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Abstract

Invasive plants seriously impact our environmental, agricultural and forestry assets, and the ornamental plant trade is a major introduction pathway. The variety and extent of ornamental plant trade is growing in reach and is increasingly facilitated by the internet (i.e., through e-commerce). A lack of surveillance and regulation of e-commerce has resulted in invasive species being widely traded on these platforms. Here, we investigated the illegal trade in invasive plant species occurring in Australia by collecting advertisements found on a popular e-commerce website. Across a 12-month period we found 155 plant taxa advertised online that were prohibited to trade in Australian. From 10,000 advertisements (4.25% of total advertisements found), we found 1,415 instances of these invasive plants advertised, of which 411 breached local jurisdictional (i.e., State or Territory) laws. *Opuntia* cacti and invasive aquatic plants were traded in the greatest quantities. A variety of uses for plants prohibited to trade were purported by sellers, where aquatic uses were the most popular (i.e., water filtering and habitat for aquatic animals). Despite Australia's strict internal biosecurity regulations, we found that trade prohibitions had no influence on the quantity and price of illegal invasive plants traded. Given this, and the extent of illegal invasive plants traded, we believe increased monitoring and regulation of online plant trade is warranted. However, to obtain the most optimal outcomes, regulations should be coupled with increased cooperation from e-commerce platforms and public awareness campaigns. Future weed risk assessments should consider online trade as a key factor in the long-distance dispersal and propagule pressure of a plant. Jurisdictions would also benefit from greater alignment on plant trade prohibitions and revision of associated compliance policies.

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Introduction

Invasive plants can cause serious negative impacts to biodiversity, human health, and primary resource industries (Pyšek et al. 2020; Ward et al. 2021). The largest vector of new plant introductions and invasions is the global trade of ornamental plants, which is continually growing in reach and quantity (Weber et al. 2008; Dodd et al. 2015; Faulkner et al. 2016; van Kleunen et al. 2018; Arianoutsou et al. 2021; Beaury et al. 2021; Rojas-Sandoval et al. 2022). Within this global trade, a pathway of serious concern is trade facilitated by the internet, termed e-commerce (Derraik and Phillips 2010; Magdalena et al. 2014; Humair et al. 2015). E-commerce platforms facilitate long distance dispersal of invasive species and can often circumvent regulations (Giltrap et al. 2009; Derraik and Phillips 2010; Magalhães and Avelar 2012; Magdalena et al. 2014; Humair et al. 2015; Beaury et al. 2021). As a result, e-commerce platforms have proven challenging to monitor and enforce for biosecurity agencies (Derraik and Phillips 2010; Lavorgna and Sajeva 2021). Many invasive plant species are being traded online despite legislative regulations (Humair et al. 2015; Munakamwe and Constantine 2017; Beaury et al. 2021). Without intervention, it is predicted that online trade will lead to further invasive plant incursions (Humair et al. 2015; Peres et al. 2018; Beaury et al. 2021).

Australia has a highly endemic floral community that has been severely impacted by plant invasions (Broadhurst and Coates 2017; Bradshaw et al. 2021). Strict importation measures and risk assessment processes have been implemented by the Commonwealth government to prevent the arrival of new alien-invasive plants (Pheloung et al. 1999; Walton 2001; Keller et al. 2007; Simberloff et al. 2013). Even so, there are already more than 29,000 introduced alien-plant species in the country (Gallagher and Leishman 2014). There are also native Australian plants which have become invasive outside their indigenous range (Rose and Fairweather 1997; Morgan et al. 2002; O'Loughlin et al. 2015). Where plant species become invasive or there is potential to be invasive, state and territory governments (‘jurisdictions’ hereafter) have lead responsibility over their management and control. A common control measure, which jurisdictions use, is to ‘declare’ invasive plant taxa in legislation as prohibited to trade within its borders (simply ‘declared plant’ hereafter). However, e-commerce websites have circumvented traditional enforcement measures resulting in a poorly regulated horticultural market (Munakamwe and Constantine 2017). Surveillance of e-commerce platforms is an essential tool for preventing future negative impacts resulting from new plant invasions (Humair et al. 2015; Lavorgna et al. 2020; Duncan 2021; Stoett and Omrow 2021; Whitehead

et al. 2021). Some efforts have been made to monitor online trade in Australia, however the focus has been limited by time and resources to a handful of problematic species (Munakamwe and Constantine 2017).

To investigate the current invasion risk of e-commerce plant trade in Australia, we applied web-scraping technology to monitor and record plant trade advertisements on a popular e-commerce website over the course of one year. We investigated five research aims: (i) determine what proportion of plants advertised are prohibited to trade; (ii) determine the quantity and taxonomic composition of declared plants traded; (iii) determine whether current regulations reduce trade quantity or influence the price of declared plants in jurisdictions which prohibit trade versus those that permit trade; (iv) characterise the most frequently traded declared plants; and (v) document advertised plant uses to inform our understanding of the desire for declared plants. Our study seeks to provide a clearer picture of the present risk of e-commerce trade and whether prescriptive laws reduce invasive plant trade. These results will help inform future policy decisions regarding the monitoring and prevention of invasive species occurring in the Australian plant trade.

Methods

Compiling Australia's declared plants

In order to investigate the trade of invasive plants online, we compiled a list of declared plants in Australia. These declared plants are prohibited from trade under jurisdictional biosecurity legislation because of their current or potential impact as invasive species (Parsons and Cuthbertson 2001). Declaration is usually based on an analysis of weed risk using various post-border weed risk management systems (Virtue et al. 2006). However, there are also Australian native plant species that have invaded beyond their natural range and are now declared, which we included in this study. To assemble a comprehensive list of declared plants, we used sources relevant to Australia's eight main jurisdictions (i.e., six states plus Northern Territory and Australian Capital Territory), including government websites, online databases, legislative acts, and gazettes (see Appendix 1 for complete list of sources). We verified our compiled list of declared plants and relevant legislation by contacting the appropriate jurisdictional officials through the Weeds Working Group of the Australian intergovernmental Environment and Invasives Committee. We standardised the taxonomy of the declared plants using the Global Biodiversity Information Facility taxonomic database (GBIF 2021). Our finalised list of declared plant taxa contained 1,236 defined taxa; comprising 1,178 species, 6 subspecies and 5 varieties, as well as 47 declared genera. Twenty-two of the declared plant species are recognised as native by the Australian Plant Census and 2 species have uncertain native status (Australian National Herbarium 2023).

E-commerce platform selection and building web scrapers

We followed established protocols to select e-commerce websites to monitor for sales of plants (Stringham et al. 2020). Specifically, we conducted a systematic web search of invasive plant species names (common and scientific) with an appropriate phrase e.g., "*Vinca major* for sale Australia" and "Periwinkle for sale Australia". To optimise the search effort in selecting e-commerce websites for further investigation, we created a short-list of declared species known to be popular in horticulture (Appendix 2) (Nursery & Garden Industry Australia 2009). Alongside our internet search, we consulted with jurisdictional biosecurity officers on their experience monitoring the online plant trade. They identified public e-commerce websites over private nursery websites as their primary concern. Based on this recommendation and the findings of our web search, we concentrated this study on one highly popular public e-commerce website. We favoured this e-commerce website for its popularity and the availability

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of location data alongside the advertisements. Location data was necessary to determine whether a plant advertisement was infringing jurisdictional law. We have kept the identity of the website anonymous in accordance with our ethics approval (Ethics approval H-2020-184).

