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Weed wide web: characterising illegal online trade of invasive plants in Australia

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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 the 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 extent of illegal trade in invasive plant species in Australia by collecting advertisements found on a popular public e-commerce website. Across a 12-month period we collected a total of 235,162 plant advertisements. From 10,000 of these advertisements (4.25% of total advertisements) we found 155 plant taxa advertised online that were prohibited to trade in at least one Australian State or Territory (12.5% of Australia's total prohibited plant taxa). We detected 1,415 instances of 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 reported by the sellers, with aquatic uses being the most popular (i.e., water filtering and habitat for aquatic animals). We used generalised linear mixed-effects models to test the effect of prohibiting the sale of invasive plants on the quantity and price of online advertisements. Despite Australia's strict internal biosecurity regulations, we found that trade prohibitions had no influence on the quantity and price of trade in illegal invasive plants. Given this, and the extent of illegal invasive plants traded, we believe increased monitoring and regulation of online plant trade is warranted. We demonstrate that targeted searches using string matching is an effective tool for detecting e-commerce trade of invasive species. 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.

Keywords
Aquatic weeds, biosecurity, e-commerce, *Opuntia*, ornamental plants, prevention, surveillance, web scraping

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 both 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, hereafter termed e-commerce (Derraik and Phillips 2010; Lenda 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; Lenda et al. 2014; Humair et al. 2015; Beaury et al. 2021). As a result, e-commerce has 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 Australian 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, Australia already has more than 29,000 introduced alien-plant species (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 the main responsibility for their management and control. A common control measure used by jurisdictions is to 'declare' invasive plant taxa in legislation as prohibited to trade within jurisdictional borders (simply 'declared plant' hereafter); with 1,236 taxa declared in one or more jurisdictions across Australia. These taxa are declared because they pose significant risks of environmental, economic and/or social impacts to natural ecosystems, agricultural and forestry production, and human communities. While legislation differs slightly between jurisdictions, generally it is prohibited to supply, sell, or transport declared plants, with fines issued for offences. However, e-commerce websites could circumvent traditional enforcement measures by trading without physical stores, sending plants by mail, or having buyers collect plants from private residences, resulting in a poorly regulated sector of the horticultural market (Munakamwe and Constantine 2017). Screening for invasive plants entering the country is also challenging due to the high volume of incoming international mail (Australian National Audit Office 2014). Therefore, surveillance of e-commerce is an essential tool for detecting and preventing plant invasions (Humair et al. 2015; Lavorgna et al. 2020; Duncan 2021; Stoett and Omrow 2021; Whitehead et al. 2021). E-commerce websites where members of the public post plant advertisements are particularly difficult to monitor. Some efforts have been made to monitor this trade within 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 within Australia (i.e., internal trade, not international shipments into Australia), we applied web-scraping technology to monitor and record plant trade advertisements on a popular Australian 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. We seek 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). Jurisdictional declarations can include Australian native plant species that have invaded beyond their indigenous range, for example a Western Australian species that is invasive in eastern Australia. Hence declared native plant species are 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 Suppl. material 1 for complete list of sources). Our compiled list of declared plants and relevant legislation was reviewed and endorsed by 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 (Suppl. material 2) (Nursery & Garden Industry Australia 2009). A total of 38 nursery websites and 4 public e-commerce websites were reviewed. We defined nursery websites as private online businesses. Public e-commerce websites host online classifieds where members of the public can post personal advertisements. We found plants considered to be invasive on nursery websites, but we did not find any that were declared in the jurisdiction the nursery was located in (i.e., no prohibited advertisements). In contrast, our initial investigations of public e-commerce yielded many prohibited advertisements for declared plants. Alongside our internet search, we consulted with biosecurity officers from each jurisdiction who had experience monitoring the online plant trade. They identified public e-commerce websites over private nursery websites as their primary concern, citing regular detections of declared plants on the former in their own investigations. The risk of public e-commerce is an under-assessed aspect of the ornamental plant trade as it is difficult to monitor and regulate. Based on this recommendation and the findings of our web search, we concentrated our study on one highly popular public e-commerce website. This allowed us to construct a reliable and consistent web scraper for a popular e-commerce website that included seller location data and which frequently traded declared plants, based on expert opinion and our preliminary search. This website hosts trade within Australia and is not specific to ornamental plants. However, the website has a 'plant' category from which we collected advertisements. Sellers advertise plants, and sales are conducted through private exchanges between traders either online, over the phone, or in person. Therefore, it is important to note that we could not determine how many plants were actually sold from the data we collected. Similarly, we could not determine how many advertisements were relisted plants that had previously failed to sell. We have kept the identity of this website anonymous in accordance with our ethics approval (Ethics approval H-2020-184). Personal and identifiable information of traders is available on this website and while publicly available our ethics involve taking a cautious approach to avoid revealing behaviour which may have legal ramifications. Additionally, identifying the website could alter the behaviour of traders which would reduce the value of ongoing surveillance research (Stringham et al. 2020).

To collect online advertisement data, 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 collected all advertisements from the designated plant category of the website. Plant advertisement data was stored on a local SQL database. For this study, we explored 12 months of plant advertisements between 1 February 2020 and 31 January 2021. Duplicate collections of advertisements were common because the web scraper ran on a daily basis. We removed these duplicate advertisements based on a unique listing identifier generated by the website. This resulted in 235,162 unique advertisements collected over the 12-month period. For our analysis we removed any advertisements that did not provide a seller location, leaving us a dataset of 233,694 advertisements.

