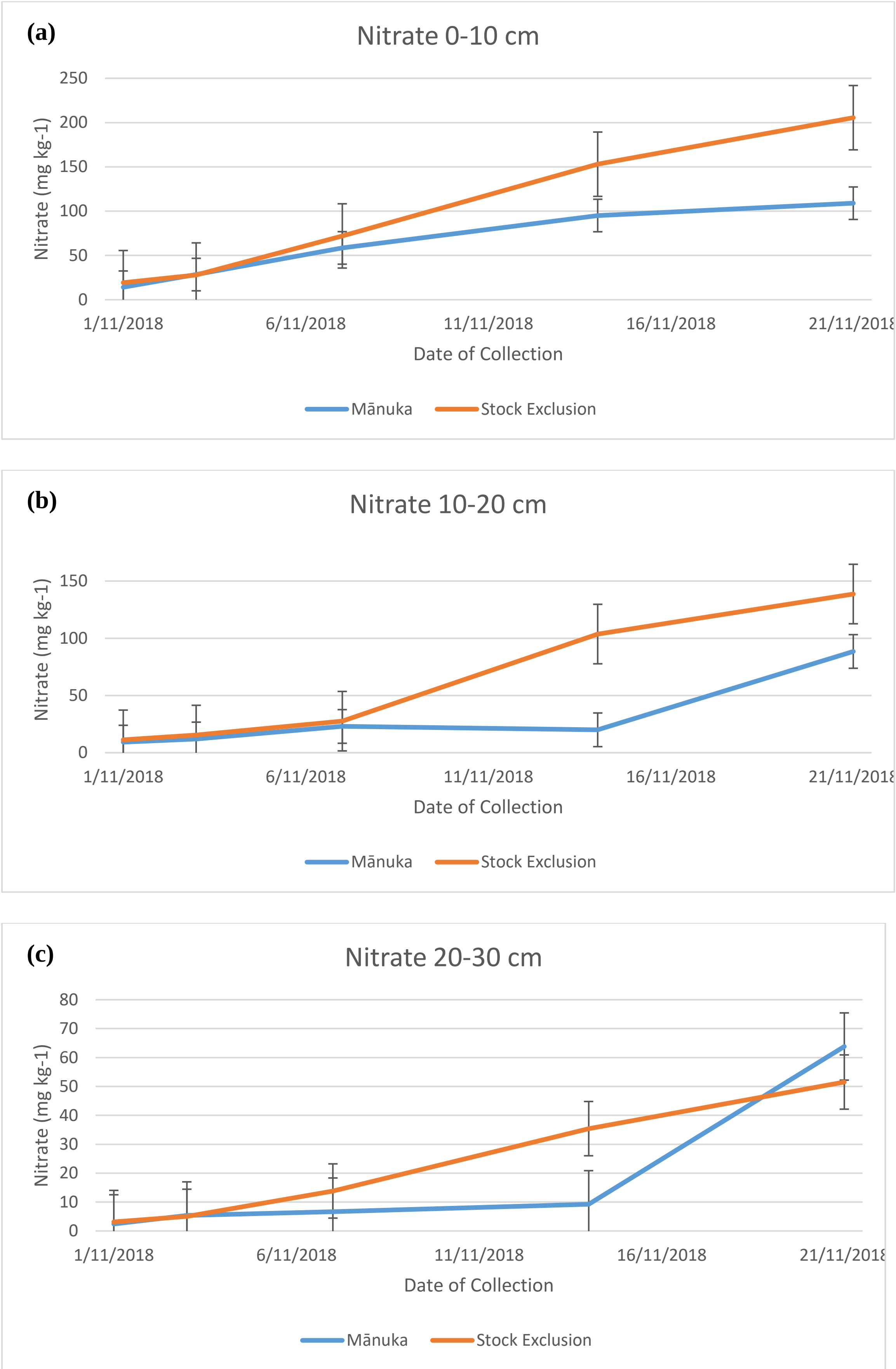


Figure 3.11: Nitrate concentrations (mg kg^{-1}) for mānuka and stock exclusion treatments with standard errors for the (a) 0-10 cm, (b) 10-20 cm, and (c) 20-30 cm horizons.

Table 3.3: ANCOVA results from nitrate concentrations

Goodness of fit statistics						
Adjusted R^2	0.719					
RMSE	0.323					
Correlation matrix						
	Depth (cm)	*Date of Collection*	*Treatment-Mānuka*	*Treatment-Stock Excl.*	*NO3-N (mg/kg dry soil)*	
Depth (cm)	**1**	0.000	0.000	0.000	-0.461	
Date of Collection	0.000	**1**	0.000	0.000	0.700	
Treatment-Mānuka	0.000	0.000	**1**	-1.000	-0.163	
Treatment-Stock Excl.	0.000	0.000	-1.000	**1**	0.163	
NOx-N (mg/kg)	-0.461	0.700	-0.163	0.163	**1**	
Analysis of variance						
Source	*DF*	*Sum of squares*	*Mean squares*	*F*	*Pr > F*	
Model	3	24.070548	8.02351599	76.7701303	**< 0.0001**	
Source	*Value*	*Standard error*	*t*	*Pr > |t|*	*Lower bound (95%)*	*Upper bound (95%)*
Intercept	1.423	0.090	15.869	**< 0.0001**	1.245	1.601
Depth (cm)	-0.034	0.004	-8.191	**< 0.0001**	-0.042	-0.026
Date of Collection	0.057	0.005	12.442	**< 0.0001**	0.048	0.067
Treatment-Mānuka	-0.198	0.068	-2.900	**0.005**	-0.333	-0.062
Treatment-Stock Excl.	0.000	0.000				

The results of the ANCOVA (Table 3.3) indicate that the independent variables explain 71.9% of the variance in nitrate concentrations. All variables are significant, with date of collection having the most evident impact. Fig. 3.12 suggests that the majority of data points (aside from one sample) fall within the model's confidence intervals.

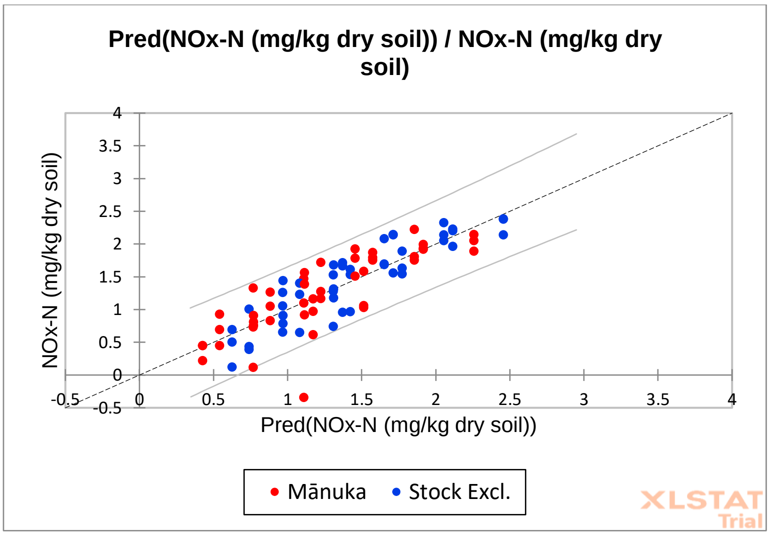


Figure 3.12: Residual plot of predicted nitrate values compared to observed nitrate values

3.5 Discussion

3.5.1 *E. coli*

The results from the field trial indicate that treatment does have an impact on *E. coli* survival rates, although major trends are explained by soil depth and date of collection. In the upper 0-10 cm and 10-20 cm horizons, the effect of mānuka appears to be commensurate to stock exclusion. In fact, at the deepest horizon (20-30 cm), *E. coli* counts were approximately an order of magnitude greater under mānuka than that observed under stock exclusion. This finding differs from observations from within the literature. In lab experiments conducted by Prosser et al. (2016), the authors found 90% reductions in *E. coli* counts in 8 days under mānuka compared to 93 days under pasture. Our results do not indicate any enhanced *E. coli* reductions by mānuka, in contrast to what was hypothesised.

Conversely, similar *E. coli* reduction rates under mānuka and stock exclusion treatments, and the strong influence of date of collection, suggests that natural factors are the primary driver affecting *E. coli* results. The results observed in the field experiment indicate that the effect of mānuka and stock exclusion treatments were the least impactful variable in the survival of *E. coli*, with the date of collection being the most significant factor, and depth to a lesser extent. This corroborates existing literature on the survival of introduced pathogens into soil systems; van Veen et al. (1997) noted that the population size of bacteria (generally) experience rapid decline following introduction to natural soil environments and stated that growth within introduced populations is exceedingly rare. According to the results found here, stock exclusion for at least 14 days is necessary to return to approximate natural *E. coli* levels.

On the other hand, results show increased *E. coli* at Day 3 within both treatments and most horizons. Mubiru et al. (2000) and van Elsas et al. (2010) discussed how *E. coli* survival and mortality rate could be influenced by a multitude of factors, including physical and chemical soil properties (e.g. water availability, pH), atmospheric conditions (e.g. temperature), and interactions between other organisms within soils (e.g. indigenous microflora). However, Mubiru et al. (2000) suggested that soil water content was the leading cause of *E. coli* survival. Precipitation data collected from the Martinborough Ews climate station (Fig. 1.5) show intermittent rainfall in the week prior to the experiment, 13 mm falling the day prior to application of solutions, and continuing rainfall until Day 3 of the experiment. The rainfall in the week preceding and during the initial days of the experiment produced higher soil moisture content which may have created favourable soil conditions for *E. coli* survival. Alternatively, although less likely, constant rainfall following a drier period beforehand may have led to overland or subsurface runoff from the surrounding paddocks, contributing additional *E. coli* inputs.

The general decline in *E. coli* counts observed following Day 3 is more akin to the broader literature reflecting *E. coli* survival rates. For example, in a greenhouse-based experiment, Avery et al. (2004) noted a significant decrease in *E. coli* 0157:H7 (a virulent strain of *E. coli*) in the week immediately following application of organic animal wastes to grass-sown (*Lolium perenne*) soil cores. This is further corroborated by Ogden et al. (2001) who suggested that exposure to UV radiation and decreasing soil moisture will assist in reducing *E. coli* counts under dry conditions. However, Nicholson et al. (2005) also noted that *E. coli* (0157:H7) from land application of solid manure typically survived within soils for approximately one month. Similarly, Gagliardi and Karns (2000) observed that manure may enhance the survival of *E. coli* in no-till soils likely due to improved microsite habitat and additional nitrogen. As *E. coli* within this experiment was cultured in the lab and applied directly to the soil, this may have facilitated a more rapid decline in *E. coli* than what may have been observed following application of actual animal waste. Projecting the results of this study, it is likely that *E. coli* may survive for around 40 days following an excrement event.

A more levelled decrease in *E. coli* observed in the deeper horizons (particularly 20-30 cm) may also reflect movement from the upper horizons down the soil profile. Within soil cores, Avery et al. (2004) determined that *E. coli* (0157:H7) took approximately six to eight weeks to reach farther into the soil profile. While there are clear reductions in *E. coli* in all horizons, a greater reduction in the 0-10 cm horizon and more gradual reduction in lower horizons could suggest movement of some *E. coli* down the profile. Higher *E. coli* counts in the 20-30 cm horizon in the mānuka treatment indicate preferential movement down the soil profile enhanced by mānuka roots, as demonstrated by Mishra (2018). Finding *E. coli* in the lower horizons even at Day 1 contradicts the slow movement observed in Avery et al. (2004), likely supported by rainfall during the initial days of the experiment.

Given the higher antimicrobial effect of mānuka leaves compared with roots (Prosser et al., 2014), it is arguable that leaf abscission and decomposition may be an equally important factor in mitigating bacterial survival and transport in the field. As the plants were only approximately 14 months old at the time of the experiment, development of antimicrobial potential among the soil rhizosphere communities caused by mānuka litter could not be studied, but this is an opportunity for further research.

The results from this experiment indicate that *E. coli* survival rates in the field are unsurprisingly more difficult to interpret than similar lab-based studies surveyed in the literature. While the results were statistically significant, treatment had the least significant impact on survival with soil depth and time explaining more variance. Likewise, other environmental conditions, such as precipitation and soil moisture, might have also contributed to responses between treatments.

3.5.2 Nitrogen

Reduced concentrations of nitrate in the mānuka treatment compared to stock exclusion support the hypothesis that mānuka roots inhibit nitrification of ammonium to nitrate in soils. This corroborates the results of Esperschuetz et al. (2017b), whereby antimicrobial properties of mānuka were argued to inhibit nitrifying enzymes therefore reducing the conversion of ammonium to nitrate. This effect was also demonstrated in a laboratory settings by Downward (2013), whereby mānuka and kānuka extracts inhibited the activity of nitrifying bacteria, Nitrosospira spp.