To collect online advertisement data of the plant trade, we constructed a custom web scraper in Python Programming Language (version 3.8.1; Python Software Foundation 2020) using the libraries bs4 (Richardson 2020), requests (Reitz 2020), and selenium (Selenium Main Repository 2020). The web scraper ran daily and stored plant advertisement data on a local SQL database. For this study, we explored 12 months of plant advertisements between 01 February 2020 and 31 January 2021. Duplicate advertisements were removed based on a unique listing identification generated by the website. We collected 235,162 unique advertisements for plants during this time period.

Sampling and detecting declared plant trade

The data we collected were not immediately ready for analysis because the advertisements from the website were composed of free-form text boxes filled out by the users, and thus the taxonomic names could not be automatically retrieved (i.e., no standardization in names). Subsequently, we explored a subset of the advertisements for this study. We extracted two separate samples of 5,000 advertisements each. The first sample focused on all plants traded and the second sample focused on declared plants.

The first sample was untargeted, we sampled from all the advertisements we collected and did not intentionally target declared plants. We sampled 5,000 advertisements, which included 625 unique advertisements from each jurisdiction. We used this as a control sample to compare the effectiveness of our targeted sampling method. To do this we compared the proportion of advertisements containing declared plants in each sample. Additionally, we used the untargeted sample to estimate the quantity of advertisements containing declared plants traded on the e-commerce website in one year. We calculated this estimate by multiplying the total number of advertisements in one year by the proportion of declared plant advertisements found in the untargeted sample. Using this calculation, we estimated the total number of declared plant advertisements and the number that would be prohibited (i.e., advertised in a prohibited jurisdiction).

For the second sample we targeted declared plant advertisements. Our objective was to identify frequently traded declared plants, and capture the composition of declared plants traded. We

aimed to capture declared plants traded anywhere in Australia regardless of whether they were advertised in a prohibited jurisdiction. This was to capture the full extent of declared plant trade in Australia. To do this we used string matching to generate a targeted sample aimed at detecting declared plant advertisements (Stringham et al. 2021). String matching is a method of finding a sequence of characters, called a string, that match a given character pattern. In our case the character patterns were the scientific and common names of declared plants. In total, we used 10,573 names to search for the 1,236 declared taxa within the text of collected advertisements. We initially sourced common names from jurisdiction legislation, followed by broader internet searches if necessary (Appendix 1) (Shepherd et al. 2001). We cleaned names by removing parentheses and punctuation, converted to lower case, and also pluralised and singularised the names. Based on findings by Munakamwe and Constantine (2017), we included common terms for some aquatic species. Our pilot investigation revealed frequent mismatches due to the inclusion of some broad search terms (e.g., ‘lily’ returned many non-target species). We created a list of match exceptions to remove the bulk of the mismatches (Appendix 3). Out of 235,162 total advertisements, text in the title or description matched to 12,751 advertisements for declared plants. From this, we took a weighted random sample of 5,000 unique advertisements. Given our interest in characterising the legality of online trade across Australian jurisdictions, we weighted the sampling to help capture trade in three smaller jurisdictions: Australian Capital Territory, Northern Territory, and Tasmania (Appendix 4).

We cleaned the sampled datasets by identifying the taxonomy of plants in each advertisement using photos and text provided by the seller. Advertisements would often contain multiple species for sale so we recorded each plant species (or lowest taxonomic rank possible) as a separate identification within an advertisement. We recorded the price and quantity for each plant identified, and the location of the advertisement. We documented and categorised advertisements that stated uses for plants when specified by sellers (i.e., used for purposes other than as a live ornamental plant, including propagules).

Once we identified the plant taxa in the advertisements, we cross referenced them with our dataset of 1,236 declared plants. We measured the number of advertisements containing declared plants and identified advertisements that were prohibited (i.e., the advertisement contained a plant that was declared in the jurisdiction where it was advertised). Multiple declared plant taxa could appear in a single advertisement. Therefore, we also measured the number of detections for declared plant taxa traded and determined how many were prohibited (i.e., the plant was declared in the jurisdiction where it was advertised). In this way we were

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able to capture prohibited trade of a declared plant and the broader extent of its trade within Australia. To help distinguish these different types of trade observations an example with term definitions is provided in Figure 1.