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 completed by the users, and thus the taxonomic names could not be automatically retrieved (i.e., no standardization in names). Identification of plants was conducted manually using text and pictures, provided by the seller, which was a time-consuming process. Subsequently, we explored a subset of the advertisements. For our study, we extracted two samples of 5,000 advertisements each. The first sample was a random sample of all plants traded stratified by jurisdiction. For the second sample we utilised natural language processing to focus specifically on detecting declared plants.

The first sample was untargeted; it sampled from all the advertisements we collected and did not intentionally target declared plants. This sample was stratified by jurisdiction with 625 unique advertisements randomly sampled from each jurisdiction, providing 5,000 advertisements in total. We used this dataset to estimate the underlying proportion of declared plant trade in each jurisdiction and to compare the effectiveness of our targeted sampling method.

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 natural language processing 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 (Suppl. material 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. String matching helped reduce the number of advertisements down to a more manageable data set with a higher probability of detecting declared plants. However, common and generic plant names are non-specific and can be shared by many species. This resulted in false positives in the targeted sample. Our pilot investigation revealed some frequent false positives due to the inclusion of certain broad search terms (e.g., 'lily' returned many non-target species). We created a list of match exceptions to remove the bulk of the false positives (Suppl. material 3). Therefore, if an advertisement contained the word 'lily' and contained a match exception such as 'peace lily' (a non-target species) it would be removed, but an advertisement for 'arum lily' would remain. This approach helped us to reduce the number of false positives while retaining the use of certain generic search terms. Out of 233,694 total advertisements, text in the title or description matched to 12,751 advertisements for declared plants. From this, we took a sample of 5,000 unique advertisements. Given our interest in characterising the legality of online trade across Australian jurisdictions, we stratified the sample by jurisdiction. Three jurisdictions had substantially fewer advertisements: Australian Capital Territory, Northern Territory, and Tasmania (Table 1). To help capture trade from these three smaller jurisdictions all advertisements that matched declared plant search terms were analysed. The remaining jurisdictions were randomly sampled until 5,000 unique advertisements was reached (Table 1).

We cleaned the sampled datasets by identifying the 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. It is important to note that recorded locations were seller locations and not where a plant may have been transported to after it had been purchased. Predominately, advertisements were for live plants, however we also captured trade of seeds and other propagules. 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 recorded the number of plant taxa identified and how many were declared plants. We used species accumulation curves to assess how well our samples captured the diversity of plant taxa and declared plant taxa traded online. 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). However, multiple declared plant taxa could appear in a single advertisement. To account for this, we also recorded each detection of a declared plant taxon in any single advertisement. To help explain these different types of trade observations an example with term definitions is provided in Fig. 1. By using these observation metrics, we were able to capture prohibited trade of a declared plant and the broader extent of its trade within Australia.

Table 1. The number of advertisements collected and sampled from an e-commerce website stratified by jurisdiction. The table provides the number of advertisements from: (i) 12 months of web scraping (Total dataset); (ii) the untargeted sample (Untargeted); (iii) the string-matching for declared plant taxa (Matched); and (iv) the targeted sample (Targeted). The targeted sample was weighted to better capture trade in three jurisdictions with comparatively lower quantities of matched advertisements: Australian Capital Territory, Northern Territory, and Tasmania (* indicates weighted samples). All advertisements that matched search terms for declared plants in these jurisdictions were cleaned. The remaining advertisements were sampled randomly across the remaining jurisdictions to total 5,000 advertisements.

Jurisdiction	Total dataset	Untargeted		Matched	Targeted
Australian Capital Territory (ACT)	7,362	625	**String matching using declared plant search terms →**	420	*420
New South Wales (NSW)	64,641	625		3,351	1,031
Northern Territory (NT)	859	625		66	*66
Queensland (Qld)	48,909	625		2,893	948
South Australia (SA)	21,121	625		1,073	539
Tasmania (Tas.)	5,991	625		308	*308
Victoria (Vic.)	41,186	625		2,567	921
Western Australia (WA)	43,625	625		2,073	767
Total	***233,694***	***5,000***		***12,751***	***5,000***

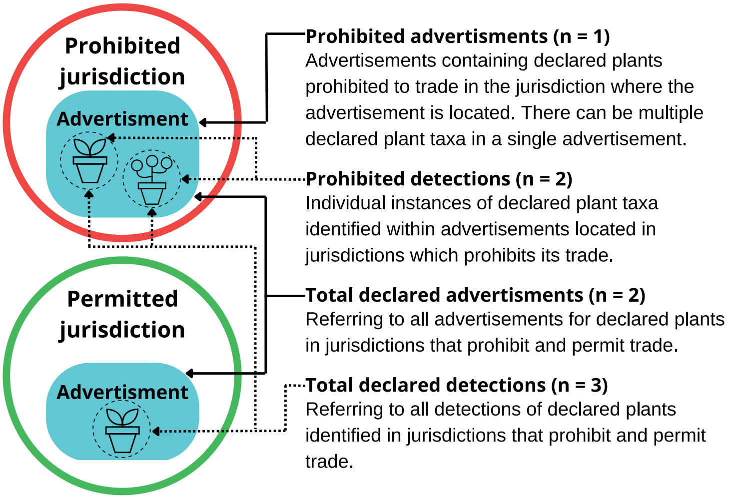


Figure 1. A diagram explaining the terms we used to define the different types of plant trade observations. This example shows two advertisements and two species of declared plant (plants prohibited to trade in a given jurisdiction). The number of observations for each term in this scenario are provided 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 prohibited trade on quantity and price