Alternatively, the lower concentrations of nitrate could be attributed to lower initial concentrations of ammonium observed in the mānuka treatment of this experiment. This could indicate that there was relatively less available ammonium to transform to nitrate. The higher ammonium concentrations in the stock exclusion treatment compared with mānuka was an unexpected finding given current literature, e.g. Esperschuetz et al. (2017b) found that ammonium concentrations accumulated more so under mānuka than kānuka and pine.

One possible driver for these findings is plant uptake of nitrogen and increased biomass production. Similar grass-sown lysimeter studies, conducted by Fraser et al. (1994) and Clough et al. (1998), that applied synthetic urinary nitrogen (^{15}N) found plant uptake was responsible for 43% and 21.6-31.4% of nitrogen reductions, respectively. Likewise, Esperschuetz et al. (2017b) noted that total nitrogen uptake to plant biomass was significantly greater under mānuka and kānuka, compared to pine. The more intricate and deeper root system of mānuka compared to pasture suggests some of the applied urea may have been quickly taken up by mānuka compared to the stock exclusion treatment, therefore leading to increased concentrations of ammonium under the latter. However, differences in ammonium concentrations (around 3.8 mg kg^{-1}) between the two treatments over the first four days from the first two soil depths (0-10 cm and 10-20 cm) following simulated excrement application far exceeds luxury uptake rates of mānuka and therefore cannot be the only reason for this difference. Similarly, as the plants were quite young, fully established root capabilities are unlikely.

Another possible explanation for the lower rates of ammonium observed in the mānuka treatment is a potential difference in ammonia volatilisation – whereby some urea is converted to ammonia gas (NH_3) – between the two treatments. Although Decau et al. (2003) found that 12-25% of urinary nitrogen can be lost through ammonia volatilisation, elevated soil moisture conditions observed in the first two weeks following application makes this option unlikely. Urease enzymes hydrolyse urea to ammonium rapidly under moist soil conditions (Clough et al., 2003), with rainfall following application considered to minimise excessive loss through volatilisation (Clough et al., 1998). Therefore, given the precipitation prior to the experiments, as well as during the first few days following application, this is likely not a key factor in nitrogen cycling within this experiment.

Instead, the effect of mānuka root systems in the activity of urease could be a plausible option, although not previously recorded in other literature. Recent research on the use of synthetic urease inhibitors in agricultural areas has demonstrated the potential of these products to reduce nitrogen losses through volatilisation and leachate after urea application (Gioacchini et al., 2002). Although this cannot be concluded from the results of this study, the possibility of mānuka inhibiting urease enzymes presents an area for future research.

The minimal responses in both ammonium and nitrate concentrations in the lowest 20-30 cm horizon also corroborates existing literature. In their grass-sown lysimeter study, Fraser et al. (1994) determined that 20% of applied synthetic urinary nitrogen remained in the soil profile. This was primarily observed in the upper 20 cm of the lysimeter (Fraser et al., 1994). This is supported by Decau et al. (2003) in a similar grass-sown lysimeter study, whereby marginal effects of urinary nitrogen were observed below 20 cm, even between three different soil types. Although inhibition of urease and nitrification enzymes seem a plausible mechanism for the changes in the nitrogen speciation in mānuka, not having completed a full nitrogen balance as part of this experiment makes it difficult to ascertain the exact mechanisms that have acted to reduce ammonium and nitrate under mānuka treatments. The response of nitrogen species to mānuka indicate that the plant does possess greater capacity to reduce nitrogenous pollutants compared to simply retiring riparian areas from grazing.

3.5.3 Wider implications and future directions

Understanding how mānuka may impact common pollutants in an agricultural area is critical to enhancing ecosystem services at Lake Wairarapa. The results of this study suggest a statistically significant impact of mānuka on *E. coli* counts and ammonium and nitrate concentrations, though it was the weakest component of the model compared to date of collection and depth. In tandem, these three factors all accounted for at least 50% of the variance in respective response variables. Challenges were expected in attempting this study in a ‘real-world’ setting; however, the results are promising.

Longitudinal studies are required to assess the validity of results presented here. At 14 months since planting, the mānuka stands are still relatively young (Marden et al., 2007). Similarly, there is disagreement in the literature concerning mānuka response to high fertility soils; Reis et al. (2017) suggested that mānuka responded positively to biosolid application, whereas Marden et al. (2007) inferred a stunted growth response in fertile soils. Further testing over time would contribute to understanding mānuka's role as a mature plant in pollutant mitigation.

Regardless, the higher values of nitrate under the stock exclusion treatment are interesting and suggest much greater potential for nitrate leaching. This is a particularly important finding, given that agricultural catchments are considered responsible for the sharp rise of nitrate in surface water and groundwater systems, mainly from urine in grazed paddocks (Di & Cameron, 2002). Many of the proposed solutions to minimising nitrate losses involve lost production costs to landowners or are time intensive (de Klein, 2001). Solutions include: reducing nitrogen fertilisation, using nitrification inhibitors, reducing stocking rates, whole farm management planning, or computer modelling of farms (Di & Cameron, 2002). One geo-engineering solution, the use of synthetic nitrification inhibitors, has proven costly; trace amounts of dicyandiamide (DCD) found in milk powder exports caused Chinese market withdrawal with Balance Agri-Nutrients and Ravensdown subsequently terminating DCD sales (Johnston, 2013; Wilcock, 2013). While planting mānuka would not be without costs (e.g. initial planting and maintenance during plant establishment), it is much less time intensive, would not involve major changes to on-farm practices, and would not put international market sales at risk. Additionally, there is added economic incentive for farmers through production of mānuka honey and essential oils, although this depends on climate and land conditions (Saunders, 2017)

Similarly, concomitant relationships between *E. coli* and nitrogen should also be considered. For example, Gagliardi and Karns (2000) found positive correlations between both ammonia and nitrogen levels with *E. coli.* Statistical analyses in this study only focused on *E. coli*, nitrate and ammonium individually, however further investigation into interactions between variable is warranted. Longer duration and/or more frequent sampling may also be required in subsequent studies. This is particularly the case for nitrate, which still was increasing in concentration at the end of this study at 21 days. Furthermore, greater accounting of the full nitrogen balance may be required to adequately account for nitrogen losses throughout the experiment. Finally, application of genuine animal excreta may give more representative results, particularly for *E. coli*, which may have better survival rates in faeces (Gagliardi & Karns, 2000).

3.6 Conclusion

Pastoral agriculture in New Zealand is a dominant contributor to economic and social wellbeing for many New Zealanders. However, such reliance on agriculture and increasing demands for New Zealand agricultural products is driving poor outcomes for environmental health in agriculture-dominated catchments (Parliamentary Commissioner for the Environment, 2015). The utilisation of native plants in riparian management is increasingly popular (Franklin et al., 2015), with laboratory-based research suggesting that mānuka has antimicrobial properties that can reduce microbial contamination and excessive nitrogen loading (Esperschuetz et al., 2017b; Prosser et al., 2014; Prosser et al., 2016).

This study has demonstrated that in situ mānuka plants do have the capacity to reduce common pollutants to New Zealand waterways, although treatment was less significant than date of collection and soil depth. Ammonium and nitrate were reduced under mānuka, compared to stock exclusion. This suggests much greater capacity of mānuka to reduce nitrate leaching compared to simply retiring riparian areas from grazing. While *E. coli* results showed generally similar or slightly increased counts under mānuka, this could potentially result of preferential flow via root networks, reduced leaf and stem litter, or under-developed root systems of juvenile plants. Thus, further longitudinal research is required in this area.

Planting mānuka riparian zones is not a complete solution for the mitigation of agricultural pollutants; it must be coupled with better on-farm management practices, whole catchment strategies, and enhanced regulatory support. However, this research presents a promising case for the environmental importance of mānuka at Lake Wairarapa and potential benefits to landowners.

Chapter Four: Future. Cultural services and future directions for Lake Wairarapa

4.1 Introduction

Building useable, evidence-based restoration plans for Lake Wairarapa that lead to positive environmental outcomes must also be balanced with societal desires and expectations. Following from Chapters 2 and 3, Lake Wairarapa and its catchment provide a multitude of provisioning and regulating ecosystem services that support the predominantly agricultural community. In the South Wairarapa District, agriculture is the main contributor to GDP and full-time employment (Stokes & Dixon, 2016). This chapter discusses the importance of cultural services to the contribution of human wellbeing in the region. Cultural services are most readily described as the intangible and non-material benefits that humans derive from landscapes, including identity formation, recreation and tourism, aesthetics, spiritual wellbeing, and educational opportunities (MEA, 2005). Additionally, within the New Zealand context, inclusion of Mātauranga Māori (traditional ecological knowledge) is increasingly important in resource management.

There is a significant paucity of research conducted in the cultural services space, both globally and within New Zealand (Ausseil et al., 2013; Van Den Belt & Blake, 2014). Furthermore, there is a tendency to only consider easily quantifiable services, namely recreation and tourism, and less so aesthetics or indigenous and spiritual relationships (Van Den Belt & Blake, 2014). At Lake Wairarapa, the Greater Wellington Regional Council (GWRC) and the South Wairarapa District Council (SWDC) are the regulatory bodies with jurisdiction under the Resource Management Act 1991 (Peart, 2007). Through the recent amendments in the National Policy Statement for Freshwater Management (NPS-FM), the need for better integration of community values has been recognised, with GWRC establishing the Ruamāhanga Whaitua committee (Ruamāhanga Whaitua Committee, 2018). Likewise, impending Treaty of Waitangi 1840 settlements for Wairarapa iwi (Ngāti Kahungunu ki Wairarapa and Rangitāne o Wairarapa) will provide local Māori with further representation in lake management.

The changing regulatory and management setting at Lake Wairarapa provides an opportunity for better inclusion of community desires in resource management decisions. Two research questions are posed:

1. In what ways are cultural services provided through Lake Wairarapa and experienced by the community?
2. What are the aspirations held by community members and how might these shape the future of Lake Wairarapa?

Given the poor representation of cultural services research nationally and internationally (Van Den Belt & Blake, 2014), research conducted at Lake Wairarapa seeks to provide insight into how cultural services might be realised at Lake Wairarapa and by what means. Similarly, this research aims to identify which cultural services are not currently provided, and therefore the areas needing improvement. Building upon work carried out by the Ruamāhanga Whaitua Committee (2018), alongside the response regarding cultural services posed in question one, the second question directs understanding at the best direction and approaches for future management of Lake Wairarapa.

4.2 Literature Review

Building a cohesive narrative that supports both environmental and societal wellbeing at Lake Wairarapa requires further investigation into the visions and desires of diverse members of the community. Through the ecosystem services framework, cultural services may be used in an attempt to appreciate the intrinsic and other values that people hold in respect to Lake Wairarapa, and how the lake contributes to their wellbeing. Indigenous Māori relationships, values, and knowledge (sometimes referred to as Mātauranga Māori) are distinct and significant in Aotearoa New Zealand. The delivery of services and facilities that support an appreciation of cultural services and Māori values are currently implemented through hierarchical regulatory bodies, such as regional and local councils, administered through the Resource Management Act 1991. Thus, consideration and analysis of how governance operates and fosters such values is paramount to enhance community wellbeing.

4.2.1 Cultural services

As part of the conceptual framework presented by the MEA (2005) and introduced briefly in Chapter 1, cultural services are described as the non-material and largely intangible services that enhance human wellbeing (MEA, 2005). These services contribute to human health and wellbeing through identity formation, enabling experiences, and developing capabilities (Fish et al., 2016). Chan et al. (2011) postulated that cultural services such as subsistence, recreation, education and research, artistic, and ceremonial services can contribute to a wide range of experiences, including: place heritage, activity, spirituality, knowledge, social capital and cohesion, aesthetic, and identity. Yet, unlike provisioning and regulating services, cultural services are neither simply provided to humans nor readily available in nature to find and allocate (Fish et al., 2016). They are active, dynamic, abstract, and are a result of cognitive processing of the environment through reciprocal and co-produced formation of meaning between humans and the non-human environment (Fig. 4.1) (Fish et al., 2016; Gee & Burkhard, 2010). Thus, cultural services are crucial in maintaining meaning between people and the environment (Chan et al., 2011).

Integration of cultural services into contemporary resource management and decision-making is crucial for many reasons. Firstly, industrialised societies such as New Zealand typically have greater rates of degraded cultural services due to advances in science and technology (e.g. agricultural intensification) whereby cultural services are diminished in favour of provisioning services (Milcu et al., 2013). However, the invaluable and intangible nature of cultural services makes remediation exceedingly challenging – if not impossible – following degradation (Hernandez-Morcillo et al., 2013). Similarly, as the reliance on ecosystems to deliver provisioning and regulating services subsides in industrialised societies, availability of cultural services becomes more prominent to people within the community (Plieninger et al., 2013).

