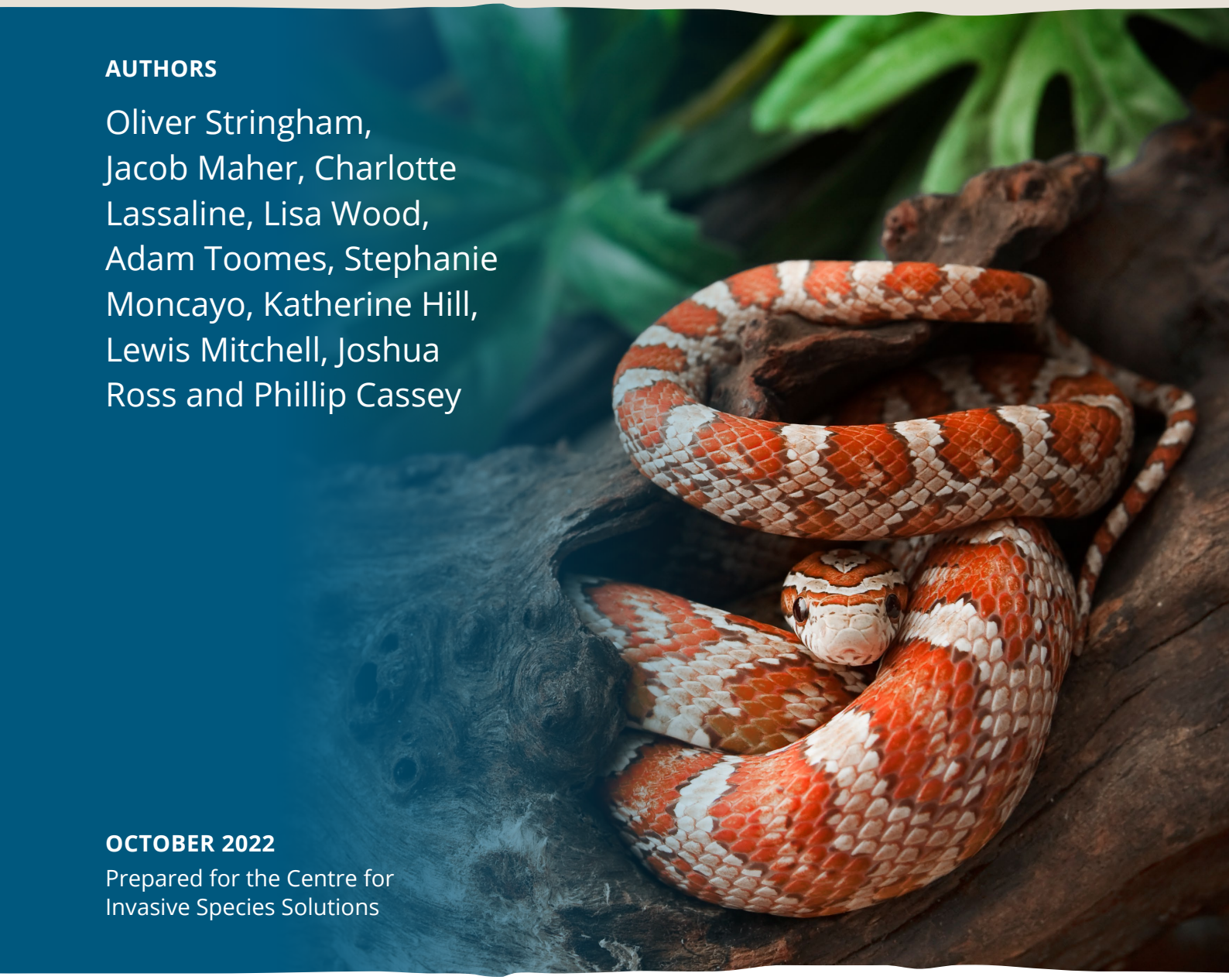
CENTRE FOR
INVASIVE SPECIES SOLUTIONS

UNDERSTANDING AND INTERVENING IN ILLEGAL TRADE IN NON-NATIVE SPECIES *and* BIOSECURITY SURVEILLANCE OF E-COMMERCE FOR ILLEGAL TRADE IN DECLARED PLANTS

FINAL REPORT FOR PROJECTS P01-I-002 AND P01-W-003



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We are a not-for-profit, member-based organisation formed to address the impact of invasive plants and animals across Australia.

We acknowledge the Traditional Custodians of the lands on which we meet and work and pay our respects to Elders — past, present and emerging.

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BUILDING AN ONLINE SURVEILLANCE SYSTEM TO MONITOR WILDLIFE TRADE FOR ENVIRONMENTAL BIOSECURITY

FINAL PROJECT REPORT FOR P01-W-003

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FOREWORD BY DR JOHN VIRTUE

The ongoing development of the internet as a marketplace for plants and animals in Australia (and elsewhere) presents a challenge for regulating the trade of declared species of high biosecurity risk. Online trade broadens the range of potential suppliers of such species and facilitates trade across state/territory borders. A further complexity is where it may be legal to keep, move and sell such a species in one jurisdiction but not in another jurisdiction.

The University of Adelaide's development of the Digital surveillance for Illegal Wildlife Trade (DIWT) website, through two related Centre for Invasive Species Solutions projects, is a key development in enabling better intervention in online trade of declared species. This surveillance tool is an opportunity for states and territories, as well as Commonwealth authorities, to efficiently gather intelligence on such illegal trade and enable early intervention to prevent further pest movement. It will be valuable for compliance operations, including interagency collaboration across borders.

It is recommended that jurisdictions work together on the efficient use and ongoing maintenance of DIWT, with the shared investment being realised through preventing future pest incursions.

Dr John Virtue

Former General Manager Strategy, Policy & Invasive Species, South Australian Government

EXECUTIVE SUMMARY

This report summarises work completed on the Centre for Invasive Species Solutions projects: Understanding and intervening in illegal trade in non-native species (P01-I-002) and Biosecurity surveillance of e-commerce and other online platforms for illegal trade in declared plants (P01-W-003).

The wildlife (animal and plant) trade has moved online, which presents researchers and enforcement agencies with an unprecedented opportunity to monitor trade activity to manage environmental biosecurity and combat illegal activities.

The invasion risk posed by ecommerce was previously identified by the Environment and Invasives Committee Scoping Study on "*E-commerce in invasive species*". There was broad acknowledgment that existing ad hoc monitoring of wildlife trade on the internet was insufficient to fully quantify risk and aid prevention.

This report can assist Australian biosecurity practitioners and decision-makers to establish their own surveillance systems to enable early preventative action to protect Australia's economy, environment, and social wellbeing from the burgeoning costs of the illegal wildlife trade.

In this report we detail the internet surveillance project we established to monitor the alien vertebrate pet trade and declared ornamental plant trade. This project contributes to Australia's implementation of Convention on Biological Diversity Aichi Target 9: By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment.

We constructed automated monitoring systems for about 90 'open-web' websites (e.g. ecommerce, stores, forums) across four continents. To date, we have collected over seven million unique, online wildlife advertisements at a rate of about 2.5 million advertisements per year.

With feedback and communication from government practitioners and stakeholders, we constructed a user-friendly website that can be used to query our database and receive email alerts. We named this website DIWT: Digital surveillance for Illegal Wildlife Trade. DIWT is different from any other surveillance platform currently being used to survey and detect online wildlife trade in Australia (Appendix S5).

We use several case studies to demonstrate how we used our dataset of online advertisements. These case studies include the illegal plant and animal trade in Australia, as well as exploring the burgeoning trade in live invertebrates as pets.

In particular, we have greatly expanded knowledge of the ecommerce pathway in Australia and implemented a more strategic and coordinated approach to ecommerce surveillance. DIWT will enable government biosecurity agencies to better manage this pathway, while future research will be required to extend our work to other ecommerce trading platforms (including user-groups and forums) and include automated approaches for combating illicit behaviour (e.g., incorporating image recognition plug-ins and machine learning).

INTRODUCTION

HOW THE INTERNET CHALLENGES COUNTRIES' BIOSECURITY

The global wildlife trade poses severe risks to environmental biosecurity and biological conservation (Cardoso et al. 2021). In particular, transporting species from their native ranges to novel locations can produce invasive alien[1] species and novel diseases (Pyšek and Richardson 2010; Stoett et al. 2019). The economic and ecological consequences of invasive alien species and novel emerging diseases (in both human and wildlife) are serious – billions of dollars are lost annually and it is a leading cause of native species extinctions (Bellard et al. 2016; Woinarski et al. 2019; Zenni et al. 2021). Further, unsustainable harvesting and removal of wild individuals from their natural populations can threaten species and risk their extinction. Harvesting for the wildlife trade is a major contributor to the decline of thousands of species (Di Minin et al. 2019), and thus contributes to degrading natural systems, which in turn threatens sustainable development and human wellbeing (Cardinale et al. 2012).

A large component of the modern wildlife trade is the trade in exotic pets and ornamental plants. The exotic pet trade involves the trade of non-domesticated animals (excluding cats, dogs, rabbits, etc.) for the purpose of being kept as household companions and living accessories, and bred and traded by collectors (Bush et al. 2014). The ornamental plant trade involves the trade of whole plants for decorative purposes (Yahia 2019). The exotic pet and ornamental plant trades represent multibillion dollar industries (van Kleunen et al. 2018; de Wit et al. 2022) and the trade occurs across complex multinational networks in the modern globalised world (Sinclair et al. 2021; Fukushima et al. 2021). Importantly, the exotic pet and ornamental plant trade are some of the largest modern-day contributors to emerging invasive species (and their negative impacts) globally (Bradley et al. 2012; Lockwood et al. 2019). Correspondingly, the demand for alien pet animals and alien ornamental plants is high (Toomes et al. 2020; Gabellini and Scaramuzzi 2022).

The proliferation of exotic pet and ornamental plant trade is further complicated by dissimilar legislation across countries and states. In Australia, it is illegal to keep all alien reptiles and amphibians (without a permit; e.g., Zoos), and most alien mammals (Department of Agriculture, Water and the Environment 2022). However, there is still demand for alien pet species in Australia, and records at the border indicate an increase in the number of smuggling attempts to bring alien vertebrate species into the country (Toomes et al. 2020). Concurrently, the international demand for Australian native species, and particularly for endemic reptiles (Heinrich et al. 2022), is a major conservation concern (Department of Agriculture, Water and the Environment 2021). In Australia, importation of plants is regulated by the Australian Government, and trade within Australia is regulated by state and territory governments. The objective is to prevent, control, contain and eliminate invasive populations of weeds (Invasive Plants and Animals Committee 2016). This is a difficult task: more than 29,000 species of plants have been introduced into Australia, of which more than 2,699 species have naturalised (Gallagher and Leishman 2014; Dodd et al. 2015). Australia can expect to encounter more invasive plant species as demand for alien species persists and horticultural trade grows (Shaw et al. 2017; van Kleunen et al. 2018).

Increasingly, wildlife trade is occurring on, and being facilitated by, the internet (Stringham et al. 2021c). While not all wildlife is traded over the internet, the exotic pet and ornamental plant trades have flourished and there are currently many hundreds of marketplaces trading tens of thousands of species globally (Humair et al. 2015; Marshall et al. 2020, 2022; Beaury et al. 2021; Hughes et al. 2021; Lavorgna and Sajeva 2021). Australian and state governments, through the Environment and Invasives Committee (EIC) and its predecessors, identified the ecommerce pathway as a significant risk. Prior to our project, most practical online-trade monitoring was conducted in an ad hoc manner.

[1] *Exotic* often refers to non-domesticated pets, as well as animals and plants that are not native. *Alien* usually means non-native plants and animals. *Restricted* means plants and animals that are a biosecurity risk. *Declared* refers to animals and plants that are pests, and is similar to 'restricted' when it means illegal to keep/trade.

EIC task forces recognised that existing surveillance techniques did not adequately match the scale of ecommerce (EIC, 2018).

To address this, our project pursued an unprecedented opportunity for researchers and government agencies to establish internet surveillance systems. Developing advanced web intelligence techniques is core to successfully disentangling online trade, and internet surveillance is an emerging tool to assist in identifying illegal wildlife trade and informing biosecurity/conservation research and objectives (Stringham et al. 2021c). This report presents the work of the authors to establish an internet surveillance system focused on the trade of Australian animals and plants for biosecurity and conservation purposes.

MONITORING ALIEN PET TRADE AND DECLARED ORNAMENTAL PLANT TRADE OCCURRING ONLINE

Our online surveillance project centred on the trade of exotic vertebrate animals and ornamental plants occurring on the surface web[2] on ecommerce[3] websites. Our overarching goal was to assist practitioners with real-time and best-practice tracking of online wildlife trade.

Overall, we sought to achieve a more efficient way to locate illegal wildlife trade, and to develop an understanding of the illegal trade to track current patterns and anticipate future biosecurity and conservation risks. In terms of biosecurity, monitoring online trade is an ideal way to track alien species and diseases very early on in the invasion process (Blackburn et al. 2011), when risks and costs are lower, and preventative actions and mechanisms are more effective.

More specifically, we aimed to:

1. establish an automated data-collection system to record online advertisements (ads) from a representative sample of websites
2. characterise the extent of the illegal trade in alien species occurring online in Australia
3. develop software (i.e. a user interface) for enforcement agencies to easily access detecting illegal trade for themselves
4. develop automated or semi-automated data cleaning and processing techniques for sorting and capturing information (i.e. machine learning).

Concurrently, this project also contributes to addressing Australia's implementation of Convention on Biological Diversity Aichi Target 9: "by 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment".