We used generalised linear mixed-effects models to test whether prohibited trade had an effect on the trade quantity and price of declared plants. These models considered declared status as the binary explanatory variable and taxa identity as a random effect (i.e., random intercept). For quantity, we hypothesised fewer declared plants are advertised in jurisdictions that prohibit their trade compared to jurisdictions that permit their trade. We based our rationale on the notion that laws prohibiting trade would reduce the number of advertisements online. For price, we hypothesised that in jurisdictions that prohibit trade, prices for declared plants would be higher compared to jurisdictions that permit trade. Our rationale was that laws prohibiting trade would result in an increased price to offset their risk; i.e., buyers paying a premium for prohibited plants. We measured the performance of the models using Nakagawa and Schielzeth's conditional R-squared (Rc2) (Nakagawa and Schielzeth 2013). For all models, we used the targeted dataset, which had the greater number of total declared advertisements compared to the untargeted. For these models, we removed nationally declared taxa, i.e., taxa declared in all jurisdictions (n = 130 taxa remaining for quantity comparison). In the quantity models, we defined quantity as the proportion of advertisements within each jurisdiction's sample. This approach was to account for differing sample sizes among jurisdictions in the target dataset (see Table 1 for sample sizes). For analysing price differences, we used unit prices (price per plant) gathered from the targeted and untargeted datasets. Further, for these price models, we excluded taxa with fewer than two advertisements in each legality category (i.e., prohibited or permitted); this limited the model to 20 taxa. There were two factors that contributed to this reduction. Firstly, a price per plant could not be determined for many advertisements. Either no clear price was provided or plants (particularly aquatic species) were priced by inconsistent container volumes (i.e., $5 for a full take-away container). Secondly, for some plants price data was absent from a legal category (i.e., no prices recorded in either a prohibited or permitted jurisdiction).

We took an additional approach to assess and visualise the difference in quantity and price by exploring the distribution of differences in quantity and price. We calculated the difference of mean quantity and price of each declared plant taxon traded in prohibited jurisdictions compared to permitted jurisdictions (i.e., the mean quantity of taxon A pooled across all prohibited jurisdictions minus the mean quantity of taxon A pooled across all permitted jurisdictions). We used this distribution to determine the degree that prohibited trade affected trade quantity and price, where a distribution centred around zero with low variation suggests little to no influence.

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 and Müller 2022). Regression model coefficients were summarised and extracted using the 'broom' package (Robinson et al. 2021). Shapefiles were obtained from the Australian Bureau of Statistics (2021) and visualised using the 'sf' package (Pebesma 2018). Species accumulation curves were calculated using the 'vegan' 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). To create and assess models we used: 'lme4' (Barton 2020), 'lmerTest' (Kuznetsova et al. 2017), and 'MuMIn' (Bates et al. 2015) packages. 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).

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 (Fig. 2a) of which 78 were declared plants prohibited to trade in the jurisdictions where they were advertised (c. 6% of declared plants). A further 77 declared plants were advertised legally in juris-

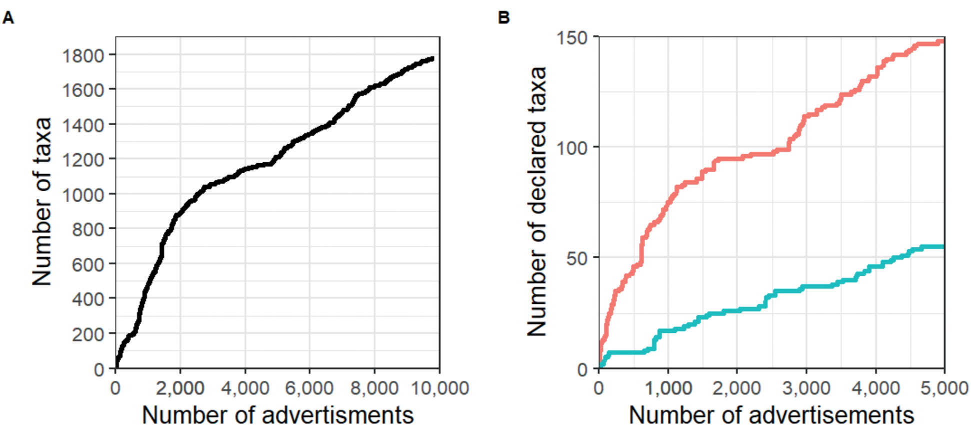
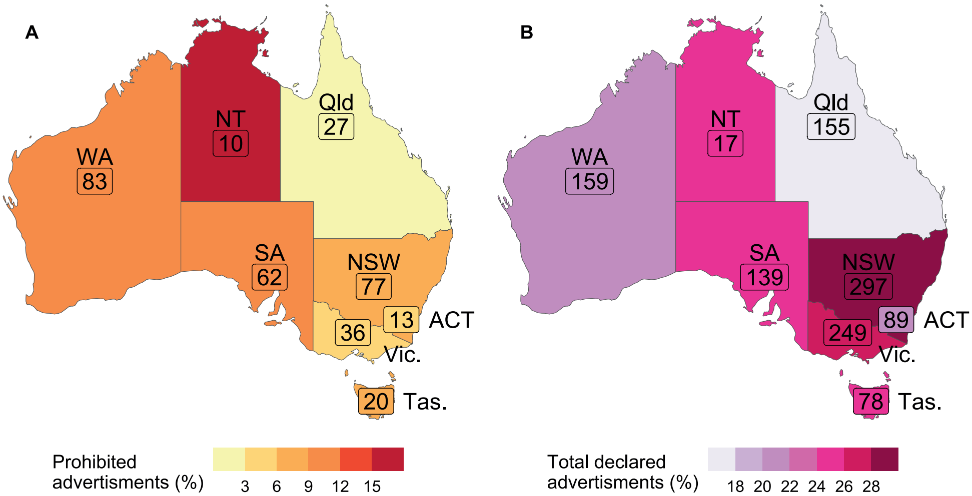