Cultural services also prompt a multi-disciplinary approach to decision-making as well as the subsequent outcomes (La Rosa et al., 2016; Milcu et al., 2013). Cultural services move beyond purely physical or economic judgements of ecosystems and services provided, entering into the lived experience of relationship creation and experiences between individuals and ecosystems (Fish et al., 2016; Plieninger et al., 2013). Finally, as individual cultural services are connected and positively correlated to one another, improvement or protection of one service will likely lead to co-benefits in others (Plieninger et al., 2013).

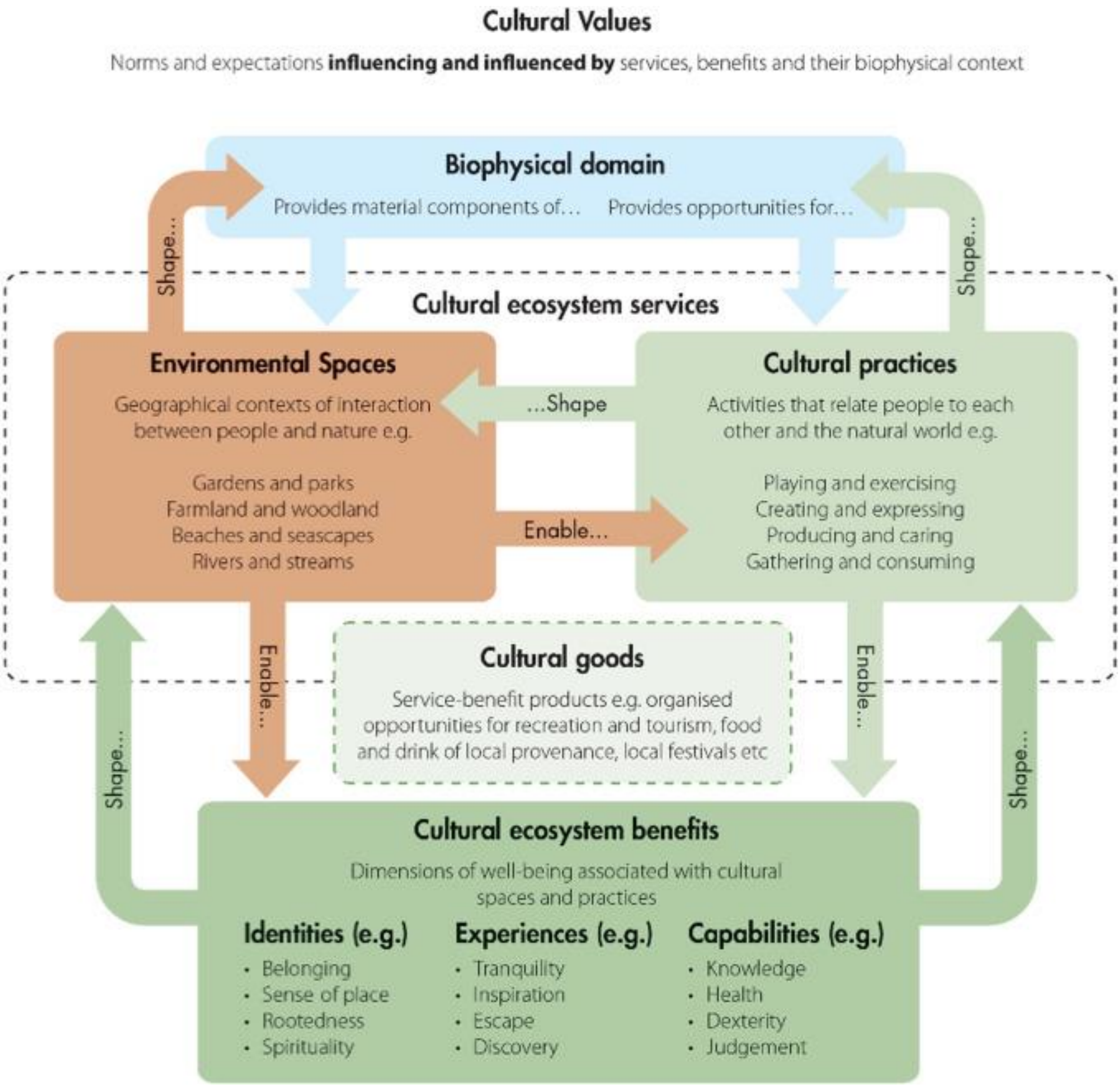


Figure 4.1: Conceptual framework depicting the formation of cultural services. This displays the interrelationships between the biophysical domain, environmental spaces, cultural practice, and cultural ecosystem benefits (Fish et al., 2016).

However, cultural services are poorly understood within the Millennium Ecosystem Assessment (MEA) framework compared to provisioning and regulating services (Fish, 2011). There is a lack of clear indicators and methodological consistency in studies applying the cultural services paradigm; only 34 of the 344 indicators of ecosystem services refer to cultural services, with a clear bias toward recreation and ecotourism (due to the ease of economic quantification), and to a lesser extent aesthetics (Hernandez-Morcillo et al., 2013; Martin et al., 2018). Furthermore, cultural services focus on the lived experience of individuals (Daniel et al., 2012). The perception of cultural services is unique to the individual and driven by personal circumstances and backgrounds, thus elucidation of values and experiences are mostly limited to that individual – even when conducting research at a local scale (Fish et al., 2016). These two factors make spatial and temporal comparisons difficult, proving an issue in upscaling approaches using cultural services (Braat & de Groot, 2012; Fish et al., 2016; Hernandez-Morcillo et al., 2013; Plieninger et al., 2013). Finally, cultural services are concomitant with other ecosystem services. Food, for example, is generally considered a provisioning service; however, food is often associated with place-making and heavily ingrained in identity formation and educational cultural practices (Fish, 2011). Despite methodological and developmental shortcomings of the cultural services component within the wider MEA framework, it remains part of a holistic approach to evaluate ecosystems and the services they provide at Lake Wairarapa.

4.2.2 Cultural services and Mātauranga Māori

In New Zealand, the subjective nature of cultural services may be evident between indigenous Māori and other New Zealanders. The holistic and interconnected characteristic of Te Ao Mārama (the natural world) means whakapapa (genealogy) is the fundamental component of understanding the world for Māori (Hikuroa, 2017). According to Māori cosmogony, all facets of the natural world originate from primeval parents, Ranginui and Papatūānuku; thus, all phenomena are connected – ki uta ki tai (from the mountains to the sea) – including humans. This living relationship is reflected in the way that Māori identify and introduce themselves geographically (in relation to their mountain, river/lake/sea, land). Likewise, relational ties are also highlighted introducing their waka (the ocean-going canoe their ancestors travelled to Aotearoa/New Zealand on), their iwi (tribe), hapū (sub-tribe) and whānau (familial) affiliations including their marae (community meeting grounds), acknowledging first their tūpuna (ancestors), before finally with saying their name at the end of their introduction (Park, 2000; Šunde, 2012).

Mātauranga Māori (Māori knowledge) is very much founded in the understanding of Te Ao Mārama and engenders the cultural practices and values of Māori. Such knowledge is generated from both modern and historical contexts, as well as traditional sources (Harmsworth et al., 2016; Hikuroa, 2017). Traditional Māori approaches to resource management come under the ethic of kaitiakitanga, typically translated simplistically as ‘guardianship’ or ‘stewardship’, and again reinforces a holistic approach to social and environmental wellbeing (Henare, 2001; Kawharu, 2000).

The ability to look into Mātauranga Māori through a solely cultural services lens is inappropriate and unfeasible. As discussed in Chan et al. (2012), inferring a value – monetary or otherwise – on concepts such as mauri and whakapapa is difficult, with an additional reluctance from Māori scholars to even engage in such research. This is exemplified in the case of genetic technology use, whereby the risks to mauri and whakapapa were considered incalculable compared to the formal risk assessment process at the regulatory agency, the Environmental Risk Management Agency (now the Environmental Protection Authority) (Satterfield & Roberts, 2008).

Similarly, value itself is considered intangible and difficult to measure. Instead, value is associated with moral and preference ordering of the individual and is far too broad and overwhelming to be accurately measured (Chan et al., 2011). This introduces the idea of incommensurability in ecological economic thinking whereby a common unit of measurement is absent (Šunde, 2008); provisioning and regulating services can be measured relatively easily in the free market, whereas determining the aesthetic value of a waterfall, for example, is more difficult (Martinez-Alier et al., 1998; Satz et al., 2013). Likewise, the holistic nature of Māori environmental care and management has been impeded through quantitative approaches and policies that alienate and disconnect people from their environments (Henare, 2001).

4.2.3 Cultural services in New Zealand

As highlighted by Ausseil et al. (2013) in their assessment of multiple ecosystem services in New Zealand, cultural services are difficult to adequately quantify due to their inherent human focus. However, Van Den Belt and Blake (2014) highlighted the opportunity to contribute to large gaps in the global and New Zealand cultural services literature, particularly in congruence with Māori values.

New Zealand cultural services literature is challenged by the same issues noted in the international literature. Clough (2013), for example, covers the market and non-market valuation tools available to quantify recreational services. Likewise, an overview of New Zealand's tourism industry in relation to ecosystem services has largely focussed on the consumption of tourism products and economic benefit (Simmons, 2013). In their discussion of aesthetic values, Swaffield and McWilliam (2013) outlined the difficulty, but pervasive use, of traditional economic tools (such as stated preference or revealed preference methods); however, these authors highlighted the emerging use of alternatives such as participatory mapping and Q-sort methods in New Zealand. In a literature survey of New Zealand agricultural-based ecosystem services conducted by Van Den Belt and Blake (2014), only 9 of the 66 works accounted for cultural services – again, with a strong focus towards recreation, tourism, and aesthetic values.

A study by Miller et al. (2015) found Māori had a 40% higher willingness-to-pay (WTP) for improved mahinga kai (food-gathering places) than other New Zealanders. However, the study overall found WTP for improved environmental quality was three times higher (NZD 123 per year) across all groups of New Zealanders compared to global estimates (NZD 24-41 per year). The authors highlighted the contention around using economic metrics to apply dollar amounts to culture and nature; however, they claimed the benefits from including monetary valuation in decision-making outweighed the potential disadvantages (Miller et al., 2015). A similar study also suggested that Māori typically have greater concern for the environment compared to non-Māori, which therefore leads to higher likelihood of paying for improvements to the environment (Awatere, 2005) .

4.2.4 Environmental decision-making in New Zealand

Incorporation of such values covered by cultural services and Mātauranga Māori are necessary to ensure adequate management of freshwater resources. Currently management of freshwater bodies, such as Lake Wairarapa, are managed under the Resource Management Act 1991 (RMA). The Act is the overarching environmental legislation that governs how natural resources are used. Sections 5-8 outline the purpose and principles of the RMA, with the purpose stated in s. 5 below:

(1) The purpose of this Act is to promote the sustainable management of natural and physical resources.

(2) In this Act, sustainable management means managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural well-being and for their health and safety while—

(a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and

(b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems; and

(c) avoiding, remedying, or mitigating any adverse effects of activities on the environment

While not explicitly stated as such, cultural services are also imbedded in the purpose and principles of the RMA. Matters of national importance (s. 6) include: (b) protection of outstanding natural features and landscapes (i.e. aesthetic quality); (e) relationship of Māori with their culture and traditions with their ancestral lands (i.e. spiritual); and (f) protection of historic heritage (i.e. sense of place/cultural heritage). Similarly, other matters (s. 7) include: (a) kaitiakitanga (i.e. identity); (c) maintenance and enhancement of amenity values (i.e. aesthetics); (d) intrinsic values of ecosystems (all cultural services); and (h) protection of the habitat of trout and salmon (i.e. recreation).

In particular, the 2014 National Policy Statement for Freshwater Management (NPS-FM) directly considers Te Mana o te Wai as a matter of national significance. Here, Te Mana o te Wai is reflected through three different forms of health: the health of the environment, waterbody, and the people (Ministry for the Environment, 2017). The NPS-FM outlines five key objectives, including: water quality, water quantity, integrated freshwater management, the role and interests of tangata whenua, and progressive implementation by regional councils. Furthermore, it establishes two compulsory national values being ecosystem health and human health for recreation. In lakes, ecosystem health is measured through phytoplankton (through chlorophyll-*a*), total nitrogen, total phosphorus, and ammonia, and human health for recreation by *Escherichia coli* (Ministry for the Environment, 2017).

The purpose of the RMA and NPS-FM is currently actioned through regional and district councils. The responsibility of the integrated management of regional physical and natural resources is overseen by regional councils and covers a wide range of environmental functions (RMA s. 30). Territorial authorities (city or district councils) are charged with controlling the effects that land use may have (RMA s. 32) (Peart, 2007). While Māori currently have few statutory powers, recent amendments in the RMA in 2017 introduced Mana Whakahono ā Rohe, which delivers a stronger mandate for iwi to participate in resource management and decision-making with local authorities in their traditional rohe (tribal area). Similarly, regional authorities must take into account any planning document (such as iwi environmental management plans) in their regional policy statements and plans.

