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Discrepancies in Australian jurisdiction-based regulation of invasive plants

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Research Article

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Abstract

Effective regulation is essential for preventing the establishment of new invasive plants and managing the environmental, social, and economic impacts of those already established. Invasive plants are regulated by jurisdictions at a mix of local, regional, national, and international levels. Enhanced coordination of policy and regulations has been identified as a key strategy for addressing the impacts of invasive species; however, coordination between jurisdictions, and even within jurisdictions, is not always considered. To review regulatory coordination in Australia, we compiled a comprehensive dataset of noxious weeds (defined as invasive plants and potentially invasive plants with controls specified in regulation) in each Australian jurisdiction (i.e., state or territory). We found that jurisdictions on average shared ca. 67% (SD = 15%) of noxious weed listings. Neighboring jurisdictions were not more similar than separated jurisdictions in their noxious weed listings. There were significant differences in the biogeographic native ranges of noxious weeds between jurisdictions, with species native to temperate Asia being most frequently listed overall. The predominant likely entry pathway for noxious weeds in Australia was the ornamental trade. Listings were primarily dedicated to proactive control, prohibiting the cultivation of noxious weeds to avoid their naturalization. There were 415 noxious weeds regulated in a harmonious manner across jurisdictions. However, there were 327 noxious weeds regulated by jurisdictions in a discordant manner, potentially leaving neighboring jurisdictions vulnerable to invasion. We suggest jurisdictions reassess the regulation of these 327 discordant noxious weeds in Australia and utilize a national taxonomic standard to avoid problematic synonyms. Improved cohesion of policies could be achieved through wider adoption of existing regulatory systems and codevelopment of regulations between government and industry.

Introduction

Invasive plants negatively impact native species, ecosystem function, primary production industries, and human health (Francis and Chadwick 2015; Mack and Smith 2011; Pyšek et al. 2020; Schirmel et al. 2016; Syed and Guerin 2004; Ward et al. 2021). The economic impacts of invasive plants are significant due to ongoing management costs, reduced agricultural yields, toxicity to livestock, product contamination, and damage to infrastructure (Bradshaw et al. 2021; Francis and Chadwick 2015; McLeod 2018). Although not all introduced plants become invasive, the increasing interconnectedness of the world has led to more plants being introduced and spread by human activities to new environments, resulting in a rising number of invasive species (Hulme 2009; Mack and Lonsdale 2001; Seebens et al. 2015, 2017; van Kleunen et al. 2015, 2018). Thus, countries must try to keep up with rapidly changing invasive plant pressures to maintain their biosecurity and protect environmental well-being.

To address the wide-reaching impacts of invasive plants, regulation has become fundamental to many prevention and management efforts (Beaury et al. 2021a; Black and Bartlett 2020; Invasive Plants and Animals Committee 2016; Lakoba et al. 2020). In Australia, invasive plants are managed both at the national border and within the country (Plant Health Australia 2021). Plant importation regulations are informed by the Australian Weed Risk Assessment (Pheloung et al. 1999). Within Australia, plants deemed to be high-risk invasive species and feasible to prevent, contain, or eradicate are formally declared under biosecurity legislation at a state and territory levels (hereafter "jurisdiction"). The term "declared" is a legal designation and refers to the legal status of a plant. A declared plant is illegal to grow or trade and/or must be controlled, while a plant that is not declared is legal to grow or trade without a legal obligation to control it. For our study, we examined all plants that are declared in at least one Australian jurisdiction. We refer to these plants as "noxious weeds" hereafter. We reserve the term "declared" to refer to

Management Implications

Regulations form a key component of effective invasive plant management. A common approach is to declare species or taxonomic groups of plants as invasive or potentially invasive in a jurisdiction and attach specific control orders (e.g., bans on trade, transport, and cultivation). Issues with this approach are that political jurisdictions often have boundaries that do not reflect natural barriers to invasion and that human transport across these boundaries may arise from unawareness or confusion over a species' legal status. Additionally, preventative invasive plant regulations are known to dramatically reduce environmental impact and economic cost compared with reactive regulations. Collating invasive plant regulations from neighboring jurisdictions can reveal whether a preventative and coordinated approach is being taken. It can also highlight regulatory discrepancies that may facilitate invasions between neighbors. We collated regulatory lists of invasive plants from Australia's eight states and territories and found they are predominantly dedicated to preventing invasion. However, we identified taxa that are currently managed in a discordant manner, which may compromise the biosecurity of a neighboring jurisdiction. Identifying these discordant taxa and reassessing their regulation will enable more coordinated management across jurisdictions. Existing cross-border coordination, such as the Weeds of National Significance initiative, has already improved the success of invasive plant control in Australia. Fostering more collaboration on invasive plant regulation between governments, industries, and the public will help minimize current and future impacts and mitigate conflicting interests around species. Furthermore, sharing and maintaining consolidated datasets of regulated invasive plants will support comanagement by jurisdictions and provide a valuable resource for horticultural industries to prevent introduction and spread of invasive species.

the legal status of a noxious weed within a given jurisdiction. In this way, we may describe a noxious weed as being declared in one jurisdiction and not declared in another.

Depending on the jurisdiction's invasive plant legislation, taxa may be declared under particular sections in the legislation (e.g., in South Australia, prohibiting the cultivation, sale, and/or transport, and/or making control mandatory for landowners under the Landscape South Australia Act 2019). Or they may be listed under a specific provision that generally prohibits all dealings with an invasive plant (e.g., in New South Wales as "prohibited matter" under the jurisdiction's Biosecurity Act 2015). In Australia, jurisdictions collaborate on invasive plant management policy via the intergovernmental Environment and Invasives Committee. There is national consensus on the 32 Weeds of National Significance (WoNS). These are recognized as current or future invasive plant taxa requiring coordinated and strategic management to prevent, eradicate, contain, or minimize impacts (Centre for Invasive Species Solutions 2021; Hennecke 2012; Invasive Plants and Animals Committee 2016; Supplementary Table S1 in Supplementary Material 1). However, each Australian jurisdiction has its own list of noxious weeds, declared under its respective legislation and associated legal instruments (Invasive Plants and Animals Committee 2016). The efficacy regarding the timing of regulation is important (i.e., preventative vs. reactive management of an invasive plant). Proactive, preventative regulation of naturalized and invasive species before their naturalization is known to minimize impact and cost considerably (Ahmed et al. 2022; Keller et al. 2007). Alternatively, reactive policies in response to naturalized (i.e., established) species can miss the most cost-effective opportunity for invasive plant control, a criticism of other jurisdiction-based systems managing invasive plants (Lakoba et al. 2020). The extent to which current noxious weed declarations reflect preventative and jurisdictionally harmonized management principles remains unexplored in Australia.

Jurisdictions prioritize regulation of different invasive species according to different environmental conditions, management goals, and regulatory capacity. However, coordination and collaboration across jurisdictions is a powerful strategic action for invasive species management (IPBES 2023). Borders are political boundaries and do not always reflect natural barriers for introduced species, especially as people move invasive plants over long distances (Banks et al. 2015; Maki and Galatowitsch 2004; Randall 2014). When cross-border coordination is implemented, it can improve the success of invasive plant control programs (Pluess et al. 2012). In some cases, disparities in regulation between jurisdictions have been attributed to the availability and spread of invasive species in the ornamental plant and pet trade (Beaury et al. 2021b; Fonseca et al. 2021; Maher et al. 2023; Reichard and White 2001; Toomes et al. 2022). Considering that the majority of invasive plants worldwide have been deliberately introduced by humans as ornamental plants (Beaury et al. 2021a; Dodd et al. 2015; Groves et al. 2005; Hulme et al. 2018; Mack and Lonsdale 2001; Virtue et al. 2004), more coordinated policies have the potential to help prevent cross-border dispersal.