Figure 2. Accumulation curves of plant taxa identified from sampling 10,000 online advertisements **A** accumulation curve of all plant taxa identified. There were 1,777 taxa observed from 10,000 advertisements **B** accumulation curves of declared plant taxa identified. The red line represents a targeted sample that utilised search terms to locate declared plant advertisements and the blue line represents an untargeted sample that did not use search terms (i.e., random sampling). There were 155 declared taxa identified in 1,415 detections of declared plants.

dictions that do not prohibit their trade. This brought the overall number of declared plants traded to 155 taxa (c. 12.5% of all declared plants in Australia) (Fig. 2b). We did not observe any of the species accumulation curves approaching a clear limit (Fig. 2).

From the 10,000 advertisements examined, we made 411 prohibited detections (from 374 advertisements) within 1,415 total declared detections (from 1,296 advertisements). 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%) (Fig. 3). New South Wales (NSW) and Victoria (Vic.) are the most populous jurisdictions in Australia (Australian Bureau of Statistics 2020) and had the greatest number of total declared advertisements. Western Australia (WA) declares the greatest number of plant taxa of any Australia jurisdiction (877 plant taxa) and had the greatest number of prohibited advertisements (Fig. 3).



C

Jurisdiction	Population	Plants declared
Australian Capital Territory (ACT)	431,484	288
New South Wales (NSW)	8,172,505	402
Northern Territory (NT)	246,561	372
Queensland (Qld)	5,194,879	354
South Australia (SA)	1,770,790	391
Tasmania (Tas.)	541,506	434
Victoria (Vic.)	6,661,736	361
Western Australia (WA)	2,670,241	877

Figure 3. The number of advertisements for declared plants detected on an e-commerce platform over a 12-month period. These detections were made from a sample of 5,000 advertisements that had been matched to search terms for declared plants (i.e., targeted sample) **A** the number of prohibited declared plant advertisements detected within the jurisdiction (i.e., prohibited in that jurisdiction, refer Fig. 2). The colour refers to the percentage of advertisements that were prohibited **B** the total number of declared plant advertisements detected in that jurisdiction that are declared anywhere in Australia. The colour refers to the percentage of advertisements that contained declared plants **C** the 2020 resident population (Population) and number of plant taxa declared in each jurisdiction (Plants declared). Population data was sourced from Australian Bureau of Statistics (2020).

Influence of trade prohibition on quantity and price

The generalised linear mixed-effects models revealed no statistically significant effect on the quantity and price of declared plants between jurisdictions that prohibited trade and those that did not. The model for quantity had a *p*-value of 0.58 for the quantity coefficient, with a sample size of 1040, which covered 130 declared taxa (quantity coefficient estimate = -0.000266 ± SE = 0.000479; *t* = -0.56; Rc2 = 0.32). The model for price had a *p*-value of 0.13 for the price coefficient, with a sample size of 652, covering 20 declared taxa (price coefficient estimate = -6.25 ± SE = 4.11; *t* = -1.52; Rc2 = 0.24).

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 (Fig. 4). The declared plants with the greatest mean differences were *Drimia maitima* (mean absolute difference c. 5 plants) which had higher quantities in

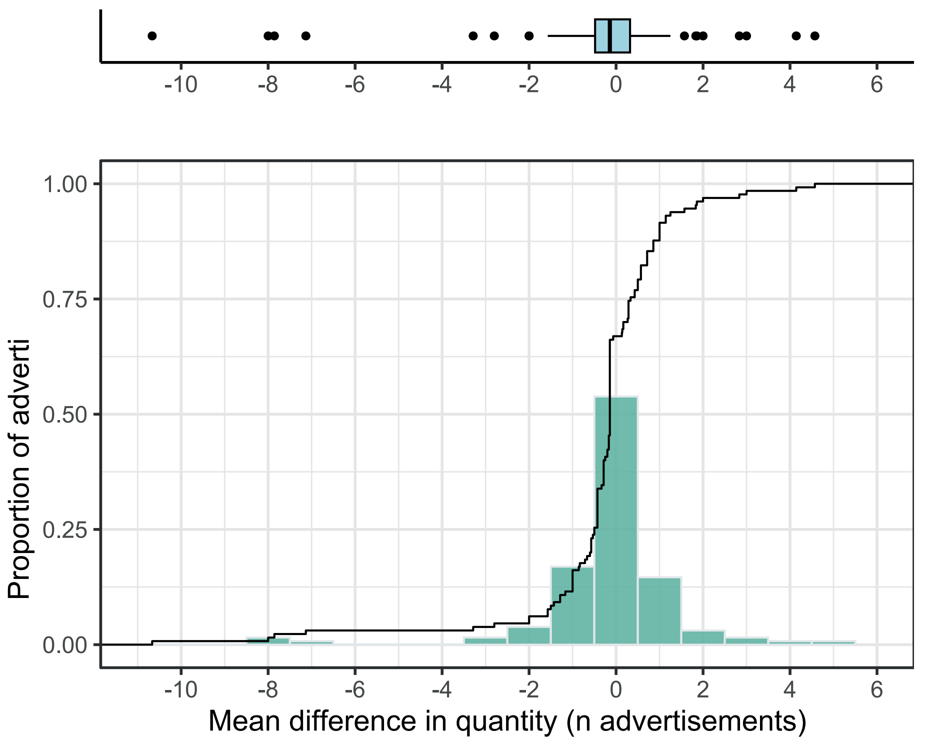


Figure 4. Distribution of the mean difference in the number of advertisements for declared plant taxa between prohibited and permitted jurisdictions. The black curve overlaying the histogram represents the cumulative distribution of mean differences in advertisement quantities. A positive mean difference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