4.2.5 Environmental decision-making at Lake Wairarapa

Greater Wellington Regional Council (GWRC) is responsible for the sustainable management of Lake Wairarapa through the RMA. The current regional policy statement and regional plan identifies Lake Wairarapa as a site with substantial amenity and recreational values. This includes water sports (kayaking, boating, and canoeing), hunting (duck shooting and fishing), and other recreational values (bird watching, photography, and walking), and significant ecosystems which support nationally threatened indigenous fish habitats and migratory indigenous fish species. The key objectives related to Lake Wairarapa include supporting healthy and functional ecosystems of the region’s lakes, rivers, and wetlands, as well as ensuring public access to regional lakes, rivers, and coastal marine areas. The regional plan also outlines the manner in which the lake level of Lake Wairarapa is seasonally maintained (Greater Wellington Regional Council, 2014b). Likewise, the 1989 National Water Conservation (Lake Wairarapa) Order prohibits the diversion of any water within Lake Wairarapa, as the natural fluctuation of the lake level has encouraged the significant wetland ecosystem to develop.

Similarly, through the Wairarapa Combined District Plan, South Wairarapa District Council (SWDC) sets out two strategic issues that relate to Lake Wairarapa. The first reinforces the importance of Lake Wairarapa and the associated Wairarapa Moana wetlands complex and highlights the importance of having a long-term and integrated approach to the allocation of resources (Masterton District Council, 2011). The second highlights that significant natural features (such as Lake Wairarapa) play an important role in the sense of identity and naturalness that the Wairarapa community value, thus these values must be adequately maintained and managed for current and future generations (Masterton District Council, 2011).

In an attempt to foster more collaborative catchment management, the Ruamāhanga Whaitua Committee was established in 2013. This is an advisory body that informs council on community desires for management of water through producing a Whaitua Implementation Plan, which was published in August 2018. The committee comprises members that represent regional council, territorial authorities, tangata whenua, and community members (Ruamāhanga Whaitua Committee, 2013). This plan defined the primary objective for Lake Wairarapa as improved lake health and resilience, primarily through meeting national bottom lines outlined by the NPS-FM and thus improvements in the trophic status of the lake (Ruamāhanga Whaitua Committee, 2018).

Alongside this is the progression of Treaty of Waitangi claims for Ngāti Kahungunu ki Wairarapa and Rangitāne o Wairarapa. The current Deeds of Settlements that have been drafted are awaiting ratification and passing of legislation, and would lead to the return of the bed of Lake Wairarapa and surrounding properties in the form of joint redress between both iwi (New Zealand Government, 2016, 2018). Similarly, it would also establish the Wairarapa Moana Statutory Board whose mandate would be to ensure guardianship and sustainable management for present and future generations for both Wairarapa Moana and the Ruamāhanga River. The Board would include representatives from Ngāti Kahungunu ki Wairarapa (two of which would represent significant marae in the area), Rangitāne o Wairarapa, GWRC, SWDC, and the Department of Conservation (New Zealand Government, 2016, 2018).

4.3 Methods

Determination of cultural services and future aspirations for Lake Wairarapa, while subjective and personal, are based on first-hand experience and expertise about the lake, its surroundings, and the communities it supports. A qualitative methodology using semi-structured interviews was best suited to explore the rich and wide-ranging knowledge held by members of the community. Interviews were audio-recorded, transcribed, and then thematically analysed to examine similarities and divergences between participants. This also enabled an overall impression of the vision for Lake Wairarapa offered by a range of interviewees.

To conduct this study, prior ethics approval was granted from the Victoria University of Wellington Human Ethics Committee (application ID: 0000026519) in August 2018. Participants were given an information sheet (Appendix A) and consent forms (Appendix B) prior to beginning the research. This ensured best practice when working with human subjects, that any potential harm to the participant is minimised, and that consent is given and confidentiality is maintained.

4.3.1 Semi-structured interviews

In this study, six qualitative, semi-structured interviews were conducted in October and November 2018. Semi-structured interviews allow for rich and in-depth verbal and non-verbal data to be generated with the discussion configured towards a topic of interest. Yet, new and emergent themes can also arise which can be further explored during the interview process (O'Leary, 2017; Schostak, 2006). Semi-structured interviews are also considered an effective method for understanding values and attitudes for cultural services (Fish et al., 2016).

Interviews were voice recorded, with a total of 16 questions asked (Table 4.1). Questions were clustered into three focus areas: values and place; mauri, ecosystem health and governance; and future aspirations. All questions were asked of all participants, with two exceptions – questions were omitted if participants discussed the answer to one question while discussing another question to avoid repetition, and question 6 (concerning mauri of Lake Wairarapa) was only asked of tangata whenua interviewees. Individual interviews ranged from 30 min to 2 hr. In total, five interviews were one-on-one and one interview involved two participants. Transcriptions were completed post-interview and returned to participants that requested a copy of the transcription.

4.3.2 Participants

A key component in selecting participants is the concept of "purposeful selection" (Creswell, 2014, p. 189), indicating participants should be recruited on the basis of benefit in understanding the research question. Yet, one critique of ecosystem service methodologies is the inclination to include 'ready-made' people of interest (i.e. those with an existing mandate to represent a group or those with expertise) (Fish, 2011). It suggests that participant recruitment ought to go beyond those typically given preference to enhance the diversity of ideas generated (Fish, 2011).

Using these justifications, six participants or groups of participants were selected to be involved in the research, which included: an employee of GWRC, representatives from local iwi Ngāti Kahungunu ki Wairarapa and Rangitāne o Wairarapa, members of an environmental non-governmental organisation (NGO), a local farmer, and a community volunteer. While some of the participants exhibit such 'existing mandate' (e.g. the voice of regional council, iwi), purposeful inclusion of other groups (e.g. community groups, farmers) was completed to address this disparity in the literature. A seventh person from the local council was contacted, but did not respond. While the views of these six participants will not reflect the entirety of views and values at Lake Wairarapa, they do provide invaluable, diverse and rich insight that would otherwise be lacking through alternative methods, such as surveys. Similarly, in interviewing six groups of participants,

Table 4.1: Questions asked during semi-structured interviews (material in square brackets were used as prompts for the interviewer)

Cluster 1: Values and Place	
1.	When you/your iwi/organisation talk about Lake Wairarapa, where does that extend to? a) If you're also familiar with the names 'Wairarapa Moana' or the 'Wairarapa Moana Complex', can you explain what those terms mean? *[From now on I'll refer to 'Lake Wairarapa', unless you prefer that I use 'Wairarapa Moana' or 'Wairarapa Moana Complex'.]*
2.	What makes Lake Wairarapa an important place for you/your iwi/organisation? a) Why do you consider those aspects valuable?
3.	Could you share a memory that you've had on or near Lake Wairarapa that illustrates these values?
4.	In what ways is Lake Wairarapa used by the community?
Cluster 2: Mauri, Ecosystem Health and Governance	
5.	How has the ecosystem health of Lake Wairarapa changed over time?
6.	How has the mauri of Lake Wairarapa changed over time? *[Ask what they mean by mauri]*
7.	What kinds of governance arrangements do you think would be most effective at bringing about positive changes for Lake Wairarapa's ecosystem health/mauri?
8.	In what ways might Treaty settlements change the way Lake Wairarapa is currently managed?
Cluster 3: Future Aspirations	
9.	Picture in your mind the ideal vision for Lake Wairarapa *[pause]* – describe what you see, feel and sense are the key elements in that picture?
10.	How can that vision become a reality? *[management and governance]*
11.	Who *[actors]* and what *[knowledge, law]* is critical to driving this vision?
12.	What are the major obstacles stopping this from happening?
13.	What knowledge, information and data are missing?
14.	How should time and resources be directed for most impact?
15.	How could the lake in your vision enhance the wellbeing of people?
16.	What can you/your iwi/organisation do in the near future to realise your vision for Lake Wairarapa?

it is unlikely that data saturation (whereby no new information is discovered that further develops the research findings) was achieved (Francis et al., 2010). While conducting more interviews to reach data saturation would have been ideal, time and resource constraints made this unfeasible.

As mentioned, these participants were selected principally due to their range of expertise and knowledge. However, due to my upbringing and work experience in the Wairarapa area (outlined in the Preface), I personally knew four participants who were recruited through my experience working with them and/or the expertise and experience they had. The other two participants were recruited through recommendations from the initial participants. It must also be noted that while individuals may be employed by an organisation or chosen as a representative of a group, their responses may not necessarily reflect the official views of that organisation, iwi, or community group they are involved in.

4.3.3 Thematic analysis

Following the interviews, thematic analysis was conducted following the six phase process outlined in Braun and Clarke (2006) (Table 4.2). Interviews were transcribed using 'intelligent verbatim' transcription whereby irrelevant words or phrases (e.g. "um" or "you know") were removed and light editing of responses conducted for grammatical/sentence cohesion (Lapadat, 2000). Smoothed transcripts were then coded using a mix of deductive and inductive coding, whereby deductive coding refers to using codes already determined by literature and inductive coding from themes that emerge from the data (Rivas, 2012). From the literature review, a list of a priori codes were used to assist and streamline coding (deductive coding), with additional inductive codes added where data moved outside these confines. Following coding of all interviews, codes were collated, and candidate themes and sub-themes produced. These were reviewed against transcribed interview data and selected extracts were refined, and a thematic map was produced.

Table 4.2: Six-phase process of thematic analysis (adapted from Braun and Clarke (2006))

Phase	Description of the process
1. Familiarisation with the data	Transcribing data, multiple readings of the data, noting initial ideas.
2. Generating initial codes	Systematic coding of interesting features in the data across the dataset, collating data relevant to each code.
3. Searching for themes	Collation of codes into candidate themes and sub-themes, gathering data relevant to each theme.
4. Reviewing themes	Revision of themes against coded data extracts and entire data set, production of a thematic map.
5. Defining and naming themes	Ongoing refining and analysis of theme specificity and overall narrative of data, definitions and names produced for themes.
6. Producing the report	Selection of data extracts, final analysis of extracts, relation back to research questions and current literature, production of final report

4.4 Results

Four primary, interconnecting themes emerged from the interviews (Fig. 4.2). Each of these primary themes consist of two or three sub-themes that were identified.

4.4.1 Theme 1: Identity Formation

The first primary theme to emerge from the interviews and transcribed data was the concept of identity formation in relation to Lake Wairarapa.

The local farmer who lives near the edge of Lake Wairarapa put it simply: “It’s home, isn’t it? It’s home”. This illustrates a strong sense of place and belonging.

More broadly, the participant from the regional council noted that engagement with the lake can contribute to the formation of identity:

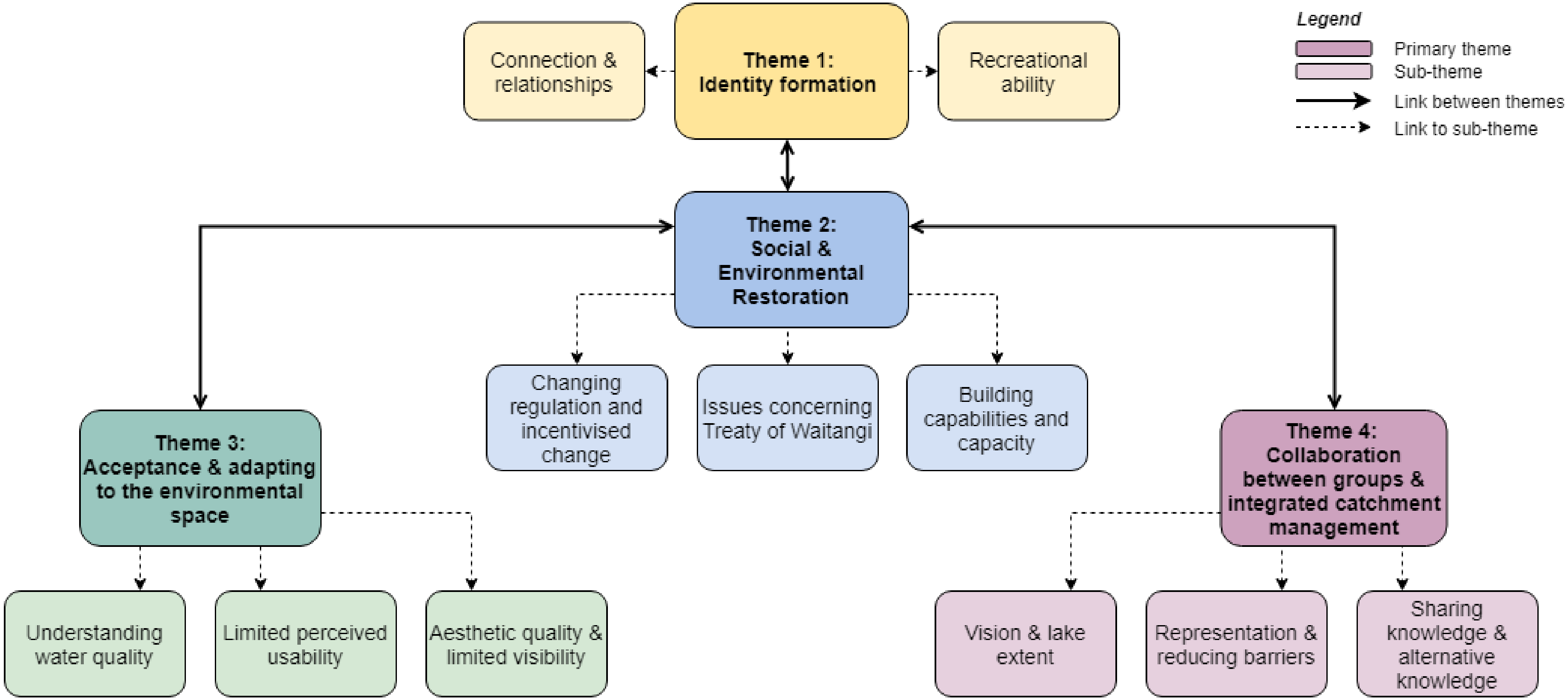


Figure 4.2: Flow diagram of primary themes and sub-themes from interviews. Primary and secondary themes are displayed in different colour variantians, with arrows representing interconnection between themes.