Here, we reviewed the regulation of noxious weeds in Australia's eight jurisdictions. We compared current legislation and compiled a comprehensive list of all the noxious weed taxa declared in each Australian jurisdiction. This allowed us to investigate the cohesiveness of Australia's jurisdiction-based regulation of noxious weeds and describe trends in Australia's noxious weeds. We used this dataset to achieve four research aims: (1) consolidate jurisdictional noxious weeds into a unified dataset and characterize its taxonomic composition; (2) compare the similarity of noxious weed lists between jurisdictions; (3) determine how proactive jurisdictional noxious weed lists are and identify noxious weeds with discordant regulation; and (4) describe trends in the native ranges, entry pathways, and perceived impact of noxious weeds.

Methods

Collating Australia's Noxious Weeds and Standardizing Taxonomy

We collated all relevant legislation and policy regarding noxious weeds in Australia. For each jurisdiction, we determined the identity of the noxious weed taxa by searching through relevant government sources, including websites, online databases, legislative acts, regulations, and gazettes (Supplementary Table S2 in Supplementary Material 1). We confirmed the accuracy of our compiled lists with government biosecurity officers in relevant jurisdictional government departments. Our compiled dataset of noxious weeds contained a total of 1,329 taxa (before taxonomic standardization) across all jurisdictions.

In Australia, jurisdictional authorities do not use a nationally standardized taxonomy for declaring plants. Therefore, we standardized the taxonomy of each declared taxon to the Global

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Biodiversity Information Facility taxonomic database (GBIF 2021). A total of 21 taxon listings were unresolved, with the majority being hybrids that were not recognized by GBIF (Supplementary Table S3 in Supplementary Material 1). We did not further consider these unresolved taxa for this study. Black poplar 'Italica' [*Populus nigra* L.] was the only declared cultivar and was treated at the species level (declared in ACT). Certain declared taxa had permitted cultivars, but these were not considered in the analysis of our study (Supplementary Table S4 in Supplementary Material 1). During taxonomy standardization, we also noted 11 species with multiple synonyms in use across jurisdictions, which we identified as potentially problematic (Supplementary Appendix S1 in Supplementary Material 1). Overall, our goal was to compare taxa declared by each jurisdiction. However, while most taxa are declared at the species level, 47 taxa are declared at the genus level. We decided not to expand the genera to include all daughter species, as some genera were hyperdiverse and would result in a cumbersome dataset (e.g., >8,000 species in *Hieracium* L.). At the same time, we found that some jurisdictions declared taxa at a genus level (e.g. *Xanthium* L.), others only by species within the genus (e.g., Victoria declares two *Xanthium* species, while Western Australia declares seven), which would hinder direct comparisons. Thus, for 37 taxa declared at the genus level with daughter-species declarations in other jurisdictions, we included all of the daughter species that were explicitly declared by another jurisdiction (details and rationale provided in Supplementary Appendix S2 in Supplementary Material 1). In addition, there were 10 genera that were declared at the genus level that did not have any daughter species declared in other jurisdictions (Supplementary Appendix S2 in Supplementary Material 1). These genera were included in the following analysis, but were excluded from native range analysis, as data were only available at the species level.

Investigating Similarities in Jurisdictional Assemblages of Noxious Weeds

We hypothesized that jurisdictions sharing a border would have more similar noxious weed lists than jurisdictions not sharing a border. Our reasoning is that neighboring jurisdictions share large areas of environmental risk along their borders, which have similar climatic and anthropogenic conditions (Stern et al. 2000). To investigate this hypothesis, we used three common community ecology metrics, treating each jurisdiction as a "site" ($n = 8$ jurisdictions): pair-wise dissimilarity (distance), nestedness, and proportion of species overlapped by jurisdiction. For pair-wise dissimilarity between jurisdictions, we used the Sørensen dissimilarity distance (Baselga and Orme 2012) and visualized the distances as a dendrogram. We visualized nestedness with a heat map and calculated the proportion of overlap. We defined the proportion of overlap as the total number of taxa shared between two jurisdictions divided by the total number of taxa in the jurisdiction of focus (i.e., number of taxa declared in jurisdiction A also declared in jurisdiction B divided by total number of taxa declared in jurisdiction A). We repeated this measurement for all pair-wise combinations of jurisdictions. We categorized these pair-wise combinations as "bordering" if the jurisdictions shared a geographic border and "separated" if they did not. Despite Tasmania being an island, we categorized Victoria and Tasmania as bordering. Freight and movement of people is frequent between these jurisdictions, and they share similar climates (Davies et al. 2023; Stern et al. 2000).

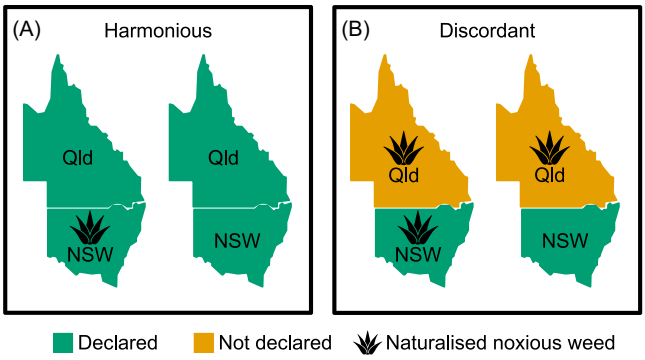

Figure 1. Visualization of harmonious and discordant regulation categories of a noxious weed. In this example, the regulation categories refer to Queensland (Qld). The plant symbol indicates that the noxious weed has naturalized in that given jurisdiction. Box A shows two examples where Qld is harmonious with New South Wales (NSW). Qld has declared the noxious weed without it naturalizing within the jurisdiction, which is in harmony with NSW. Box B shows two examples where Qld is discordant with NSW. Qld has not declared the noxious weed, despite it naturalizing within the jurisdiction. This is discordant with NSW, which has declared the noxious weed.

Comparing Declaration and Naturalization Status of Noxious Weeds

We classified noxious weeds into regulation categories by comparing naturalization status and declared status within each jurisdiction. Naturalization status for noxious weed taxa was collected from the Australian Plant Census (APC) (Australian National Herbarium 2023). The APC is a list of vascular plants and some nonvascular plants (hornworts [Anthocerotophyta Stotler & Stotl.-Crand.] and liverworts [Marchantiophyta Stotler & Stotl.-Crand.]) that are accepted and classified by the Australian National Herbarium as native or introduced in Australia. We used the APC to determine the naturalized or native status for each noxious weed in each jurisdiction from our compiled dataset. Taxa declared at the genus level were included. For noxious weed taxa that are absent from Australia, we retained the jurisdiction-assigned names for this standardization. More detail on the rationale for utilizing both APC and GBIF in this study can be found in Supplementary Appendix S3 in Supplementary Material 1.

