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ARTICLE

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A global review of socioeconomic and environmental impacts of ants reveals new insights for risk assessment

Monica A. M. Gruber[1,2] | **Davide Santoro**[1,2] | **Meghan Cooling**[2] | **Philip J. Lester**[1,2] | **Benjamin D. Hoffmann**[3] | **Christina Boser**[4] | **Lori Lach**[5]

[1]Centre for Biodiversity and Restoration Ecology, School of Biological Sciences, Victoria University of Wellington, Wellington, New Zealand

[2]Pacific Biosecurity, Wellington UniVentures, Victoria University of Wellington, Wellington, New Zealand

[3]CSIRO, Health & Biosecurity, Tropical Ecosystems Research Centre, Winnellie, Northwest Territories, Australia

[4]The Nature Conservancy, San Francisco, California, USA

[5]College of Science and Engineering, James Cook University, Cairns, Queensland, Australia

Correspondence
Monica A. M. Gruber
Email: monica.gruber@vuw.ac.nz

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Abstract

Risk assessments are fundamental to invasive species management and are underpinned by comprehensive characterization of invasive species impacts. Our understanding of the impacts of invasive species is growing constantly, and several recently developed frameworks offer the opportunity to systematically categorize environmental and socioeconomic impacts of invasive species. Invasive ants are among the most widespread and damaging invaders. Although a handful of species receives most of the policy attention, nearly 200 species have established outside their native range. Here, we provide a global, comprehensive assessment of the impacts of ants and propose a priority list of risk species. We used the Socioeconomic Impact Classification for Alien Taxa (SEICAT), Environmental Impact Classification for Alien Taxa (EICAT) and Generic Impact Scoring System (GISS) to analyze 642 unique sources for 100 named species. Different methodologies provided generally consistent results. The most frequently identified socioeconomic impacts were to human health. Environmental impacts were primarily on animal and plant populations, with the most common mechanisms being predation and competition. Species recognized as harmful nearly 20 years ago featured prominently, including *Wasmannia auropunctata* (little fire ant, electric ant), *Solenopsis invicta* (red imported fire ant), *Anoplolepis gracilipes* (yellow crazy ant), and *Pheidole megacephala* (African big-headed ant). All these species except *W. auropunctata* have been implicated in local extinctions of native species. Although our assessments affirmed that the most serious impacts have been driven by a small number of species, our results also highlighted a substantial number of less well publicized species that have had major environmental impacts and may currently be overlooked when prioritizing prevention efforts. Several of these species were ranked as high or higher than some of the previously recognized "usual suspects," most notably *Nylanderia fulva* (tawny crazy ant). We compared and combined our assessments with trait-based profiles and other lists to propose a consensus set of 31 priority species. Ever-increasing global trade contributes to growing rates of species introductions. The integrated approaches we used can contribute to robust, holistic risk assessments for many taxa entrained in these pathways.

KEYWORDS
EICAT, environmental impact, GISS, Hymenoptera, invasive ants, SEICAT, socioeconomic impact

INTRODUCTION

The increasing spread of species globally through trade (Essl et al., 2011; Seebens et al., 2017) drives a continuing and growing need for evidence-based risk assessments of invasive species. Risk assessments are fundamental to invasive species actions as they enable prioritization of taxa to guide biosecurity legislation, policy, and regulation of trade, and provide targets for biosecurity surveillance and response, and for management of resident invasive species. Risk assessments rely heavily on the accurate and comprehensive characterization of impacts.

Our understanding of the impacts of invasive species is constantly growing. Although the environmental impacts of invasive species have received considerable attention over several decades, the socioeconomic impacts of these species have been less well studied. Increasing recognition is being given to the multiplicity of impacts of invasive species on many aspects of human interest, including environment, human health, agriculture, culture, and economies, but these costs are likely to have been underestimated and will escalate over time (Bradshaw et al., 2016). The relative lack of published evidence on socioeconomic impacts represents a missed opportunity to incentivize policy-makers to prioritize biological invasions in economic terms (Hanley & Roberts, 2019). As well as having financial benefits, a more cross-sectoral holistic approach should also result in improved outcomes for biodiversity, particularly for species that have impacts in multiple sectors.

Until relatively recently, studies of the impacts of invasive species have typically used nonstandard approaches. Although informative for their own purposes, nonstandard assessments may have limited utility when assessing the impacts of groups or guilds of species or when comparing among species. Moreover, standardized assessments enable comparisons among different types of impacts. Recently, methodologies have been developed to overcome the lack of consistency in assessment by providing a standardized framework to objectively compare the impacts of species or guilds in different domains of impact (e.g., the Environmental Impact Classification for Alien Taxa [EICAT], Hawkins et al., 2015; the Generic Impact Scoring System [GISS], Nentwig et al., 2016; and the Socioeconomic Impact Classification for Alien Taxa [SEICAT] Bacher et al., 2018). These new methodologies incorporate a more holistic and integrated perspective on invasive species impacts (e.g., Bacher et al., 2018; Nentwig et al., 2016), and have been used to assess a broad range of taxa (e.g., Bacher et al., 2018; Galanidi et al., 2018; Hagen & Kumschick, 2018); the International Union for the Conservation of Nature (IUCN) has adopted EICAT as a standard. However, global analyses using these methodologies are still rare, having been completed only for birds (Evans et al., 2016), ungulates (Volery et al., 2021), and insects (Clarke et al., 2021).

Ants have been introduced outside their native ranges to all continents except Antarctica. Nineteen ant species are currently listed in the IUCN Global Invasive Species Database (GISD) (ISSG, 2015). Many more ant species have been recorded as introduced to new areas (178 species; AntWeb, 2020). Many examples have demonstrated the devastating and widespread negative ecological and environmental effects of invasive ants (e.g., Holway et al., 2002; O'Dowd et al., 2003; Plentovich et al., 2018). Invasive ants are known to harm other human interests, including infrastructure, agriculture and the economy, and human health (e.g., Fasi et al., 2016; Holway et al., 2002; Rosselli & Wetterer, 2017; Wylie & Janssen-May, 2016). However, only a handful of "usual suspects" of introduced ant species has been routinely cited as responsible for the most widespread impacts (e.g., Gruber et al., 2017; Holway et al., 2002; Lowe et al., 2004). Ever-increasing global trade contributes to growing rates of species introductions in new areas (Essl et al., 2011; Seebens et al., 2017). Therefore, additional ant species are increasingly being transported and having significant impacts (e.g., Bertelsmeier et al., 2017; Kumar et al., 2015). Assessing which species are currently responsible for the greatest impacts will assist with risk assessments and guide targeted prevention and management actions for priority species.

Several lists have provided guidance on prioritization of invasive ants, particularly the 19 species of concern in the GISD (ISSG, 2015). However, systematic assessments of invasive ants are rare. Recently Clarke et al. (2021) used EICAT to identify the environmental impacts of 17 invasive ants among other insects, and Fournier et al. (2019) used trait-based modeling to predict species that are or may become invasive. No studies have comprehensively or systematically assessed the socioeconomic and environmental impacts of all ant species. Objective and comprehensive assessments of impacts are critical for risk assessment and prioritization to understand the potential implications of the increased spread of current and potential future invasive ants.

Our goal was to assess the global socioeconomic and environmental impacts of invasive ants to assist with risk assessment. We compared the species lists and rankings produced by our SEICAT, EICAT, and GISS assessments with other lists of introduced ants to circumscribe a consensus set of priority species.

METHODS

We used the SEICAT, EICAT, and GISS methodologies to qualitatively assess the impacts of ants. Applying the methodologies together provides a more holistic assessment of impacts (Hagen & Kumschick, 2018). These methodologies can lead to very similar assessments of impact levels, but scores from the schemes are not equivalent, and scores from one method should not be derived directly from others (Kumschick, Vimercati, et al., 2017). Different scoring schemes assess different aspects, and this may influence assessment outcomes (Turbé et al., 2017). Although using multiple methodologies is time consuming, it improves our understanding of the various facets of the impacts, especially for socioeconomic sectors (Hagen & Kumschick, 2018). The most time-consuming aspect of the process is collating the literature, but once data have been accumulated for the GISS assessment, the same sources can be used to complete the other assessments (Hagen & Kumschick, 2018).