> *"I think it would enhance your cultural [wellbeing], reconnecting with quite a sacred place that's got quite a history and if you identify with the Wairarapa, your identity at the same time because Lake Wairarapa is a very significant place."*

Similarly, for the Rangitāne o Wairarapa participant, the formation of identity to Lake Wairarapa is intrinsic and inseparable from the self:

> *"It's part of who we are, and it's part of our identity, it's part of our mana"*

These quotes all illustrate that identity formation to a landscape such as Lake Wairarapa is both the product of intrinsic and familial ties to the land, as well as a relationship that is formed through engagement and involvement.

Sub-theme 1: Connections and relationships

Under this primary theme are two key sub-themes: connection and relationships, and recreational ability.

The first sub-theme relates to the connections and relationships between people and Lake Wairarapa. The participant from Ngāti Kahungunu ki Wairarapa reflected on how connection to a place is seen as an impetus to enhance more environmentally friendly actions:

> *"What makes people stand up and say, 'this is my home, this is the place I want to be, I feel thrill by being here'? That's that part that will motivate people to do better."*

This illustrates that without some form of identification to a place, namely Lake Wairarapa, motivation to engage may be limited.

Likewise, the community volunteer also reflected on this and the need for community engagement:

> *"Some of it is just the community involvement, so if they feel like they've had a chance to contribute, that adds an overall sense of wellbeing and ownership so if people feel like they've got some ownership or responsibility for looking after the environment, that will be good."*

Here, the ability to have a positive influence on the environment and a feeling that individual actions can make a difference may also lead to positive impacts on human wellbeing.

Sub-theme 2: Recreational ability

The second sub-theme considers recreational ability and the production of sense of place that such activities may hold for individuals. One participant from a NGO mentioned friends who have regularly engaged with Lake Wairarapa:

> *"I know some guys that have been shooting there for 50 years. Every year for 50 years they've been going down to the same place."*

The ability to routinely engage in activities that bring satisfaction may increase identity formation with such individuals, alongside identity forming with the lake.

Similarly, passive forms of engagement equally have a positive benefit. The same participant discusses the ability to enjoy restored wetland complexes at Lake Wairarapa:

> *"If you go down there half a dozen times over a two to three month period and I'll just about guarantee you every time someone will be down there taking pictures because it has a walking track around the whole thing ... Overseas visitors, I've seen Australians and English people walking around there. It's pretty amazing, it really is. They do get a benefit from it."*

Here, even individuals that are not from the area achieve a sense of place and an amenity benefit from engaging their interactions with Lake Waiararapa and its environs.

4.4.2 Theme 2: Social and environmental restoration

The second primary theme to emerge from the interviews was the concept of restoration, both social and environmental. This theme also encompassed three sub-themes: changing regulation and incentivised change, issues concerning the Treaty of Waitangi, and building capabilities and capacity.

Under the social and environmental restoration primary theme, the participant from Ngāti Kahungunu ki Wairarapa discusses the multiple ways that Wairarapa (which they translated and described as the 'land of glistening waters') can be interpreted while reflecting on their vision for Lake Wairarapa:

> *"While we're trying to get people to think about glistening water throughout Wairarapa, it's about the people and their thinking as opposed to what's the biophysical nature of water and does it glisten."*

Here, the framing of the term "glistening waters" not only refers to Lake Wairarapa itself and improved lake water quality, but also how it can enhance and support people within the community.

However, this is not an easy task. From the perspective of environmental restoration, a participant from the NGO reflected on how mammoth the task of restoration in New Zealand is:

> *"The realisation started to grow around New Zealand that the restoration, environmental restoration work in New Zealand was enormous … they really need to mobilise every living soul to do it."*

The quote illustrates that restoration, such as what is desired at Lake Wairarapa, cannot be completed by a few key interest groups and people but requires buy-in from the whole community.

Should this happen, the participant from the regional council believes the product would be greater valuing by people in the community and wider New Zealand:

> *"I just see people valuing it more because it's been really cared for, it's been cared for in a big way and it's recognised as something that is special to everyone, well especially in the Wairarapa, the Wellington region, and also recognises a significant place in the New Zealand context."*

These quotes illustrate that restoration is not purely environment, but there are many potential benefits that would arise for the lake and for diverse groups of people in the community as a result of community-focussed and enhanced environmental restoration and protection.

Sub-theme 1: Changing regulation and incentivised change

Likely changes to environmental practices will affect some participants more than others. The local farmer discusses their relationship with the regional council:

> *"[The regional council] said I had to fence my [sic] lake off so I've done that … Phosphate and nitrogen are going to become a problem, but it's hard to farm without them."*

Similarly, the community volunteer touches on potential incentive structures to support those that may be unfairly impacted through changing regulation:

> *"…maybe with an incentive to the farmers and the landowners because the decisions they've made have all been supported by local government and central government."*

These quotes illustrate how the farming community around the lake will likely be impacted by regulation to improve water quality.

More broadly, the regional council participant discusses how approval of Ramsar status would also lead to changes in regulation and potentially increased funding for restoration work.

> *"It looks like it [Lake Wairarapa] might get Ramsar status, which elevates the lake's national and international significance. [This] would help bring in some more funds, so anything that's going to bring in funds that can be used specifically for lake enhancement or lake rejuvenation type work are going to help."*

Thus, to ensure collaboration and an integrated approach, providing support to such industries will be necessary and external funding will support the work that is ongoing.

Sub-theme 2: Issues concerning the Treaty of Waitangi

The second sub-theme in this category involves issues concerning the Treaty of Waitangi. When reflecting on the Treaty settlements, the participant from Rangitāne o Wairarapa discusses the social restoration it supports:

"I think through the Treaty Settlement process that's actually given the ownership back to iwi/Māori has restored that mauri as well because now we're responsible for it again."

The participant also reflects on the challenge that the Treaty settlement poses in terms of behaviour change:

"The settlement challenges us to do things differently. It challenges us to step it up a gear because settlements are a contract between the Crown and iwi to do things better, for our people and for our land."

Similarly, the participant from Ngāti Kahungunu ki Wairarapa reflects on the settlement offer as an opportunity to grow together:

"In terms of the Treaty, we have an opportunity to work and grow things ... sitting down, educating each other, so that we can grow [through] this coming together."

Through the Treaty settlement, the increased responsibility and mandate to be involved in decision-making is said to have restored some of that mauri (life force, vital essence) for iwi at Lake Wairarapa as well as enhancing the "weaving together" of different people and communities.

Sub-theme 3: Building capabilities and capacity

The final sub-theme in the social and environmental restoration theme is building capabilities and capacity, including investing in people within the community.

The community volunteer discusses the importance of supporting schools in making environmental change: "I think the school community is really important because then they share that with family and friends." This is supported by the NGO, where one participant reflects on their engagement with schools:

"We've got a school and some kids involved in wetland restoration and they actually took it back to their own school, talked to a neighbour and got a bit of land, and they've got their own wetland!"

The regional council participant also reflects on community leadership as a form of advancing restoration:

> *"Key roles that are missing that might help to establish and initiate change, maybe one of the things is a few farming leaders that really get the big picture vision, but farmers that are seen as leaders within their community can actually have quite a big influence on impacting change."*

These quotes illustrate the need to build capacity across a range of sectors in the region to promote future environmental change.

4.4.3 Theme 3: Acceptance and adapting to the environmental space

The third emergent theme from the interviews was acceptance and adapting to the environmental space. This incorporated many of the more physical aspects of Lake Wairarapa and the perspectives held about them.

This is illustrated by one participant that discusses how Wairarapa Moana (which includes Lake Wairarapa) ought to be accepted on its own terms rather than through comparative evaluation to other lakes or waterbodies:

> *"One thing that we do to try and make things relevant for other people is compare things, but in the comparison, we lose the character of our lake … Rather than presenting the comparison, we appreciate Wairarapa Moana for what Wairarapa Moana is."*

This recognises the intrinsic qualities that Lake Wairarapa possesses and the acceptance needed in this space.

A similar sentiment was expressed by the local farmer:

> *"If you could snap you fingers and turn it into Taupō overnight, it would be fantastic but it never was that and it never will be that, but you can certainly try and improve things."*

Here, acceptance of the environmental space for its current condition is crucial; however, this does not mean that improvements are unnecessary or impossible.

Sub-theme 1: Understanding water quality

Under this primary theme are three sub-themes: understanding water quality, limited perceived usability, and aesthetic quality and limited visibility.

As part of understanding the water quality sub-theme, one key component that emerged was the difficulty in distinguishing sedimentation from pollution. This is illustrated by one participant from the NGO who suggests this is due to poor education of the public:

> *"About cleaning up the lake, I think there's an education issue there that people ought to be told that this is a supertrophic lake; it's shallow and then when a certain condition occurs, it will be coloured ... It's easy to shout and scream about pollution, so people will shout and scream about pollution and say that brown is pollution, it is not."*

Due to the shallow water depth and wind action at Lake Wairarapa, an abundance of suspended sediment is common. Therefore, appreciating the lake for what it is requires greater education of people in the community.

Sub-theme 2: Limited perceived usability

The second sub-theme in this group is limited perceived usability. When reflecting on their vision for Lake Wairarapa, the community volunteer noted that the first step of engagement was crucial to get people interacting with the lake:

> *"I mentioned Masterton and the greater Wairarapa but even the Wellington area, so people have come over from Wellington to help with the kākahi monitoring, and iwi people that I've worked with, the people had never been down there or visited any of the sites, but they have now. Until you actually get there, and usually it's for some particular reason, otherwise they don't know."*

Involvement of some kind, in this case citizen science, was a good segue for people to grow awareness and familiarity with the lake.

The Ngāti Kahungunu ki Wairarapa participant noted the primary use of the landscape was for agriculture:

> *"The use has been for flood protection and farmlands, but it's been against the quality of water, and it's been against the natural habitat of fish."*

The predominant land use around the lake in this example has led to the decline of indigenous fish species.

Sub-theme 3: Aesthetic quality and limited visibility

The final sub-theme that emerged was aesthetic quality and limited visibility, which relates quite closely to the second sub-theme in this area. The Rangitāne o Wairarapa participant reflects on the aesthetic quality of the lake, particularly the windy conditions:

> *"It's certainly not attractive, it's not an attractive place. I say that in the context that it's an ugly, brown colour and when you got down there when the wind's blowing, it's just not a nice place to be … But when I see it, and when I see it on the train, it means so much."*

Similarly, the regional council participant reflected on how the ability to see the lake gives it value to them.

> *"Just seeing the lake is something that gives it value for me, but the roads and the areas around Lake Wairarapa don't give the public much opportunity to visually see it. You could drive all the way down to Lake Ōnoke, or Lake Ferry, or go down to Cape Palliser and you wouldn't even know the lake was there … Those visuals, every time you see it, you're like it's there, it's cool, and it's big – it's surprising how big it is."*

These examples illustrate that the ability to see the lake, whether by the roads or train, was something that increased its value and contributed to a sense of belonging.

4.4.4 Theme 4: Collaboration between groups and integrated catchment management

Through the interviews, the final theme that emerged was the strong desire for collaboration between groups in the community and an integrated approach when considering the management of Lake Wairarapa. This reflected on both past involvements that participants had engaged with during their experiences, as well as reflecting on which direction future management might lead.

In the case of the former, an iwi participant reflected on their involvement in the Whaitua committee and the positive experience that had emerged through that involvement:

> *"I'd rather be working alongside people – yes, the Whaitua took four and a half years but I'm proud of the result we got to, and proud that I worked with people, proud that I represented our iwi."*

This quote illustrates that, while a collaborative approach took a long time, the opportunity for involvement with other people and the ability to represent members of a community was beneficial.