Once naturalization status was obtained, all noxious weed taxa in Australia were placed into four regulation categories within each jurisdiction: (1) prevention—the noxious weed has not naturalized but is declared within the jurisdiction; (2) managed—the noxious weed has naturalized and is declared; (3) unregulated—the noxious weed has naturalized but is not declared; and (4) absent—the noxious weed has not naturalized in the jurisdiction and is not declared. These categories were used to compare how jurisdictions are currently managing Australia's noxious weeds. We sought to quantify the allocation of plant declarations to proactively controlling noxious weeds (i.e., prevention vs. managed). Then we compared the regulation of naturalized noxious weeds within each jurisdiction (i.e., managed vs. unregulated). Finally, we compared the regulation of noxious weeds that have not naturalized in each jurisdiction (i.e., absent vs. prevention).

Using our regulatory classification, we examined how harmonious and discordant the regulation of noxious weeds is between jurisdictions. For each jurisdiction, we recorded the number of prevention declarations of noxious weeds that are also declared in a neighboring jurisdiction (either prevention or managed) (Figure 1A). We considered this to be harmonious regulation,

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as the declaration of the plant is aligned with a neighboring jurisdiction, despite not having naturalized within the subject jurisdiction's borders. Likewise, we recorded the number of unregulated noxious weed taxa that are declared in a neighboring jurisdiction (either prevention or managed) (Figure 1B). We considered this to be discordant regulation between jurisdictions, as a lack of regulation from the subject jurisdiction is discordant with its at-risk neighbor. We did not consider regulation of noxious weeds to be discordant if the taxa were native to or recorded as doubtfully naturalized in the subject jurisdiction. The suitability of taxa falling into this discordant category to become naturalized (or invasive) will vary given the range of possible factors, such as climate suitability, propagule pressure, and perceived risk. However, while our approach is coarse, we suggest it is an effective starting point to highlight noxious weeds worth reassessing for broader regulation in Australia.

Native Range, Entry Pathway, and Perceived Impact of Noxious Weeds

We examined: (1) native range, (2) entry pathways, and (3) perceived impacts of identified noxious weeds. For each category, we described national trends and identified statistical differences in the number of taxa between jurisdictions. We excluded noxious weeds declared only at the genus level in Australia from this analysis, as data are more relevant to and available for species and infraspecies (genera excluded are outlined in Supplementary Table S6 in Supplementary Material 1).

We collected native distribution data for species of noxious weeds from the Plants of the World Online database (POWO 2023). We obtained native range data for 96.7% of the noxious weed species and infraspecies. POWO utilizes the World Geographical Scheme for Recording Plant Distributions (WGSRPD), of which there are four geographic units for distribution (Brummit 2001). Level 3 records distribution at the country scale or by political subdivisions for large countries (e.g., Brazil). Level 1 records distributions within nine large-scale biogeographic regions: Africa, Antarctica, Asia–temperate, Asia–tropical, Australasia, Europe, Northern America, Pacific, and Southern America. The shapefiles and geographic unit codes were obtained from the WGSRPD GitHub repository (Brummit 2001). We used level 3 for finer-scale visualization and descriptive analysis and level 1 for testing independence in native range across jurisdictions (outlined in the final paragraph of this section). We hypothesized that noxious weeds would predominantly be native to Europe, given Australia's colonial history and acclimatization schemes (Dodd et al. 2015). However, we expected to find some differences between jurisdictions in geographic origin due to the variation in climates across Australia.

The majority of naturalized flora in Australia has entered through the ornamental pathway (Dodd et al. 2015; Virtue et al. 2004). We hypothesized that this trend would be reflected by the national and jurisdictional assemblages of noxious weeds, but we also aimed to identify any significant difference between jurisdictions. Here, we explored the five entry categories defined by *A Global Compendium of Weeds*: ornamental, crop, pasture, forestry, and herbal (i.e., medicinal purposes) (Randall 2017).

For perceived impacts, we were interested in the proportions of noxious weeds known to impact the environment or agriculture within their introduced ranges. These are impacts that have been documented globally and not necessarily in Australia. We hypothesized that jurisdictions would tend to declare more taxa that impact agriculture over natural landscapes, indicating a preference toward human asset protection. These impact data were obtained from *A Global Compendium of Weeds* (Randall 2017). We obtained entry pathway and perceived impact data for 97.4% of the noxious weed species and infraspecies.

We produced two-way contingency tables of the number of noxious weed taxa in each categorical variable within each jurisdiction. We then fit log-linear models to test the independence of the categorical variables of jurisdiction and trait (i.e., native ranges, entry pathways, and perceived impacts) with the frequency of noxious weed taxa. Mosaic plots were produced to visualize and assess significance of the models using Pearson's residual (Meyer et al. 2013; Zeileis et al. 2012).

Data and Software Resources

We conducted all taxonomic standardization and analyses in R software for statistical and graphical computing (R Core Team 2021). We used the *get_gbifid* function from the TAXIZE package to help automate taxonomic standardization (Chamberlain et al. 2020). We collected upstream taxonomy (i.e., family, class, order) for each species using the *classification* function in the TAXIZE package (Chamberlain et al. 2020). We used the *beta.pair* function from the BETAPART package to calculate a pair-wise distance matrix (Baselga et al. 2022). We used the *nestedtemp* function from the VEGAN package to determine the nestedness (Oksanen et al. 2020). We used *mosaic_plot* function from VCD package to visualize and assess the independence of the categorical variables (Meyer et al. 2013).

Results and Discussion

Australia's Noxious Weeds and Similarity between Jurisdictional Lists

In total, we identified 1,236 unique plant taxa that are explicitly declared as noxious weeds in at least one Australian jurisdiction, composed of 511 genera and 126 families (Supplementary Appendix S4 in Supplementary Material 2). Of those 1,236 taxa, 206 are declared in every jurisdiction (16.7%). There are 47 whole genera declared across all jurisdictions. Twenty-two of the noxious weed species are recognized as native by the APC (i.e., they were declared in a jurisdiction outside their Australian native range) and two species have uncertain native status (Australian National Herbarium 2023). Of the 1,236 noxious weeds, ca. 95% were angiosperms (948 dicots and 233 monocots). The remaining ca. 5% were 50 pteridophytes, 3 gymnosperms, 1 lycophyte, and 1 bryophyte. The five major contributing families were Fabaceae (178 taxa), Asteraceae (166 taxa), Poaceae (96 taxa), Salicaceae (86 taxa), and Cactaceae (39 taxa), making up ca. 45% of all noxious weeds (Figure 2A). The five major contributing genera were *Salix* L. (82 taxa), *Prosopis* L. (52 taxa), *Hieracium* L. (42 taxa), *Equisetum* L. (34 taxa), and *Rubus* L. (22 taxa), comprising ca. 19% of all noxious weeds (Figure 2B).