Literature search

Our literature search targeted all the available information on any ant species impact at a global scale (i.e., the search was not constrained to a single geographical area). As recommended (Kumschick, Measey, et al., 2017), we assessed impacts for all publications that yielded relevant information according to the specific methodology. This approach improves the applicability of the results to management and prioritization of future research. To identify peer-reviewed information sources for our analyses, we conducted systematic and exhaustive searches of literature published in English prior to March 2019 in Web of Science, JSTOR, Google Scholar, and FORMIS, a curated database of all ant literature (Wojcik & Porter, 2018). In our search terms we used "ant" with the additional key words "sting," "bite," "damage," "cost*" and "impact*."

As we wished to also identify ants that may potentially have impacts in novel locations or were not currently recognized as invasive, we deviated slightly from the search guidelines (Bacher et al., 2018; Hawkins et al., 2015) by not restricting our searches with terms such as "invasive," "alien" or "introduced." Technically, the assessment tools we used were targeted at invasive species only. However, because we also wanted to predict potential future threats we did not limit our search to only species already deemed invasive. Although impacts in the native range may not translate into invasiveness for the majority of invasive species, many invasive ants are associated with human disturbance (one of the traits recorded in the AntProfiler database [Bertelsmeier, Luque, Confais, et al., 2013]). In addition, the invasive little fire ant *Wasmannia auropunctata*, Roger, 1863 (little fire ant, electric ant) causes socioeconomic impacts in its native and invaded ranges (e.g., punctate corneal lesions; Rosselli & Wetterer, 2017). The probability of transportation and establishment for these species also requires consideration in risk assessment.

For the environmental impact assessments, we included only papers that documented the negative effects of ants. A minor body of literature documenting positive effects (e.g., predation of pests in crops, negative effects on other pest species, dispersal of native/endemic plant seeds) was not included, as the intent of the methodologies used was to identify negative impacts only. Because sources could describe multiple impacts or multiple species, a single source could result in multiple records.

Literature assessment and analysis

Although the SEICAT/EICAT and GISS methodologies provided a structured way to assess impact, uncertainties can arise (Clarke et al., 2021; Probert et al., 2020). Like less formalized approaches, the assessments can be subjective depending on the views of individual assessors, regardless of their expertise in the subject matter. To achieve consistency and consensus, two authors (Meghan Cooling, Davide Santoro) extracted the text citations/impact descriptions from the sources and initially assessed each impact description. To minimize the possibility of bias, at least two additional authors independently assessed a subset of 100 citations, including all those that were assigned the highest scores/categories. The final scores were agreed by consensus.

To assess the equivalence of the methodologies, we tested for a positive association between the EICAT/SEICAT categories and the maximum scores per GISS category and GISS total scores (separated by type of impact, i.e., socioeconomic or environmental) for each named species using Spearman's rank correlation coefficients in R (R Core Team, 2021).

SEICAT and EICAT analysis

The SEICAT and EICAT methodologies categorize invasive species by the magnitude of their impacts, subdivided according to the mechanism of the impact. For

SEICAT, the mechanisms are the components of human wellbeing affected by the target species and include safety; material and nonmaterial assets; health; and social, spiritual, and cultural relations. Each record is assessed in one of five impact categories ranked by increasing magnitude of impact: (1) Minimal Concern (MC); (2) Minor (MN); (3) Moderate (MO); (4) Major (MR); and (5) Massive (MV). Taxa with no information were classified as data deficient (DD), those with no populations outside the native range were classed as NA, and taxa not evaluated were classed as NE. For each record, the highest impact category for each mechanism was recorded. Each record was also categorized by degree of confidence in the original source (low, medium, high) following a 1–12 points rationale. When there were multiple impacts for a mechanism, the highest impact category with lower confidence was recorded. For SEICAT/EICAT analysis, only the maximum impacts across all mechanisms and records are reported, as recommended for the methodologies (Bacher et al., 2018).

For EICAT, the mechanisms of impact are also categorized according to the effects of the target species at the species, population, or ecosystem level, and include competition; predation; hybridization; transmission of disease to native species; parasitism; poisoning/toxicity; bio-fouling; grazing/herbivory/browsing; chemical, physical, or structural impact on ecosystem; and interaction with other introduced species (Hawkins et al., 2015).

As recommended (Bacher et al., 2018; Hawkins et al., 2015), we recorded our confidence in the impact level, according to the methodology guidelines. Each study was assessed on its merits, considering the length of the study, its spatial scale, the number of replicates, and potential confounding ecological factors, such as disturbance. Laboratory-only studies that documented impacts were typically assigned low confidence (4: "the impact is recorded at the local scale"). In studies of invasive ants, negative co-occurrence patterns between the focal species and other taxa are often used to infer impacts. When the reported impacts were correlated with more general environmental degradation (e.g., associations with disturbance), and the study was limited to describing negative co-occurrence patterns, these were assigned medium confidence (7: "the interpretation of the data is to some extent ambiguous or contradictory"). Studies that described negative co-occurrence patterns and provided additional information suggesting the direct impacts of ant invasions (e.g., laboratory experiments, density-dependent effects, large spatial scale, or substantial replication, i.e., three or more populations spatially segregated, or a combination of multiple experiments suggesting causality) were assigned high confidence. In many cases we were unable to score maximum confidence (12: "data/information are not controversial, contradictory"), as studies were often correlational and/or short term.

GISS analysis

The GISS methodology is a combined assessment for environmental and socioeconomic impacts. Records are classified into six categories for socioeconomic impact, each with six subcategories, that is, impacts on: (1) agricultural production; (2) animal production; (3) forestry production; (4) human infrastructure and administration; (5) human health; (6) human social life and six environmental categories, that is impacts on: (1) plants or vegetation; (2) animals through predation, parasitism, or intoxication; (3) other species through competition; (4) ecosystems; (5) through transmission of diseases or parasites to other species; (6) through hybridization. Impact was measured on a scale of 0 to 5, with 0 indicating no detectable impacts and 5 the most severe impacts. As recommended, the GISS final impact score for each species was obtained by summing the highest scores for each of the 12 impact categories (Nentwig et al., 2016). Using this approach, the maximum theoretical impact score for a species was 60, although in practice few, if any, species are likely to have maximum impacts in all categories, so GISS impact scores were generally lower than 60.

Comparison with other lists

Once we had derived the lists of ant species with impact records appropriate to the methodology, we compared these with four other lists of invasive or introduced ant species to search for a consensus of priority species: (1) AntWeb provides descriptive information for most described ant species. The data set identifies 179 species that have been introduced outside their native range (AntWeb, 2020); (2) The GISD lists 19 species that are considered invasive in their introduced range, that is, those with negative effects (ISSG, 2015); (3) trait-based profiles (Fournier et al., 2019) were derived from the AntProfiler database (Bertelsmeier, Luque, Confais, et al., 2013) of ants possessing traits associated with invasiveness. Thirty-seven species have been assigned "superinvasive" or "invasive" profiles, including some native species that are not recorded as introduced elsewhere, which may be future invaders (Fournier et al., 2019); (4) A global assessment of uncertainty in EICAT studies using insects as a model included a priori 17 ant species (Clarke et al., 2021).

Although other lists also include invasive ants, their records are either equivalent to, or a subset of, the above-mentioned data sets, such as the commonly cited subjective selection of the "world's worst" invasive species, which includes five ant species (Lowe et al., 2004). For example, the Global Ant Biodiversity Informatics (GABI) Project (implemented as AntMaps) complements the AntWeb taxonomic list by providing detailed distribution data (Guénard et al., 2017), whereas the species list on AntWeb is taxonomically comprehensive.

RESULTS

We found 641 unique records for impacts of 100 named ant species that met the assessment requirements of one or more of the three methodologies. A greater number of studies and higher scores were recorded for environmental relative to socioeconomic impacts (Figures 1, 2). Socioeconomic impacts were attributed to more species ($n = 65$) than environmental impacts were ($n = 59$). Relatively few species were responsible for the highest impact levels (Table 1; Figure 2; Appendix S1: Tables S1, S2; Gruber, Santoro, et al., 2021). Species recognized as having impacts nearly 20 years ago (Holway et al., 2002) figured prominently in our results: *Wasmannia auropunctata*, *Solenopsis invicta* Buren, 1972 (red imported fire ant), *Solenopsis geminata* Fabricius, 1804) (tropical fire ant), *Linepithema humile* Mayr, 1868 (Argentine ant), *Pheidole megacephala* Fabricius, 1793 (African big-headed ant), and *Anoplolepis gracilipes* Smith, F. 1857 (yellow crazy ant).