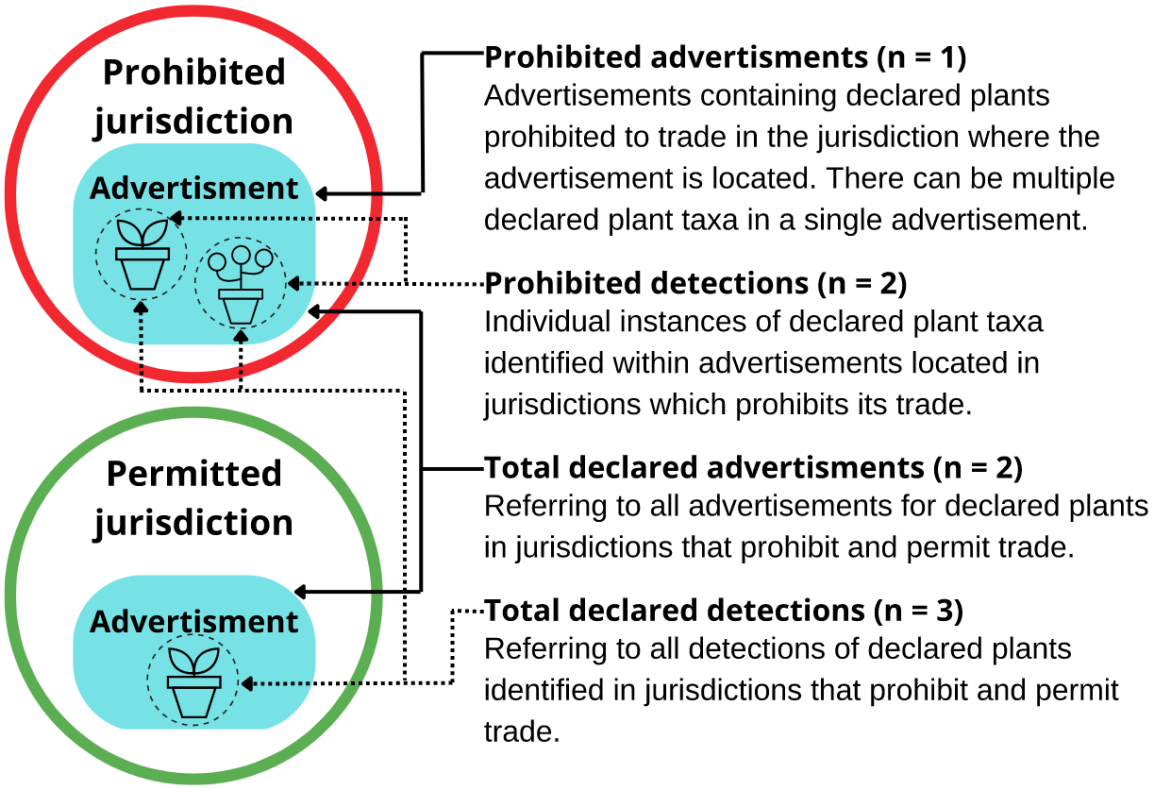

Figure 1: A diagram explaining the terms we used to define the different types of plant trade observations. This diagram shows two advertisements and two species of declared plant (plants prohibited to trade in a given jurisdiction). The number of observations for each term in this scenario are provided in parentheses. In the 'prohibited jurisdiction' there is one advertisement with two plant species, both species are prohibited to trade in this jurisdiction. One of these plant species is sold by itself in the 'permitted jurisdiction'. In this case we refer to it as a declared plant, but it is permitted to trade in that jurisdiction.

Analysis of trade prohibition on quantity and price

We used linear regression to explore whether trade prohibition had an effect on the trade quantity and price of declared plants. We extracted the mean difference (i.e., coefficient estimate) in quantity and price of each declared plant taxon traded in prohibited jurisdictions compared to permitted jurisdictions (i.e., we set the response variable as either quantity or price and the explanatory variable as whether the taxon was traded in a state that prohibits its trade). We applied this linear regression individually for each plant taxon and examined the distribution of coefficient estimates. We used this distribution to determine the degree that trade prohibition affected trade quantity and price, where a distribution centred around zero with low

variation indicates little to no influence. We tested these models using the targeted dataset, which had the greater number of declared plant advertisements compared to the untargeted. For these analyses, we removed nationally declared taxa, i.e., taxa declared in all jurisdictions (n = 130 taxa remaining for quantity comparison). For analysing price differences, we excluded taxa with less than 2 advertisements in each legality category (i.e., prohibited or permitted; n = 20 taxa remaining).

Data and software resources

We conducted data analysis and visualisation using the R software environment for statistical and graphical computing (version 4.1.1; R Core Team 2022) and used the following packages for our analyses. We verified taxonomy by using the ‘taxize’ package (Scott Chamberlain 2013) and to acquire information from the Global Biodiversity Information Facility taxonomic database. Plant search terms were pluralised using the ‘pluralize’ package (Rudis and Embrey 2020) and string matching was performed using the ‘stringr’ package (Wickham 2019). Collected data was accessed from MySQL database using the ‘DBI’ package (Wickham et al. 2022). Regression model coefficients were summarised and extracted using the ‘broom’ R package (Robinson et al. 2021). Shapefiles were obtained from the Australian Bureau of Statistics (2021) and visualised using the ‘sf’ R package (Pebesma 2018). Species accumulation curves were calculated using the ‘vegan’ R package (Oksanen et al. 2020). The following packages were used for handling and manipulating data: ‘tidyverse’ (Wickham et al. 2019), ‘dbplyr’ (Wickham et al. 2021), ‘lubridate’ (Grolemund and Wickham 2011), and ‘sampler’(Baldassaro 2019). The following packages were used for data visualisation: ‘tidyverse’ (Wickham et al. 2019), ‘cowplot’ (Wilke 2020), ‘ggalluvial’ (Brunson and Read 2020), ‘ggrepel’ (Slowikowski 2021), ‘ggpubr’ (Kassambara 2020), and ‘scales’ (Wickham and Seidel 2022). The data underpinning the methods and analysis of this study have been deposited on the Figshare Repository at https://doi.org/10.6084/m9.figshare.22493944 (Maher et al. 2023).

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Results

Overall richness, trade proportion, and detection rate

From the 10,000 advertisements we examined (i.e., 5,000 each for the untargeted and targeted samples), we made 13,619 plant identifications (average c. 1.4 identifications per advertisement). We identified 1,777 unique plant taxa (Figure 2a) of which 78 were declared plants prohibited to trade in the jurisdictions where they were advertised (Figure 3a). A further 77 declared plants were advertised legally in jurisdictions that do not prohibit their trade. This brought the overall number of declared plants traded to 155 taxa (Figure 2b, Figure 3b). We did not observe the species accumulation curves approaching a limit (Figure 2). We made 411 prohibited detections (from 374 advertisements) and 1,415 total declared detections (from 1,296 advertisements) (Figure 3b). From our untargeted sample, we found 59 prohibited advertisements (c. 1%) and 150 total declared advertisements (detection rate of 3%). In comparison, our targeted sample contained 328 prohibited advertisements (c. 7%) and 1,183 total declared advertisements (detection rate of c. 24%). Based on the quantity of declared plant trade observed in the untargeted sample, we estimate this e-commerce platform could be facilitating approximately 2,800 prohibited advertisements and 7,000 total declared advertisements per year.

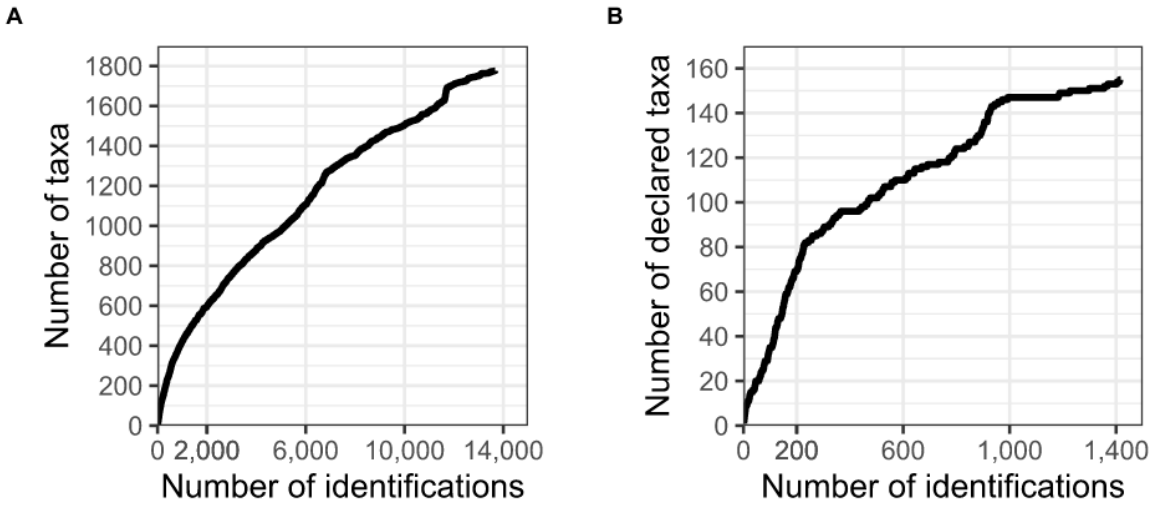

Figure 2: Accumulation curves of plant taxa identified from sampling 10,000 online advertisements. **A** Accumulation curve of all plant taxa identified. There were 1,777 taxa observed from 13,619 identifications. **B** Accumulation curve of declared plant taxa identified. There were 155 declared taxa identified in 1,415 detections of declared plants.