We found that neighboring jurisdictions do not have more similar lists of noxious weeds compared with separated jurisdictions (Figure 3A). On average, jurisdictions share ca. 67% (SD = 15%) of noxious weed listings. Neighboring jurisdictions share an average of ca. 70% (SD = 13%), and separated jurisdictions shared an average of ca. 66% (SD = 16%). Victoria (Vic) and Tasmania (Tas) had the most similar noxious weed lists while Western Australia (WA) was the least similar jurisdiction (Figure 3B). New South Wales (NSW) and Queensland (Qld) were another similar pair, and so were Northern Territory (NT) and South Australia (SA). The jurisdictional assemblages of

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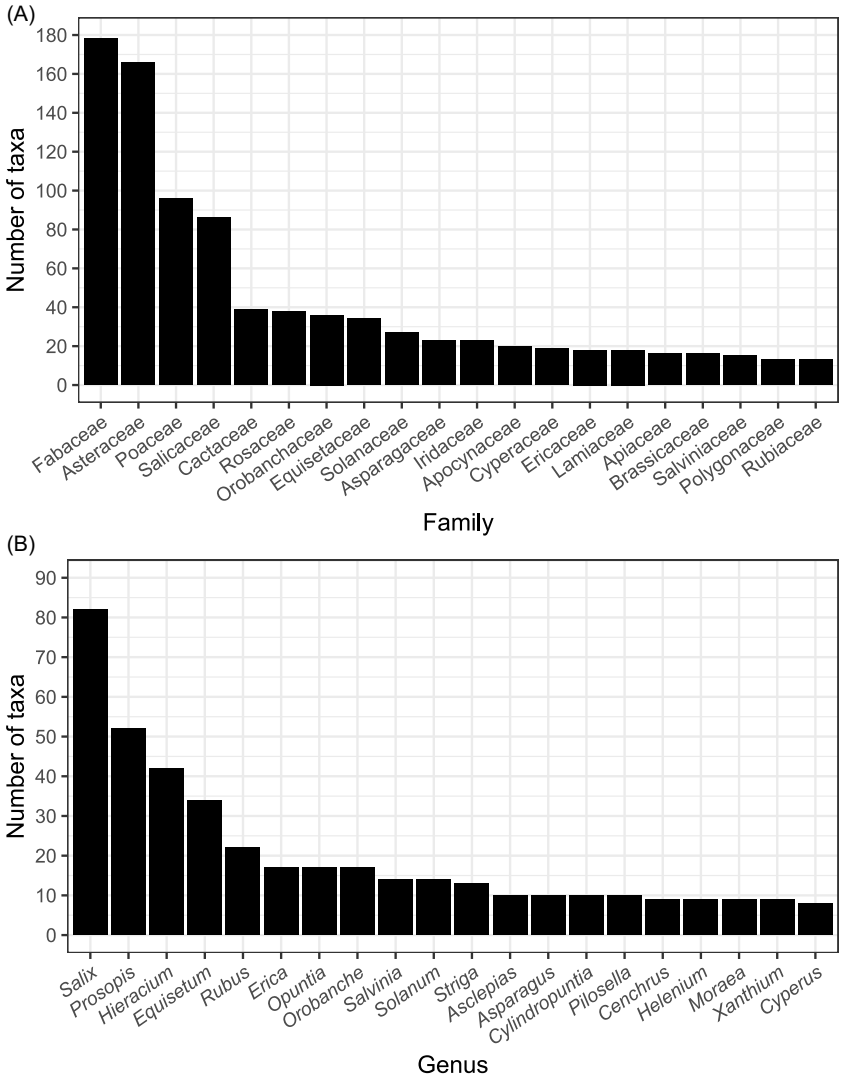

Figure 2. The twenty most common (A) families and (B) genera of explicitly declared plant taxa (noxious weeds) in Australia. The families in A represent ca. 72% of noxious weed taxa. The genera in B represent ca. 33% of noxious weed taxa. The taxonomy is according to the Global Biodiversity Information Facility taxonomic database (GBIF 2021).

noxious weeds are nested with 206 taxa declared in all jurisdictions (Figure 3C). WA had the largest number of noxious weeds and the largest number unique to the jurisdiction, 459/877 of WA's noxious weeds were only declared within WA (Figure 3C). Australian Capital Territory (ACT) had the highest proportion of shared species and the smallest assemblage of noxious weeds.

Our expectation was that neighboring jurisdictions would be more similar than separated jurisdictions in their noxious weed listings. While particular pairs of neighboring jurisdictions were similar, noxious weed listings were generally not more similar in neighboring than separated jurisdictions. However, we suggest this is not necessarily poor coordination between neighbors but demonstrates there is some regulatory consensus on noxious weeds across the country. A component of the calculated similarity in noxious weed lists is inherently due to the WoNS initiative (Hennecke 2012), which coordinates management to prevent, eradicate, contain, or minimize impacts in all jurisdictions. The WoNS declared in all jurisdictions account for ca. 13% of noxious weeds (159 species and 2 subspecies). Another component is that all jurisdictions share a history of European colonization, which facilitated many hundreds of intentional and unintentional plant introductions that are native to Europe or were popular in European horticulture (Dodd et al. 2015). The jurisdictions also utilize broadly similar approaches to evaluating invasive plant risk, drawing on a national standard (Virtue et al. 2006). While neighboring jurisdictions are not more similar in their noxious weed lists, consensus is much greater across Australian jurisdictions compared with the United States, which also has jurisdiction-based regulation (Beaury et al. 2021a). This current consensus should help to promote and build even stronger cohesion in invasive plant regulation in Australia.

A further measure to improve cohesion in invasive plant regulation would be to adopt a national taxonomic standard. Declaration of a noxious weed species is mostly at the discretion of the jurisdiction, and accepted taxonomy is determined by each jurisdiction's herbarium (Centre for Plant Biodiversity Research 2004). We encountered 11 problematic synonyms in use for noxious weeds and were unable to resolve a further 21 taxa. Accurate identification of invasive taxa is central to forming robust risk assessments and carrying out appropriate management actions (Pyšek et al. 2013). This can be hindered by a conflicting and unresolved taxonomy (Aguilar et al. 2022; Carlton 2009;

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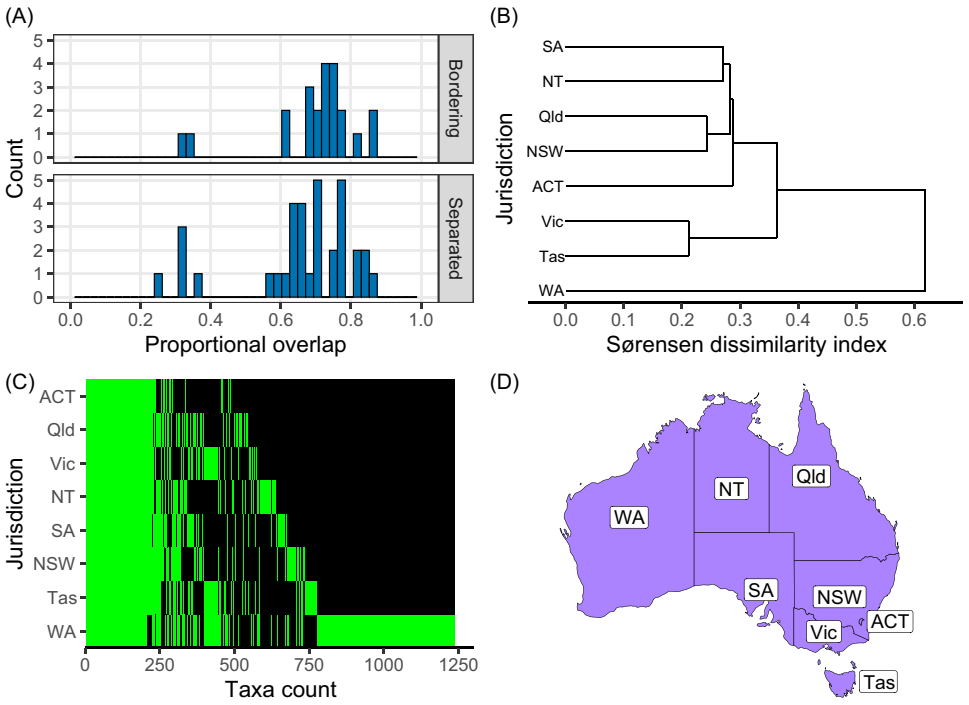

Figure 3. Similarity among Australian jurisdictions in the noxious weeds they regulate. (A) Histograms comparing the proportion of overlap in noxious weeds between bordering (sharing a geographic border) and separated jurisdictions (no geographic border). Victoria and Tasmania are considered to be bordering. Count represents number of pair-wise jurisdictional companions. (B) Dendrogram showing the similarity between jurisdictions, more closely linked jurisdictions share more noxious weeds. (C) Heat map representing nestedness across the eight jurisdictions. Green represents presence and black represents absence of noxious weed taxa. Jurisdictions that share a green line share that taxon. (D) A map of Australia with jurisdictions labeled: ACT, Australian Capital Territory; NSW, New South Wales; NT, Northern Territory; Qld, Queensland; SA, South Australia; Tas, Tasmania; Vic, Victoria; and WA, Western Australia.