The different methodologies yielded relatively consistent results across all species (Figure 1). We found significant positive associations between the results of the methodologies: EICAT category versus GISS total score ($\rho = 0.923$, $S = 2624$, $p = <0.001$), SEICAT category versus GISS total score ($\rho = 0.608$, $S = 17{,}934$, $p < 0.001$), EICAT category versus maximum score per GISS category ($\rho = 0.912$, $S = 3026$, $p < 0.001$), SEICAT category versus maximum score per GISS category ($\rho = 0.455$, $S = 24{,}920$, $p < 0.001$). If the associations between the pairs of variables are high, Spearman's rank correlation coefficient (ρ) is close to 1, whereas no association is 0 and negative association is -1.

When grouped by region of study, most records were from North America, and the majority of these were for *S. invicta* (Figure 3). Our full assessment data sets including study locale, confidence scores, rationale and source references are publicly available from Dryad (Gruber, Santoro, et al., 2021).

SEICAT analysis

We collected 550 records from 272 sources that documented the socioeconomic impacts of 65 named species (Appendix S1: Table S1). Of the 550 records, 464 were applicable for assessment using the SEICAT methodology. Records of impacts were from 50 countries and territories, with most records from the United States (36%), Brazil (22%), Australia (5%), and Malaysia (5%). Forty-eight taxa (59% of records; Appendix S1: Table S1) were reported only once. The most frequently identified socioeconomic impact categories were health (60.6% of records) and material assets (35.1%). The remaining impacts were on nonmaterial assets (1.9%), social (4.7%), cultural (2.4%), and spiritual relations (0.4%). No records identified "safety" as a mechanism of impact.

Wasmannia auropunctata was categorized in the SEICAT analysis as the most serious socioeconomic threat, with massive impacts (Table 1; Figure 2; Appendix S1: Table S1). This categorization was derived from a single record describing a French Polynesian farmer's inability to tend her land, and abandonment of properties by her extended family (Strohecker, 2012). As this was a single anecdotal report, the classification was assigned with low confidence.

Solenopsis invicta and *A. gracilipes* were assessed as having major socioeconomic impacts (Table 1; Figure 2). All other species were ranked as having moderate or minor impacts. *S. invicta* was the most reported species, having 94 records (20.2%).

EICAT analysis

We collected 731 records from 324 sources that documented the environmental impacts of 59 named ant species (Appendix S1: Table S2). Of these records, 646 were suitable for assessment using the EICAT methodology. Records of impacts were from 55 countries and territories, with an additional nine laboratory-based studies through which impacts were inferred. Most records were from the United States (50%), Australia (7%), Spain (6%), and China (3%). *S. invicta* was the most studied species (215 records; 33.8%; Appendix S1: Table S2). Forty-three taxa (61%) appeared in only one record. Most records were categorized as having impacts on animal and plant populations (58%), single species (32%), and ecosystems (10%). The most common impact mechanisms reported were predation (40%) and competition (36%), followed by multiple mechanisms (10%, mostly predation and competition), interaction with other species (7%) and poisoning/toxicity (2%), whereas the mechanisms were unclear in 5% of cases.

The EICAT analysis categorized *S. invicta*, *A. gracilipes* and *P. megacephala* as having massive impacts (Table 1; Figure 2). *Anoplolepis gracilipes* has been implicated in the decline and likely extinction of the endangered Christmas Island Shrew (*Crocidura attenuata trichura* Dobson, 1888)

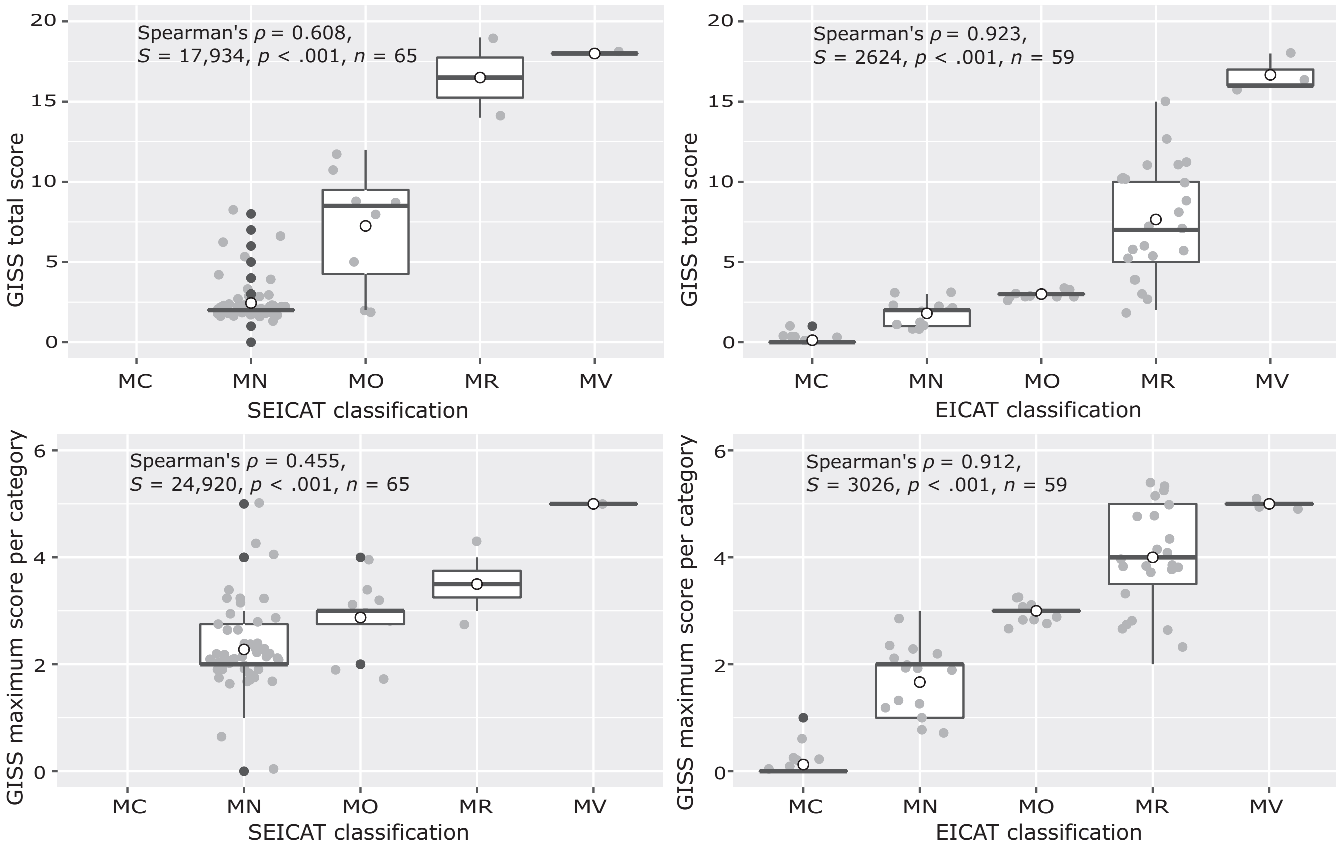

FIGURE 1 Classifications by SEICAT and EICAT compared with corresponding (i.e., either environmental or socioeconomic) GISS total score and maximum score per GISS category for each species. Boxplots show the highest and lowest values (vertical lines), median (thick line), mean (white circle), quartiles, interquartile ranges (boxes) and outliers (black points) for GISS scores and SEICAT/EICAT rankings. Jittered gray points indicate scores for each species. Spearman's ρ shows the strength of the relationship between the SEICAT/EICAT rankings and GISS scores. SEICAT, Socio-Economic Impact Classification for Alien Taxa (Bacher et al., 2018); EICAT, Environmental Impact Classification for Alien Taxa. (Hawkins et al., 2015); GISS, the Generic Impact Scoring System (Nentwig et al., 2016)). SEICAT/EICAT impact categories are: MC, Minimal concern; MN, Minor; MO, Moderate; MR, Major; MV, Massive

(Meek, 2000). *Pheidole megacephala* has been cited in extinctions of several land snails (*Garrettia rotella* Pease, 1868, *Libera subcavernula* Tryon, 1887, eight species of *Minidonta*, six species of *Sinployea*, and *Liardetia discordiae* Garrett, 1881) in the Cook Islands in the Pacific, although modification and loss of habitat was also a likely contributor (Brook, 2010). Records from Hawai'i deemed the local extinction of the Dark-bellied Copper-striped Skink (*Emoia impar* Werner, 1898) (Fisher & Ineich, 2012) and a damselfly (*Colpocaccus tantalus* Blackburn, 1877) to be mostly likely caused by *P. megacephala* (Liebherr & Polhemus, 1997). In the Florida Keys, the extinction of the Stock Island Tree Snail (*Orthalicus reses* Say, 1830) in its native range was attributed to *S. invicta* (Forys et al., 2001). Confidence in all these impact classifications was assessed as low, as the evidence was ambiguous and/or indirect.