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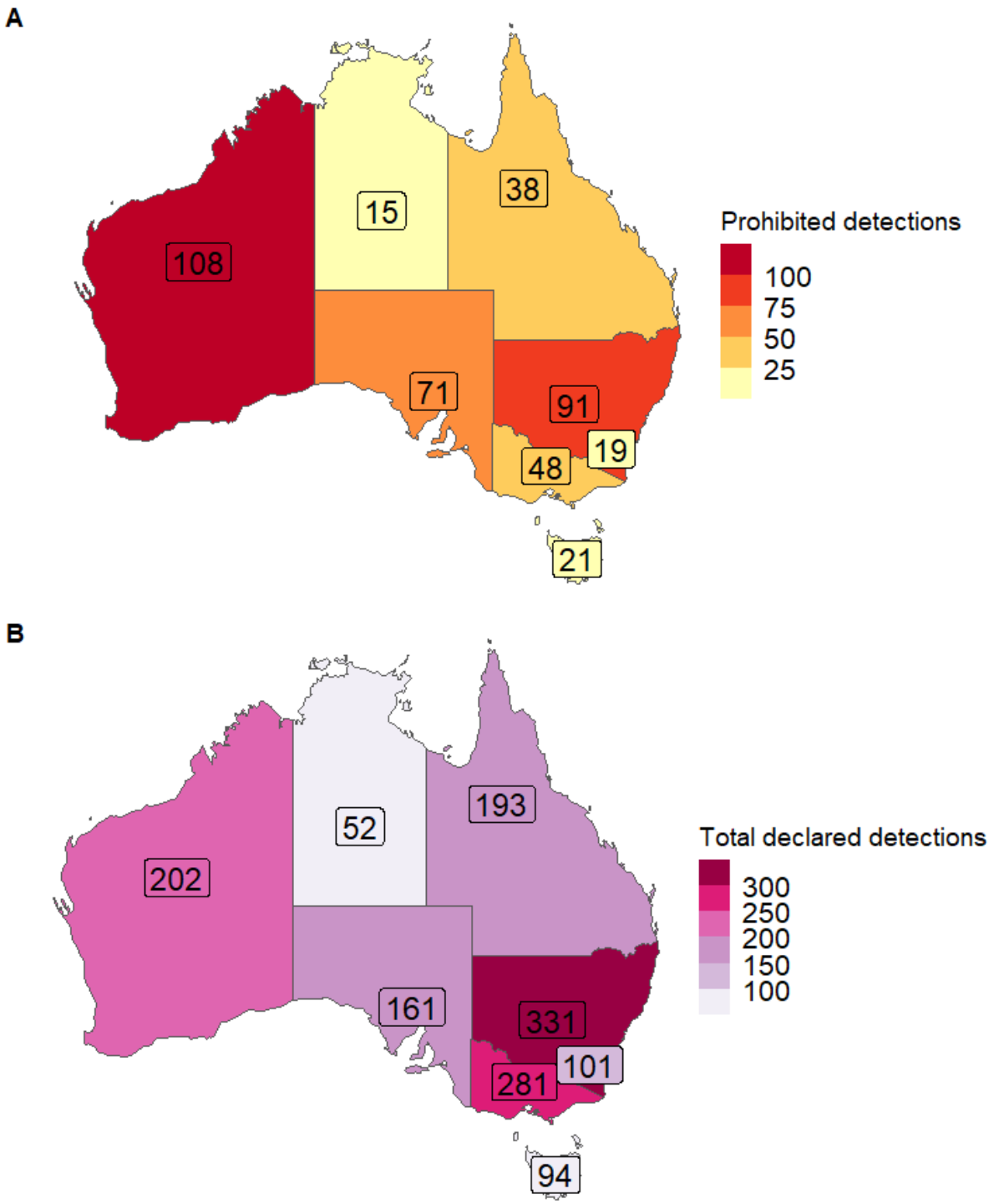

Figure 3: The number of declared plants detected on an e-commerce platform over a 12-month period for each jurisdiction. **A** The number of detections for plants declared within the jurisdiction (i.e., prohibited in that jurisdiction) (78 taxa advertised). **B** The total number of plants detected in that jurisdiction that are declared anywhere in Australia (155 taxa advertised).

Influence of trade prohibition on quantity and price

We found that the quantity and price of a declared species was not significantly different between jurisdictions that prohibited trade and those that did not (Figures 4 & 5). Specifically, for over 80% (104/130 taxa) of declared taxa analysed, the mean difference in the number of advertisements between prohibited and permitted jurisdictions was less than one advertisement (Figure 4). The declared plants with the greatest mean differences were *Drimia maitima* (mean difference c. 5) which had higher quantities in prohibited jurisdictions, and *Opuntia ficus-indica* (mean difference c. -11) with higher quantities in permitted jurisdictions. The price of declared plants also showed no discernible trend regarding prohibited status (Figure 5). On average, prices were only $1.25 (Australian dollars; AUD) more in prohibited jurisdictions with 60% (12/20 taxa) of observed taxa having a mean price difference within $5. Of the greatest differences, *Ziziphus mauritiana* (mean difference c. 26.56) was more expensive in prohibited jurisdictions, and *Asparagus densiflorus* (mean difference c. -12.21) was more expensive in permitted jurisdictions.