prohibited jurisdictions, and *Opuntia ficus-indica* (mean absolute difference c. 11 plants) with higher quantities in permitted jurisdictions. We found far fewer advertisements for declared plants in the untargeted sample compared to the targeted sample (Table 2). Across jurisdictions the proportion of prohibited advertisements was c. 0.2–2% and total declared advertisements was c. 1–5% in the untargeted sample (Table 2). The highest proportion of prohibited advertisements was observed in South Australia (SA) and NSW for the untargeted sample. In comparison, the detection rate in the targeted sample rose to c. 3–15% for prohibited and c. 16–28% for total declared advertisements across jurisdictions (Table 2 and Fig. 3). The highest proportion of prohibited advertisements was observed in Northern Territory (NT), SA, and WA for the targeted sample (Table 2 and Fig. 3).

The distribution of plant prices was similar across jurisdictions, typically ranging from \$5 to \$40 for a potted plant (Australian dollars; AUD) (Suppl. material 4). On average, prices were only \$1.25 more in prohibited jurisdictions with 60% (12/20 taxa) of observed taxa having a mean price difference within \$5 (Suppl. material 5). However, the sample size for the price model was greatly reduced compared to the quantity model, with only 20 declared plant taxa included.

Most frequently traded declared plants and advertised uses

The most frequently advertised declared plants were *Opuntia* cacti and aquatic weeds (Fig. 5). The declared plant with the greatest number of prohibited advertisements was *Opuntia microdasys* (bunny ears cactus) (Fig. 5b). Other *Opuntia* species were frequently traded, including *Opuntia monacantha* (drooping prickly pear) and *Opuntia*

Table 2. Summary of advertisements for declared plants in Australia's eight jurisdictions. Results are presented from two samples collected across 12 months of e-commerce activity. The untargeted sample represents a consistent number of plant advertisements sampled for each jurisdiction, based on the location of the seller. The targeted sample is a focused search for advertisements matching declared plant search terms, resulting in a variable number of advertisements sampled for each jurisdiction. The 'Prohibited' column indicates the count of advertisements (Ads) containing plants declared within the respective jurisdiction where the advertisement is located. The 'Total Declared' presents the number of advertisements (Ads) containing plants declared anywhere in Australia. The percentages (%) are calculated based on these observations and the respective sample sizes, with darker colours for higher relative percentages. The sample sizes represent the total number of advertisements considered in each jurisdiction.

Jurisdiction	Untargeted Sample					Targeted Sample				
	Prohibited		Total declared		Sample size	Prohibited		Total declared		Sample size
	Ads	%	Ads	%		Ads	%	Ads	%	
Australian Capital Territory (ACT)	7	1.12	19	3.04	625	13	3.10	89	21.19	420
New South Wales (NSW)	11	1.76	19	3.04	625	77	7.47	297	28.81	1031
Northern Territory (NT)	9	1.44	32	5.12	625	10	15.15	17	25.76	66
Queensland (Qld)	7	1.12	13	2.08	625	27	2.85	155	16.35	948
South Australia (SA)	13	2.08	21	3.36	625	62	11.50	139	25.79	539
Tasmania (Tas)	1	0.16	10	1.60	625	20	6.49	78	25.32	308
Victoria (Vic)	9	1.44	28	4.48	625	36	3.91	249	27.04	921
Western Australia (WA)	2	0.32	8	1.28	625	83	10.82	159	20.73	767
Total	59	1.18	150	3.00	5000	328	6.56	1183	23.66	5000