Our first key step was to engage relevant end users in enforcement agencies (i.e. government scientists working in biosecurity). We actively met with end users to understand what websites they are currently monitoring manually (i.e. human visits to websites) and what kind of software would be most useful and desirable to make finding illegal wildlife trade online easier for them. In August 2019, we ran an Illegal Wildlife Trade Workshop for the Environmental Biosecurity Office at the Department of Agriculture in Canberra (Appendix 6). The workshop was attended by 54 practitioners and decision-makers from across environmental biosecurity and government enforcement agencies in Australia. A key recommendation from the workshop was that "trade data collected by researchers, or availability of new technologies developed by practitioners, could be fed into a chosen platform for sharing ecommerce data on wildlife trade". After acquiring a list of websites from end users, we performed an additional systematic internet search of our own to add more websites we considered to be important

[2] The part of the internet that is readily available to the general public and searchable with standard web search engines
[3] The activity of electronically buying or selling products online, over the internet

for online wildlife trade. From there, we coded custom web scrapers[4] for each website to automatically record and store the advertisements on a given website at regular intervals (e.g. daily).

To aid practitioners in their mission to find illegal wildlife trade, we sought to create software that compiled all of the collected data in a way that was easy to search. We did so by creating a trial (i.e. mock) website to show a reference group of practitioners for initial feedback. This trial website consisted of a simple search form, where the user could check off certain parameters such as the website names and input search phrases. Once the search was conducted, the matching advertisements were returned in a user-friendly table. We conducted a demonstration of the trial website to ascertain if this format was acceptable and useful, and surveyed key practitioners across stakeholders (including four EIC specialist groups) (n = 34 respondents, representing every Australian state/territory). By and large, the practitioners agreed that a website of this design would suit their needs, with some requests for additional minor features. From there, we built a full-scale website (i.e. web application) we called this application DIWT – Digital surveillance of Illegal Wildlife Trade. We asked for beta testers among the practitioners to trial the website and requested each beta tester fill out a survey (n = 15 respondents, representing every Australian state except Northern Territory) to indicate how well the website worked for them and what could be improved. Overall, beta testers found the website useful to their daily practice and easy to use. The website is now available for use within the Australian Government, and for academic research.

[4] Automated software tools that accurately and quickly harvest/extract data from a webpage

METHODS: INTERNET SURVEILLANCE OF WILDLIFE TRADE

WILDLIFE TRADE ON THE INTERNET – THE 'ONE-STOP SHOP'

The internet has greatly facilitated wildlife trade, connecting buyers and sellers in a way that was previously impossible (Lavorgna 2014). For many aspects of wildlife trade there has been a shift from physical stores to ecommerce trade over the internet (Nijman 2020). Since data on wildlife trade is vital to the biosecurity decision-making process, creating systems to monitor and collect internet data should be a priority. In some ways, monitoring internet wildlife trade is more feasible and cost effective compared to monitoring physical marketplaces. Specifically, the internet provides a 'one-stop shop' for researchers to monitor, assuming that access to websites of interest can be obtained, and the technology and resources to automate data collection is available.

It is important to note that not all types of wildlife trade occur online. For example, the pet trade and ornamental plant trade has flourished online, but there is little evidence that the bushmeat trade occurs online (Humair et al. 2015; Sung and Fong 2018).

There are several types of websites and online data sources relevant to online wildlife trade, including: online stores (e.g., pet stores and plant/seed suppliers); classifieds websites, including ecommerce marketplaces; forums; lost-and-found websites (i.e., where people report lost pets); pet adoption websites; news websites, including news reporting on wildlife seizures; social media (e.g., Facebook, Instagram, Youtube and Sina Weibo); and private messaging apps (e.g., WhatsApp, Facebook messenger and WeChat). For a full discussion on the different types of websites and the possible kinds of data they can provide see Stringham et al. (2021c).

The internet is divided into three distinct 'layers': the surface web, the deep web, and the dark web (Stringham et al. 2021c) (Figure 1).

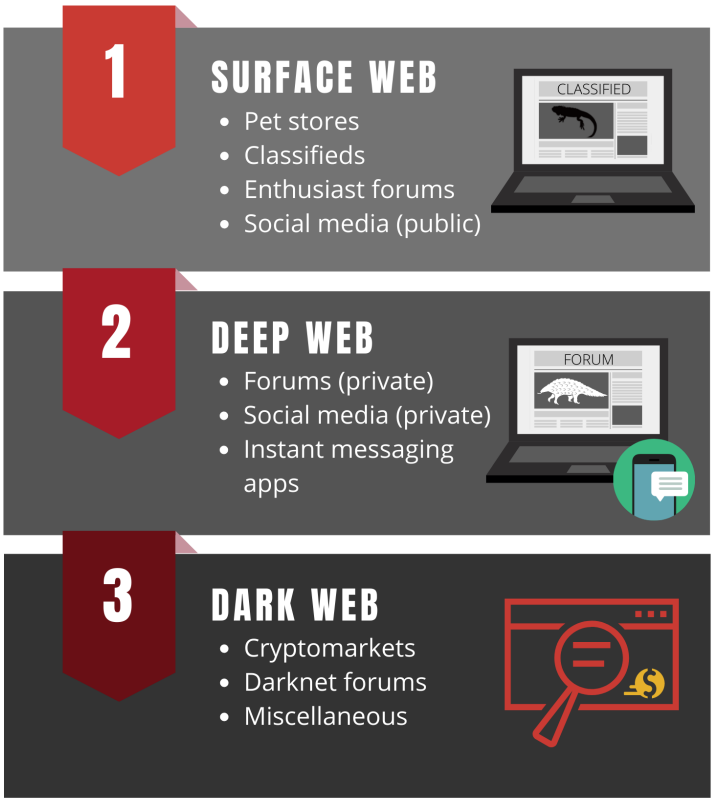


Figure 1. The three layers of the internet. Wildlife trade can occur on any layer. However, peer-reviewed research indicates that wildlife trades occur most frequently on the surface web and deep web on ecommerce websites and social media platforms. Source: Stringham et al. (2021c).

The surface web contains websites that are publicly viewable without the need of a login. The surface web includes most ecommerce websites, including classifieds. The surface web may also include taxa-specific forums (e.g. reptile keepers) and social media, as long as a login is not required to view the content. The second layer, the deep web, includes websites and apps that require a login to view. This includes most social media sites (including 'groups' within a site), private forums and instant messaging apps (including direct messaging on social media). Finally, the dark web requires special software to access and does not contain a search engine to find relevant websites (website domains must be known *a priori*). Sites on the dark web may further require logins or require access to be granted from an administrator. Most known sites on the dark web are marketplaces and forums.

Current scientific knowledge suggests that almost all online wildlife trade occurs on both the open and deep web (e.g. Hinsley et al. 2016; Stringham and Lockwood 2018; Van et al. 2019; Sánchez-Mercado et al. 2020; Ye et al. 2020). Increasingly, social media is implicated in wildlife trade (e.g. Xu et al. 2020). There have been only a few studies of wildlife trade on the dark web and, to date, the amount of trade has been negligible (Harrison et al. 2016; Roberts and Hernandez-Castro 2017; Stringham et al. 2022).

HOW WE USED THE INTERNET TO MONITOR AND QUANTIFY WILDLIFE TRADE

There were no prior standards for wildlife e-surveillance methods, including protocols to find wildlife trade on the internet, or collect data. We developed a guide based on our prior expertise and based on other studies in the scientific peer-reviewed literature. Our published guide (Stringham et al. 2021c) is designed to fill this knowledge gap, and provide scientists and practitioners a resource to initialise their own e-surveillance programs. This guide simplifies the process of wildlife e-surveillance into six steps: (i) define the scope and purpose of the project, (ii) gather a list of candidate websites,

(iii) select target websites to monitor, (iv) collect data from websites, (v) clean the data, and (vi) analyse the data.

We outline each step here and explain in the next section how we adopted this guide to develop an internet surveillance system of our own for exotic pet and ornamental plant trade.

Step 1: Define the scope and purpose of the project. Since the internet is vast, there is no possibility of monitoring every single website that trades wildlife. Therefore, limiting the scope is an important first step to locating the most relevant websites that trade wildlife of interest. There are several factors to consider when defining the scope and purpose, including: which layer/s of the internet to monitor (e.g. surface, deep, dark), what kinds of websites (store, social media, forums), what countries, what languages, and which taxa or taxon are of greatest relevance and interest.

Step 2: Gather a list of candidate websites. From the selected scope of the project, a user can now search for relevant websites and platforms that trade wildlife online. Here, we outline two different ways of gathering candidate websites. The first method is to perform a systematic internet search. By this, we mean creating a combination of search phrases reflecting the criteria/scope of the project. These search phrases then get put into a search engine or social media search. All of the websites/groups/accounts that the search returns can be considered candidates as long as they meet the criteria defined in step 1. The second method to find candidate websites is to elicit expert opinion. By experts, we mean anyone with intimate knowledge of the trade on the internet of the taxa of interest.

Step 3: Select target websites to monitor. From the candidate list of websites, a user should choose a subset (or all) of these websites to monitor (i.e. collect data). The criteria to choose which websites to monitor will vary by project. Some factors to consider include: the popularity of the website, how many people access the website, and how many posts/advertisements are added to the website daily. This step is subjective because accurate information about website popularity is not readily available for all websites. Finally, the number of websites chosen will depend on the capacity of the user to collect and clean the data received.

Step 4: Collect data from websites. Collecting data from target websites can occur in two ways. The first way to collect data from a website is manually. Manual data collection involves a person visiting a website at regular intervals (e.g. every day, or once a week) to record in a spreadsheet or database what is being traded. The second method is to use automated tools to extract relevant information directly from posts and advertisements. Automated tools include web scrapers, which is computer code that automates ‘visiting’ a website and converting the contents of a webpage into a data table that can be stored as a spreadsheet or in a database. A different web scraper is required for each website being monitored because the web scraper examines the underlying HTML code of a website, which differs between sites. Finally, expertise in the form of a software engineer or data scientist is usually required to code web scrapers.

Step 5: Clean the data. Data collected from the internet might not be readily usable for analysis. For instance, on many websites such as social media and classifieds sites, wildlife is advertised as an open text box, meaning a user can write any details they wish. In many instances, sellers do not use standardised names for wildlife such as common names or scientific names. Oftentimes, sellers use trade names (i.e. names of wildlife only used in wildlife trade, and that are not scientifically accepted) and/or may misspell common names. Other times, sellers may try to conceal what they are trading or genuinely don’t know what they are trading, and thus do not list a name or list a higher-level taxonomic name (e.g, ‘bird’ or ‘plant’). Data cleaning usually involves the manual processing of advertisements to identify attributes of interest, such as species name and quantity traded. Data cleaning is usually the most time-consuming step of monitoring the internet for wildlife trade. Some data may already be standardised from the data-collection process and does not need to be cleaned, such as the date. In some cases, specialised marketplaces might require a scientific name and, thus, for these sites data cleaning may not be needed. When cleaning species names, we recommend selecting an accepted taxonomic database to avoid duplicated species names, such as synonyms.

Step 6: Analyse data. This last step involves performing summary statistics and analyses of the cleaned data. The analyses to perform will be unique to the question at hand. Basic summaries include which species were traded and how popular they are (i.e. how many advertisements). For enforcement, what is most relevant will likely be *what* species and *where* they were traded.

OUR INTERNET SURVEILLANCE PROJECT: MONITORING THE PET AND ORNAMENTAL-PLANT TRADE OCCURRING ONLINE

Our project centred around the online trade of exotic pet vertebrate animals and declared ornamental plants occurring on the surface web (on ecommerce websites).

Here we report on our methodology to find relevant websites and collect data from websites, which includes steps 1 to 4 of the guide outlined previously. For the final two steps (steps 5 and 6), we present several case studies demonstrating how this data can be used (see Case studies using data collected from the internet). At the end of this section, we provide metadata summary statistics about the websites we are continuing to monitor, including how many websites we have monitored, how many advertisements we are collecting, and at what rate we are collecting advertisements. We chose to keep the names of websites anonymous; this is considered good ethical practice so as not to interfere with or compromise trading behaviour (Hinsley et al. 2016; Stringham et al. 2021c).

OUR SCOPE AND AIMS

ANIMALS

For animal trade, our aim was to target the online trade of non-domesticated vertebrate animals as exotic pets, including the following taxa: birds, reptiles, amphibians and fish. Our target regions for websites were: Australia, Europe (EU), the United States (US), and Japan. In addition, we aimed to include a variety of different website types: pet stores, enthusiast forums, classifieds and adoption websites. We restricted the project scope to the surface web.

PLANTS

For plant trade, our aim was to detect and characterise the online trade of invasive plants that were prohibited to trade in all states and territories in Australia. We focused on trade occurring domestically within Australia and excluded importation into, and trade outside of, Australia. We aimed to capture trade on the surface web, including ecommerce websites and online nursery stores. We did not capture trade on the deep web, such as in private forums or social media groups. Based on our aim, we focused on sites trading alien plant species.

FINDING CANDIDATE WEBSITES WHERE WILDLIFE IS TRADED

ANIMALS

For animals, we undertook a systematic internet search to find candidate websites for wildlife traded in the target regions of Australia, EU, US and Japan. We defined a series of search terms and phrases (see Appendix S1) centred around the vertebrate taxa of interest (freshwater aquarium fish, marine aquarium fishes, reptiles, amphibians and birds), the type of websites (store, classifieds, forum, adoption) and region. In total, through all combinations of keywords, we created 105 search phrases. We used the Google search engine to explore our search phrases and stored the top 50 results per search (e.g. five pages of results with 10 URLs per page). We retrieved 5,250 search results (URLs) and, applying our inclusion criteria, were left with 304 candidate websites.