We assessed *L. humile*, *W. auropunctata*, *S. geminata*, and 20 other species as having major environmental impacts (Table 1; Figure 2). Five species that had not been recorded as introduced outside their native range (AntWeb, 2020) were assessed as having major environmental impacts: *Azteca sericeasur* Longino, 2007, *Camponotus conspicuus zonatus* Emery, 1894, *Formica aquilonia* Yarrow, 1955, *Formica paralugubris* Seifert, 1996 and *Pheidole radoszkowskii* Mayr, 1884 (Table 1; Figure 2).

GISS analysis

We found 1161 records of impacts relevant to GISS analysis from 642 sources, for 100 named species (Gruber, Santoro, et al., 2021; Table S3) from 80 geographical areas. Most reports were from the United States (43%), Brazil (9%), Australia (8%), and Spain (3%).

The records we assessed resulted in a combined total of 2517 impact points. Overall, 1509 impact points (60%) originated from environmental impacts and 1008 (40%)

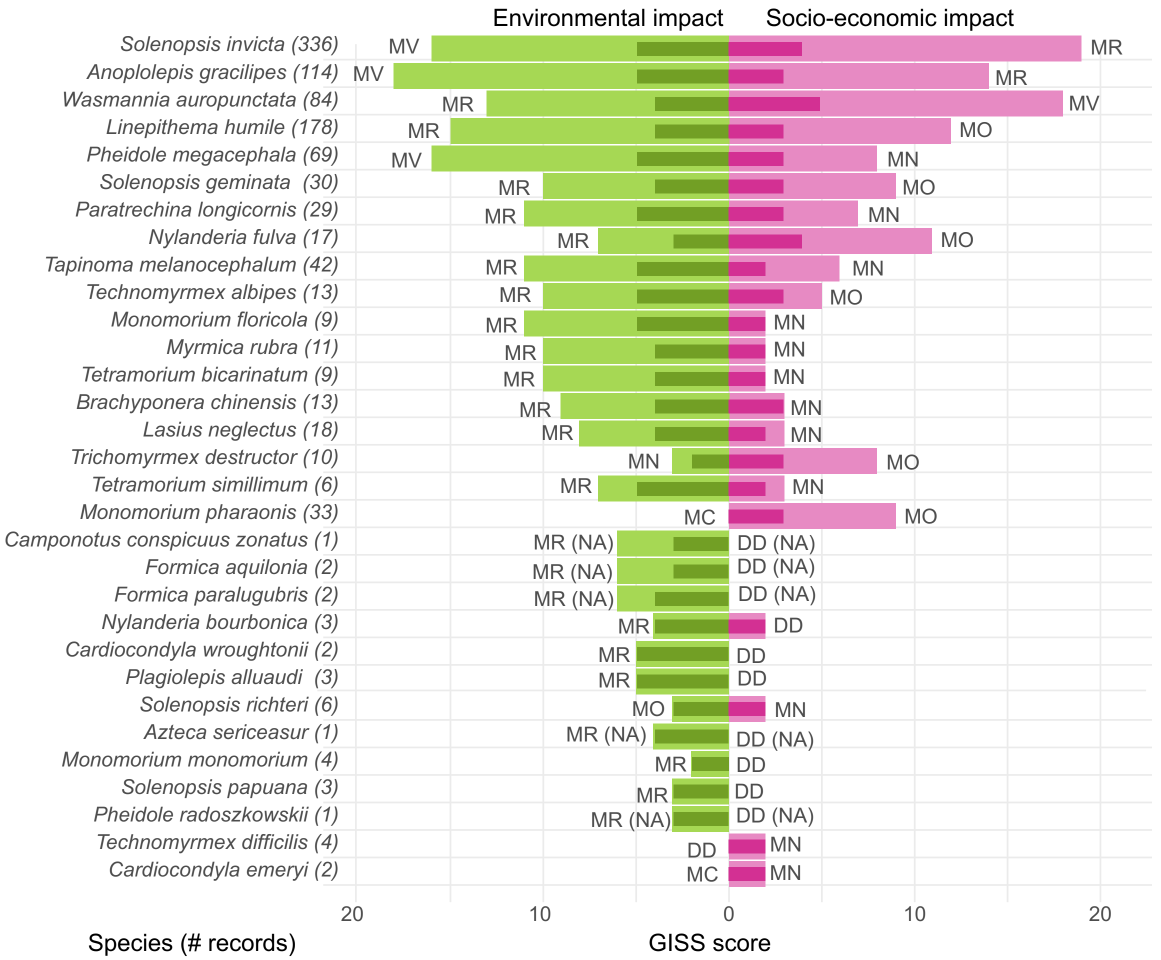

FIGURE 2 Mirror plot of Generic Impact Scoring System (GISS; Nentwig et al., 2016) environmental (green bars) and socio-economic (pink bars) impact scores for the 31 highest ranked species in our assessments, together with the highest impact categories for Socio-Economic Impact Classification for Alien Taxa (SEICAT; Bacher et al., 2018), and Environmental Impact Classification for Alien Taxa. (EICAT; Hawkins et al., 2015). Darker, thinner bars represent maximum score per GISS category. Longer, thicker bars represent GISS total score. Impact categories for SEICAT/EICAT are: DD, data deficient; MC, Minimal concern; MN, Minor; MO, Moderate; MR, Major; MV, Massive; NA, no alien populations. Figure created using R package *ggplot2* (Wickham, 2016) and Inkscape™ (https://inkscape.org/)

from economic impacts. Among the environmental impact categories, the most frequently documented impact was predation on other animals (48%) followed by competition with other animals (33%), impacts on plants or vegetation (13%) and impacts on ecosystems (6%). For socioeconomic sectors, the impacts were mostly on human health (43%), agricultural production (25%), human infrastructure and administration (19%), human social life (7%) and animal production (5%). The overall confidence level on the GISS 1–3 scale was 2.0 ± 0.9 (mean $\pm$ SD).

The species with the highest total score across GISS environmental impact categories was *A. gracilipes* (18 points; Table 1; Figure 2). *Solenopsis invicta* had the highest socioeconomic impact (19), as well as the highest total score (35). The six highest total scores (Table 1; Figure 2) were also those ant species previously cited as having high impacts (Holway et al., 2002). However, several other species also ranked relatively highly in either the socioeconomic or environmental impact scores or both, including *Nylanderia bourbonica* Forel, 1886, *N. fulva* (Mayr, 1862), *Tapinoma melanocephalum* (Fabricius, 1793), and *Technomyrmex albipes* (Smith, 1861). *Nylanderia fulva* scored higher than *P. megacephala* and *S. geminata* for socioeconomic impact (11 vs. 8 and 9, respectively). *Tapinoma melanocephalum* and *Monomorium floricola* (Jerdon,1851) both scored higher for environmental impact (11) than *S. geminata* (10). *Technomyrmex. albipes*, *Myrmica rubra* (Linnaeus, 1758), and *Tetramorium bicarinatum* (Nylander, 1846) all scored 10.