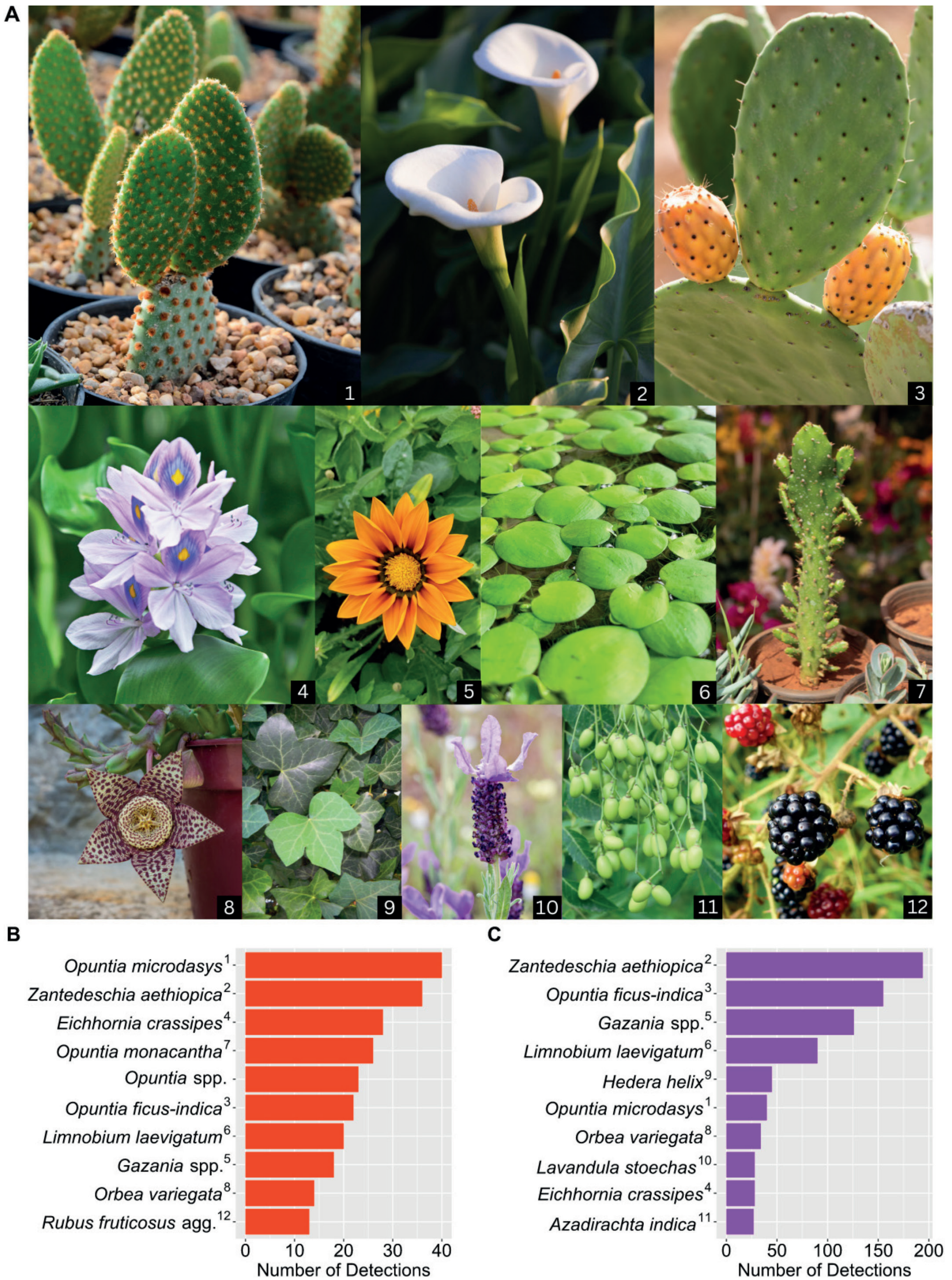


Figure 5. Invasive plants most frequently advertised on an e-commerce platform during a 12-month period. These plants are prohibited to trade in one or more Australian jurisdictions (i.e., declared plants) **A** the size of the declared plant photos is approximately scaled by their relative frequency in trade **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 next to species names correspond to the plant photos. Photos are sourced from Getty Images and are credited to: (1) Boonsom, (2) TopPhotoImages, (3) Wjarek, (4) Igaguri_1, (5) Reginaldo Bergamo, (6) Jonnyjto, (7) ePhotocorp, (8) Radka Danailova, (9) Belizar73, (10) Membio, (11) Bdspnimage, (12) Paulfjs.

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 (Fig. 5). 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) (Fig. 5). *Limnobium laevigatum* was an example of a highly traded declared species with a far greater number of detections in jurisdictions that did not declare it. We made 19 detections for *L. laevigatum* in three prohibited jurisdictions and 69 in five permitted jurisdictions. A complete list of all declared species found and the number of prohibited and total declared detections are provided in Suppl. material 6.

We recorded the following eleven suggested uses for declared plants (Fig. 6):

1. Aquatic – filters and conditions water and provides habitat for aquatic animals (n = 72).
2. Decorative – floral arrangements, bonsai, and materials for craft projects (n = 32).
3. Groundcover – grows and covers ground well, may inhibit other plant growth or prevent erosion (n = 22).
4. Food – edible fruits, vegetables, herbs, spices, or advertised as a superfood (n = 17).
5. Medicinal – provides medicinal benefit (n = 11).
6. Screening – privacy screening, hedging, or a wind break (n = 10).
7. Cosmetic – used for cosmetic purposes such as skin care (n = 4).
8. Insectary – attracts pollinating insects (n = 4).
9. Insecticide – kills or repels insects (n = 3).
10. Air – provides oxygen and purifies air (n = 2).
11. Spiritual – incorporated into spiritual beliefs and practices (n = 1).

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). *L. laevigatum* was the declared plant most often advertised with a use, all of which were for aquatic purposes (Fig. 6). 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 Suppl. material 7.

Discussion

Ornamental plant trade is the world's leading pathway for invasive plant introductions and is greatly facilitated by internet e-commerce (Humair et al. 2015; Munakamwe and Constantine 2017; Peres et al. 2018; van Kleunen et al. 2018; Beaury et al. 2021).