Further, we consulted several Australian government employees and wildlife trade scientists who actively monitor the internet for illegal wildlife trade. They provided the names of websites they monitor. All of the websites they provided were captured in our candidate website list, except for social media sites, which were not included here.

We classified each search result as relevant (or irrelevant) depending on the following inclusion criteria: (1) the target taxa are being traded on this website, and (2) website users are trading in one of the target locations. Since all online transactions are potentially representative of animals being

traded, we considered all websites where one can acquire an animal directly (i.e. direct shipping) or indirectly (i.e. facilitating in-person exchange).

For our target region of Japan, we collaborated with a team of scientists based in Japan and the US who are familiar with the Japanese language and culture. They undertook a similar systematic internet search for websites using search terms in the Japanese language.

PLANTS

For plants, we underwent initial consultation with biosecurity professionals in the Australian Environment and Invasives Committee, who provided recommendations to monitor two online marketplaces and one social media website. These recommendations were largely based on previous known detections of invasive plants.

To expand the pool of considered websites, we conducted a systematic web survey to gather candidate websites for monitoring. We conducted internet searches of invasive plant species names (common and scientific) with an appropriate phrase; for example, “Acacia baileyana for sale Australia” and “Cootamundra wattle for sale Australia”. Since there were many species prohibited to trade in Australia (over 1,000 species), we created a short list of species that are declared ‘prohibited to trade’ and appeared on the Grow Me Instead website (Nursery & Garden Industry Australia 2009). This provided us with a list of invasive species that are known to be popular in horticultural trade (Appendix S2).

SELECTING TARGET WEBSITES TO MONITOR

ANIMALS

For animals, we gathered available relevant metadata on each candidate website. For each website we retrieved the Alexa (a global website ranking system) web ranking and the number of page visits per month (if available). For each classifieds and forum website, we calculated the approximate rate of new listings (i.e. how many listings posted in the last month). In addition, we calculated the number of times a website showed up in all searches and considered this to be an approximate metric of popularity. We used the metadata to subjectively choose which websites to collect data from (i.e. our target websites). Further, we wanted a representative number of each type of website (forum, classifieds, store) for each taxa and location. Therefore, we chose at least three target websites (if available) for each combination of website type, taxa and location.

From the 304 candidate websites, we selected 66 websites to collect data from. Each website traded/sold one or more of our target vertebrate taxa as pets in one of our target locations: US, EU or Australia. For our target region of Japan, the team we collaborated with chose their own set of websites (n = 15 websites) they considered most important to monitor.

PLANTS

For plants, we found a total of 38 websites advertising prohibited invasive plants. However, many of the advertisements on online nurseries were listed as ‘out of stock’ or ‘sold out’. Follow-up visits to these websites rarely indicated any change in availability. We suspected that some of the surveyed sites had discontinued production of these prohibited invasive species. Websites that had stock available were generally located in a state where the given species was not prohibited to trade.

To inform our website selection we consulted with nursery industry representatives and government biosecurity departments. Their concerns aligned towards public ecommerce websites being the primary source of prohibited trade. They also raised concerns around high-profile and popular trade in cacti, succulents and aquatic plants as an existing source of invasive plant species. Based on these concerns and our survey results, we selected four public ecommerce platforms and eight online nurseries to monitor. Of the eight online nurseries, three were large-scale nurseries, two specialised in aquatic plants, two specialised in cacti and succulents, and one specialised in native Australian plants.

COLLECTING AND STORING DATA FROM WEBSITES

For each target website, we coded our own custom web scrapers to collect data in the programming language Python using the libraries `bs4`, `requests` and `selenium`. We chose how often to collect data depending on the type of website. For pet stores, we collect data once a week; for popular classifieds websites, once a day; and for less popular classifieds and forums, once every two to three days. The web scrapers are run via two computers hosted at the University of Adelaide and scheduled runs are automated via the Task Scheduler program in Windows.

Web scrapers were constructed in a manner that did not unduly impact the selected websites (i.e. ecommerce sites) and were compliant with the University of Adelaide Human Research Ethics Committee approved projects 'Semi-automated monitoring of international online wildlife trade' and 'Semi-automated monitoring of international online wildlife trade on social media' (Projects H-2020-184 and H-2020-256; approved on 9 September 2020 and 10 December 2020 respectively). Specifically, our ethics approval allowed for the semi-automated collection of trade data containing personal and re-identifiable information, on the condition that such information is only accessible to the researchers named in the application; or to government biosecurity practitioners via the DIWT website, with access controlled by researchers named in the application.

We stored all collected data on a local MySQL database hosted at the University of Adelaide. Duplicate listings are detected and marked after every data-collection event. For online stores, we decided that if two or more listings share the exact title and exact text description, they are duplicates. For classifieds websites, we decided that if two or more listings share the same title and the same username, they are duplicates.

CREATING AN ONLINE WILDLIFE TRADE DATABASE

ONLINE WILDLIFE TRADE DATA, SUMMARISED

We collected a total of 7,203,971 unique advertisements from 93 websites, encompassing four regions: Australia, US, Europe and Japan (as at 12 May 2022).

The total annual rate of collection is about 2.5 million advertisements per year.

Most advertisements come from websites from the US (about 4.8 million ads) followed by Australia (about 1.6 million).

Classifieds and forum websites comprise the vast majority of all advertisements (about 91%), followed by lost-and-found sites (about five per cent), then pet stores and plant shops (about three per cent).

The median rate of new advertisements per website is 2,400 ads per year per website.

Classifieds websites, on average, have 20 times more advertisements (median about 20,000 ads per year per website) than online pet stores and plant shops (median about 1,000 ads per year per website).

One popular Australian classifieds website contained the overwhelming majority of advertisements we collected from Australia (about 78%; about 491,000 ads per year).

CHARACTERISTICS OF ONLINE WILDLIFE TRADES FROM OUR DATA

To date, as of 12 May 2022, we are using web scrapers to automate the data collection of advertisements from 93 websites across four regions. The region with the most websites monitored is Australia with 32 websites, followed by the US (29), Europe (19) and Japan (15) (abbreviated in figures as AU, US, EU and JP respectively). The most common type of website we are monitoring is pet stores and plant shops (n = 59 websites), followed by classifieds and forums (n = 28), lost-and-found sites (n = 4) and adoption sites (n = 2) (Figure 2).

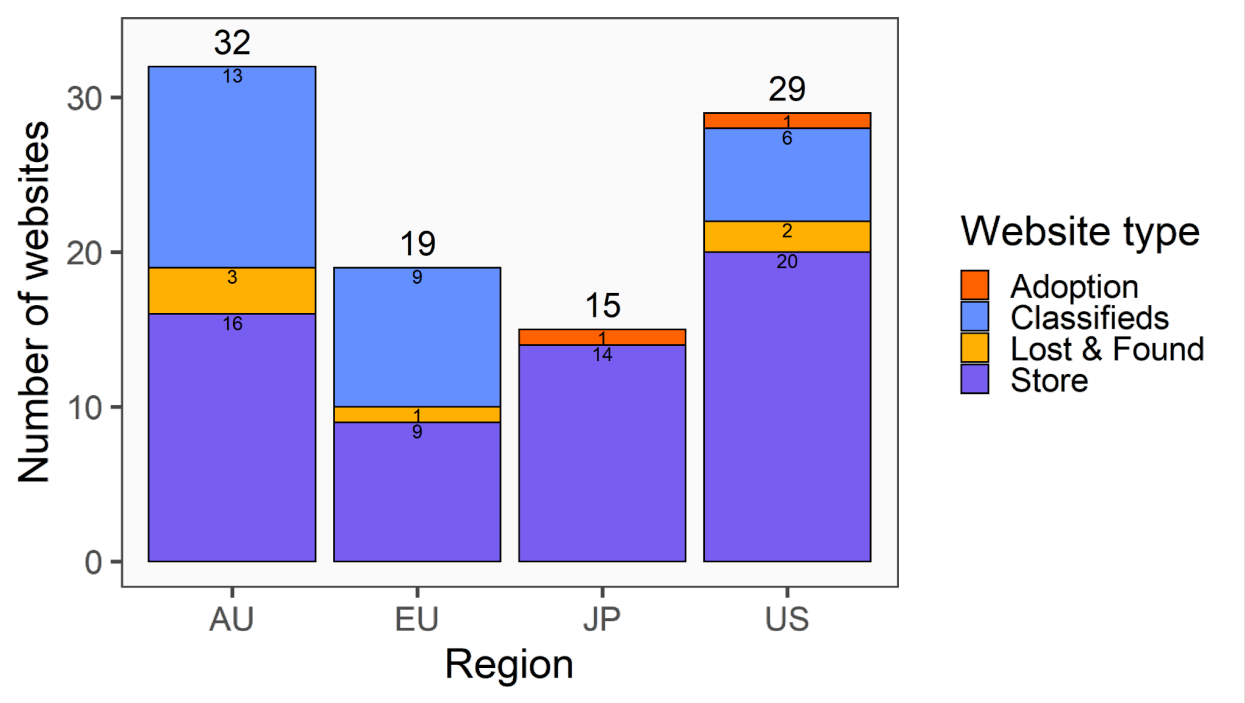


Figure 2. The number of websites being monitored by region and website type in 2022. Classifieds websites include both classifieds and forums. Stores include both pet stores and plant shops. Note: one lost-and-found website services three regions (AU, EU and US).

Most web scrapers were implemented by the end of 2019. However, more were created towards the end of 2020 as the plants surveillance project (P01-W-003) commenced (Figure 3).

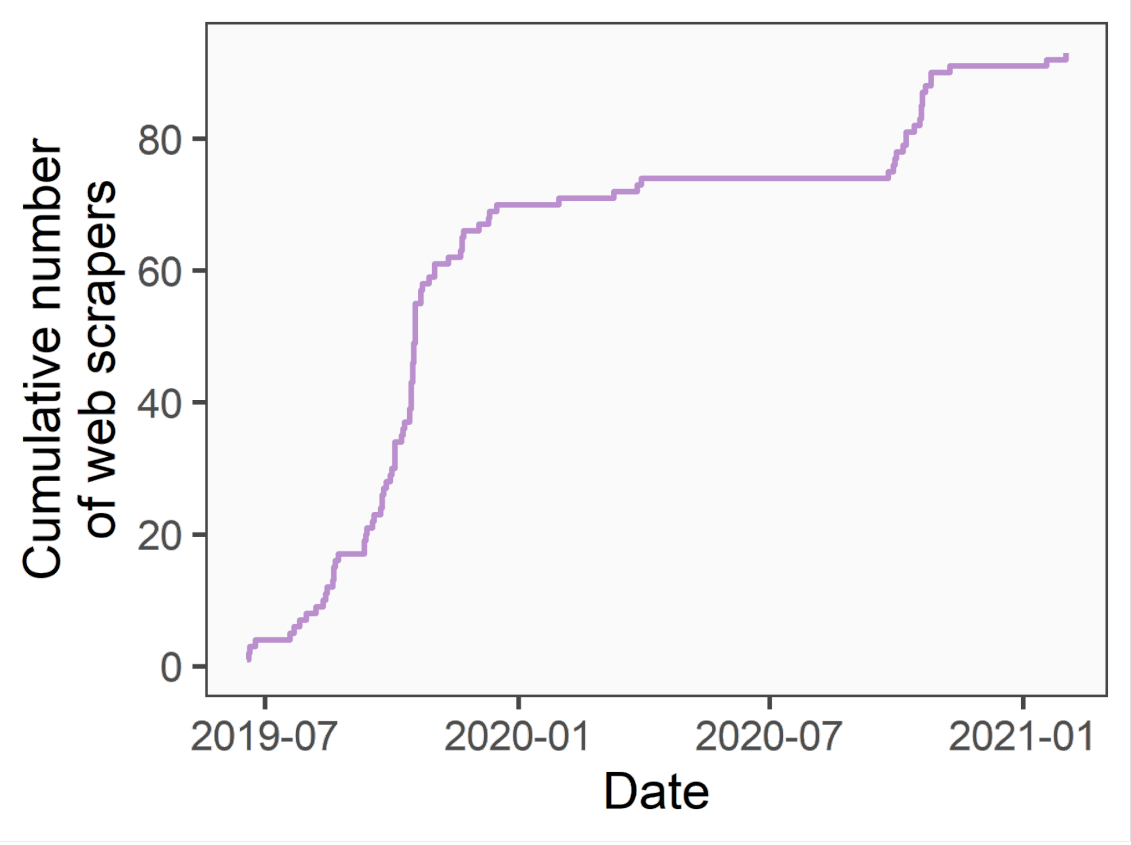


Figure 3. Cumulative number of operational web scrapers implemented over time. One web scraper represents one website monitored.

The region with the most advertisements was the US with about 4.8 million advertisements collected by May 2022 (Figure 4). Websites from the US had three times more advertisements than websites from Australia – the region with the second most advertisements. European websites had about 700,000 advertisements and Japanese websites had about 140,000.