Comparison with other lists

Many of the species in our lists were among those recorded as having populations outside their native range

TABLE 1 Comparison of ant species with the highest scores in our study together with scores assigned in other lists (the trait-based scores of Fournier et al. (2019) and EICAT scores of Clarke et al. (2021))

Priority rank	Scientific name	Common name	Highest SEICAT score	Highest EICAT score	GISS socioeconomic score	GISS environmental score	Total GISS points	Trait-based score	EICAT Clarke et al., 2021
1	***Solenopsis invicta*** [a]	**Red imported fire ant**	**MR**	**MV**	**19**	**16**	**35**	**0.87 ± 0.02**	**MR**
2	***Anoplolepis gracilipes***	**Yellow crazy ant**	**MR**	**MV**	**14**	**18**	**32**	**0.83 ± 0.02**	**MV**
3	***Wasmannia auropunctata***	**Little fire ant/ electric ant**	**MV**	**MR**	**18**	**13**	**31**	**0.83 ± 0.02**	**MR**
4	***Linepithema humile***	**Argentine ant**	**MO**	**MR**	**12**	**15**	**27**	**0.83 ± 0.02**	**MR**
5	***Pheidole megacephala***	**African big-headed ant**	**MN**	**MV**	**8**	**16**	**24**	**0.39 ± 0.05**	**MV**
6	***Solenopsis geminata***	**Tropical fire ant**	**MO**	**MR**	**9**	**10**	**19**	**0.87 ± 0.02**	**MO**
7	***Paratrechina longicornis***	**Black crazy ant**	**MN**	**MR**	**7**	**11**	**18**	**0.83 ± 0.02**	**MR**
8	*Nylanderia fulva*[b]	Tawny crazy ant	MO	MR	11	7	18	…[c]	MR
9	***Tapinoma melanocephalum***	**Ghost ant**	**MN**	**MR**	**6**	**11**	**17**	**0.83 ± 0.02**	**MO**
10	***Technomyrmex albipes***	**White-footed house ant**	**MO**	**MR**	**5**	**10**	**15**	**0.87 ± 0.02**	**MR**
11	***Monomorium floricola***	**Bi-colored trailing ant**	**MN**	**MR**	**2**	**11**	**13**	**0.13 ± 0.02**	**NE**
12	***Myrmica rubra***	**European fire ant**	**MN**	**MR**	**2**	**10**	**12**	**0.83 ± 0.02**	**MR**
13	***Tetramorium bicarinatum***	**Bi-colored pennant ant**	**MN**	**MR**	**2**	**10**	**12**	**0.13 ± 0.21**	**NE**
14	***Brachyponera chinensis*** [d]	**Chinese needle ant**	**MN**	**MR**	**3**	**9**	**12**	**0.17 ± 0.04**	**MR**
15	***Lasius neglectus***	**Invasive garden ant**	**MN**	**MR**	**3**	**8**	**11**	**0.87 ± 0.02**	**MO**
16	***Trichomyrmex destructor*** [e]	**Singapore ant**	**MO**	**MN**	**8**	**3**	**11**	**0.87 ± 0.02**	**MN**
17	***Tetramorium simillimum*** [f]	**Similar groove-headed ant**	**MN**	**MR**	**3**	**7**	**10**	**0.13 ± 0.02**	**NE**
18	***Monomorium pharaonis***	**Pharaoh ant**	**MO**	**MC**	**9**	**0**	**9**	**0.83 ± 0.02**	**MN**
19	*Camponotus conspicuus zonatus*		DD (NA)	MR (NA)	0	6	6	…	NE
20	*Formica aquilonia*	Scottish wood ant	DD (NA)	MR (NA)	0	6	6	…	NE
21	*Formica paralugubris*	European wood ant	DD (NA)	MR (NA)	0	6	6	…	NE
22	*Nylanderia bourbonica*[g]	Bourbon ant	DD	MR	2	4	6	…	NE
23	*Cardiocondyla wroughtonii*		DD	MR	0	5	5	…	NE
24	*Plagiolepis alluaudi*	Little yellow ant	DD	MR	0	5	5	…	NE
25	*Azteca sericeasur*		DD (NA)	MR (NA)	0	4	4	…	NE
26	*Monomorium monomorium*		DD	MR	0	2	2	…	NE
27	***Solenopsis papuana***	**Papuan thief ant**	**DD**	**MR**	**0**	**3**	**3**	**0.13 ± 0.02**	**MN**
28	*Technomyrmex difficilis*	Difficult white-footed ant	MN	DD	2	0	2	0.87 ± 0.02	NE
29	*Pheidole radoszkowskii*		DD (NA)	MR (NA)	0	3	3	…	NE
30	*Lepisiota canescens*		DD (NA)	DD (NA)	…	…	…	0.83 ± 0.12	NE
31	*Nylanderia pubens*[h]	Hairy crazy ant	DD	DD	…	…	…	0.83 ± 0.02	NE
	Anoplolepis custodiens		MN	DD	2	…	2	0.38 ± 0.04	NE
	Solenopsis richteri	Black imported fire ant	MN	MO	2	3	5	0.17 ± 0.01	MR
	Ochetellus glaber		MN	DD	2	…	2	0.17 ± 0.16	NE
	Tapinoma sessile		MN	DD	2	0	2	0.17 ± 0.01	NE

(Continues)

TABLE 1 (Continued)

Priority rank	Scientific name	Common name	Highest SEICAT score	Highest EICAT score	GISS socioeconomic score	GISS environmental score	Total GISS points	Trait-based score	EICAT Clarke et al., 2021
	Cardiocondyla emeryi		**MN**	**MC**	**2**	**0**	**2**	**0.13 ± 0.01**	**NE**
	Formica yessensis		DD (NA)	DD (NA)	...	...	...	0.23 ± 0.01	NE
	Tapinoma litorale		DD (NA)	DD (NA)	...	...	...	0.17 ± 0.01	NE
	Aphaeonogaster spinosa		DD (NA)	DD (NA)	...	...	...	0.16 ± 0.02	NE
	Lasius fuliginosus		DD	DD	...	...	...	0.14 ± 0.02	NE
	Cardiocondyla minutior		DD	DD	...	...	...	0.13 ± 0.01	NE
	Neivamyrmex pilosus		DD (NA)	DD (NA)	...	...	...	0.13 ± 0.02	NE
	Dolichoderus bispinosus		DD (NA)	DD (NA)	...	...	...	0.13 ± 0.01	NE
	Lasius sabularum		DD (NA)	DD (NA)	...	...	...	0.13 ± 0.01	NE
	Monomorium minimum		DD (NA)	DD (NA)	...	...	...	0.13 ± 0.01	NE
	Neivamyrmex nigrescens		DD (NA)	DD (NA)	...	...	...	0.13 ± 0.01	NE
	Acromyrmex octospinosus		DD	DD	...	...	...	0.00 ± 0.01	NE

Note: Species are presented in rank order first by total GISS points, then by SEICAT/EICAT score and then by trait-based score. We propose the numbered species on the list as priorities for risk assessment, based on impacts and consensus among the lists. The 31 species proposed are those with total GISS points of nine and higher or classified as having major or massive impacts in SEICAT or EICAT or having "superinvasive" trait-based profiles (Fournier et al., 2019). For completeness, all "superinvasive" and "invasive" species from the trait-based list are included in the table as they are potential horizon species, even if there are no reported impacts (the unnumbered species at the end of the list). SEICAT, Socio-Economic Impact Classification for Alien Taxa (Bacher et al., 2018); EICAT, Environmental Impact Classification for Alien Taxa (Hawkins et al., 2015); GISS, the Generic Impact Scoring System (Nentwig et al., 2016). SEICAT/EICAT impacts are: DD, data deficient; MC, Minimal concern; MN, Minor; MO, Moderate; MR, Major; MV, Massive; NA, no alien populations; NE, not evaluated; (NA), species we assessed with impacts only in the native range, which would strictly be assigned in SEICAT/EICAT as NA. For GISS and trait-based scores "..." indicates no data. Species shared by AntWeb, our lists (excluding DD), and trait-based modeling are in bold text. Scores for all 100 named species we assessed are in Appendix S1: Tables S1, S2, and Gruber, Santoro, et al. (2021) Table S4). The number of records assessed and other details for all named species are in Gruber, Santoro, et al. (2021).

[a]Includes *Solenopsis wagneri* records because *S. wagneri* is a suppressed synonym for *S. invicta*.

[b]Formerly *Paratrechina fulva*.

[c]Not included in the trait-based analysis, but likely to share similar traits to *N. pubens*.

[d]Formerly *Pachycondyla chinensis*.

[e]Formerly *Monomorium destructor*.

[f]Formerly *Paratrechina bourbonica*.