The regional council participant advocated for collaborative efforts to be completed spatially across the region through an integrated catchment approach:

> *"We would need a big integrated catchment approach that would see changes across the whole catchment to reduce nutrients and sediment, and also provide corridors and landscapes that allow native biodiversity to flourish and connect all the way back up with Lake Wairarapa."*

Due to the geographical location of Lake Wairarapa at the terminus of the catchment, ensuring a comprehensive catchment approach is deemed necessary. This is in regards to both improvements in water quality as well as diversity of native bird species.

Sub-theme 1: Vision and lake extent

Under this broader theme of collaboration between groups and integrated catchment management also emerged three sub-themes: shared vision and lake extent, representation and reducing barriers, and sharing knowledge and accepting alternative knowledge.

Under the sub-theme of shared vision and lake extent, a strong desire emerged to see the lake return to a pre-existing state. For one NGO participant, this meant a return to what was seen prior to the arrival of humans into the area:

> *"The kind of vision that we had was to recreate the wetland that would have been there in pre-human times … We accept that as a vision, but we also realise that it's been so modified that that's never going to happen. We want to get back to 70% or something, 80%, of what it was before."*

The significant wetlands around Lake Wairarapa prove to be a particular focal point for the vision. However, it also acknowledges that complete return to a ‘natural’ wetland ecosystem would be unlikely due to the amount of modification that has occurred in the catchment.

Regarding the extent of Lake Wairarapa, some participants took a catchment scale approach. For example, the community volunteer describes the extent of Lake Wairarapa as:

> *“Lake Wairarapa, Lake Ōnoke, and the wetlands that encompass the lake, but then also aware of that it’s within a greater catchment and all the tributaries that contribute to it.”*

However, other participants took a more conservation estimate of the lake extent. For example, the Rangitāne o Wairarapa participant describes lake extent to cover just the lake:

> *“So, I … would describe Lake Wairarapa as Wairarapa Moana on its own because Ōnoke is a different place and there are names for places everywhere in between … It’s strictly the lake”*

Therefore, there are some discrepancies in understanding lake extent and potentially building a cohesive vision for the lake and its catchment.

Sub-theme 2: Representation and reducing barriers

The second sub-theme – representation and reducing barriers – discusses the voices that ought to be heard within a collaborative and integrated catchment management approach and associated challenges. The community volunteer noted the difficulties that might arise in arranging such an approach and the allocation of resources within a collaborative process:

> *“To make progress will probably be a collaborative effort, but not just with the Department of Conservation, Greater Wellington Regional Council, and South Wairarapa District Council … Collaboration is really complicated, because each organisation has its own mandate and they’ve got to work out how they contribute and how much.”*

Here, the participant touches on how collaboration ought to go beyond the traditional governmental resource management bodies and include other groups or individuals. They also touch on how organisations have to negotiate their position and ability to be involved in such collaborative processes.

Regarding barriers, an NGO participant explained that financial resources were often a constraining factor affecting positive change for Lake Wairarapa:

> *"We certainly do need to do more with what's going into [Lake Wairarapa] … and all it takes is money, lots of money. A bit of good will too, but lots of money."*

This highlights that while the intent is often there for lake improvements, sufficient capital is necessary to produce effective results.

Sub-theme 3: Sharing knowledge and alternative knowledge

Sub-theme 3 discusses sharing knowledge and accepting alternative forms of knowledge. Here, the regional council participant discussed that adequate knowledge was available through the vast experience that people had working with the lake:

> *"I think the information and the people with the knowledge are there, there's a lot of people that know a lot about the area and [are] very invested in the lake and the area."*

However, this knowledge is not necessarily adequately acknowledged or accessed, as described by a NGO participant:

> *"People probably don't tap into that [knowledge]. It comes down through the bureaucracy a wee bit more – where's the file on this – rather than going out and tapping into that."*

This reflects that while there is a lot of knowledge available about the lake, a more collaborative approach that allows for non-traditional forms of knowledge to be recognised is necessary.

4.5 Discussion

As discussed by Poe et al. (2014), cultural ecosystem services are intertwined and entangled among each other. Similarly, cultural services are also deeply embedded within provisioning and regulating services (Chan et al., 2016). Initially, this research sought to identify the key cultural services that are present at Lake Wairarapa, and which areas required future attention. However, it soon became apparent that it was difficult to examine these factors in isolation. Following from the results, place attachment emerged as a key idea. Thus, the discussion firstly outlines how place attachment is the underlying factor crucial for individuals to realise the full range of ecosystem services at Lake Wairarapa. Subsequently, grounding in place attachment and cultural services allow for actualisation of future collaboration and restoration. Finally, the desires regarding future restoration are discussed.

4.5.1 Place attachment engendering cultural services

Within this study, all participants exhibited clear place attachment to Lake Wairarapa. As not all of the participants live at the lake, this would likely reflect the engagement participants have had over their professional or personal engagements with Lake Wairarapa. Place attachment is defined as a positive emotional connection with a landscape, and reflects both environmental and social elements associated with that landscape (Clarke et al., 2018).

Place attachment engenders high satisfaction for end users and serves to reinforce multiple ecosystem services. One factor under place attachment is the concept of place identity; place identity is constructed through important activities conducted in and around home and is a necessary component for personal identity formation and emotional wellbeing (Lengen & Kistemann, 2012). Many participants reflect on how they consider Lake Wairarapa as ‘home’ and how that is inextricably linked to their identity and mana. Relationships of place identity was also observed at Banks Peninsula on the eastern South Island, whereby sense of place was developed through agrarian society of Pākehā participants and indigenous societies for Māori participants (Hay, 1998). Similarly, among West Coast communities in the South Island, the remote, isolated nature of the region forged a proactive and resourceful identity among ‘Coasters’ and strong community bonds (Sampson & Goodrich, 2009). Likewise, new migrant communities in New Zealand engaged in place-based activities like gardening have a greater sense of belonging and social interaction than those that did not participate in such activities (Wen Li et al., 2010).

Place identity is indeed firmly rooted in the natural environment. Research suggests that the environmental setting supersedes factors including emotion, cognition, and social context in favourite memory recollection (Ratcliffe & Korpela, 2017). Construction of identity incorporates the environment; however, identity construction is grounded upon having multiple, repeated experiences through time (Clayton, 2012). A challenge now faced to place identity is the shift towards increasingly disconnected, globalised, and individualistic societies that draw away the formation of identity from place-based factors like the home region (as well as ethnic and class factors) (Paasi, 2003). Place identity, developed over time through a consistent integration with an environment such as Lake Wairarapa, can engender strength and resilience in communities and support individual wellbeing and feelings of belonging.

Place attachment can also support enhanced satisfaction when engaging in recreational activities (Beery & Jönsson, 2017). Lake Wairarapa supports multiple active and passive forms of recreation. Most participants touch on watersport opportunities, hunting and fishing, and the recreational opportunities to engage in nature and biodiversity. In the Pirongia Forest Park in Waikato, relaxation (both active and passive forms) was the greatest motivating factor to visit the park (Pan & Ryan, 2007). Likewise, higher satisfaction levels were attributed to those that had strong motivation to visit the park, proximity to the location, and repeat visitors – i.e. locals and frequent park users were more satisfied (Pan & Ryan, 2007). The factors of proximity and accessibility to recreational activities are noted by similar studies as key factors in determining use and usability by the public (Beery & Jönsson, 2017). However, there appears to be some disagreement within the literature, with some arguing that it is the desired recreational activity that drives satisfaction among recreationists, rather than the setting (Parry & Gollob, 2018). Here, recreationists are more readily able to substitute the setting rather than the activity (Parry & Gollob, 2018). However, place attachment is also argued as the antecedent variable to engage in recreational activities; place attachment enhances recreational satisfaction, and satisfying experiences reinforce place attachment (Budruk & Wilhelm Stanis, 2013).

Place attachment and identity are further reinforced by spiritual connections to landscapes. Spiritual-based cultural services are vague, but can mean religious connections, connectedness to nature, awe, as well as feelings of insignificance to the larger universe and a debt to nature (Cooper et al., 2016). For Māori connected to Lake Wairarapa, spiritual connections are reflected through references to old ancestral and familial ties. It reflects the harvest of eel for sustenance and the movement around the Wairarapa Valley to meet with whānau. Place attachment for Māori is manifest through the oral and written histories that surpass the experiences of the individual and are passed down through generations (Smith, 2004). The impact of colonisation and land displacement on Māori were also recognised among participants (both Māori and Pākehā), with the Treaty settlements recognised as a way to begin acknowledging these injustices and challenge movement toward a more inclusive future. It is undoubtable that the impact of land alienation has impacted place attachment among Wairarapa Māori; loss of connections with ancestral lands can have harmful effects on place identity and attachment (Butcher & Breheny, 2016).

One challenge to cultural service provision potentially faced at Lake Wairarapa is aesthetic conditions. Here, participants noted that the opportunity to see the lake provided value to them. However, participants also touched on how windy conditions at Lake Wairarapa often suspended sediments resulting in a displeasing brown colour, confused by some less informed members of the public as pollution. Aesthetic quality of landscapes and natural features are considered a large factor in helping build place attachment, although individual willingness to assign spiritual value was a more important factor (Brown & Raymond, 2007). Despite the sometimes conventionally unpleasing aesthetics of Lake Wairarapa, environments must not necessarily be aesthetically pleasing as they do not exist solely for human enjoyment (Saito, 1998). To overcome this, greater scientific understanding of the intricacies of natural processes and disregard of Westernised ideals of beauty can assist in stimulating greater appreciation of typically ‘unscenic’ landscapes (Saito, 1998).

A potential response to perceptions of the lake’s poor visual aesthetics during particularly windy conditions is education and research opportunities (Chan et al., 2011). Participants offered two interesting points: that the colour of the lake often led to assumptions that the lake was polluted, and secondly that educational activities can foster greater environmental awareness and concern for lake restoration. Chiesura and de Groot (2003) identified that landscapes can serve as a basis for scientific development (as is the case for this thesis) and educational tools (inclusion of youth into lake restoration). This example also reflects the integrated nature of cultural ecosystem services; recreation, for example, can foster further interest and action in biodiversity conservation, thus improving educational capabilities (Beery & Jönsson, 2017).

Overall, place attachment is forged through multiple, repeated experiences with the landscape – something all seven participants of this study demonstrated. From this, greater appreciation of the landscape is realised, and multiple cultural services observed.

4.5.2 Place attachment and cultural services informing future directions

A firm foundation in place attachment and actualised cultural services created a desire for change (albeit to varying degrees) by all participants. The results suggest that restoration is desired for Lake Wairarapa, both in the environmental and social spaces (discussed below in section 4.5.3). However, a prelude to long-lasting and universally accepted change is achieved through a collaborative approach to resource management.

Place attachment (in particular, place dependence) can be a strong demotivating factor to change (Anton & Lawrence, 2016). Those with strong place attachment typically perceive change to be negative and threatening; however, alleviation of such perceptions can be achieved through collaborative measures and consultation of community members in the change process (Anton & Lawrence, 2016). At Lake Wairarapa, introduction of the Ruamāhanga Whaitua Committee allowed for the voices of multiple of stakeholders (including iwi and community members) to be heard concerning the future of the Ruamāhanga catchment (Ruamāhanga Whaitua Committee, 2018). Likewise, ratification of the Treaty settlements would see greater collaboration with iwi through the establishment of the Wairarapa Moana Statutory Board (New Zealand Government, 2016, 2018). However, other participants felt that their voices were not listened to in current collaborative processes.

Collaborative resource management offers a multitude of benefits, if done correctly. It provides a mechanism for all parties to educate, persuade, and develop skills and legitimacy in the decision-making process, thus achieving better policy decisions, reduced barriers, and control over outcomes (Irvin & Stansbury, 2004). Effective collaborative resource management also enhances acceptability of decisions among the community (although decisions should be tailored on a case-by-case basis) (Lennox et al., 2011). Collaborative decision-making and implementing change is by no means easy. These approaches must attempt to bring together scientific knowledge, different stakeholder values, social and cultural settings, and environmental outcomes, as well as ensuring adequate time to reach agreements (Lennox et al., 2011). It can also be detrimental if decisions agreed to are not implemented or if bad decisions, driven by special interest groups, are enacted (Irvin & Stansbury, 2004).

Collaborative resource management in New Zealand must also involve Māori – exhibited at Lake Wairarapa through the Whaitua committee and likely soon through the Wairarapa Moana Statutory Board. Well-formulated collaborative resource management can allow for the contribution and integration of both scientific knowledge and Mātauranga Māori (Stephenson & Moller, 2009). Working with Māori communities involves time to build relationships and trust, as well as long-term, consistent commitment from researchers often beyond the initial scope of the project (Lyver, 2005). Barriers also exist for Māori communities where there is inadequate funds and resources for Māori groups. Chronic under-resourcing prevents engagement in environmental programmes beyond those locally focussed, with poor coordination and inability to disseminate findings more widely (Jollands & Harmsworth, 2007). Although, positive developments in the Māori resource management space are also highlighted in the designation of ‘legal personhood’ for the Whanganui River (Te Awa Tupa) and Te Uruwera (Gordon, 2018; Hutchison, 2014).