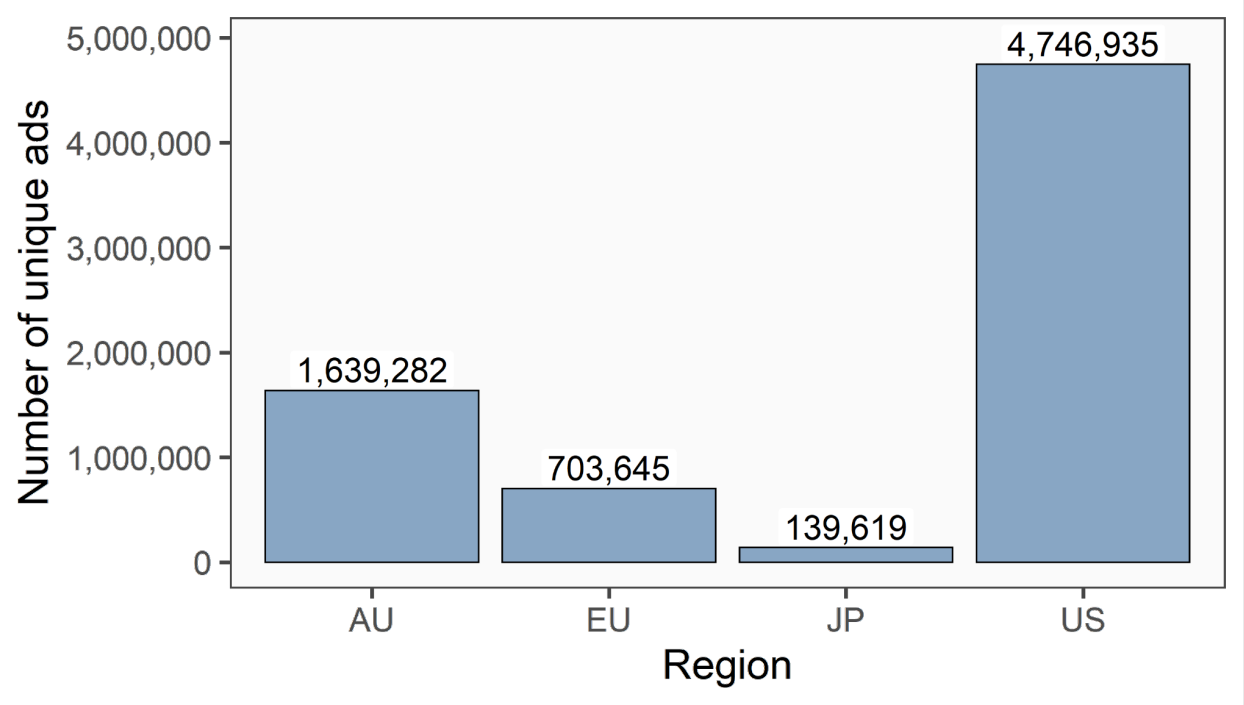


Figure 4. Total number of unique advertisements collected by region until 12 May 2022

The website type with the most advertisements was classifieds and forums, consisting of 6.6 million advertisements – about 90% of all advertisements (Figure 5). Lost-and-found websites were the next most numerous website type (about five per cent), followed by stores (about three per cent) and adoption sites (about one per cent).

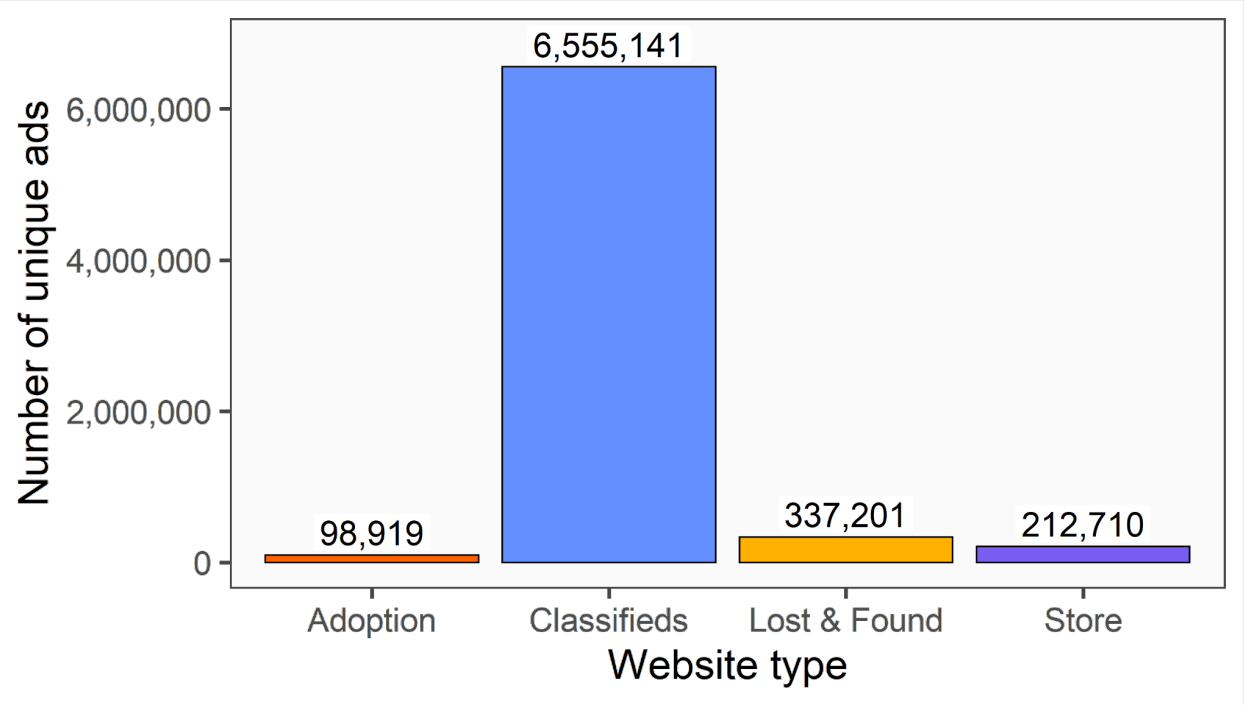


Figure 5. Total number of unique advertisements collected by website type until 12 May 2022

Given that, for each website, the web scraper's collection of data has been operational for different lengths of time, we decided to use a rate to compare them. We calculated the annual rate of new unique advertisements by website, *r*, as follows:

$$r = (n_{ads} \div n_{days}) \times 365.25$$

where n_{days} is the number of days the web scraper was in operation, and n_{ads} is the total number of unique advertisements collected for the specified website.

The average rate of new advertisements per website was 32,406 and the median rate was 2,400 (Figure 6). There was large variation in this rate of collection: some websites had between 100 and 1,000 advertisements per year, and others had over 10,000 (standard deviation of the rate = 147,000). The website with the highest annual rate of new advertisements was a classifieds website from the US with a rate of about 1.4 million ads per year.

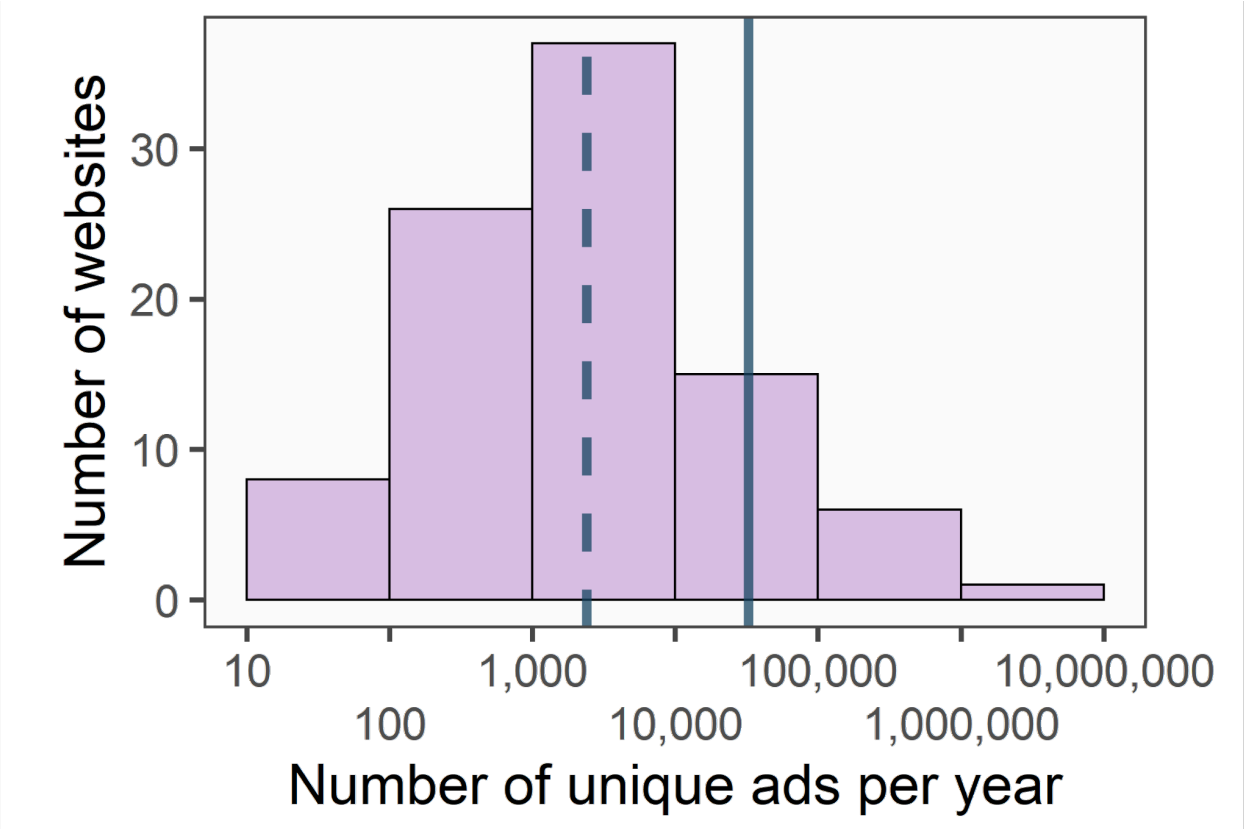


Figure 6. The rate of new advertisements collected from a given website per year. The dotted vertical line represents the median (2,400 ads per year) and the solid vertical line represents the mean (32,406 ads per year). Note: the x-axis is log-transformed.

The median rate of new advertisements per year per website was similar across our four target regions – the median ranging from 1,600 to 2,400 new ads per year per website (Figure 7). Europe had the highest median rate of ads per website (about 2,600 ads per year per website), followed closely by Australia (about 2,400 ads per year per website). The US had the highest average rate of ads per website (about 66,000 ads per year per website), followed by Australia (22,000 ads per year per website).

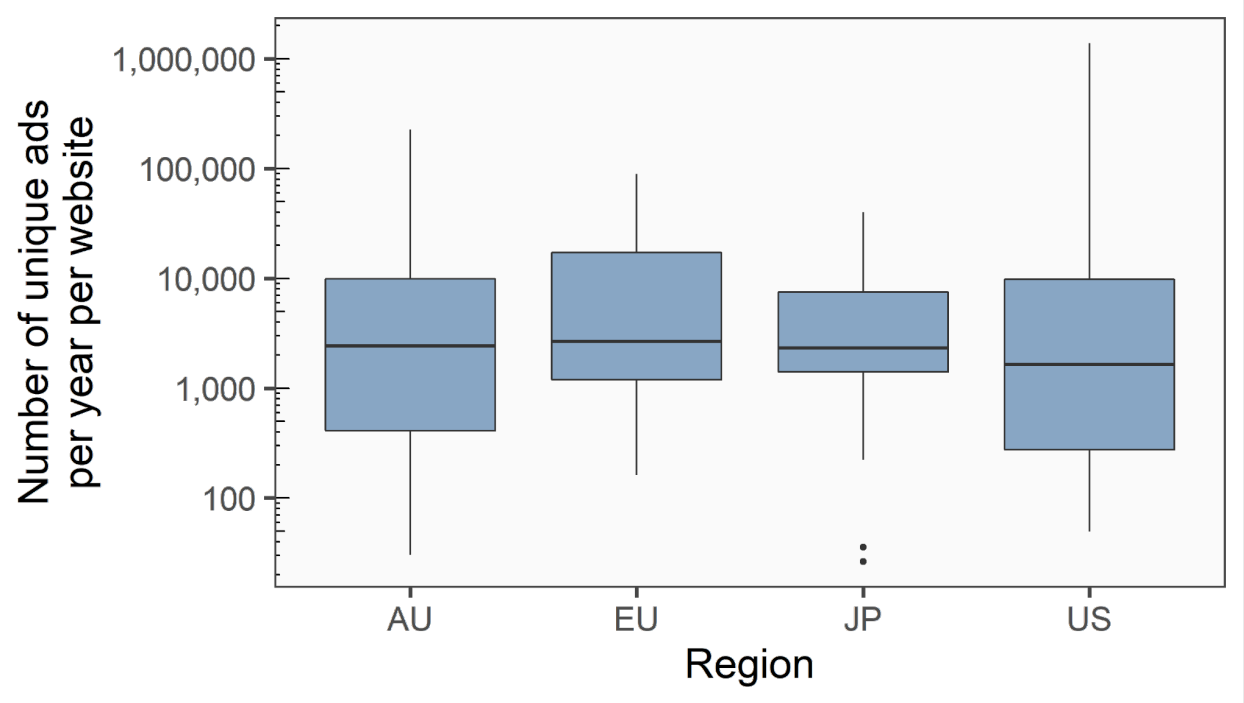


Figure 7. The median number of advertisements per year per website by region (solid horizontal lines). The boxes indicate the interquartile range for each region. Note: the y-axis is log-transformed.

Overall, stores listed fewer advertisements per year compared to other website types (Figure 8). Classifieds websites had the highest rate and highest variation in the rate of new advertisements. The median rate of advertisements collected for classifieds websites was about 25,000 ads per year per website; compared to about 1,000 for stores, 5,000 for lost-and-found sites and 20,000 for adoption sites. The standard variation of advertisements collected for classifieds websites was about 259,000 ads per year per website; compared to 57,000 for lost-and-found sites, 16,000 for adoption sites and 5,600 for stores.