Hirsch et al. 2017). Incorrect labeling has been attributed to the sale of prohibited invasive plants (La Canna 2016; Van den Neucker and Scheers 2022). Standardization of plant taxonomy between Australian jurisdictions has been recommended and sought out previously (Centre for Plant Biodiversity Research 2004; Martín-Forés et al. 2023). Particularly in the face of new and emerging invasive species, a unified national taxonomic standard will ensure accurate identification and effective regulation of invasive plants across all Australian jurisdictions.

Identifying Proactive and Discordant Regulation of Noxious Weeds

Australia's noxious weeds were standardized as 1,229 taxa using the APC to determine naturalization status (Australian National Herbarium 2023). The majority of declarations in jurisdictions are dedicated to preventing noxious weeds establishing rather than managing those already present (Figure 4A). All jurisdictions had more harmonious regulation of noxious weed taxa (i.e., prevention declarations aligned with neighboring jurisdictions) than discordant regulation (i.e., unregulated noxious weed taxa that are declared by a neighboring jurisdiction) (Figure 5). There were 415 noxious weed taxa with harmonious regulation and 327 with discordant regulation (Supplementary Appendix S5 in Supplementary Material 3).

Approximately 50% (618 taxa) of the noxious weeds have naturalized in Australia. For these noxious weeds, the number of unregulated taxa was greater than the number of managed taxa in six of the eight jurisdictions (Figure 4B). For noxious weeds that have not naturalized, WA was the only jurisdiction to have more taxa with regulation than without (i.e., prevention vs. absent regulation) (Figure 4C). WA had a substantially higher number of taxa with preventive regulation compared with the rest of Australia (Figure 4C).

Australian jurisdictions take a proactive stance to biosecurity related to invasive plants, with many declarations dedicated to preventing invasion of noxious weeds. Yet by combining the lists and regulations of noxious weeds in Australia, we have revealed regulatory vulnerabilities that have potential and existing impacts to Australia's biosecurity. Importantly, there are 327 noxious weeds that are regulated in a discordant manner. These are taxa that have naturalized in a jurisdiction but are not declared despite a neighboring jurisdiction declaring the taxa. This is not an isolated issue, with similar problems in the coordination of managing invasive species occurring in other regions around the globe (Aizen et al. 2019; Beaury et al. 2021a, 2021b; Beninde et al. 2015; Bradley et al. 2022; Epanchin-Niell et al. 2010; Gichua et al. 2013; Lakoba et al. 2020; Xu et al. 2022).

Interestingly, eight discordant noxious weeds were WoNS, which are intended to be declared in all jurisdictions. Four of these eight species were permitted in WA and not assigned any control category for local government Madeira Vine [*Anredera cordifolia* (Ten.) Steenis], Flax leaf broom [*Genista linifolia* L.], Montpellier broom [*Genista monspessulana* (L.) L.A.S. Johnson], and African boxthorn [*Lycium ferocissimum* Miers]. Three of the eight were unlisted organisms in WA and thus not permitted entry into WA according to the jurisdiction's legislation (Government of Western Australia 2020). However, the APC considers these species to already be naturalized in WA (Ground asparagus [*Asparagus aethiopicus* L.], Bridal veil creeper [*Asparagus declinatus* L.], and Snakefeather [*Asparagus scandens* Thunb.]) (Australian National Herbarium 2023). The final member of the eight species was

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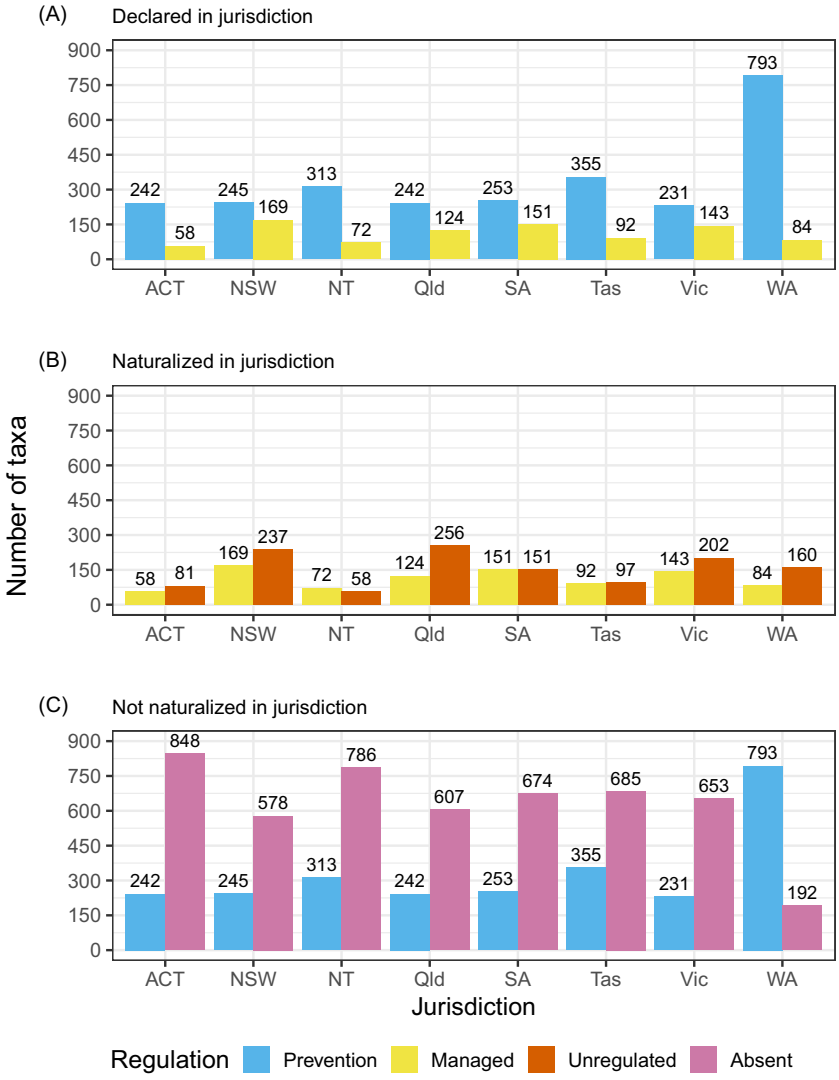

Figure 4. Comparison of the regulation of noxious weed taxa in each Australian jurisdiction. A noxious weed is defined as a plant that is legally declared as invasive in at least one Australian jurisdiction. The comparisons of regulations displayed are: (A) noxious weeds that are declared in the jurisdiction; (B) noxious weeds that have naturalized in the jurisdiction; and (C) noxious weeds that are not naturalized in the jurisdiction. Regulation categories are based on naturalization and declared status in each jurisdiction. Prevention: noxious weeds that are declared invasive by the jurisdiction but have not naturalized. Managed: noxious weeds that are declared invasive by the jurisdiction and have naturalized. Unregulated: noxious weeds that are not declared invasive by the jurisdiction but have naturalized. Absent: noxious weeds that are not declared invasive by the jurisdiction and have not naturalized. Jurisdictions are: ACT, Australian Capital Territory; NSW, New South Wales; NT, Northern Territory; Qld, Queensland; SA, South Australia; Tas, Tasmania; Vic, Victoria; and WA, Western Australia.