[g]*Tetramorium simillimum* is a highly variable species (Wetterer & Hita Garcia, 2015). In some areas of the introduced range *T. simillimum* co-occurs with *Tetramorium caldarium* and the two species can be conflated (Deyrup, 2016).

[h]Formerly *Paratrechina pubens*.

in AntWeb and appeared in the trait-based list of current and potential invasive ants (Figure 4; Fournier et al. (2019); Gruber, Santoro, et al. (2021); Table S4). Of the 179 species recorded as introduced outside their native range in AntWeb, 128 had no impacts recorded in our GISS, SEICAT, or EICAT rankings, and were not identified as having invasive potential according to trait-based modeling (Fournier et al., 2019). Fifty-two of the 100 species with recorded impacts were not listed as introduced species in AntWeb (i.e., they are species with impacts in their native range or not recorded as being introduced elsewhere in AntWeb; Gruber, Santoro, et al. (2021) Table S4). Most of these species had only one record and only six of these species were included in our proposed consensus priority list (Table 1). Ten species assessed by trait-based modeling were not present in any of our lists or listed as being introduced elsewhere on AntWeb (Figure 4; Table 1). Nineteen species were common to our lists, AntWeb, and the trait-based modeling lists (Figure 4; Table 1 species shaded gray). Of these 19 species, three do not appear in the GISD list (*T. bicarinatum*, *T. simillimum* (Smith, 1851), and *Cardiocondyla emeryi* Forel, 1881).

Although all the species for which we recorded moderate or higher impacts appear in the GISD database, of the 19 listed in the GISD, two did not appear in our SEICAT, EICAT, or GISS lists: *Acromyrmex octospinosus* Reich, 1793 and *N. pubens*. A third species, *Solenopsis papuana* Emery, 1900 (Papuan thief ant), appeared in our EICAT and GISS (but not SEICAT) analyses and was assessed in EICAT as a species that has had a major impact.

Although our rankings supported much of the trait-based modeling of potential future invasive ants, some differences were apparent. Ten of the 15 species with "superinvasive" trait-based profiles (Fournier et al., 2019) have had major or massive environmental impacts according to our EICAT assessments, and three of these species have had major or massive impacts according to SEICAT assessments (Table 1). Like Fournier et al. (2019) we did not find evidence to support *A. octospinosus* classification as invasive. We did not find evidence of

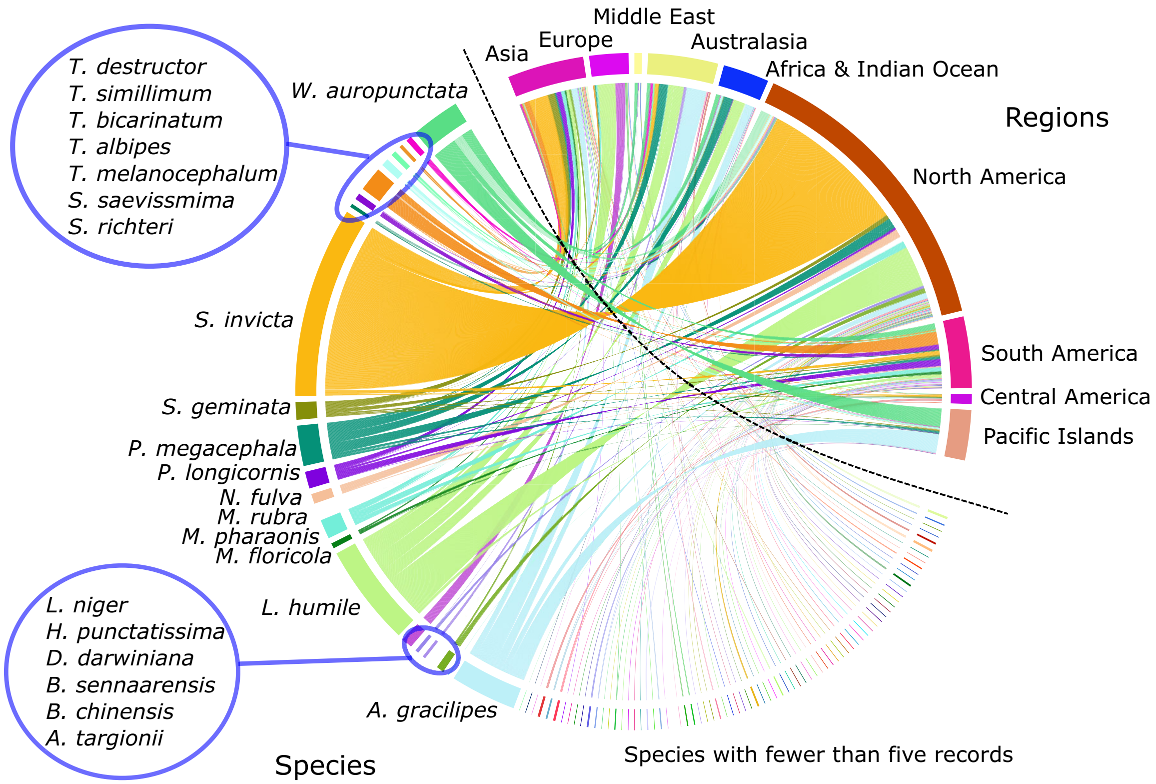

FIGURE 3 Chord diagram showing the variation in number of records among species (left of dashed arc) and geographic regions (right of arc) for all 100 named species in the assessments. The width of the bars represents the number of records. Most records for the red imported fire ant (*Solenopsis invicta*) and Argentine ant (*Linepithema humile*) were from North America. Most records for little fire ant (*Wasmannia auropunctata*) and yellow crazy ant (*Anoplolepis gracilipes*) were from the Pacific region. Many species had fewer than five records. Species with few records whose name does do not fit next to their bar are grouped in blue circles. Figure created using R package *circlize* (Gu et al., 2014) and Inkscape™ (https://inkscape.org/)

environmental or socioeconomic impacts for 11 species classed by trait-based modeling as "invasive" or "superinvasive": *Lepisiota canescens* Emery, 1897, *Formica yessensis* Wheeler, 1913, *Tapinoma littorale* Wheeler, 1905, *Aphaenogaster spinosa* Emery, 1878, *Lasius fuliginosus* (Latreille, 1798), *Cardiocondyla minutior* Forel, 1899, *Neivamyrmex pilosus* (Smith, 1858), *Dolichoderus bispinosus* (Olivier, 1792), *Lasius sabularum* (Bondroit, 1918), *Monomorium minimum* (Buckley, 1867) and *Neivamyrmex nigrescens* (Cresson, 1872) (Table 1). Although most of the species to which we assigned MR—and all of those we assigned MV—environmental impacts corresponded to "superinvasive" species, several with major impacts were ranked relatively low on the trait-based scale, for example, *P. megacepahala*, *T. bicarinatum*, *M. floricola*, *T. simillimum*, *S. papuana*, *Cardiocondyla wroughtonii* (Forel, 1890), and *Brachyponera chinensis* (Emery, 1895).

Our EICAT assessments differed for six out of the 17 species assessed by Clarke et al. (2021), with a variation of only one category in all cases (Table 1). We classed *M. pharaonis* (Linnaeus, 1758)) as having impacts of minimal concern (MN) versus minor concern (MC) by Clarke et al. (2021). *Solenopsis geminata*, *T. melanocephalum* and *Lasius niger* (Linnaeus, 1758) were classed as having MR impacts by us, and MO impacts by Clarke et al. (2021). We classed *S. invicta* as having MV impacts, and this species was classed by Clarke et al. (2021) as having MR impacts. Clarke et al. (2021) classed *S. richteri* as having major impacts, whereas we classed it as having MO impacts.