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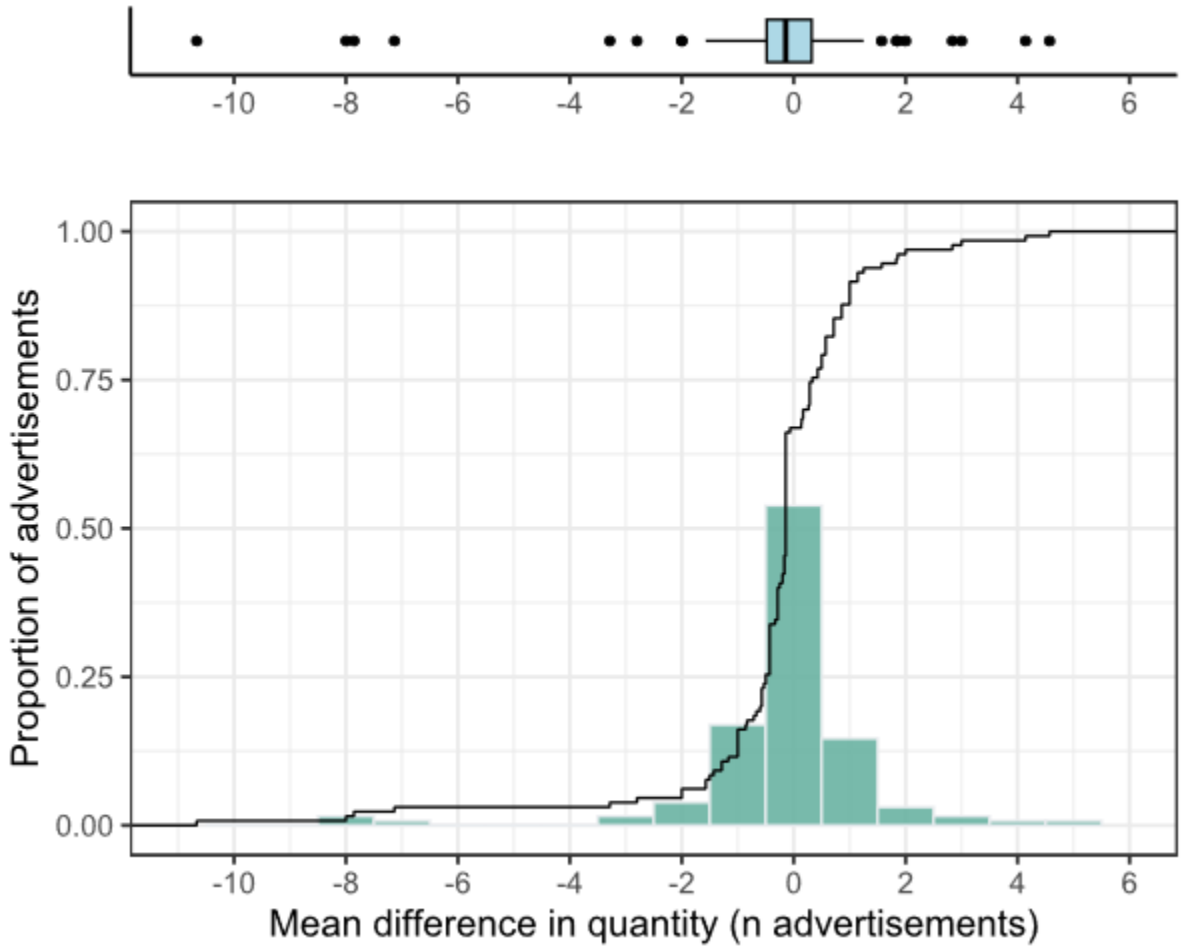

Figure 4: Distribution of the mean difference in the number of advertisements for declared plant taxa between prohibited and permitted jurisdictions. The black curve overlaying the histogram represents the cumulative distribution of mean differences in advertisement quantities. A positive mean difference translates to comparatively more advertisements in prohibited jurisdictions and fewer in permitted jurisdictions. Negative mean difference translates to comparatively more advertisements in permitted jurisdictions and fewer in prohibited jurisdictions. The distribution represents 130 plant taxa and each bar represent 1 advertisement. We removed taxa that are declared in all jurisdictions and those with less than 2 advertisements in each legality category (i.e., prohibited or permitted) as there was nothing to compare against.

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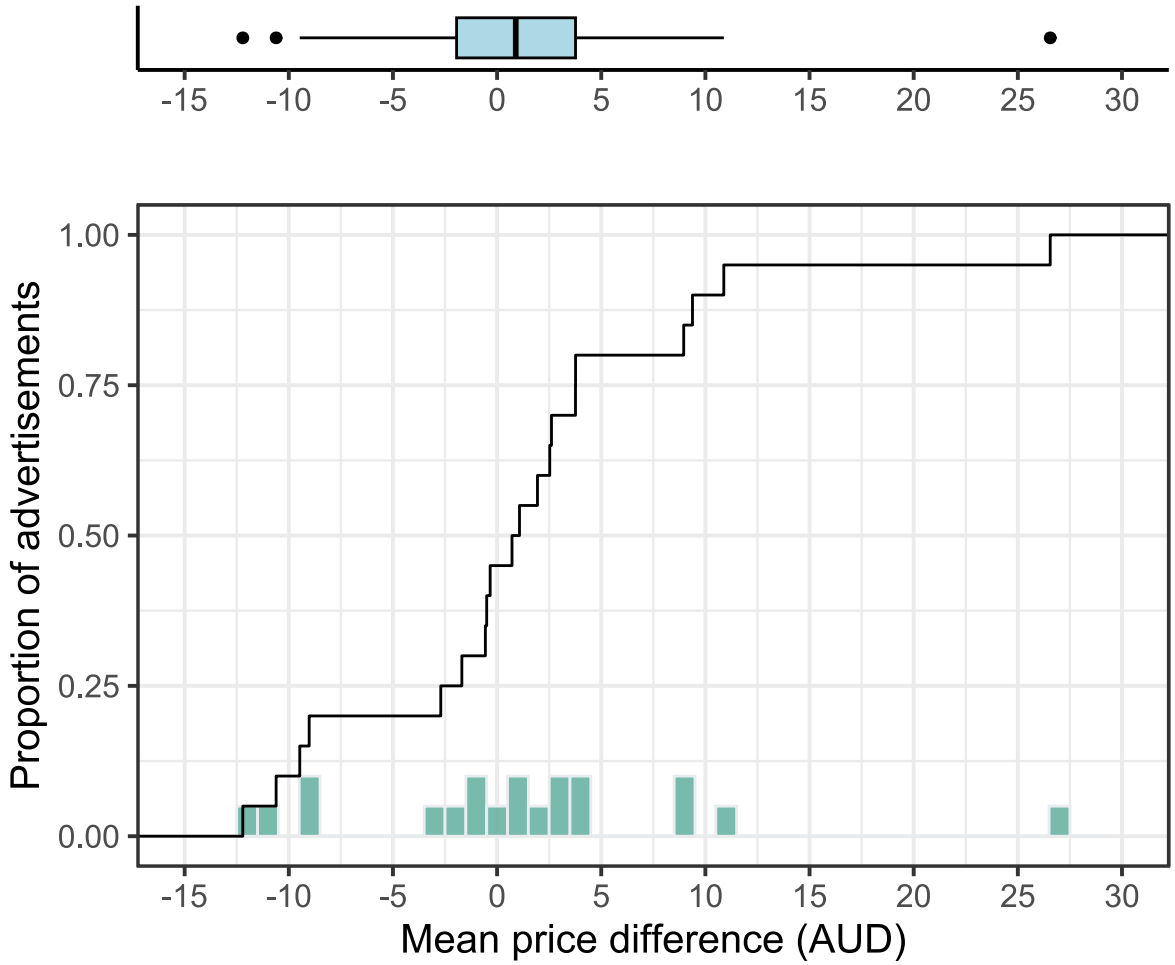

Figure 5: Distribution of the mean difference in price for declared plant taxa between prohibited and permitted jurisdictions. The black line on the histogram represents the cumulative distribution of mean price differences. A positive mean difference translates to comparatively more expensive prices in prohibited jurisdictions and cheaper in permitted jurisdictions. Negative mean difference translates to comparatively more expensive prices in permitted jurisdictions and cheaper in prohibited jurisdictions. The distribution represents 20 plant taxa declared and one unit represents 1 AUD. Taxa that are declared in all jurisdictions and those with less than 2 advertisements in each legality category (i.e., prohibited or permitted) were removed as comparisons could not be made.