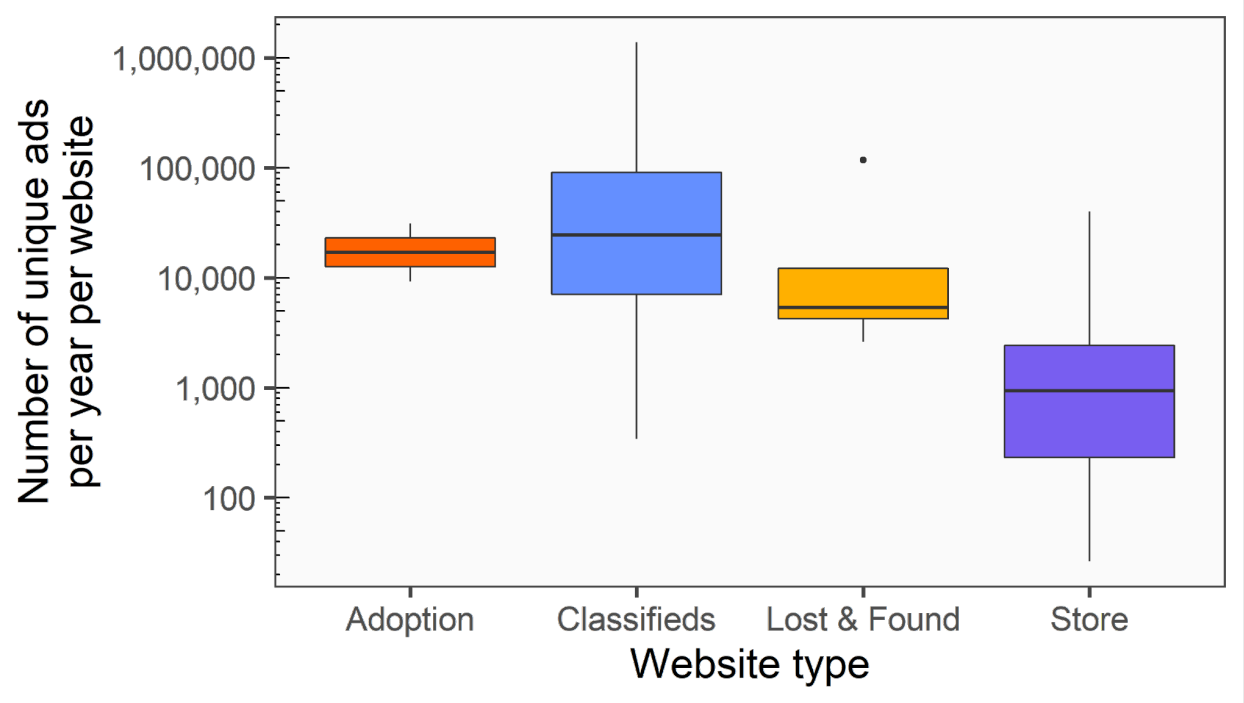


Figure 8. The median number of advertisements per year per website by website (solid horizontal lines). The boxes indicate the interquartile range for each type. Note: the y-axis is log-transformed.

EXPLORING WILDLIFE TRADE ON A POPULAR AUSTRALIAN WEBSITE

We now detail data summaries from one very popular Australia-based classifieds website because this website contained the overwhelming majority of advertisements we collected from Australia (about 78%; about 491,000 ads per year). We therefore suspect these data summaries illustrate broad trends in wildlife trade occurring online in Australia.

This classifieds website contained the following subsections for different kinds of pets: “birds”, “fish”, “reptiles and amphibians”, and “plants”. These subsections provide a useful way to partition the data into rough taxonomic groups for data summaries.

The plants subsection had the highest rate of new advertisements (about 225,000 ads per year), followed by birds, fish, then reptiles and amphibians (Figure 9).

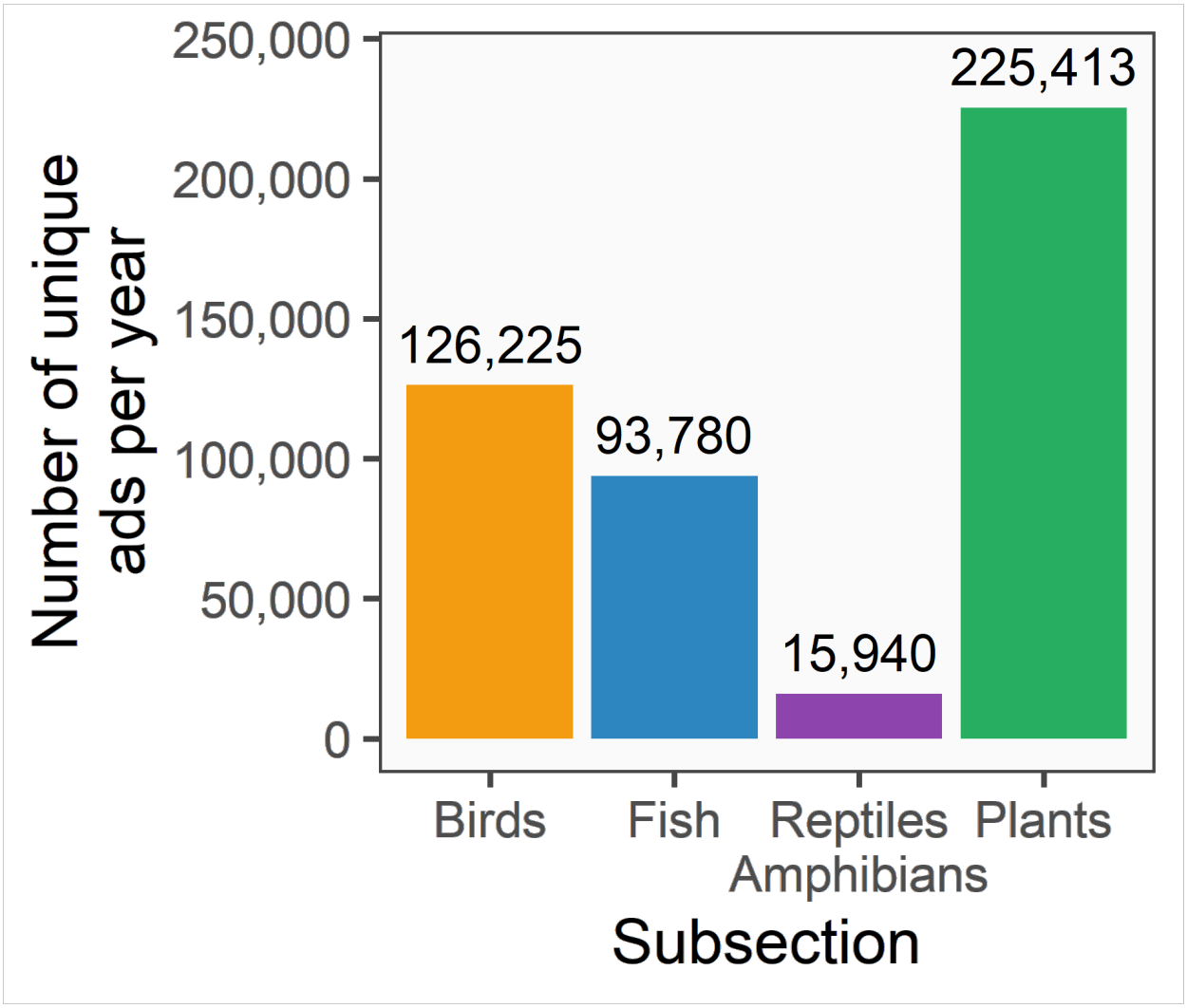


Figure 9. The number of advertisements per year for each subsection of a popular Australian classifieds website

The daily rate of new advertisements collected varied over time, with no apparent trends detectable (Figure 10). New bird advertisements hovered between about 250 and 450 per day (20th and 80th percentiles). New fish advertisements dropped off from about 500 to about 250 per day in mid-2020. New advertisements for reptiles and amphibians remained relatively consistent and low at an average of about 44 advertisements per day. New ads for plants hovered between about 500 and about 800 per day (20th and 80th percentiles), with an average rate of 664 advertisements per day.

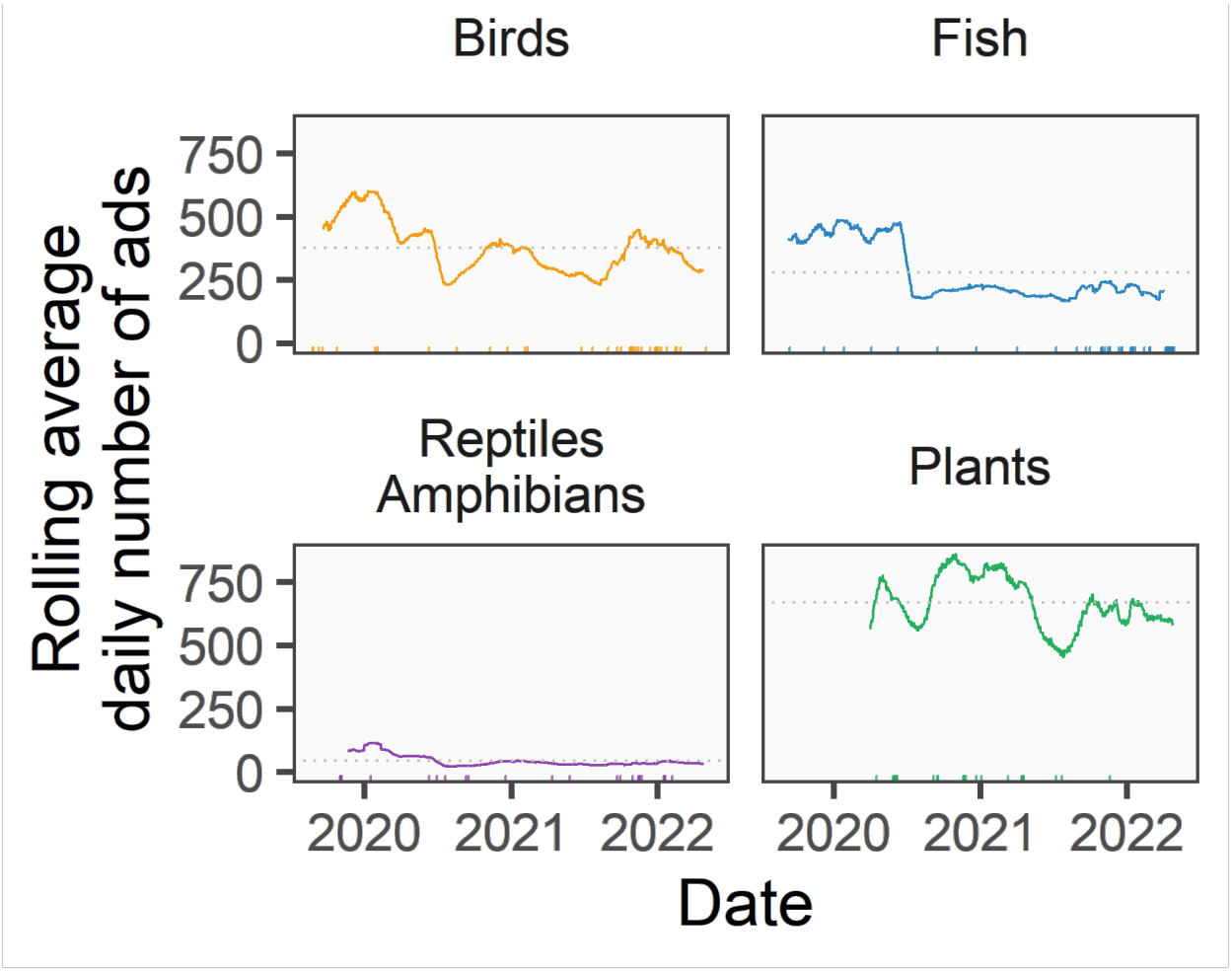


Figure 10. The 30-day rolling daily average of the number of unique advertisements collected from one popular Australian classifieds website that delineates taxa by subsections of the website. Dotted horizontal lines represent the average daily rate. Rug ticks along the bottom of each panel indicate days the web scraper was broken (thus no data was collected).

The spatial distribution of advertisements, from all subsections, roughly followed the human population for each state (Figure 11). We found that New South Wales had the most ads per year (about 121,000 ads per year), followed by Queensland, Victoria, Western Australia, South Australia, Tasmania, ACT and Northern Territory.