DISCUSSION

Our goal was to assess the socioeconomic and environmental impacts of invasive ants to assist with risk assessment. Ours is the first comprehensive global assessment of ant impacts using multiple systematic assessment tools. Although our assessments affirmed that the most serious impacts to date have been driven by a relatively small number of species, our results also highlight that there are a greater number of less well publicized species that have had major environmental impacts and may currently be overlooked when prioritizing efforts in prevention. We found that socioeconomic impacts of

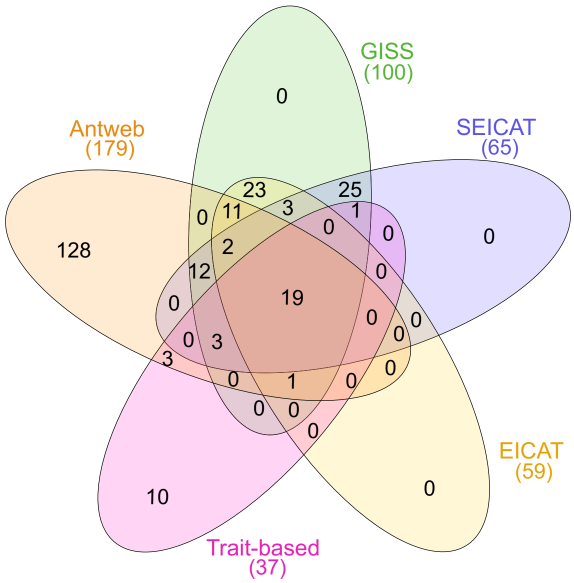

FIGURE 4 Venn diagram showing the number of species shared among our assessments (SEICAT, Socio-Economic Impact Classification for Alien Taxa (Bacher et al., 2018), EICAT, Environmental Impact Classification for Alien Taxa. (Hawkins et al., 2015); GISS, the Generic Impact Scoring System (Nentwig et al., 2016)), lists of introduced ant species from AntWeb (2020), and species assessed as "superinvasive" or "invasive" through trait-based modeling (Fournier et al., 2019). * Includes all 19 GISD species that are discussed in the text. Our SEICAT, EICAT, and GISS lists include all the species assessed by Clarke et al. (2021). Figure created using InteractiVenn (Heberle et al., 2015) and Inkscape™ (https://inkscape.org/)

invasive ants were categorized as less severe than environmental impacts, which may arise from the relative recent focus on the former rather than differential impacts. This difference may change in the future if socioeconomic impacts are increasingly targeted for study. Lists that are commonly used for prioritization should be updated to reflect the current understanding of impacts, and correct the confusion caused by historical misidentification. Despite our approach deviating somewhat from the prescribed methodologies, our species-specific assessments are compliant with their fundamental principles and provide baselines for many new species.

Impacts attributed to more than "the usual suspects"

The six species identified nearly 20 years ago as having major impacts (Holway et al., 2002) still feature prominently in our results (*W. auropunctata*, *S. invicta*, *S. geminata*, *L. humile*, *P. megacephala* and *A. gracilipes*). However, other species ranked as high or higher than some of these "usual suspects" for some assessment methods.

Nylanderia fulva emerged as an important species in our analysis. This species was categorized in EICAT as having major (MR)environmental impacts despite having been reported as a problem relatively recently and understudied compared with species such as *L. humile*, which had the same classification. *Nylanderia fulva* scored higher in GISS than *P. megacephala* and *S. geminata* for socioeconomic impact, despite a relatively recent focus of studies on socioeconomic impacts. *Nylanderia fulva*'s relatively high ranking, despite few studies, indicates that it could be a major emerging threat species for many countries, dependent on habitat suitability, climate matching, and probability of arrival. To date, impacts have primarily been recorded in the southern United States and Caribbean (Wetterer, 2014), when anecdotal reports indicated that the public perception of *N. fulva* is worse than *S. invicta*, due to the high numbers that they attain (e.g., Toohey, 2016). We recommend that the impact of the ant is reassessed regularly as more information becomes available.

Twenty other species also had EICAT scores indicating major environmental impacts that make them potential threats in new locations. *Tapinoma melanocephalum* and *M. floricola* both scored higher in GISS for environmental impact than *S. geminata*, whereas *T. albipes*, *M. rubra*, and *T. bicarinatum* all equaled *S. geminata*'s GISS score. Although some of these species already have relatively cosmopolitan distributions, their potential distributions under climate change scenarios (Bertelsmeier, Guénard, et al., 2013; Bertelsmeier, Luque, & Courchamp, 2013; Bertelsmeier, Blight, et al., 2015; Bertelsmeier, Luque, et al., 2015) also warrant consideration in risk assessment.

As with the six "usual suspects," *N. fulva* is prone to "boom-and-bust" population dynamics, with rapid increases in numbers followed by dramatic collapse (Lester & Gruber, 2016). Although earlier work has proposed that this ant may have few long-term impacts because of frequent collapses (Wetterer, 2014), the acute short-term impacts of "booms" may cause significant harm. For example, *A. gracilipes* also has demonstrated widely fluctuating dynamics in different ecological contexts (e.g., Christmas Island, Indian Ocean, Abbott, 2005; Tokelau, Pacific Ocean, Gruber et al., 2013; Northern Territory, Australia, Cooling & Hoffmann, 2015), with occasional devastating impacts (O'Dowd et al., 2003). *Technomyrmex albipes* is also reported to have population explosions that worsen its impact (Thaman, 2018). The underlying causes of these dynamics are often not well understood (Lester & Gruber, 2016), and the unpredictability of outcomes supports the need for a precautionary approach for risk assessments of these species.

Species-specific biological traits are an important factor in predicting risk. Our impact-based assessment did not always align with the results of trait-based modeling by Fournier et al. (2019). As a predictive exercise, trait-based modeling naturally would not always correspond with species for which impacts have already been reported. However, differences in underlying data also contribute to the variation. Many species in our lists were not included a priori in the trait modeling, and some shared species did not have trait data, that is, of the 100 named species for which we assessed records, 22 were not present in the AntProfiler database used for assessing traits (Bertelsmeier, Luque, Confais, et al., 2013). We also note that for some species the AntProfiler database has missing values for ecologically important drivers of impact, such as colony size, that should be checked as part of risk assessment. We encourage ant researchers to add information to the AntProfiler database to make it even more useful. The precautionary principle would suggest that, despite a lack of impacts in some cases, the trait-based species list should be considered in risk assessments, particularly those species ranked as "superinvasive," but also those with lower scores that have recorded impacts, as we have suggested in our priority list. Assessing trait-based potential invasiveness for more of the species for which we found impacts would also further validate trait-based modeling as a useful tool for horizon-scanning. This is particularly true for *N. fulva* owing to the historic misidentification issues discussed below. The approaches we used, together with trait-based analysis, may be useful for identifying emerging invasive species.

Although our EICAT results also differed from the only other standardized study of the impact of invasive ants (Clarke et al., 2021) for six out of 17 species, this was only by one category in each instance. In all cases the classifications of both ours and Clarke et al. (2021) fell within the broader "harmful" EICAT grouping (MO or higher; Kumschick et al., 2020). All the species assessed by Clarke et al. (2021) are included in our recommended consensus list.

Because habitat and climate matching are also important factors to consider in risk assessment, the geographic scale of impact assessment is also important (Kumschick et al., 2020). In addition to the variables required by the methodologies, we recorded the geographical context of the records assessed (country and state/province). We recommend that when using our impact assessment data, the individual records for the target species (Gruber, Santoro, et al., 2021) are reviewed to confirm geographic matching with the context being assessed. We acknowledge that impacts in the native range might not always translate to impacts in the introduced range, although they do for *W. auropunctata* (Rosselli & Wetterer, 2017). Given the unprecedented rate of habitat modification (which can often favor invasive ants), and environmental change more broadly, including unpredictable consequences of climate change on invasive species, we considered that including these species was useful for risk assessment. It was beyond the scope of our study to consider likelihood of introduction and establishment as these are also dependent on the context of the recipient locale as well as species' biology, but these are also critical components of a comprehensive risk assessment.

Do environmental impacts of ants outweigh their socioeconomic impacts?

On face value, our data would support the assertion that invasive ants have more severe environmental than socioeconomic impacts, with fewer records of socioeconomic impacts, and those impacts generally lower than environmental impacts. Although this may be the case, several systemic factors also contribute to the discrepancy, including fewer studies and a lack of reliable, freely available quantified data on socioeconomic impacts (Bradshaw et al., 2016). The relative sparseness of data for socioeconomic impacts potentially contributed to the weaker association that we found between the SEICAT and GISS socioeconomic impacts compared with environmental impacts.