Cabomba [*Cabomba caroliniana* A. Gray], which does not appear in Vic's list of noxious weeds (Victorian Government 2017). These examples demonstrate that even the WoNS, a well-established and successful initiative, can suffer from practical and legislative challenges in coordinating the regulation of invasive species.

The predominance of prevention rather than management declarations (i.e., noxious weeds that have already naturalized) is, in part, a likely result of implementing weed risk assessments as strategic policy (CAST 2024; Virtue et al. 2006). Application of these assessments can help shift the regulation of invasive plants from a reactive to proactive strategy. Paired with this may be an avoidance to declare plants that have already naturalized, given that we found six out of eight jurisdictions have more naturalized noxious weed taxa that are unregulated than managed. We suggest there are three key reasons why jurisdictions choose not to regulate a naturalized plant taxon: (1) realized risk—some of these naturalized taxa may not be declared because their likelihood of becoming invasive is deemed to be low due to unsuitable conditions such as climate; (2) conflicting interests—some naturalized taxa may be invasive, but conflicting motivations from agriculture, forestry, and horticulture are preventing their regulation (e.g., olives [*Olea europaea* L.]) are invasive in SA but are an agricultural crop) (Crossman et al. 2002; Nicholson 2006; Randall 2001; Virtue and Melland 2003); and (3) feasibility—enforced regulations may be deemed impractical with a low benefit relative to cost. For example, post-border trade prohibitions are less effective for already abundant and widely distributed species (Hulme et al. 2018).

While realized risk, conflicting interests, and regulation feasibility can affect the decision to regulate a naturalized plant, these decisions should be subject to a review cycle. We recommend Australian jurisdictions evaluate the biosecurity risk of the 327 noxious weed taxa with discordant regulation (Supplementary Appendix S5 in Supplementary Material 3). These are taxa that have naturalized in a jurisdiction but remain unregulated, despite a

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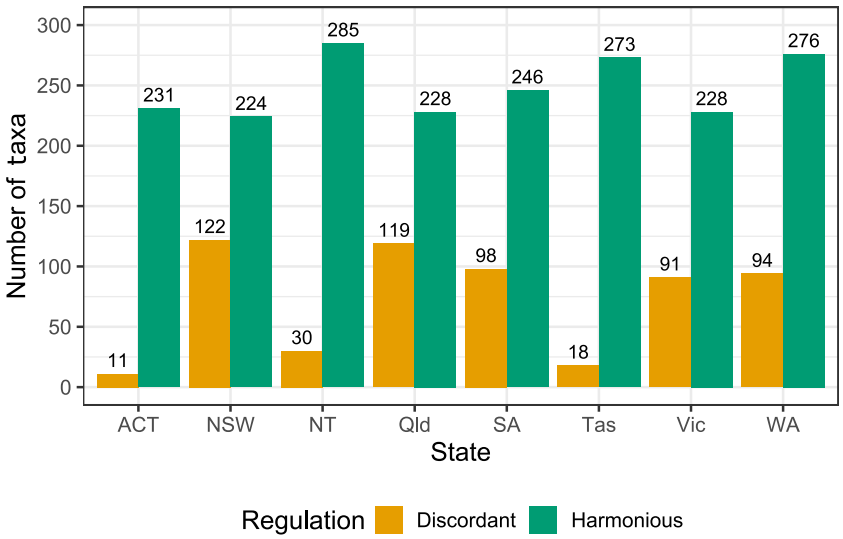

Figure 5. Number of noxious weeds in Australia that are regulated in a harmonious and discordant manner in each Australian jurisdiction. Harmonious regulation: noxious weeds that are declared but have not naturalized within a jurisdiction's borders and are also declared by a neighboring jurisdiction. Discordant regulation: noxious weeds that have naturalized but are not declared within a jurisdiction's borders and are declared by one or more neighboring jurisdictions (excluding native and doubtfully naturalized taxa). Jurisdictions are: ACT, Australian Capital Territory; NSW, New South Wales; NT, Northern Territory; Qld, Queensland; SA, South Australia; Tas, Tasmania; Vic, Victoria; and WA, Western Australia.

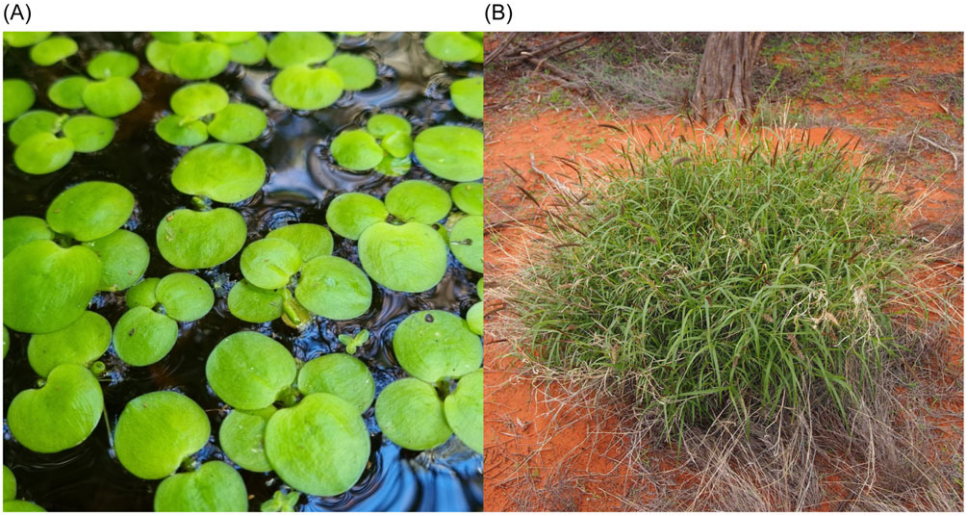

Figure 6. Two invasive plant species with differing feasibility for aligning regulation across Australian jurisdictions. (A) Amazon frogbit [*Limnobium laevigatum* (Humb. & Bonpl. ex Willd.) Heine] is a highly feasible subject for aligned regulation. While it is popular as an ornamental aquatic, declaring the species invasive has community support, and prohibiting its trade has real potential to prevent further spread. (B) Buffel grass (*Cenchrus ciliaris* L.) is a much less feasible subject for aligned regulation, because it has invaded extensive areas of arid Australia and is also used as a pasture grass. Image credits: (A) Phillip Cassey; (B) Mark Marathon.

neighboring jurisdiction regulating them. Not considering the impact to a neighboring jurisdiction of these taxa could jeopardize the neighbor's biosecurity. The compiled list of discordant species we have provided is a valuable reference point for Australian jurisdictions to engage and methodically work toward greater harmonization of invasive plant management.