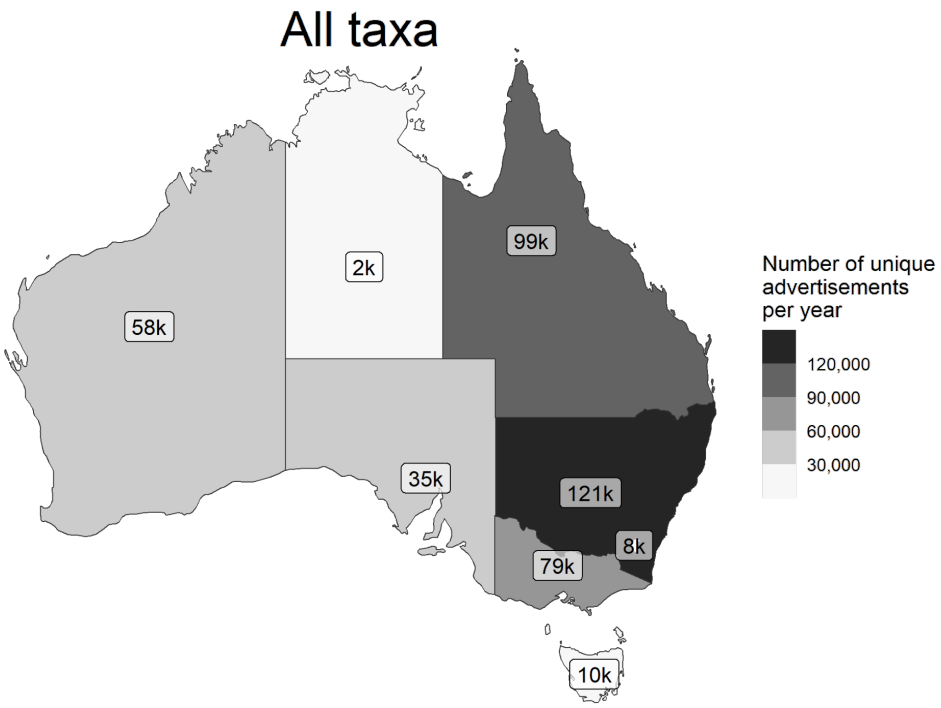


Figure 11. Annual rate of locations of unique advertisements collected from one popular Australian classifieds website by Australia state. Note: 'k' indicates a multiplier of 1,000.

The spatial distribution of advertisements differed slightly by subsection (Figure 12). Notably, for reptiles and amphibians, we found that Queensland had the highest rate of advertisements, followed by Victoria, then South Australia.

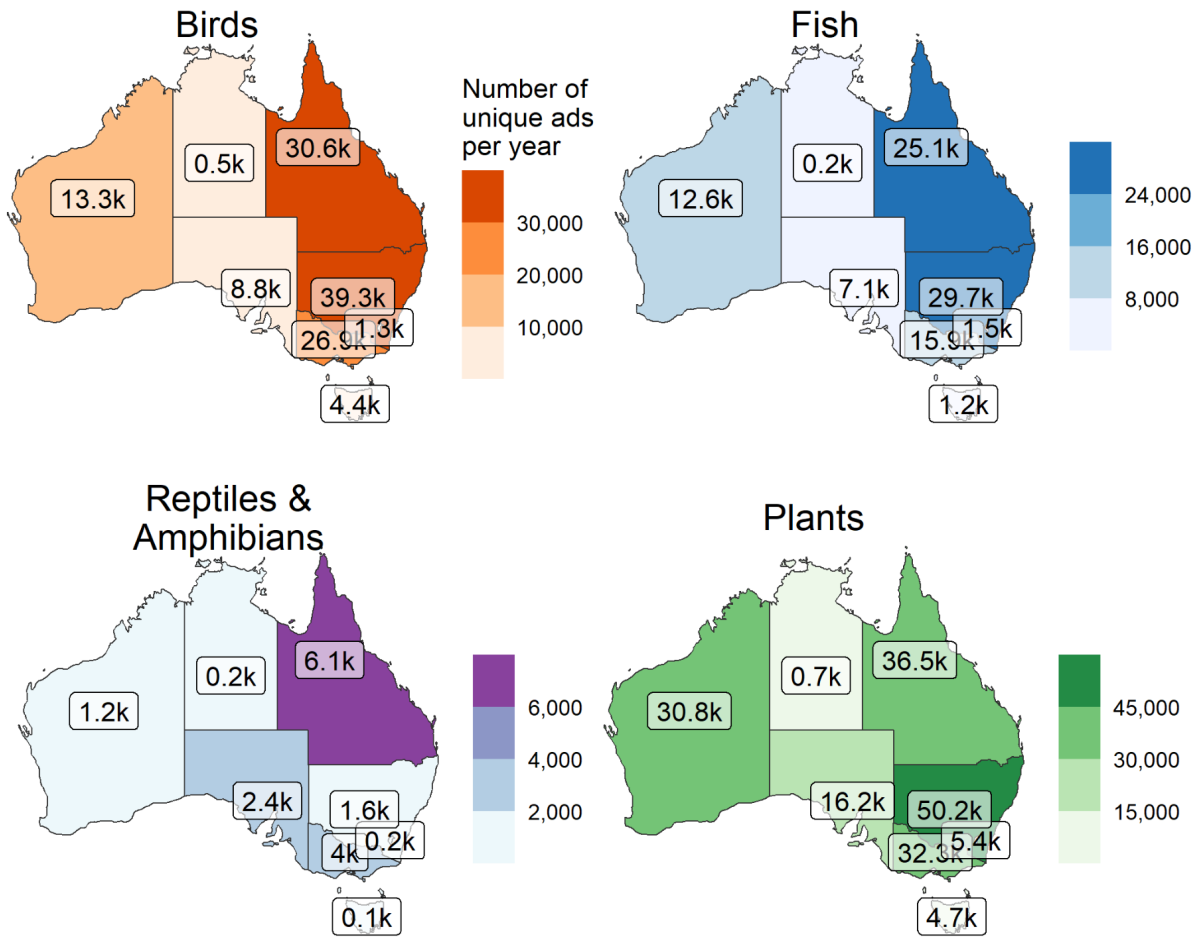


Figure 12. Annual rate of location of unique advertisements collected from one popular Australian classifieds website by taxa. Note the different colour scales for each taxa.

RESULTS: DIWT – DIGITAL SURVEILLANCE FOR ILLEGAL WILDLIFE TRADE WEBSITE

The Digital surveillance for Illegal Wildlife Trade website (DIWT) is a website interface to access the data collected through our internet surveillance project.

DIWT allows practitioners in government and research to access the database of online wildlife trade advertisements.

Users of the website can search multiple websites and locations, using unlimited search phrases.

Users can receive email notifications for new advertisements matching their search parameters.

In this section, we provide a high-level description of DIWT and how it works.

We also provide a step-by-step user guide and a guide to understanding the data outputs.

ABOUT DIWT

We developed the DIWT software for end users to access our wildlife trade advertisements database (Figure 13). We monitor over 80 ecommerce websites and store *all* wildlife advertisements that are posted. The website https://diwt.org is an interface to our database. Currently, we have collected over 7.2 million advertisements. DIWT was designed to improve monitoring and enforcement of illegal wildlife trade in Australia, and is available to government and university employees. The complete DIWT User Guide can be found in Appendix S3 of this report.

KEY ADVANTAGES OF DIWT

DIWT offers a number of features designed to make searching the web-scraping database powerful and convenient. DIWT is different from any other surveillance platform currently being used to survey and detect online wildlife trade in Australia (Appendix S5). For example, users can:

- establish automated email alerts based on keywords
- narrow searches to a specific state/territory of interest
- download results to a *.csv or Excel sheet
- create a search with unlimited search words
- search any 30-day period since records commenced.

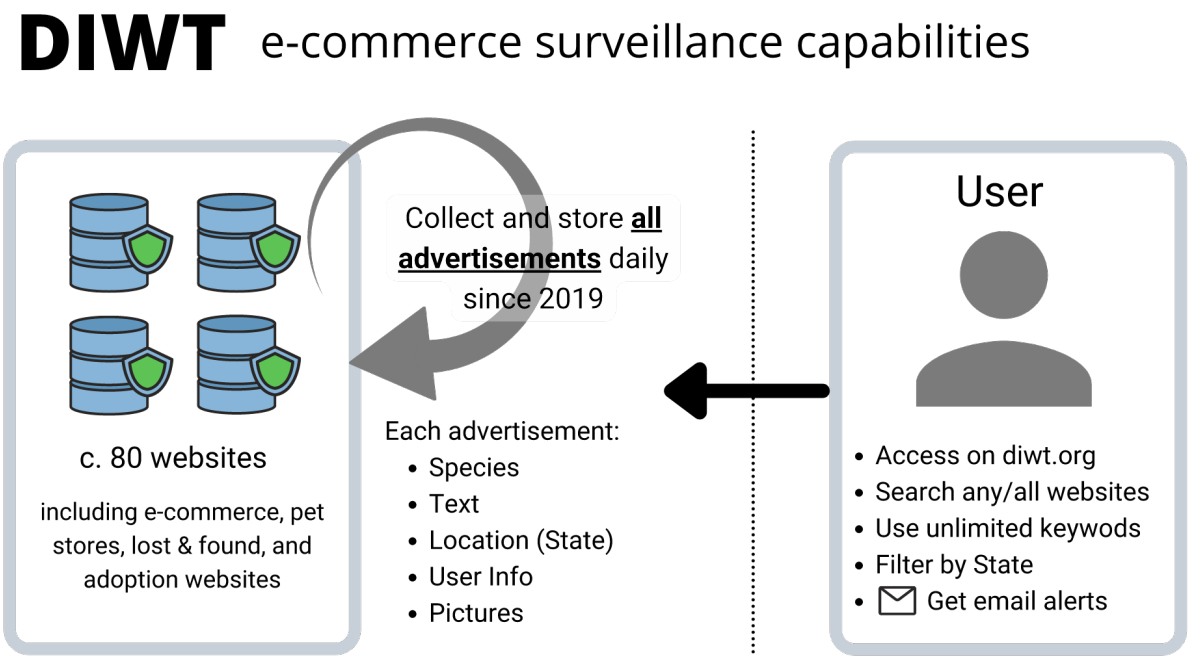


Figure 13. DIWT basics for users. Web scrapers collect automated data (text and images) from trade websites and data is stored in a relational database. Users query the database in real time or via email alerts for particular user-defined search terms.

HOW WE COLLECT DATA

Each website we monitor is 'scraped' either once a day or once a week, depending on how often advertisements are posted (Figure 14). The periodicity can be changed to reflect changing threats and increase the likelihood of early detection and intervention. We automated monitoring by using 'web scrapers', which are custom computer code we wrote to extract attributes from advertisements such as text, price and location.

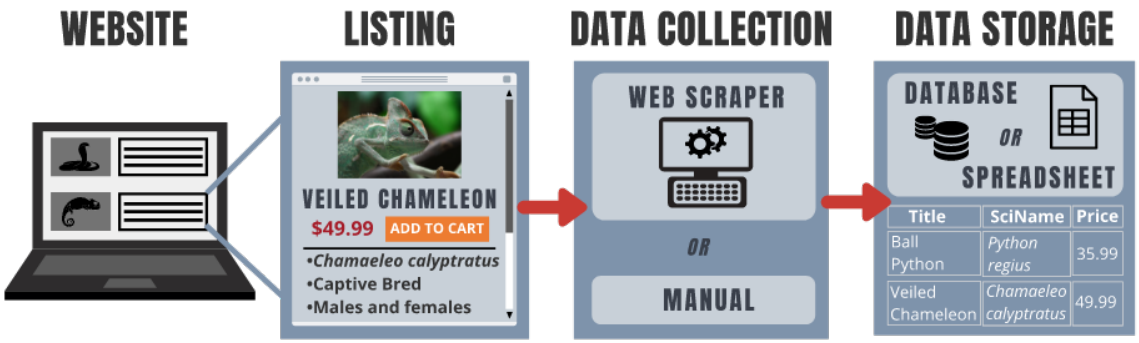


Figure 14. Web scraping for wildlife trade (Stringham et al. 2021c)

WHAT KIND OF DATA WE COLLECT

The data we collect depends on what is provided by the website. We attempt to extract every piece of information possible. The fields we collect include: text description, price, species name, user information, location and picture URLs. When a user searches the DIWT database, they can see all the attributes which have been collected.

WEBSITES AND TAXA THAT ARE MONITORED

DIWT was originally constructed to collect online wildlife trade data for detecting alien vertebrates and ornamental plants declared as alien weeds. We systematically chose the most popular wildlife

ecommerce websites in four regions (Figure 15). There is some wildlife trade of other taxa occurring on these websites (e.g., pet invertebrates). DIWT has the capabilities to expand to new taxa and new websites in the future. You can check the DIWT website to view the specific websites we currently monitor.

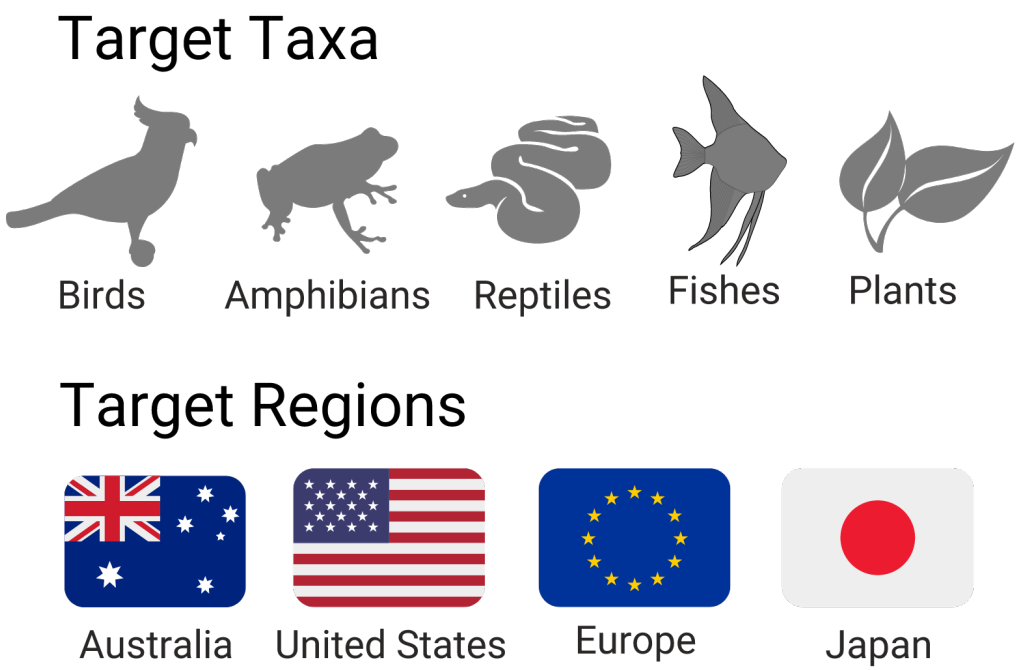


Figure 15. Existing characteristics of DIWT

HOW YOU CAN SEARCH DIWT

To search DIWT after you have signed up and been registered for an account, simply select the "New Search" option. See the full User Guide (Appendix S3) for specific instructions.