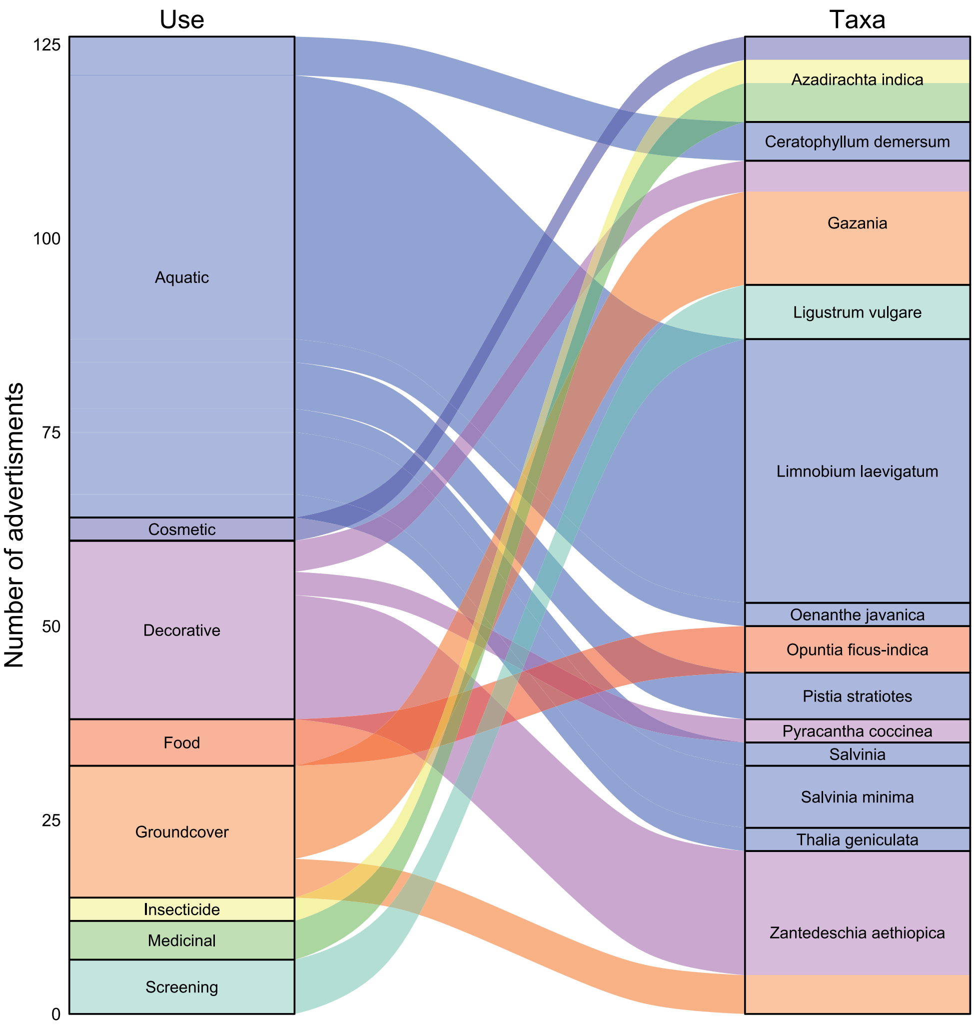


Figure 6. Thirteen invasive plant taxa prohibited to trade (termed declared plants) that were most frequently advertised with a use. In total, 50 declared plant taxa had uses reported in advertisements. The number of advertisements is stratified by the promoted use for the plant. These uses were reported by traders and were not verified in this study.

Our study represents the first investigation into the presence of the complete set of Australia's declared invasive plants on e-commerce. 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. This is despite the country's strict biosecurity policies and a weed risk assessment that has been adopted by other countries (Gordon et al. 2008). Trade of invasive plants through e-commerce has been documented in other regions such as New Zealand (Derraik and Phillips 2010), the United States (US) (Maki and Galatowitsch 2004; Beaury et al. 2021) and European Union (EU) (Lenda et al. 2014; Humair et al. 2015). Australia shares similarities with the US and EU, having accessible e-commerce platforms and easily facilitated trade across jurisdictions with differing biosecurity regulations. Our findings contribute to this growing body of evidence calling attention to e-commerce as an invasion risk pathway that is establishing globally. In particular, we have quantified the risk of illegal online plant trade conducted by individuals rather than commercial nurseries, which is a challenging aspect of e-commerce to monitor and regulate. We highlight the need to review our approaches to managing invasive species in the face of an increasingly interconnected world.

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). Given this growth and the availability of invasive plants, online trade poses a serious invasion threat and demands greater scrutiny. 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). Low detection rates emphasise the challenge of capturing and regulating this trade. Given that our species accumulation did not approach a limit, it is likely that we have not 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). Additionally, we only studied one e-commerce platform. A broader analysis of additional e-commerce platforms may reveal more declared invasive plant species that are available to the public.

In addition to the prohibited trade, declared plants were widely advertised in jurisdictions where they are currently permitted to trade. Just under half of the declared taxa and more than double the number of detections we found were located in the jurisdictions that did not prohibit sale. Some of the most frequently traded declared species are only prohibited to trade in one or two jurisdictions, despite many being known to be invasive in permitted jurisdictions. Some examples of invasive populations in permitted jurisdictions include: *Lavandula stoechas* in SA (Nicholson 2006), *Orbea variegata* in NSW (Hamilton et al. 2013), and *Limnobium laevigatum* in Queensland (Bickel et al. 2022). *L. laevigatum* was a particularly concerning example traded to a much larger extent in jurisdictions that did not prohibit its trade. We made 19 detections for *L. laevigatum* in prohibited jurisdictions and 69 in permitted jurisdictions. 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. A similar situation has been observed in the US (Beaury et al. 2021), another geographically large country with multiple states with their own governing legislations. Like in the US, we argue this type of trade can compromise the biosecurity of neighbouring jurisdictions (Beaury et al. 2021). For example, we found NSW and Vic. traded large quantities of species declared in neighbouring jurisdictions. This is especially concerning because the plant trade facilitates long-distance dispersal from plants mailed over long distances (Maki and Galatowitsch 2004). Despite the limitations of online trade data, it is still a valuable resource to help identify species or areas of concern (Kikillus et al. 2012). Thus, we suggest future weed risk assessments utilise data collected from monitoring e-commerce to factor in trade of invasive plants as a risk factor, even if occurring in other jurisdictions. Incorporating this may lead jurisdictions to consider a nationally consistent approach to plant declarations, similar to other control programs which have benefited from cross-border coordination (Pluess et al. 2012). As long as the trade of invasive plants persists somewhere with a country, 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 may suggest this is not a cure-all. We found that across declared plant taxa, there was no difference in the quantities of advertisements observed in prohibited and permitted jurisdictions. We also saw no significant effect on price, however our sample size was reduced to 20 declared taxa, making it difficult to draw a meaningful conclusion across all declared taxa traded. It is likely that jurisdictional regulations are reducing the total abundance of declared taxa in Australian plant trade, through compliance from traditional "brick-and-mortar" nurseries. It is important to note that the lack of effect on quantity we saw could be due to the limited size of our sample. Investigations across larger datasets, and across more e-commerce platforms, may reveal different results. However, if trade prohibition is not having an effect on the quantity of online trade, explanations from other plant trade studies may provide an answer. For one, sellers may perceive online trading of declared plants as low risk. This perception 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). Another reason may be a lack of awareness that these plants are invasive and that their trade is prohibited. 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 websites to prevent illegal trade (Derraik and Phillips 2010; Munakamwe and Constantine 2017). For example, e-commerce websites could provide information to people creating plant advertisements, warning them of plants that cannot be sold and to help identify those plants.