The feasibility of broadening declarations will vary considerably among the 327 noxious weed taxa with discordant regulation. An example of a species with feasible opportunity to align regulations is Amazon frogbit [*Limnobium laevigatum* (Humb. & Bonpl. ex Willd.) Heine] (Figure 6A). Declared in NSW and NT, it is not declared in the shared neighbor Qld. It grows rapidly and can reproduce vegetatively, which enables it to colonize waterways (Bickel et al. 2022; Madsen and Morgan 2021). It is popular as an ornamental aquatic and is known to be traded online within Australia (Maher et al. 2023). Declaring the species within Qld has community support, and prohibiting its trade has potential to stem its spread (Willis and Brandel 2021). Conversely, a notoriously difficult species to coordinate is buffel grass (*Cenchrus ciliaris* L.) (Figure 6B). It is declared in SA but not in the surrounding jurisdictions of NSW, Qld, and WA. Introduced repeatedly as a pasture grass, it has become an extensive invader of arid ecosystems in Australia (Marshall et al. 2012). The economic benefit has prevented the species being more widely regulated. This

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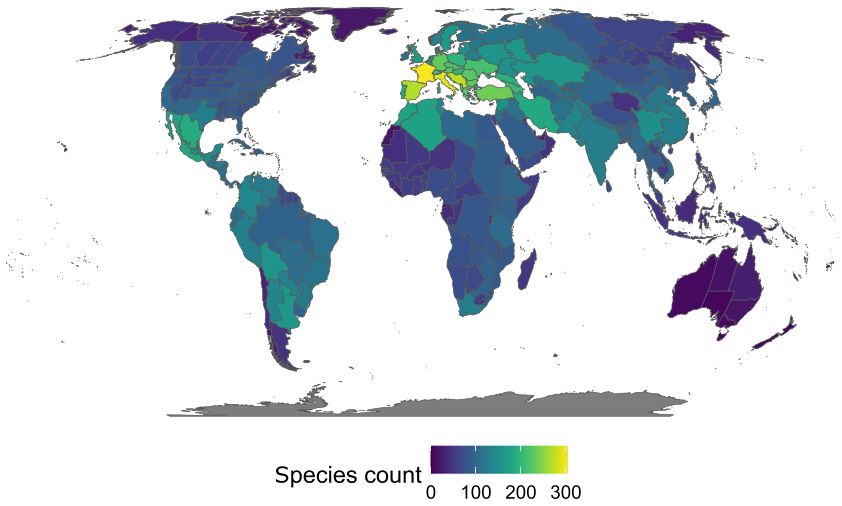

Figure 7. Native range of plant species declared in Australia (noxious weeds). The color scale represents the number of species in a geographic unit. The map is divided into countries and by political subdivisions for large countries (Argentina, Australia, Brazil, Canada, Chile, China, India, Mexico, Russia, South Africa, and United States) in accordance with level 3 of the World Geographical Scheme for Recording Plant Distributions (Brummit 2001).

is despite the damaging impacts *C. ciliaris* has to native plant diversity, natural fire regimes, and Aboriginal cultural sites and traditional resources (Bach et al. 2019; Miller et al. 2010; Wright et al. 2021). Yet, given its widespread distribution and continued desirability as a pasture grass, broader declaration has been in doubt (Grice et al. 2012). Prohibition and eradication at regional scales have been suggested as viable alternatives for managing its impact (Grice et al. 2012; Wright et al. 2021). However, until very recently, NT was also discordant with SA regarding *C. ciliaris*, but in the time since our study was conducted, the plant has been declared in NT (BGWAC 2024). This development demonstrated that greater regulatory harmonization can be reached with even highly challenging invasive plants.

Although current conditions may diminish the invasive potential of a naturalized plant species, increased propagule pressure, land-use changes, and climate change can all alter future naturalization potential (Duncan 2021; Gallagher and Leishman 2014; Haeuser et al. 2018). While conflicting interests around invasive species management can be unavoidable, opinions and interests from relevant parties can also change over time. Anticipating rather than reacting to conflicts can help in reaching balanced resolutions with education and transparency in decision making (Crowley et al. 2017). Surveying public opinions, consultations with interested parties, and seeking feedback are all methods that can help anticipate where conflicts will arise around invasive species (Crowley et al. 2017; Graham et al. 2022; Novoa et al. 2018). We recommend that jurisdictions incorporate these collaborative decision-making approaches and continually involve neighboring jurisdictions in their weed risk-assessment process. Despite the varied outcomes in feasibility of aligning declarations, we recommend that the discordant noxious weeds we have identified serve as a starting point for collaboratively reviewing regulatory coordination.

Trends in Noxious Weed Native Range, Entry Pathway, and Impact

We found that the native ranges of noxious weed species in Australia are concentrated in western Europe around the Mediterranean basin (Figure 7). However, on average (across jurisdictions), the greatest number of noxious weed taxa were native to the Asia–temperate region (Figure 8). We found statistically significant differences in the native biogeographic regions of noxious weeds between jurisdictions (χ^2 (35, 5,417) = 125.12, $P < 0.001$) (Figure 9). We found a significantly greater than expected number of noxious weeds native to: Asia–tropical for WA; Europe for Tas and Vic; Northern America for Qld; and Southern America for Qld and NT. There was a significantly lower than expected number of noxious weeds native to: Africa for ACT, Europe for NT and Qld, Northern America for Tas, and Southern America for WA.

The predominant entry pathway associated with Australia's noxious weeds was the ornamental trade (Figure 7). The second was herbal, which is plants considered to be of medicinal use. This was followed by the crop, pasture, and forestry pathways. We found statistically significant differences in the entry pathways of noxious weeds between jurisdictions (χ^2 (28, 6,279) = 42.99, $P = 0.035$). We found ACT was significantly more likely to declare noxious weeds associated with the forestry pathway (Supplementary Figure S1A in Supplementary Material 1), which may reflect a mass introduction of trees and shrubs during the early 20th century (Mulvaney 2001). WA was significantly more likely to declare noxious weeds associated with the herbal pathway, and less likely to declare those from the forestry pathway (Supplementary Figure S1A in Supplementary Material 1). Overall, a greater number of noxious weed taxa impact agriculture than the natural environment (Figure 8). However, no jurisdictions were significantly more or less likely to declare noxious weeds that impact agriculture or the environment (χ^2 (7, 3,420) = 7.686, $P = 0.361$) (Supplementary Figure S1B in Supplementary Material 1).

Understanding the current trends in a jurisdiction's noxious weeds reveals current management priorities, but also where shifts will be needed. Predictably, jurisdictions declare noxious weeds native to similar climatic regions, and ornamental horticulture is a major entry pathway. However, as globalized horticulture trade continues to increase in scope and diversity, we can expect to see an increase in the number of invasive species and shifts in their biogeographic origin (Dehnen-Schmutz et al. 2010; Dodd et al. 2015; Hulme et al. 2018; Pyšek et al. 2020; Seebens et al. 2015; van