None of the methodologies we used quantifies the economic cost of invasive species in impact assessment. Quantifiable socioeconomic data for invasive species are still lacking (Bradshaw et al., 2016) and limited in their taxonomic coverage. Although the cost of invasive ants as a group has recently been estimated (Angulo et al., 2021), species-specific data, which are required for targeted impact assessment are still sparse, except for *S. invicta*, whose impact, prevention, and management costs have received more attention. For example, the eradication of three small *S. invicta* nests in New Zealand cost more than NZ$10 million (>US$7 million), but this was estimated to avoid a potential economic impact of NZ$665 million (>US$476 million) over 23 years (Goldson et al., 2015). In the United States the ant's economic impact has been estimated at US$6 billion annually (Drees & Lard, 2006). Quantifying the potential impact of these species may be critical for decision making regarding the effort and cost to be expended on prevention or eradication. For example, extrapolated costs to Australia of more than A$1.65 billion/year (>US$ 1.2 billion/year) if *S. invicta* were allowed to spread (Wylie & Janssen-May, 2016) supported the commitment to an additional A$411 million (US$316 million) eradication program there (Wylie & McNaught, 2019). Similar extrapolations have been used to justify prevention of *S. invicta* in the Pacific Islands region (Gruber, Janssen-May, et al., 2021). A better ability to quantify the costs of invasive species is essential to ensure appropriate efforts and prioritization in prevention and management.

The recent development of the InvaCost database signals an opportunity to increase the ability to assess and incorporate these quantifiable costs (Diagne et al., 2020). Complementary initiatives that assess the impact of invasive species on ecosystem services are also being developed. The proposed initiatives use the SEICAT and EICAT methodologies, extending them to incorporate both the impacts and benefits of invasive species (Gallardo et al., 2019). All the approaches to quantify socioeconomic costs need reliable information, which may make jurisdictions that freely share information appear to suffer a greater share of the costs than those that do not. Data transparency is therefore likely to be a key issue to enable accurate assessment of these costs.

Due to increasing attention on the socioeconomic impacts of invasive species, studies are likely to increase in number over time, as are the impacts of invasive insects such as ants (Bradshaw et al., 2016). As risk assessment for prevention and management of invasive species and impact assessments are not one-off exercises, risk assessment frameworks need to allow for uncertainty and regular revisions to incorporate new information.

Justification for revising the GISD priority ant list

As the current GISD information on invasive ants was compiled ~15 years ago, the biological knowledge of ants, their invasiveness, impacts and management has increased substantially, and a revision is timely. The consensus priority list that we have developed provides a useful starting point to revising the GISD, together with our extensive bibliography that summarizes the impacts of these species.

As part of the IUCN's ISSG initiatives, the GISD is widely used by practitioners and is an undeniably crucial source of information on invasive species. The GISD ant list should reflect best available knowledge. Our results, together with those of Fournier et al. (2019) indicate that the GISD list should be revised for several ant species. We recommend *N. pubens* is replaced by (or supplemented with) *N. fulva*, *A. octospinosus* removed, and several other species added. The major differences between our lists and the GISD (the absence of *N. pubens* and *A octospinosus* from all analyses) reflects historical misidentification and an absence of verifiable impacts. These issues are examined here to justify the inclusion or exclusion of these species in lists used for prioritization or otherwise in future.

Nylanderia pubens and *N. fulva* have historically been difficult to delineate, and this lack of distinction has caused persistent issues for identification and attributing impact. When first detected in the United States, some early publications were later found to incorrectly identify *N. fulva* as *N. pubens* (Wang et al., 2016). Recent trait-based modeling also identified *N. pubens* as being "superinvasive" but did not mention *N. fulva* (Fournier et al., 2019) owing to the authors using the listed GISD species an a priori reference point for their assessment. Evidence suggests that only *N. fulva* is invasive in the United States and elsewhere, with considerable impacts (Wetterer & Keularts, 2008; Sharma et al., 2013, this study). The two species are very similar ecologically, and it may well be correct to include *N. pubens* as a potential invasive species, but currently we only have evidence of impacts for *N. fulva*.

The GISD records the leaf-cutter ant *A. octospinosus* among its 19 species. From the same genus, *Acromyrmex* sp. (which admittedly could possibly be *A. octospinosus*) and *A. niger* each appeared once in our SEICAT records, with impacts in the native range. It is possible that *A. octospinosus* did not appear in our list because the original sources for it on the GISD (and elsewhere) do not mention impacts, are not in English, or are no longer accessible online. However, *A. octospinosus* also does not possess a trait profile common to other invasive ants, and is not easily transported inadvertently by people (Fournier et al., 2019). We agree with Fournier et al. (2019) that the presence of *A. octospinosus* on the IUCN GISD list should be revised, or more specific analysis undertaken to assess the extent of its impacts.

Although *S. papuana* did not appear in our SEICAT list, it featured in our EICAT analysis as a species that has caused major impacts, which we consider justifies its retention in the GISD list. For the same reason, we also recommend that all the species we classed as having major environmental (or socioeconomic impacts) be considered for addition to the GISD list, that is, those listed from 1–27, except those classed as (NA). We also suggest that the records for all species currently on GISD can be revised to include the impact data we have collated (Gruber, Santoro, et al., 2021).

Our approach complies with but extends the methodologies

Our approach differed from the standardized approaches in two ways: we did not limit our search to a prescribed list of species, and we did not limit our search to invasive ants. These deviations were necessary as we wanted to be able to use our results in a more predictive way than the methodologies originally intended. Despite these differences, our classifications conformed with the intended use of the methodologies. The IUCN has adopted EICAT as a standard (IUCN, 2020) and it is planned that EICAT assessments lodged with IUCN are populated into the GISD through an approval process (Kumschick et al., 2020). Although we have used a broader approach than the standard methodology, EICAT requires information only by species, which makes our individual assessments suitable for IUCN use. Because we did not limit our search to specific ant species, the many for which we found no impacts can be classified as DD. The strict EICAT categorization "no alien populations" can simply be derived for the species we have assessed with impacts in their native range using AntWeb's list of species that have been introduced outside their native range.

The question of preferred methodology was not a focus of our work, however we assessed how generally the methodologies aligned. The relationships between the results for the different methodologies were broadly consistent although stronger for environmental data than socioeconomic. However, GISS scores did not naturally translate into discrete SEICAT/EICAT categories. Classification into discrete categories is useful for grouping and direct comparisons, and EICAT has been adopted as a standard by IUCN. Conversely, the GISS total scores may better represent species whose impacts span a range of mechanisms, although may also be biased toward species that have received more attention. We recommend a combination of SEICAT/EICAT and GISS methodologies to capture a broader picture of invasive species impacts.

CONCLUSIONS

The methodologies we used have typically been applied to species that have already been defined as invasive. Although necessary to assist prioritization of management activities, this narrower scope could overlook potential future threats. Our approach highlighted several species that are possibly underappreciated relative to potential risk, such as *N. fulva*, suggesting closer attention to these species is needed. Our assessments provide a standardized baseline for revised assessments as new insights become available, particularly an increased focus on socioeconomic impacts. Managing established invasive ant species, let alone eradicating them, is costly and difficult (Hoffmann et al., 2016). Comprehensive risk assessments that draw on standardized methodologies and implementation of risk management actions are needed to prevent further spread and impacts of invasive ants.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Christina Boser, Benjamin D. Hoffmann, Lori Lach, Monica A. M. Gruber, and Philip J. Lester conceived the work. Monica A. M. Gruber designed the study. Meghan Cooling and Davide Santoro collected the data and completed the assessments for the SEICAT/EICAT/GISS analyses. Philip J. Lester, Benjamin D. Hoffmann, Christina Boser and Lori Lach reviewed the assessments. Monica A. M. Gruber and Davide Santoro analyzed the results. Monica A. M. Gruber wrote the manuscript with contributions from all authors.

DATA AVAILABILITY STATEMENT

Data (Gruber, Santoro, et al., 2021) are available in Dryad at: https://doi.org/10.5061/dryad.2280gb5t2.

ORCID

Monica A. M. Gruber https://orcid.org/0000-0001-6780-8838
Davide Santoro https://orcid.org/0000-0001-6284-168X
Meghan Cooling https://orcid.org/0000-0002-7057-3125
Philip J. Lester https://orcid.org/0000-0002-1801-5687
Benjamin D. Hoffmann https://orcid.org/0000-0002-4010-4723
Christina Boser https://orcid.org/0000-0001-7665-8878
Lori Lach https://orcid.org/0000-0001-5137-5185

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