With an understanding of place attachment and cultural services with respect to Lake Wairarapa, and interest and willingness to engage in a collaborative resource management approach, then progress can occur in the restoration space. Suggestions from the Ruamāhanga Whaitua Implementation plan regarding Lake Wairarapa recommend that the council investigate in-lake management options (Ruamāhanga Whaitua Committee, 2018). Such management options include re-diverting the Ruamāhanga back into Lake Wairarapa, changes in management of Lake Wairarapa’s water level, and changes in management of the mouth openings at the Ōnoke Spit (Ruamāhanga Whaitua Committee, 2018). Any of these options will no doubt have implications for landowners around Lake Wairarapa, with the need to work alongside landowners – rather than against them – as highlighted by participants. While the Whaitua Committee involves community members, many of whom are farmers or come from farming backgrounds, wider collaboration will be required with those directly affected in the lower Wairarapa Valley. Those with a rural outlook and concern of the continuity of agricultural functions of a landscape) might pose opposition to waterbody restoration projects and, while often a small group, can be influential in garnering public resistance (Brower, 2008; Buijs, 2009). Therefore, educational awareness about the issues facing the catchment as well as transparency and availability of decision-makers will be crucial in enhancing positive attitudes to change (Clarke et al., 2018).

4.5.3 Moving forward: visions and aspiration

Moving forward, the aspirations that participants had for the future of Lake Wairarapa involve both environmental and social restoration. Environmental restoration varied between the participants: some wanted to see a return to natural conditions pre-dating human arrival in the region, although they acknowledged the unlikelihood of that being achieved in the contemporary setting. Others saw a combination of agricultural and horticultural land use intertwined with better functioning and protected natural environments. Still others aspired for the re-development of traditional industries, such as eel fisheries. Underlying everyone’s aspirations was the desire for a well-managed ecosystem that further supported the wellbeing of people living in the Wairarapa.

Socially, acknowledgement and greater understanding of the grievances of Wairarapa Māori through the Treaty settlements process is recognised as important for social restoration for local iwi. Greater governing capacity for Māori not only ensures adequate representation in decision-making, but also allow iwi to internally build capacity and capabilities. Educational opportunities similarly provide capacity building among other groups of Wairarapa citizens and can assist in fostering greater environmental awareness and stewardship. Finally, social restoration is not at the expense of landowners; land use and regulatory changes that will affect landowners need to be further endorsed and facilitated through government action and community support.

Restoration for both environmental and social concerns requires collaborative approaches; however, the process of restoration is not straightforward, with uncertainty and trade-offs likely throughout the decision-making process (Bullock et al., 2011). Likewise, restoration of degraded landscapes and improved biodiversity and ecosystem services – while critical – will not necessarily replicate those observed in intact landscapes (Benayas et al., 2009). This is where educational support will be necessary to ensure clear communication of achievable outcomes to the community (Aronson et al., 2010).

4.6 Conclusion

Cultural services provide a wealth of immaterial and intangible benefits to people within the community. Unfortunately, they are also highly neglected in ecosystem services literature, both at national and international scales (Van Den Belt & Blake, 2014). Regulatory bodies in New Zealand must take account of social values and benefits, alongside inclusion of Mātauranga Māori, to ensure adequate and robust resource management approaches.

This study demonstrated that place attachment was the primary factor underpinning the positive actualisation of cultural services at Lake Wairarapa. All seven participants in this study demonstrated strong place attachment at Lake Wairarapa which was built upon numerous experiences at the lake and surrounding environment. Strong place attachment forged better cultural service provision including identity formation, recreational enjoyment, and spiritual connection. While lake aesthetics were perceived as a barrier to cultural services, this simultaneously provides scientific and educational opportunities for the community. In congruence to place attachment, collaboration was highlighted as a key dimension within future management approaches to ensure positive outcomes. The key aspirations among participants was environmental and social restoration at Lake Wairarapa. Here, a well-supported and healthy ecosystem was envisaged, alongside a community that had adequate tools and capabilities to support themselves.

To enhance the provision of cultural services at Lake Wairarapa, greater emphasis on fostering strong place attachment is needed for people in the Wairarapa community. Currently, poor knowledge of the lake and its environmental condition acts as a barrier to increased place attachment, and therefore more opportunities for the public with the lake are recommended. Likewise, emphasis on collaborative approaches to resource management will encourage adequate representation of interested parties, and may reduce opposition to management changes at the lake. Through these mechanisms, cultural services of Lake Wairarapa may be more fully recognised and widely valued.

Chapter Five: A synthesis of past, present and future.

5.1 Importance of the study and general overview

Lake Wairarapa holds significant economic, environmental, social, and cultural importance to many people in the Wairarapa region (Ruamāhanga Whaitua Committee, 2018; Trodahl et al., 2016). However, ongoing environmental pressures have minimised the capacity of Lake Wairarapa to provide many essential ecosystem services.

Ecosystem services are the many benefits provided by ecosystems, which incorporate provisioning, regulating, cultural, and supporting functions (MEA, 2005). The extent to which each of these services are sustained has subsequent consequences to human wellbeing, including security, materials for successful lives, health, social relations, and thus freedom of choice and action (MEA, 2005).

Using the conceptual framework developed by the MEA (2005), this study sought to analyse how ecosystem services were provided by Lake Wairarapa, how these have shifted through time, and what needs to be improved in the future. A pragmatic epistemology was employed to accomplish this aim, utilising a multi-disciplinary to achieve predicative capabilities and actionable remediation (Creswell, 2014). Therefore, this study incorporated a mixed methods approach. Firstly, a palaeo-environmental reconstruction from proxies archived in lake sediments informed environmental changes in the lake and in the surrounding catchment over the past 2,000 years. Then, a field trial using soil, plant, and microbiology methodologies investigated the potential of mānuka in the mitigation of diffuse agricultural pollutants. Finally, a social science approach investigated cultural services and future aspirations through interviewing seven people of interest in the Wairarapa region.

This final chapter will explore and summarise the interwoven and interconnected presence of ecosystem services at Lake Wairarapa. The results of this final discussion will provide recommendations for relevant organisations such as Greater Wellington Regional Council, South Wairarapa District Council, local iwi Ngāti Kahungunu ki Wairarapa and Rangitāne o Wairarapa, among others, to assist in future policy and management decisions for Lake Wairarapa.

5.2 The Past

Historical environmental records at Lake Wairarapa clearly show the impact of anthropogenic changes on the delivery of ecosystem services at the lake. Following human arrival around 800-700 cal yr BP (Waters et al., 2018), the landscape was adapted and altered in a way to support the varying demands of different inhabitants.

Prior to human arrival, the longer-term trends from existing literature suggest that Lake Wairarapa was in disequilibrium between freshwater and marine realms, whereby the system had not reached a steady state (Bracken & Wainwright, 2006). Hayward et al. (2011) and Trodahl et al. (2016) discuss that ongoing transition from an oceanic embayment to a coastal freshwater lake around 3,400 cal yr BP, alongside changing inputs from the Ruamāhanga River, continually changed the conditions of Lake Wairarapa. However, using the dates derived from Waters et al. (2018), this study determined that the state of Lake Wairarapa prior to Polynesian arrival between 2,300-1,300 cal yr BP was relatively stable, characterised by a well-vegetated catchment with mānuka lining the lake margins and tributaries, which likely intercepted finer sediments. Marine influences persisted throughout this phase, exhibiting ongoing influence from the Ōnoke Spit.

When Polynesian settlers arrived in New Zealand around 1280 CE (McGlone & Wilmshurst, 1999), this demarcated an environmental shift at Lake Wairarapa and landscape alteration by humans to meet their needs. The growth and management of food supplies, such as bracken (Waters et al., 2018) and the eel trade (Ruamāhanga Whaitua Committee, 2018), highlights food provisioning services available to Māori at Lake Wairarapa. The clearance of the landscape through fire observed in this thesis perhaps also suggests the use of fuel sources as a provisioning service. Similarly, when European settlers arrived during the 1840s, the landscape was further altered for provisioning services through pastoral agriculture (McWethy et al., 2010), such as wetland drainage, with increasing intensification toward the present.

As demonstrated by this thesis, alteration of the landscape to enhance provisioning services came at the expense of robust, well-functioning regulating services. Clearance of the landscape through fire and removal of mānuka and tree ferns that formerly grew around the margin of Lake Wairarapa and its tributaries (Waters et al., 2018) promoted increased inputs of fine sediments as observed in this research. Many regulating services including soil loss prevention, water purification, and water flow regulation were therefore likely impacted as unvegetated soils were more easily eroded from the landscape. This finding is supported by Waters et al. (2018), who determined that Lake Wairarapa was deeper and clearer prior to the arrival of humans, suggesting resilient regulating services. While there were clear impacts on regulating services since initial Māori occupation, the most notable and distinctive impact can be seen with the 'Great Acceleration' over the latter 20th Century (Steffen et al., 2015). Widespread land clearance, intensified agriculture, and implementation of the Lower Wairarapa Valley Development Scheme to enhance provisioning services coincide with diminished regulating services at Lake Wairarapa, evidenced in this research in where most recent past suggests large increases in nutrient runoff (particularly phosphorus) and increased lake productivity (identified via elevated cyanobacterial presence). Sacrificing regulating, and other, services for the sole sake of provisioning is clearly not a pathway to sustained, healthy ecosystems (Foley et al., 2005).

Cultural services, however, were likely much better in the past. Development of place attachment is formulated through repeated experiences with a landscape. A less globalised society, interconnected local communities, and greater place dependence (i.e. relying on the land to support individual and group survival) would have promoted greater identity formation, knowledge and educational benefits, and social capital and cohesion (Chan et al., 2011). Oral and written histories outline the spiritual connection early Māori had with the land which, stems from Māori cosmogony and understanding of Te Ao Māori (Smith, 2004). Following European settlement, land alienation and privatisation around Lake Wairarapa likely reduced place identity for many Māori. As demonstrated by this thesis, reduced perceived accessibility may have inhibited other Wairarapa citizens from engaging with the lake.

5.3 The Present

Building upon the understanding of the past, the current status of Lake Wairarapa and the surrounding catchment is clearly reflective of environmental adaptation over the past centuries of human occupation. Its supertrophic status is governed by high phosphorus and poor clarity; however, nitrogen is also an important component (Perrie & Milne, 2012). Increased cyanobacterial presence, increased sediment inputs, and elevated phosphorus and manganese seen in this thesis evidence how sedimentation and nutrient runoff are likely large drivers that both maintain the lake's current state and contribute to further degradation.

The land surrounding Lake Wairarapa currently support an intensive agricultural industry (Perrie & Milne, 2012). Again, enhancement of provisioning services are dominant, whereby 54% of the catchment supports pastoral agriculture, with around half of that being high producing agriculture (Perrie & Milne, 2012). Agriculture is also the largest contributor to local GDP and full-time employment opportunities in the region (Stokes & Dixon, 2016).

While agriculture is an important sector in the contemporary Wairarapa economy and way of life, this research displays that changes are required to address diminishing regulating services of Lake Wairarapa. While on of many mitigation options, current literature and government focus are on the use of plants in riparian management to mitigate diffuse pollution (McKergow et al., 2016). However, barriers to implementation include direct costs to landowners (although some subsidies are available) and lost opportunity costs through land retirement (Di & Cameron, 2002). Based on palynological evidence, mānuka was a critical component in the pre-human landscape at Lake Wairarapa (Waters et al., 2018). Furthermore, laboratory and greenhouse have demonstrated the immense capacity this species has for regulating microbial and nutrient pollution (Downward, 2013; Esperschuetz et al., 2017b; Prosser et al., 2014; Prosser et al., 2016); however, this capacity had not been directly observed in the field. In this research, field trials established mānuka had a significant negative correlation with ammonia and nitrate, suggesting potential to mitigate these nutrients. The effect mānuka had on *E. coli*, however, was less supporting as pasture outperformed the juvenile shrubs.

Nitrogen held as ammonia, rather than nitrate, reduces the potential of leaching into Lake Wairarapa. Similarly, if nitrogen is a limiting nutrient in the lake (Perrie & Milne, 2012), then mānuka could considerably reduce further degradation. The results observed here somewhat corroborate those of Prosser et al. (2014), Prosser et al. (2016) and Esperschuetz et al. (2017b) although to a much lesser extent – although results from the field trial are much less conclusive, suggesting much more complex interactions within the natural environment. Congruently, planting riparian areas would likely intercept phosphorus and sediments present in runoff (Ballantine & Davies-Colley, 2013; Li et al., 2015). Thus, planting mānuka in riparian areas can enhance regulating services by preventing soil loss, aiding water filtration, and minimising overland flow intensity.