Most frequently traded declared plants and advertised uses

The most frequently advertised declared plants were Opuntia cacti and aquatic weeds (Figure 6). The declared plant with the greatest number of prohibited advertisements was *Opuntia microdasys* (bunny ears cactus) (Figure 6b). Other *Opuntia* species were frequently traded, including *Opuntia monacantha* (drooping prickly pear) and *Opuntia ficus-indica* (Indian fig). Aquatic weed species were particularly common, including *Eichhornia crassipes* (water hyacinth) and *Limnobium laevigatum* (Amazon frogbit). *Zantedeschia aethiopica* (arum lily), an invasive geophyte, had the highest total number of advertisements for a declared plant, and the second highest number of prohibited advertisements (Figure 6). Other frequently detected invasive plants were *Gazania* spp. (gazanias), *Hedera helix* (English ivy), *Lavandula stoechas* (topped lavender), *Rubus fruticosus* (Blackberry), *Orbea variegata* (carrion flower), and *Azadirachta indica* (neem) (Figure 6). A complete list of all declared species found and the number of prohibited and total declared detections are provided in Appendix 5.

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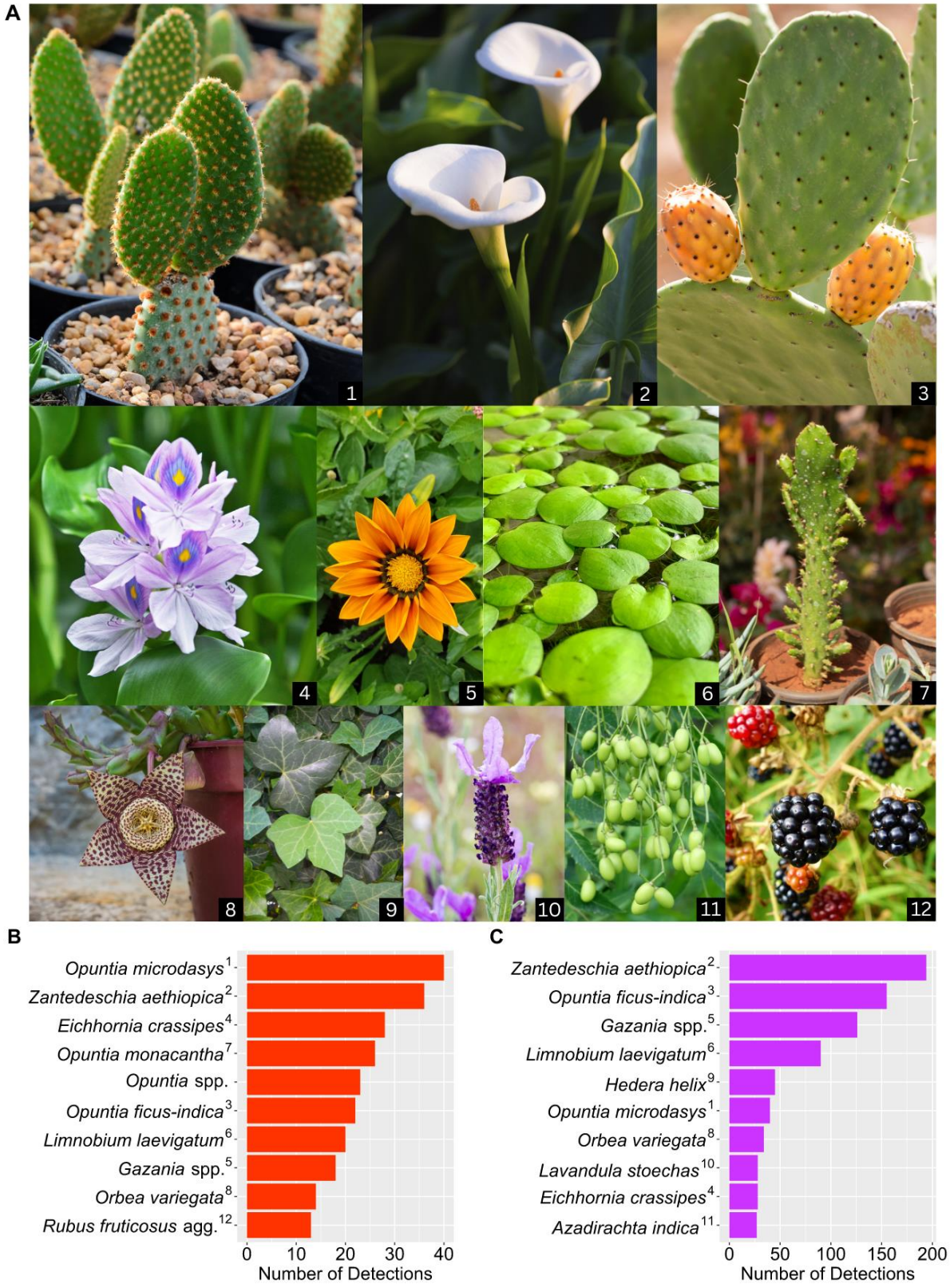

Figure 6: Invasive plants most frequently advertised on an e-commerce platform during a 12-month period. These plants are prohibited to trade in one or more Australia jurisdictions (i.e., declared plants). **B** Lists the 10 declared plants that were most frequently advertised in jurisdictions where they are prohibited to trade (i.e., advertised illegally). **C** Lists the 10 most frequently advertised plants declared in any jurisdiction. The superscript numbers correspond to the plant photos in **A**. The size of the photos is approximately scaled by their relative

319 frequency in trade. Photos are sourced from Getty Images and are credited to: (1) Boonsom,
320 (2) TopPhotoImages, (3) Wjarek, (4) Igaguri_1, (5) Reginaldo Bergamo, (6) Jonnyjto, (7)
321 ePhotocorp, (8) Radka Danailova, (9) Belizar73, (10) Membio, (11) Bdspnimage, (12)
322 Paulfjs.
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We recorded a variety of suggested uses for declared plants (Figure 7). Sellers explicitly mentioned uses for plants in only 148 of the 1,296 advertisements of declared plants (c. 11%; 50 taxa). The most advertised use was for aquatic purposes, which encompassed actions such as improving or maintaining water quality and providing habitat for aquatic animals (n = 72) (Figure 7). *L. laevigatum* was the declared plant most often advertised with a use, all of which were for aquatic purposes (Figure 7). The invasive attributes of some plants interplayed with their proposed uses. For example, gazanias were advertised as groundcovers as they spread easily and form dense mats, and *Ligustrum vulgare* (privet), known for its dense vegetation, was promoted as a screening plant. A complete list of all declared species advertised with uses is provided in Appendix 6.