Given that plant trade is fundamentally human driven, we expected to observe a higher number of advertisements matching search terms and corresponding to declared plants in jurisdictions with larger populations. Consequently, in the targeted sample, we observed this trend with NSW and Vic. having the greatest number of total declared advertisements. Interestingly, NSW and Vic. also had the greatest proportion of total declared advertisements. However, in terms of prohibited advertisements, WA, SA, and NT had the highest proportions in the targeted sample. To explain this, we should consider the plants that jurisdictions have chosen to declare. Regulations are jurisdiction based, therefore differences in declarations arise between jurisdictions. WA declares the greatest number of plant taxa of any Australia jurisdiction (877 plant taxa), more than double that of the next highest jurisdiction. As a result, WA prohibits a larger proportion of Australia's assemblage of declared plants. Complementary to this is that NT, SA, and WA declare highly traded declared species that other jurisdictions do not. *Zantedeschia aethiopica* is only declared in SA and WA, *Opuntia ficus-indica* is only declared in NT and WA, and *Gazania* spp. are only declared in SA. These species were frequently traded in SA and WA, thus the higher proportions are indicative of the regulations of these jurisdictions. However, NT prohibited advertisements were predominately for aquatic declared plants that are not exclusively declared in the jurisdiction. Evidently this is a popular group of plants traded in the jurisdiction, one that may benefit from targeted management campaigns.

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 *L. laevigatum* (Riches 2001; Tidwell and O'Donnell 2010; Villamagna and Murphy 2010). It is possible that some traits that aid their invasion success could also lend to their popularity in trade. *Opuntia* cacti 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. However, without further investigation into seller behaviour we cannot say how common this is. Similarly, it has been suggested that some *Opuntia* protective traits (e.g., spines and glochids) eventually lead owners to dispose of them. Smith et al. (2011) suggested that the irritating hairs (glochids) of *Opuntia microdasys* drive owners to dispose of the plants through dumping. We spoke with a compliance officer investigating *Opuntia* sales, who reported that sellers mention a desire to sell the plants in order to be rid of them (D. Swan 2021, pers. comm., 3 November). The high number of advertisements we observed of these taxa may indicate selling plants is an attractive alternative to disposal but this would require further investigation.

We demonstrated that targeted searches using string matching was a more effective means of detection than random sampling. We took a conservative approach by including common and generic names (e.g., pond plant) alongside scientific names in our effort to detect declared plants. Common and generic names are non-specific and can be shared by many plant species, contributing to a higher rate of false positives. However, we believe this approach is necessary to reduce the chance of missing advertisements for invasive species. 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 decoration (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 dams), 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 people's intended use of an invasive plant because 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

We observed the prohibited advertisement of invasive plants online in all Australian 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 halted 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 sought 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 could contribute to the persistence of invasive species being distributed within a country. Australia's biosecurity, and that of other countries and regions, would benefit from more coordinated approaches to controlling the online trade of invasive species.

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Supplementary material 1

This table details the relevant legislation identifying declared plants in each jurisdiction

Author: Jacob Maher

Data type: Legislation references

Link: https://doi.org/10.3897/neobiota.87.104472.suppl1

Supplementary material 2

Short-list of invasive plants used for surveying candidate Australian websites

Author: Jacob Maher

Data type: species list (PDF file)

Link: https://doi.org/10.3897/neobiota.87.104472.suppl2

Supplementary material 3

List of search term exceptions used to remove the majority of false positives in target sample dataset

Author: Jacob Maher

Data type: Search term exceptions (PDF file)

Link: https://doi.org/10.3897/neobiota.87.104472.suppl3

Supplementary material 4

The price of plants advertised online in Australia from a random sample of 625 advertisements from each jurisdiction

Author: Jacob Maher

Data type: Boxplot (PDF file)

Link: https://doi.org/10.3897/neobiota.87.104472.suppl4

Supplementary material 5

Distribution of the mean difference in price for declared plant taxa between prohibited and permitted jurisdictions

Author: Jacob Maher

Data type: image (PDF file)

Link: https://doi.org/10.3897/neobiota.87.104472.suppl5

Supplementary material 6

Total number of detections for invasive plants which are prohibited to trade in at least one Australian jurisdictions

Author: Jacob Maher

Data type: Table: Species detections (PDF file)

Link: https://doi.org/10.3897/neobiota.87.104472.suppl6

Supplementary material 7

The number of observations for plant taxa prohibited to trade (i.e., declared plants) that were advertised with uses by traders

Author: Jacob Maher

Data type: table: Species detections with uses (PDF file)

Link: https://doi.org/10.3897/neobiota.87.104472.suppl7