Cultural services present at Lake Wairarapa today are plentiful, as expressed by those who have established a strong place attachment to the lake and the surrounding areas. Participants in this study exhibited strong place attachments, and therefore experienced strong place identity, enjoyed a number of recreational pursuits, spiritual connection, and involvement in educational opportunities. However, there were also remarks around the poor aesthetics and a lack of visibility of the lake for passive, scenic enjoyment. For these participants, the lake held great importance and value to them and opportunities to see the lake brought forth positive responses. However, there was an underlying assumption that, for many people in the Wairarapa and wider greater Wellington region, Lake Wairarapa was not well known or used by the majority of community members. They noted a lack of educational awareness and integration into the wider community.

5.4 The Future

The future of provisioning services at Lake Wairarapa are unlikely to change substantially – at least in the short term. Agriculture will continue to be the economic powerhouse of the region; although, a shift to a service economy may see further decline in agricultural prioritisation (Stokes & Dixon, 2016). The results of the mānuka study could be used to encourage financial investment in a diversification of incomes among landowners. As a growing industry, development of mānuka honey and essential oil generation could facilitate movement away from intensive farming. However, issues such as the quality of mānuka honey determined through Unique Mānuka Factor (UMF) grading (Stephens et al., 2005), ideal climate and land requirements, and minimum planting areas (Saunders, 2017) are among the many factors needing consideration that are currently underexplored in the literature. Development of mānuka honey and oil industries as provisioning services may also contribute to improved regulating services.

Continuing a business-as-usual trajectory in pastoral agriculture needs to be countered with integrated development and enhancement of regulating services. Mānuka and/or other riparian management strategies ought to be adopted more widely to minimise nutrient and sediment runoff. Currently, riparian incentives offered by the regional council only apply to certain areas, although this could easily be extended. Similarly, implementation of shelterbelts enhance regulating services and could further mitigate excessive nutrient loading and faecal contaminant runoff. Shelterbelts also produce other co-benefits and regulating services including shelter for cattle and pollinators, reduction in wind speed which improves microclimate, soil moisture and reduces soil erosion, and can lead to increased crop yield (McDowell et al., 2006; Sandhu et al., 2008). As riparian areas are no panacea for improved water quality, employment of mānuka in shelterbelts can further improve regulating services by intercepting pollutants earlier. Likewise, this should be supported with further on-farm management practices that reduce pollutants (Di & Cameron, 2002; Wilcock et al., 2009).

Another factor that may contribute to changes in agricultural provisioning services is the proposed Ramsar status at Lake Wairarapa, currently under consideration by the New Zealand government. International status, significance, and interest would likely lead to increased measures to protect and develop the Wairarapa Moana wetlands (Denyer & Robertson, 2016). Ramsar status and development of the Wairarapa Moana wetlands will likely also assist in the further regulating services through sequestration of nutrients and sedimentation. Likewise, the proposed changes through the Ruamāhanga Whaitua Implementation Plan would likely bring back regulating service capabilities for Lake Wairarapa for flood regulation and support the significant wetland complex margining the lake.

However, these changes will not be easy and will require support both for and from landowners. Strong place attachment values shown by those working directly on or near the lake may lead to scepticism of any changes, therefore a collaborative approach will be necessary to ensure that conflict is minimised and a positive outcome achieved (Buijs, 2009). Not only will changes require additional resources for an incentive scheme, but collaborative approaches can also be costly and time intensive for community representatives. Where place attachment has not been established, further emphasis also needs to be placed on developing stronger community connections with Lake Wairarapa and the wider Wairarapa Moana complex. This may involve engaging in more community outreach in schools as well as community events and could be activated through recreational and educational means. Recreation creates hands-on, fun activities that can assist in developing place attachment. This could be complemented with educational programmes to enlighten community members around the significance of Lake Wairarapa and its multiple values to the region and residents.

5.5 Recommendations and final conclusion

The results of this research contributes to a broader understanding of ecosystem services delivered at Lake Wairarapa. It has highlighted some of the many ecosystem services that are currently provided, alongside opportunities for growth and areas that need to be cultivated and improved. Based on this research, the following four recommendations are outlined as a means to continue improving ecosystem services at Lake Wairarapa.

1. Develop ecologically appropriate restoration plans

   The result of the palaeo-reconstruction (Chapter 2) and the mānuka field trial (Chapter 3) should be consulted when implementing restoration plans for Lake Wairarapa as well as the wider Wairarapa Moana complex. Results show that the lake and its catchment were relatively stable in the preceding 1,000 years prior to human arrival at the lake, with a well vegetated catchment supporting better ecological health. Removal of native forests in favour of exotic grasses has destabilised the landscape, contributing to large increases in nutrient and sediment loading into the lake. Currently, as a predominantly agricultural catchment wired for development of provisioning services through food production, a focus on improving regulating services is required, and can be achieved through improved riparian on-farm management practices. Bioremediation strategies through mānuka planting in riparian areas and shelterbelts can greatly improve the efficiency and efficacy of regulating services through pollution control. Therefore, significant resourcing should be put into planting and re-establishing mānuka around the margins and tributaries of Lake Wairarapa.

2. Continue and adapt collaborative management approaches

   The success of the first recommendation will be contingent on ensuring a collaborative approach is taken when disseminating information and deciding future directions. Collaborative resource management is widely considered as a key mechanism in garnering support from constituents. As highlighted in the interviews (Chapter 4), collaboration is a crucial component for success in environmental restoration work in the Wairarapa leading participants to feel empowered and take ownership of their accomplishments. When considering mānuka planting around Lake Wairarapa, and any further changes, a collaborative approach will be necessary and invitation must be extended to all affected residents. This may deviate from already established collaborative or governance groups; however, as these residents would likely have high place attachment and would experience direct impact on their lives and livelihoods, an independent collaborative group may need to be formed to adapt to the needs of the situation at hand.

3. Further studies into mānuka honey quality in agricultural and mixed land use areas
   The results from the mānuka study (Chapter 3) need to be further investigated in multiple areas. Results suggest varying influences of mānuka on key environmental pollutants; however, as this was a pilot study, these results need to be supported with further research at greater spatial scale, over prolonged periods of time, as well as with more mature mānuka stands. From an environmental perspective, mānuka is suitable for the area, although developing community support may need further evidence. In particular, there is a paucity of evidence around the impacts of surrounding land use on UMF factors in mānuka honey. Support for landowners interested in diversifying incomes will be required due to the many conditions and requirements needed for both honey and essential oil production.

4. Community engagement programmes
   The results of the interviews (Chapter 4) suggest that place attachment was the underlying factor in fostering strong cultural services at Lake Wairarapa and that knowledge and visibility of the lake was limited for the majority of the community. Participants reflected on successes in fostering interest in Lake Wairarapa and restoration efforts when working with the community. Therefore, the final recommendation is to develop and build community engagement programmes to foster greater interest in Lake Wairarapa and assist in building place attachment. This could come in variety of forms such as developing projects with local schools, holding community events at the lake, improved facilities at Lake Domain and other lake access points, and education and involvement of locals in restoration programmes.

Despite continued land degradation and advancement of provisioning services at the expense of regulating and cultural services, Lake Wairarapa continues to offer many ecosystem services for people in the Valley. Further development and strengthening of the whole range of ecosystem services would facilitate the development of a robust and well-functioning environment, promoting health and happiness for people in the area.

Through a pragmatic epistemology and mixed methods approach, this research has concluded by outlining four key ways that provisioning, regulating, and cultural ecosystem services can be improved at Lake Wairarapa: ecologically appropriate restoration plans, fostering collaborative management, further investigation of environmental and economic properties of mānuka, and development of community engagement programmes.

Improving ecosystem services at Lake Wairarapa will be a long and arduous journey. While these recommendations are a useful first step for improvements, it will be necessary to support and integrate ongoing research at Lake Wairarapa in a variety of fields. Likewise, continued community engagement will ensure that management is directed towards a vision that everybody can support. With strong ecosystem services, a healthy environment, and resilient people, the Valley will truly become Wairarapa – *the land of glistening waters*.

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Appendix A

Investigating Ecosystem Services at Lake Wairarapa

INFORMATION SHEET FOR PARTICIPANTS FOR INTERVIEWS

You are invited to take part in this research. Please read this information before deciding whether or not to take part. If you decide to participate, thank you. If you decide not to participate, thank you for considering this request.

Who am I?

My name is Sky Halford and I am a Masters student in the Masters of Environmental Studies Programme at Victoria University of Wellington. This research project is work towards my thesis.

What is the aim of the project?

This project is looking at the benefits that the Lake Wairarapa ecosystem provide to humans and contribute to overall wellbeing. This involves both generating physical knowledge of the environment through lake sediments, a riparian field trial, and greenhouse experiment, as well as social knowledge about the lake and how we use it (and want to use it in the future). This project aims to deliver usable outcomes and information and guide successful future management for Lake Wairarapa.

This research has been approved by the Victoria University of Wellington Human Ethics Committee. Application number: 0000026519

How can you help?

You have been invited to participate because of your experience in working and being involved at Lake Wairarapa. If you agree to take part, I will interview you at a meeting space in your place of work. I will ask you questions about ecosystem services provided by Lake Wairarapa. The interview will take approximately one hour. I will audio record the interview with your permission and write it up later. You can choose to not answer any question or stop the interview at any time, without giving a reason. You can withdraw from the study by contacting me at any time before 31 December 2018. If you withdraw, the information you provided will be destroyed or returned to you.

What will happen to the information you give?

You will not be named in the final report but your organisation will be named (provided you have the authority to agree to this on behalf of the organisation). All attempts will be made to uphold your confidentiality, however, you should be aware that in small projects your identity might be obvious to others in your community

Only my supervisors and I will read the notes or transcript of the interview. The interview transcripts, summaries, and any recordings will be kept securely and destroyed on 15 March 2029.

What will the project produce?

The information from this research will be used in my Masters thesis, a smaller summary that will be provided to key organisations and contributors (including, but not limited to, Greater Wellington Regional Council, Ngāti Kahungunu ki Wairarapa, ESR, Cawthron Institute, and Victoria University of Wellington), as well as potential future academic work and opportunities (e.g. academic conferences, academic publications, etc.).

If you accept this invitation, what are your rights as a research participant?

You do not have to accept this invitation if you don't want to. If you do decide to participate, you have the right to:

- choose not to answer any question;
- ask for the recorder to be turned off at any time during the interview;
- withdraw from the study before 31 December 2018;
- ask any questions about the study at any time;
- receive a copy of your interview recording;
- receive a copy of your interview transcript*;*
- read over and comment on a written summary of your interview*;*
- be able to read any reports of this research by emailing the researcher to request a copy.

If you have any questions or problems, who can you contact?

If you have any questions, either now or in the future, please feel free to contact myself or my supervisors:

Student:
Name: Sky Halford
Email: sky.halford@vuw.ac.nz

Social Science Supervisor:
Name: Charlotte Šunde
Role: Social Scientist in the Coastal and Freshwater Group
Organisation: Cawthron Institute
Phone: 03 548 2319 ext 255
Email: charlotte.sunde@cawthron.org.nz

Overall Thesis Supervisor:
Name: Andrew Rees
Role: Lecturer
School: School of Geography, Environment and Earth Sciences

Phone: 04 463 9396
Email: andrew.rees@vuw.ac.nz

Human Ethics Committee information

If you have any concerns about the ethical conduct of the research you may contact the Victoria University HEC Convenor: Dr Judith Loveridge. Email hec@vuw.ac.nz or telephone +64-4-463 6028.

Appendix B

TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

Investigating Ecosystem Service at Lake Wairarapa

CONSENT TO INTERVIEW

This consent form will be held for 10 years.

Researcher: Sky Halford, School of Geography, Environment and Earth Sciences, Victoria University of Wellington.

- I have read the Information Sheet and the project has been explained to me. My questions have been answered to my satisfaction. I understand that I can ask further questions at any time.
- I agree to take part in an audio recorded interview.

I understand that:

- I may withdraw from this study at any point before 31 December 2018, and any information that I have provided will be returned to me or destroyed.
- The identifiable information I have provided will be destroyed on 15 March 2019.
- Any information I provide will be kept confidential to the researcher and the supervisors.
- I understand that the results will be used for a Masters thesis and potential academic publications and/or presented to conferences.
- I consent to information or opinions which I have given being attributed to my organisation in any reports on this research and have the authority to agree to this on behalf of the organisation: Yes ☐ No ☐
- I would like a copy of the recording of my interview: Yes ☐ No ☐
- I would like a copy of the transcript of my interview: Yes ☐ No ☐
- I would like a summary of my interview: Yes ☐ No ☐
- I would like to receive a copy of the final report and have added my email address below. Yes ☐ No ☐

Signature of participant: ______________________________

Name of participant: ______________________________

Date: ______________________________

Contact details: ______________________________