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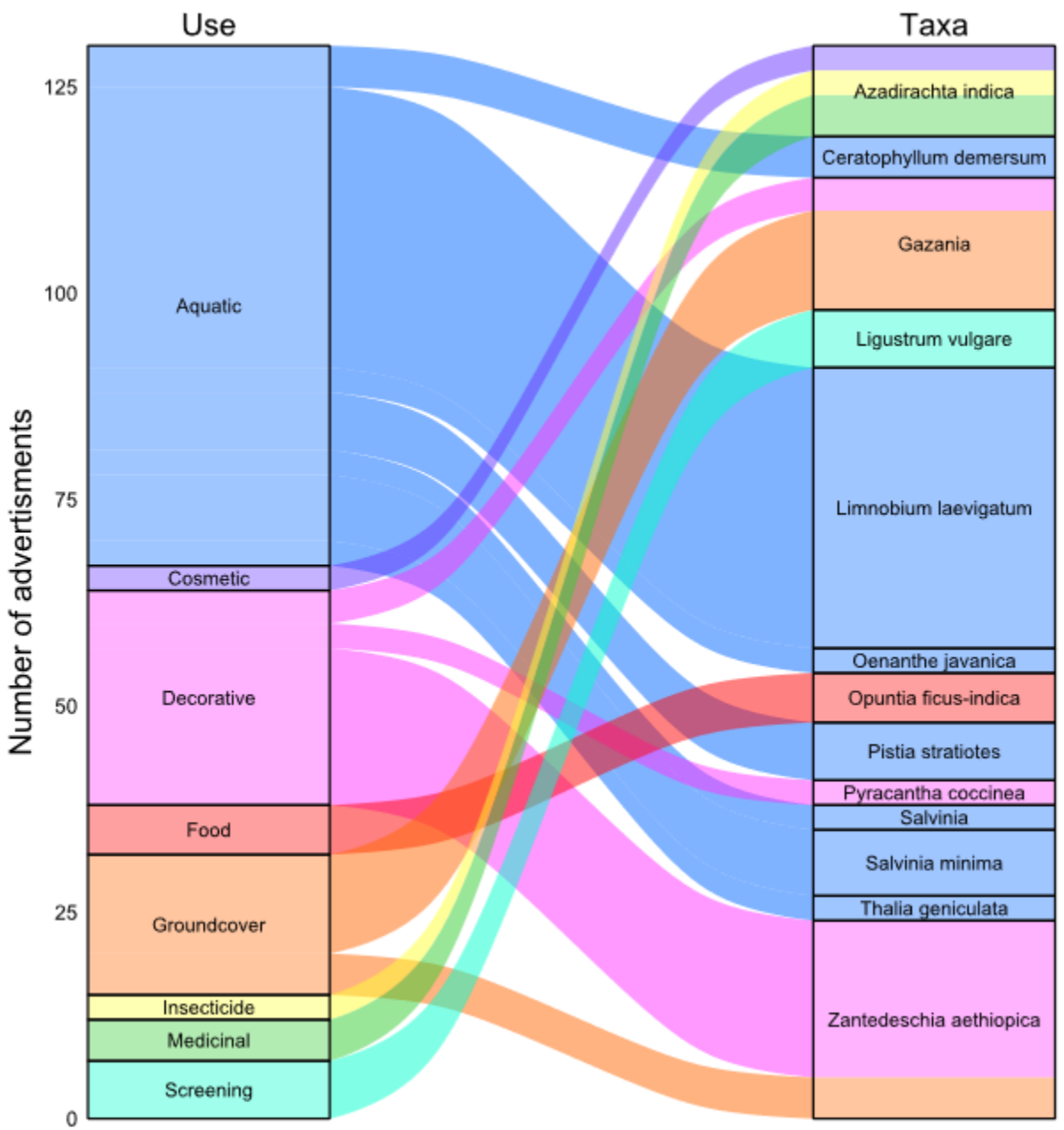

Figure 7: Thirteen invasive plant taxa prohibited to trade (termed declared plants) that were most frequently advertised with a use. In total 50 declare plant taxa had uses reported in advertisements. The number of advertisements is stratified by the promoted use for the plant. These uses were reported by traders and were not verified in this study. Here we provide the use definitions and the number of advertisements the use was promoted in. Aquatic - filters and conditions water and provides habitat for aquatic animals (n = 72). Decorative - floral arrangements, bonsai, and materials for craft projects (n = 32). Groundcover - grows and covers ground well, may inhibit other plant growth or prevent erosion (n = 22). Food - edible fruits, vegetables, herbs, spices, or advertised as a superfood (n = 17). Medicinal - provides medicinal benefit (n = 11). Screening - privacy screening, hedging, or a wind break (n = 10). Cosmetic - used for cosmetic purposes such as skin care (n = 4). Insectary - attracts pollinating insects (n = 4). Insecticide - kills or repels insects (n = 3). Air - provides oxygen and purifies air (n = 2). Spiritual - incorporated into spiritual beliefs and practices (n = 1).

Discussion

Ornamental plant trade is the world's leading pathway for invasive plant introductions and is clearly aided by e-commerce (Humair et al. 2015; Munakamwe and Constantine 2017; Peres et al. 2018; van Kleunen et al. 2018; Beaury et al. 2021). The online trade of invasive plant species within Australia is occurring, despite the country's strict biosecurity policies. On a single popular e-commerce website, we found hundreds of opportunities to purchase a wide variety of declared plants over the course of one year. Given the differences in the legal status of plants between jurisdictions, we highlight the need for greater policy coordination and effective surveillance between jurisdictions. Further, we suggest pursuing cooperation from e-commerce platforms to prevent trade of prohibited plants as well as pursuing more public education of this issue. Without continued surveillance and more intervention, we expect these negative impacts will continue to occur.

We found that about 1% of plant trade on a popular Australian e-commerce platform was prohibited (i.e., illegal). This translates to an estimated 2,800 advertisements that are illegally trading declared plant taxa each year on just one e-commerce platform. Thus, the scale of online trade poses a serious invasion threat and demands greater scrutiny. The pace of the ornamental plant trade in Australia is increasing, where 2020 saw a record high number of plant sales in the nursery industry (Horticulture Innovation Australia 2021). Since declared plant taxa have already been determined as serious biosecurity concerns (i.e., declared in State/Territory laws), we argue that monitoring and interception of this trade is certainly warranted and should continue (Munakamwe and Constantine 2017). Moreover, given that our species accumulation did not approach a limit, it is likely that we have not (yet) captured the full diversity of declared plants traded online. It should also be noted that our study focussed on a narrow group of invasive plants (i.e., those that are currently declared as illegal to trade). Beyond the declared plants there are likely many other non-regulated, invasive plant species being traded on these e-commerce platforms that may still cause environmental harm (Beaury et al. 2021).