WHAT ABOUT SOCIAL MEDIA SITES?

Currently, DIWT is monitoring the surface web: ecommerce, pet stores, classifieds, forums, lost-and-founds and adoption websites. We are trialling methods to monitor social media (deep web) and the dark web. Including social media within DIWT is a future goal of ours. We have acquired Adelaide University Human Research Ethics Committee approval to monitor social media sites and have trialled a preliminary method, although this is currently in a process of refinement.

USER ADOPTION AND RESPONSE

The DIWT is currently available to government agencies' staff and researchers who monitor trade in wildlife and invasive species. DIWT currently has 67 active users, comprised of 47 users from government agencies and 17 from research groups. The government users cover all states and territories across 16 state departments, regional land services and local councils. The 17 users from research groups come from universities in Australia, Japan and the United States.

Jurisdiction	Department (*n* users)	Total users
Australian Government	Department of Agriculture, Fisheries and Forestry (3)	3
ACT	Environment, Planning and Sustainable Development Directorate (4)	4
NSW	Department of Primary Industries (6) Local Land Services (4) Port Macquarie Hastings Council (1)	11
NT	Department of Environment, Parks and Water Security (2)	2
Qld	Department of Agriculture and Fisheries (6)	6
SA	Department for Environment and Water (3) Department of Primary Industries and Regions (1) Landscape Board (5)	9
Tas	Department of Natural Resources and Environment (3)	3
Vic	Department of Jobs, Precincts and Regions (3) Department of Environment, Land, Water and Planning (2)	5
WA	Department of Primary Industries and Regional Development (3) Department of Biodiversity, Conservation and Attractions (1)	4

FEEDBACK ON DIWT'S BETA VERSION

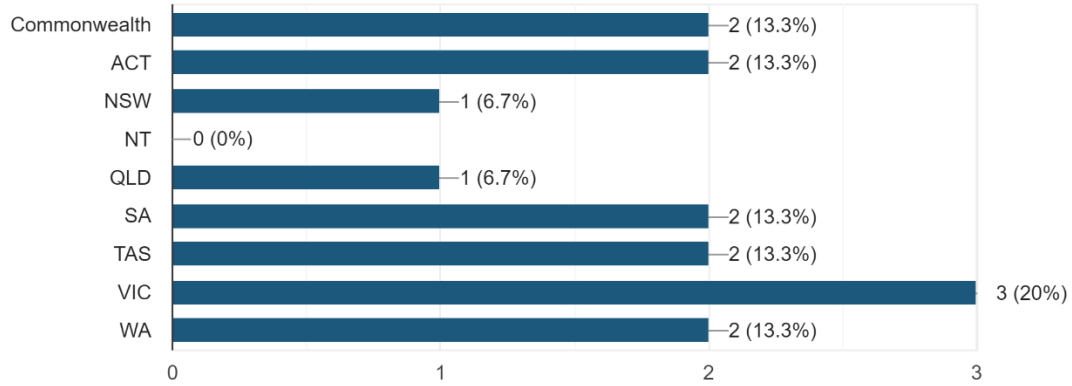
During beta-testing we sought feedback from government users at the Australian Government and state/territory level on the application and usability of the database. To date we have received 15 formal responses, representing 11 departments, through the online survey. More than a third of respondents said they worked with both plants and animals (40%), another 40% said they worked with exclusively with plants, and 20% said they worked exclusively with animals.

The majority reported that the DIWT database search and email alert system met their needs for monitoring ecommerce wildlife trade. Most respondents also found the website interface easy to use and to set up email alerts. Some of the suggested improvements included greater coverage of social media websites. The feasibility of wider social media capture is something that could be explored, but would require increased resources and funding. A few respondents wished to be able to search for specific sellers by name/usernames. While possible, the legal and ethical boundaries of this would need to be carefully examined. Another request was to be able to open links from within Microsoft Excel once a spreadsheet had been downloaded from the database. This is already possible from within Excel, so instructions could be included on the website to assist with this. Finally, some users requested that lists of species prohibited to trade be included on the website. In practice, this would require relevant jurisdictions to provide and update these proposed lists to ensure accuracy. We have suggested on the website that users keep spreadsheets or text files of their target species which can then be copied into the free-text search words box.

Next, we illustrate this feedback in a series of graphs.

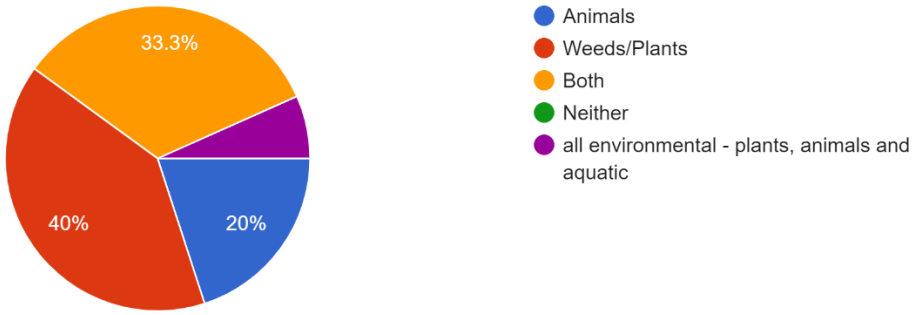
2. Which jurisdiction do you work for?

15 responses



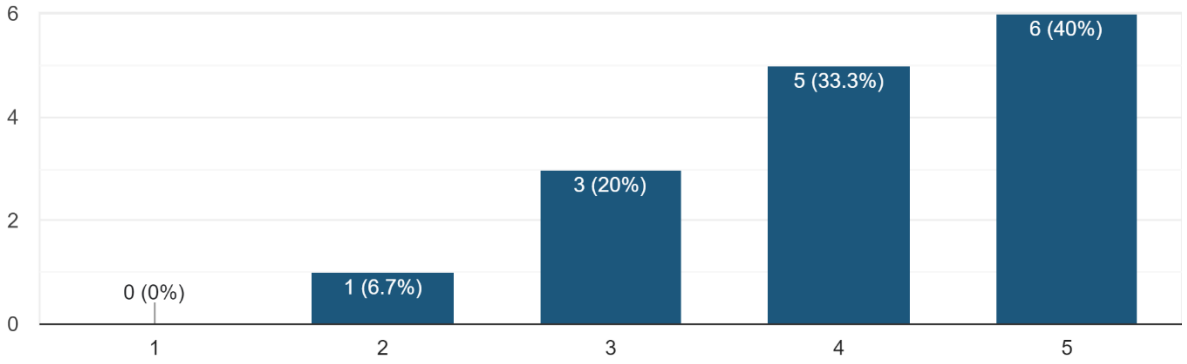
5. Which taxonomic group do you 'work' with?

15 responses



6. How useful did you find DIWT? Specifically, were the search and email alert system adequate to meet your needs of monitoring e-commerce wildlife trade?

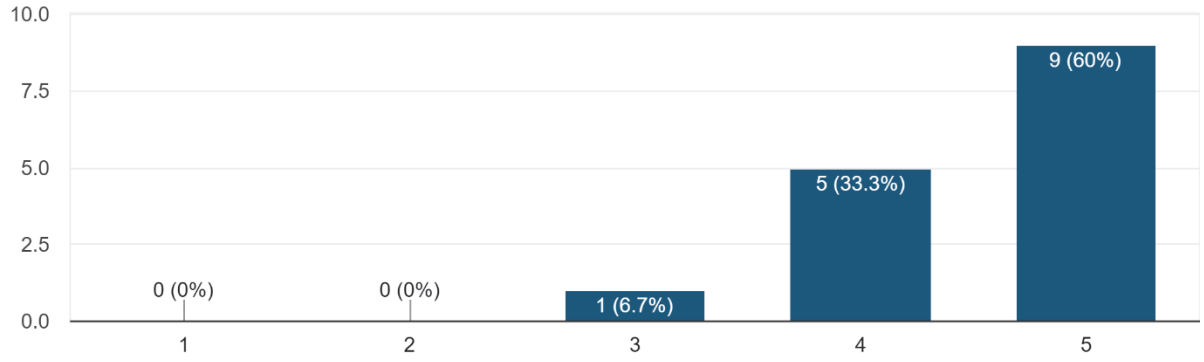
15 responses



Note: 1 is 'not very useful', up to 5 which is 'very useful'

8. How would you rate the ease of use of the DIWT website? Specifically, how easy or difficult was it to search for e-commerce wildlife trade or set up email alerts using the DIWT website interface?

15 responses



Note: 1 is 'not very easy', up to 5 which is 'very easy'

SELECTED USER TESTIMONIALS FROM FEEDBACK [UNEDITED]

"I already have 4 or 5 significant hits with a small range of search terms!" – Department of Agriculture and Fisheries, Queensland

"I have started the testing and so far so good. Wow, the database is a beaty and I am loving it!! You will be please [*sic*] to know that I have already detected a water hyacinth trade on … Right now we are sending some officers to seize the plants and initiate some compliance activities on this detection. This is how handy and effective the database is." – Agriculture Victoria, Department of Jobs, Precincts and Regions, Victoria

"DIWT is a great tool, it saves a significant amount of time scrolling through websites looking for ads." – Department of Agriculture and Fisheries, Queensland

"The user software interface and guides were quick and easy to understand and use." – Department of Primary Industries, New South Wales

"The daily email allows me to check for online sales of weed species." – Department of Natural Resources and Environment, Tasmania

"I really liked the 'search' function once a list of ads was returned." – Department of Jobs, Precincts and Regions, Victoria

"I liked that I could put various plant species in at once and easily duplicate the search and then use different names (rather than setting up a search again)." – Department of Agriculture, Fisheries and Forestry, Australian Government

"I think it is a potential gamechanger on the way we monitor online activities for detection of illegal trade of invasive species due to its effectiveness." – Agriculture Victoria, Department of Jobs, Precincts and Regions, Victoria

"Really good initiative that retrieved more sites quickly - more quickly and successfully than my own search attempts over a much longer time period." – Department of Agriculture, Fisheries and Forestry, Australian Government

"Great tool. I hope it continues to be supported." – Department of Natural Resources and Environment, Tasmania

“Very straightforward and easy to use.” – Department for Environment and Water, South Australia

“Easy to search a range of platforms.” – Department of Primary Industries and Regional Development, Western Australia.

CASE STUDIES SHOWING HOW DIWT DATA HAS BEEN USED

In this section, we include case studies that demonstrate how practitioners can use wildlife trade data collected on the internet in relation to biosecurity, by using data collected by DIWT.

The themes of our case studies range from characterising trends in the illegal trade of vertebrates, invertebrates and weeds to predicting future incursion risks. Each case study is at varying levels of readiness: some are existing published peer-reviewed papers, some are preliminary results to be published in the future, and one is an internal study we performed and do not plan to publish except in this report.

CASE STUDY 1: THE PAUCITY OF ILLEGAL ALIEN TERRESTRIAL VERTEBRATES TRADED IN AUSTRALIAN SURFACE WEB

This case study was led by Oliver C. Stringham. There are no plans to publish this study elsewhere.

SUMMARY

We investigated the illegal trade of alien birds, reptiles and amphibians on a popular Australian classifieds website.

We found no illegal sales of alien reptiles or amphibians out of the approximately 13,000 advertisements we analysed.

We found very few illegal sales of alien birds, representing 14 species in 310 advertisements – roughly about one per cent of the total alien bird trade we analysed (about 94,000 advertisements).

All species illegally traded in a state were legal to trade in at least two other states.

Overall, the illegal trade of alien terrestrial vertebrates appears almost non-existent on the surface web (e.g. ecommerce) in Australia.

OBJECTIVES

Our objective was to identify and quantify the illegal wildlife trade of alien birds, reptiles and amphibians occurring over the Internet in Australia. We focused on species of birds, reptiles and amphibians that are not native (i.e. alien) to any part of Australia. We performed this analysis at the level of Australian States (including Northern Territory), specifically gathering state-specific laws around the trade of alien species. Our secondary objective was to characterise the laws governing the trade of alien species.

METHODS

We monitored a very popular Australian classifieds website for the trade of alien birds, reptiles and amphibians. We collected advertisements from the website for a one-year period between 7 July 2019 and 6 July 2020. We collected 94,289 advertisements from the bird section of the website and 25,132 advertisements from the reptiles and amphibian section of the website. Advertisements were collected as text and thus were not readily available for analysis. To address this, we chose a subset of advertisements to ‘clean’ for analysis. Our cleaning process consisted of extracting the following: the scientific name(s) of the species traded, the quantity traded and the price per individual. The location (i.e. state) was hard-coded into the advertisement and thus did not require manual cleaning.