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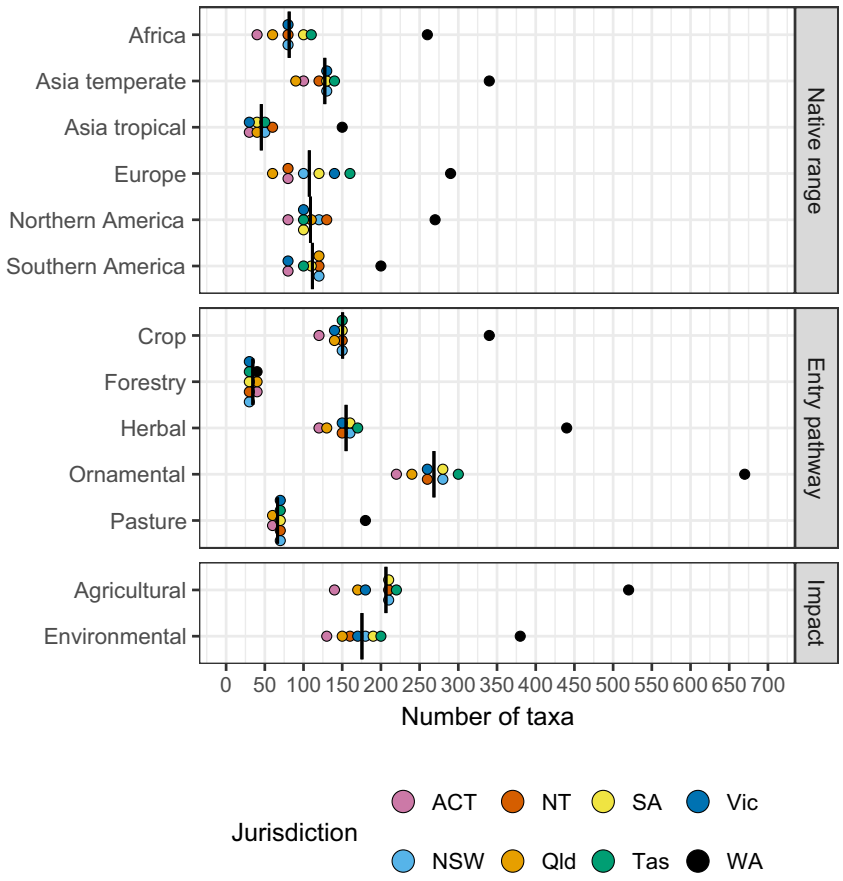

Figure 8. Number of noxious weed taxa in each native range, entry pathway, and impact category across jurisdictions. The medians are indicated by vertical lines. Data points are distributed with a bin width of 10 and colored using the Okabe-Ito color palette to assist visualization (Okabe and Ito 2002). Jurisdictions are: ACT, Australian Capital Territory; NSW, New South Wales; NT, Northern Territory; Qld, Queensland; SA, South Australia; Tas, Tasmania; Vic, Victoria; and WA, Western Australia.

Kleunen et al. 2015, 2018; Westphal et al. 2008). For Australian jurisdictions, a shift toward preventing and managing the establishment of invasive plants from warmer, drier climates will be necessary (Bradley et al. 2012; Whetton et al. 2016). Drought-tolerant ornamental plants should draw attention for weed risk assessment, and species with medicinal use (i.e., herbal) may also emerge as new weeds. Currently, Australia's management of invasive plants tends toward prevention, which will be beneficial under climate change. However, assessments should not overlook species that have already naturalized, as climate shifts will facilitate the shift from naturalization to invasion status (van Kleunen et al. 2018; Webber et al. 2014).

Recommendations

We have provided a current consolidated dataset and analysis of noxious weeds in Australian jurisdictions. Encouragingly for biosecurity, noxious weeds tend to be declared proactively, and broad similarity exists in declared lists across the country. However, differences in jurisdiction-based declarations reveal vulnerabilities in Australia's biosecurity. We recommend three actions for Australia's jurisdictions to achieve a more cohesive effort against the impact of noxious weeds. (1) Jurisdictions should reevaluate the 327 noxious weeds whose current regulation status may place neighboring jurisdictions at risk. (2) Reevaluations and future weed risk assessments should collaborate with, and continually involve, neighboring jurisdictions. These codeveloped regulations should extend to relevant industries and the public to help anticipate and resolve conflicts around invasive taxa. (3) Jurisdictions should explore existing alternative regulatory approaches to jurisdiction-based declarations, as these alternatives will provide flexibility and/or greater national harmonization in regulations. The currently underutilized National Categorisation System for Invasive Species proposed coordinated bans on entry and trade of plants within Australia (AWC and VPC 2012). More flexible approaches, such as a general biosecurity duty, may prove useful, because it relies on a "duty" to control any invasive species rather than explicitly declaring specific taxa (New South Wales Biosecurity Regulation 2017, Queensland Biosecurity Act 2014, Tasmania Biosecurity Act 2019; Martin and Taylor 2018). By addressing discrepancies in jurisdiction-based declarations we can achieve a nationally cohesive approach to noxious weeds. The international community has agreed that enhanced coordination and improving policy coherence across international and regional mechanisms is a key strategy for mitigating the impacts of invasive alien species (IPBES 2023). One specific way to achieve this is providing current data on invasive species and their governance to prioritize actions and improve management outcomes (IPBES 2023). We have realized this for Australia by providing a consolidated dataset of noxious weeds (Supplementary Appendix S4 in Supplementary Material 2) and identifying current vulnerabilities in invasive plant regulation.

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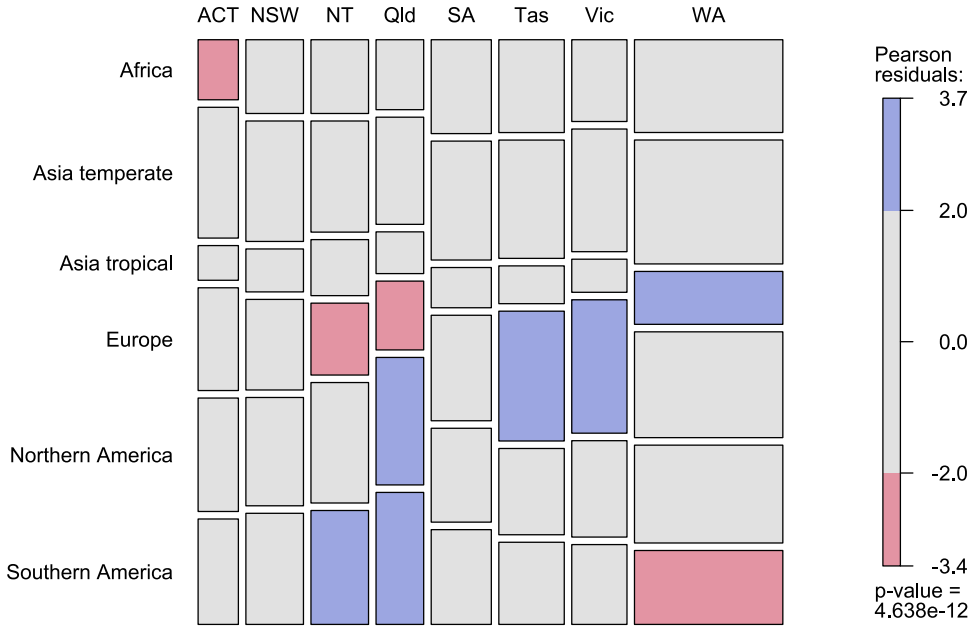

Figure 9. Mosaic plot of the deviation in independence between noxious weeds declared in Australian jurisdictions and their native biogeographic regions. The size of each rectangle is proportional to the observed number of noxious weed taxa in each trait. The residual shading reflects the deviation of observed from expected quantities. The colored shading indicates observed quantities that are significantly higher (blue) or significantly lower (red) than the expected quantities ($\alpha = 0.05$). Gray shading indicates nonsignificance. We removed three biogeographic regions that had relatively low numbers of observations from our analysis: Australia (43 species), Pacific (25 species), and Antarctic (2 species). Jurisdictions are: ACT, Australian Capital Territory; NSW, New South Wales; NT, Northern Territory; Qld, Queensland; SA, South Australia; Tas, Tasmania; Vic, Victoria; and WA, Western Australia.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/inp.2024.26

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