In addition to the prohibited trade, declared plants were widely advertised in jurisdictions where they are currently permitted to trade. Incorporating this aspect of trade resulted in an estimated 7,000 declared plant advertisements per year. Some of the most frequently traded declared species are only prohibited to trade in one or two jurisdictions, despite being invasive in some permitted jurisdictions. Some examples of invasive populations in permitted jurisdictions include: *Lavandula stoechas* in South Australia (Nicholson 2006), *Orbea*

variegate in New South Wales (Hamilton et al. 2013), and *Limnobium laevigatum* in Queensland (Bickel et al. 2022). A similar situation has been observed in the United States (Beaury et al. 2021), another geographically large country with multiple states with their own governing legislations. Like in the United States, we argue this type of trade can compromise the biosecurity of neighbouring jurisdictions (Beaury et al. 2021). This is especially concerning since the plant trade facilitates long-distance dispersal from plants mailed over long distances (Maki and Galatowitsch 2004). Thus, we suggest future weed risk assessments should factor in the occurrence of e-commerce trade in other jurisdictions as a key dispersal pathway. For example, *Limnobium laevigatum* is currently declared in only three Australian jurisdictions but was traded in all eight. By using online trade data, we argue that jurisdictions should reconsider the risk of invasive species like *L. laevigatum* to determine if prohibition is warranted. Jurisdictions should also consider a nationally consistent approach to plant declarations similar to control programs which are known to benefit from cross-border coordination (Pluess et al. 2012). As long as the trade of declared plants persists somewhere in Australia, the risk of natural or human mediated dispersal into vulnerable landscapes will remain.

While more consistent regulations among jurisdictions would provide the legal framework to address invasive plant trade, our results suggest this is not a cure-all. We found that across declared plant taxa, similar quantities of advertisements were observed in prohibited and permitted jurisdictions. This suggests jurisdiction-based regulation is currently proving unsuccessful at impacting the trade of declared plants on this public e-commerce website. There was also no meaningful influence on price, however we only had 100 observations for price to make this estimate. Jurisdictional regulations are likely reducing the total abundance of declared taxa in Australian plant trade, but more so through compliance from traditional nurseries. The lack of effect on quantity and price we observed could indicate either online sellers perceive trading declared plants as low risk or lack the awareness that these plants are invasive and that their trade is prohibited. A perception of low risk by sellers may be in part due to limited enforcement of e-commerce due to surveillance and legal challenges (Lavorgna and Sajeva 2021; Whitehead et al. 2021). Public awareness has been suggested by other studies into invasive plant trade, reporting that people are often unaware, lack the ability to correctly identify plants, or are misinformed about relevant legislation rather than knowingly breaking the law (Derraik and Phillips 2010; Martin and Coetzee 2011; Munakamwe and Constantine 2017). We suggest implementing web scraping surveillance tools to improve enforcement and to enhance public knowledge through awareness campaigns which improve invasive species

management (Novoa et al. 2017; Cordeiro et al. 2020; Li et al. 2021). Further, e-commerce platforms can also play a role in prevention and should be engaged as a biosecurity stakeholder. Specifically, in agreement with other studies of the illegal plant trade, we recommend that relevant governments coordinate with e-commerce platforms to prevent illegal trade (Derraik and Phillips 2010; Munakamwe and Constantine 2017).

We found that *Opuntia* cacti and aquatic invasive plants were among the most frequently traded declared plants. This is concerning given the historical extent of *Opuntia* impact on the Australian environment (Freeman 1992), and the invasiveness of the traded aquatic weeds *Eichhornia crassipes* and *Limnobium laevigatum* (Riches 2001; Tidwell and O'Donnell 2010; Villamagna and Murphy 2010). We propose that some traits that aid their invasion success also simultaneously lend to their popularity in trade. *Opuntia* cacti are hardy, drought tolerant plants that require low maintenance making them desirable options for people with less horticultural experience. They are easily propagated from cuttings and will do so readily when discarded from gardens (Smith 2006; Smith et al. 2011). *E. crassipes* and *L. laevigatum* can also reproduce vegetatively and in good conditions growers will quickly have an overabundance (Madsen and Morgan 2021; Prasetyo et al. 2021). This ease of excess could present sale as an attractive option to get rid of surplus plants, thus facilitating invasions. In the case of *Opuntia*, some of the cacti's protective traits (e.g., spines) can make them undesirable to an owner but may contribute to their trade. For example, the glochids of *O. microdasys* can cause severe irritation if they enter the eye (Whiting and Bristow 1975; McGovern and Barkley 1998). Smith et al. (2011) suggest that these problematic glochids drive owners to dispose of the plants through dumping. The high number of advertisements we observed of these taxa may indicate that selling off the plant is an attractive alternative to disposal. This is evidenced from compliance officers investigating *Opuntia* sales, who report that sellers mention a desire to sell the plants in order to be rid of them (D. Swan 2021, pers. comm., 3 November).

We demonstrated that web scraping paired with targeted string matching was a more effective means of detection than random sampling. Image recognition technology could be employed to further increase detection rate (Di Minin et al. 2019). However, the accuracy of image recognition is dependent on large, pre-identified image datasets and the quality of images provided (Xiong et al. 2021). The quality of images that we observed in advertisements varied greatly in resolution and often had complex backgrounds, a feature known to hinder the accuracy of image recognition (Xiong et al. 2021). We propose that string matching and other

natural language processing methods are a cost-effective means for the semi-automated detection of invasive plants on e-commerce platforms.

The advertised uses for declared plants revealed some reasons why people desire them, which may complicate their management. We discovered a variety of uses advertised for declared plants, including food, medicine, cosmetics, and decorative (e.g., floral arrangements). However, the most commonly advertised uses fell into the 'aquatic' category; uses such as water-conditioning and providing habitat for aquatic pets. Perceived water-conditioning abilities could encourage people to introduce the plant into waterbodies (e.g., ponds and damns), risking dispersal into the surrounding environment. For example, we found *E. crassipes* traded which has been known to be intentionally introduced into waterbodies to help prevent algal blooms (Villamagna and Murphy 2010). It is important to consider peoples intended use of an invasive plant since prevention is often more of a cultural challenge than biological (Pfeiffer and Voeks 2008). Understanding the public's desire for an invasive plant could help to tailor education campaigns or promote non-invasive alternatives. It is also important that public attitudes are understood to establish collaborative efforts between invested communities and policymakers, which will lead to optimal social and biosecurity outcomes (Virtue et al. 2004; Head 2017).

Conclusion

The online trade of invasive plants is occurring in Australia, with prohibited advertisements found in all jurisdictions. This online trade creates many opportunities for the public to purchase and spread declared invasive plants around the country. As it stands, laws prohibiting the trade of declared plants have not been effective at stopping prohibited advertisements of declared plants on public e-commerce. We suggest enhancing detection methods of illegal trade using web scraping techniques to improve enforcement. Jurisdictions should also focus on educating the public that certain plants are prohibited to trade while considering the desire that people have for these plants to help promote safe alternatives. Cooperation should be sort from e-commerce websites to prevent instances of illegal trade being facilitated on their platforms. For now, monitoring e-commerce is still needed and we have demonstrated that web-scraping is an effective tool. Data collected from monitoring e-commerce could also be utilised in future weed risk assessments with online availability incorporated as a risk factor. Beyond surveillance, jurisdictions should seek to better align the taxa they choose to regulate as the existing legal disparities are likely to contribute to the persistence of invasive species within

479 the country. Australia's biosecurity, and that of other regions, would benefit from more
480 coordinated approaches to controlling the online trade of invasive species.

481

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