For reptiles and amphibians, we chose a random sample of 50% of the advertisements (n = 12,659) to manually clean. For birds, we chose a random sample of 25% of the advertisements from the first five months of the data (n = 16,509) to manually clean. For birds, we further processed the remaining data using a variety of automated methods. Specifically, we used text classification to remove listings that were predicted to be junk, as well as removing wanted advertisements and non-target taxa

(waterfowl, gamebirds, pigeons) (detailed in Stringham et al. 2021b). Next, we used a fuzzy string matching[5] model to predict which species were being sold in each advertisement. We tested (i.e. validated) the fuzzy string matching model with our manually cleaned data (i.e. labelled data), and found the fuzzy string matching model predicted the correct species for about 98% of the advertisements. For any illegal alien species found via the fuzzy string matching model predictions, we manually validated that the correct species was predicted. Therefore, for birds, we examined the entire year's advertisements (n = 94,289). For all taxa, we chose to only analyse advertisements of live animals (e.g. no body parts, derivatives or medicinals). For birds, we chose to focus our analysis on the most common orders in the bird trade: parrots (psittaciformes), songbirds (passeriformes) and doves (columbiformes).

We compiled laws relating to the keeping and trading of alien species for each Australian state and the Northern Territory (henceforth, simply 'state') (Table 1). We contacted representatives in each state to verify our understanding of the laws were correct. We note that states may have since updated their laws. However, for this study, we use and report on the laws that correspond with the timeframe of our study period (i.e. laws that were in force on July 2020). We categorised the type of laws each state had as being either: an allow list (also known as a whitelist) or a deny list (also known as a blacklist). Further, we kept records of each alien species (or taxa) that are on each state's allow or deny list.

We standardised species names in advertisements and laws using the Global Biodiversity Information Facility taxonomic database (GBIF 2022). To identify the illegal trade of species, we cross-referenced the location of the advertisement with the legality status in the state laws. Further, we characterise trends in the overall trade of alien species, illegal trade of alien species, and patterns in state laws.

[5] An artificial-intelligence and machine-learning technology that identifies similar, but not identical, elements in datasets

Table 1. State laws regarding the keeping and trading of alien terrestrial vertebrates

State/territory	Law	Applicable section or specified category name
South Australia	Natural Resources Management Act 2004 ** Note, subsequently Landscape South Australia Act 2019	Classes 4, 5, 11, 12, 13, 14, 15, 17, 19, 20, 23
Queensland	Biosecurity Act 2014	Schedule 1
	Nature Conservation (Wildlife) Regulation 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013	Schedule 7
	Nature Conservation (Wildlife Management) Regulation 2006	Schedule 3
New South Wales	Biosecurity Act 2015	Schedule 3, Division 2
Victoria	Catchment and Land Protection Act 1994	Schedules 1, 2, 3A, 4B
Tasmania	Nature Conservation Act 2002	Part 4, section 32(1)
Western Australia	Biosecurity and Agriculture Management Regulations 2013	Western Australian Organism List: K4, K5, No Category
Northern Territory	Territory Parks and Wildlife Conservation Act 1976	Part 4, Division 5 and Division 6:55

RESULTS

REPTILES AND AMPHIBIANS

We found no alien reptiles traded and thus no illegal sales of alien reptiles. We found one species of alien amphibian traded: the axolotl (*Ambystoma mexicanum*), which is legal to trade in all states except for Northern Territory and Tasmania. While we found 74 advertisements of the axolotl (representing 310 individuals), we found no axolotls traded in Northern Territory nor Tasmania, and thus no illegal sales of alien amphibians. There were, however, expressions of interest in the illegal alien corn snake (*Pantherophis guttatus*).

BIRDS

We found 95 species of alien birds traded in 33,246 advertisements (Figure 16). The volume of alien birds traded (i.e. number of advertisements) was about 39% of the total bird trade (86,270 advertisements of native and alien species). The alien bird trade comprised about 60% of all species traded (158 species in total).

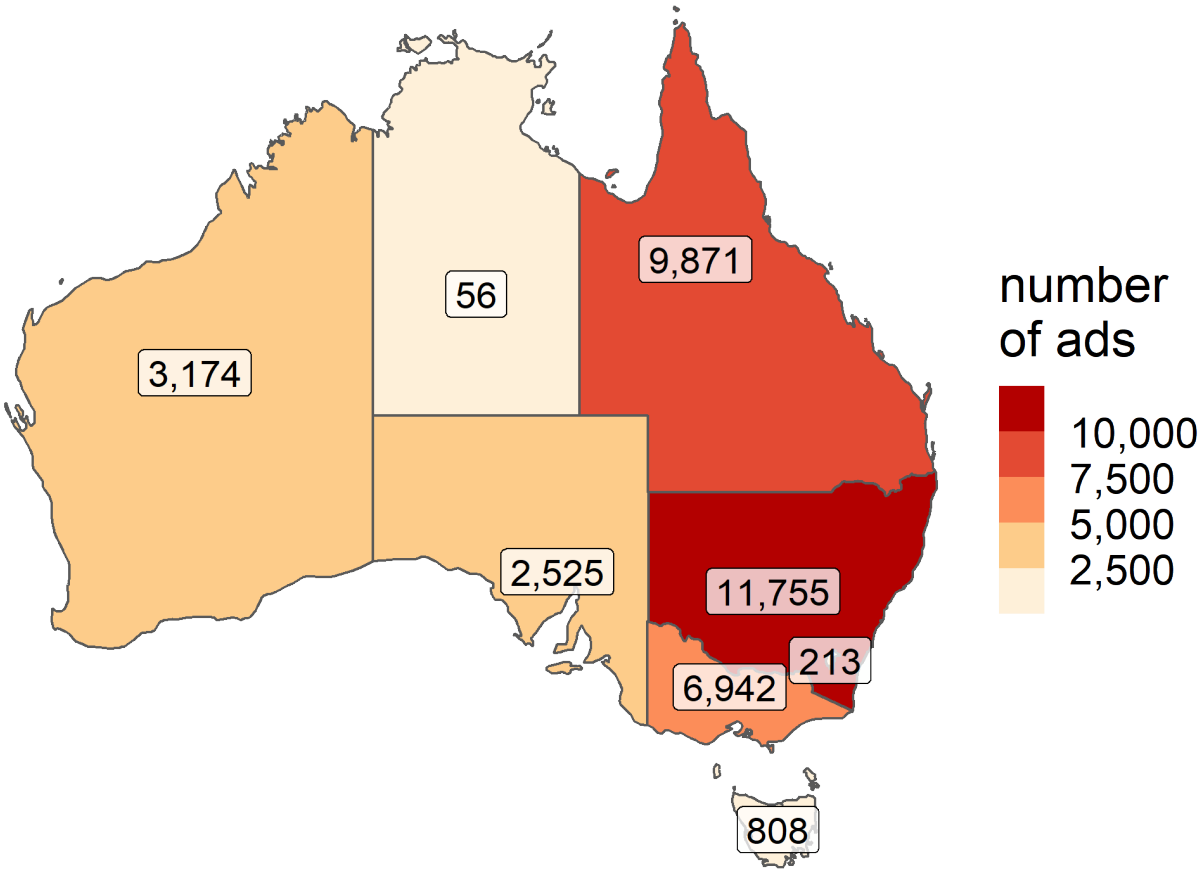


Figure 16. Alien birds traded (legally and illegally) (n = 636). Note: some ads did not have location for birds.

We found 14 species of birds illegally offered for trade in 310 advertisements (Figure 17). This consisted of two dove species, two songbirds and 10 parrots. This illegal trade represented about 15% of the total number of alien species and about one per cent of the total number of alien bird advertisements.

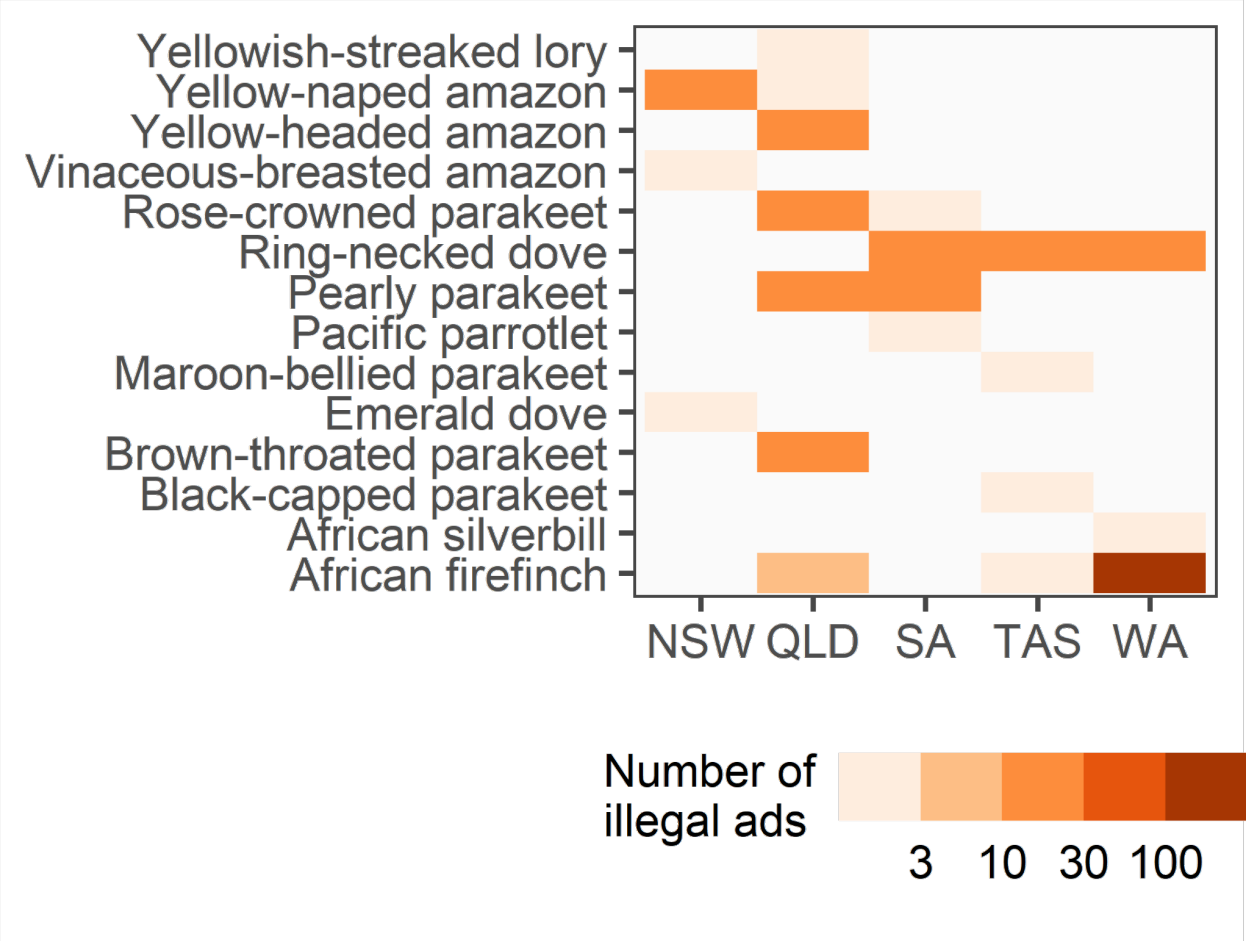


Figure 17. Frequency of illegal bird trade by species and state

Queensland had the most illegal species traded (*n* = 7 species), while Western Australia had the most illegal advertisements (*n* = 124 ads). All species illegally traded were legal to trade in another state. However, the vinaceous-breasted amazon (*Amazona vinacea*) was illegally traded in New South Wales, and is only legal to trade in Victoria and Northern Territory because it does not appear on those states' deny lists. In other words, the vinaceous-breasted amazon was the only species illegally traded in Australia that was not explicitly legal in any state's allow list (Figure 18).

Figure 18. Bird species traded illegally in Australia

Species	State(s) species was illegally traded	State(s) legal to trade species
Yellowish-streaked lory (Chalcopsitta sintillata)	Qld	NSW, Vic, NT
Yellow-naped amazon (Amazona auropalliata)	NSW, Qld	SA, Vic, NT
Yellow-headed amazon	Qld	SA, NSW, Vic, NT

(Amazona oratrix)		
Vinaceous-breasted amazon (Amazona vinacea)	NSW	Vic, NT
Rose-crowned parakeet (Pyrrhura rhodocephala)	Qld, SA	NSW, Vic, NT
Pearly parakeet (Pyrrhura lepida)	Qld, SA	NSW, Tas, Vic, NT
Pacific parrotlet (Forpus coelestis)	SA	Qld, NSW, Vic, NT
Maroon-bellied parakeet (Pyrrhura frontalis)	Tas	SA, Qld, NSW, Vic, NT
Brown-throated parakeet (Aratinga pertinax)	Qld	NSW, Vic, NT
Black-capped parakeet (Pyrrhura rupicola)	Tas	SA, Qld, NSW, Vic, NT
Emerald dove (Chalcophaps indica)	NSW	WA, Tas, Vic, NT
Barbary/African collared dove (Streptopelia roseogrisea)	SA, Tas, WA	Qld, NSW, Vic, NT
African silverbill (Euodice cantans)	WA	SA, Qld, Vic, NT
African firefinch (Lagonosticta rubricata)	Qld, Tas, WA	SA, NSW, Vic, NT

LAWS

Victoria and Northern Territory implemented a deny list (also known as a blacklist) explicitly stating which species are illegal to trade and keep. In most cases, a deny list implicitly signifies that all species not on the list are *legal* to trade and keep. All other states (Qld, NSW, Tas, SA and WA) implemented an allow list (also known as a whitelist) explicitly stating which species are legal to trade and keep. An allow list implicitly signifies that all species not on the list are *illegal* to trade and keep.

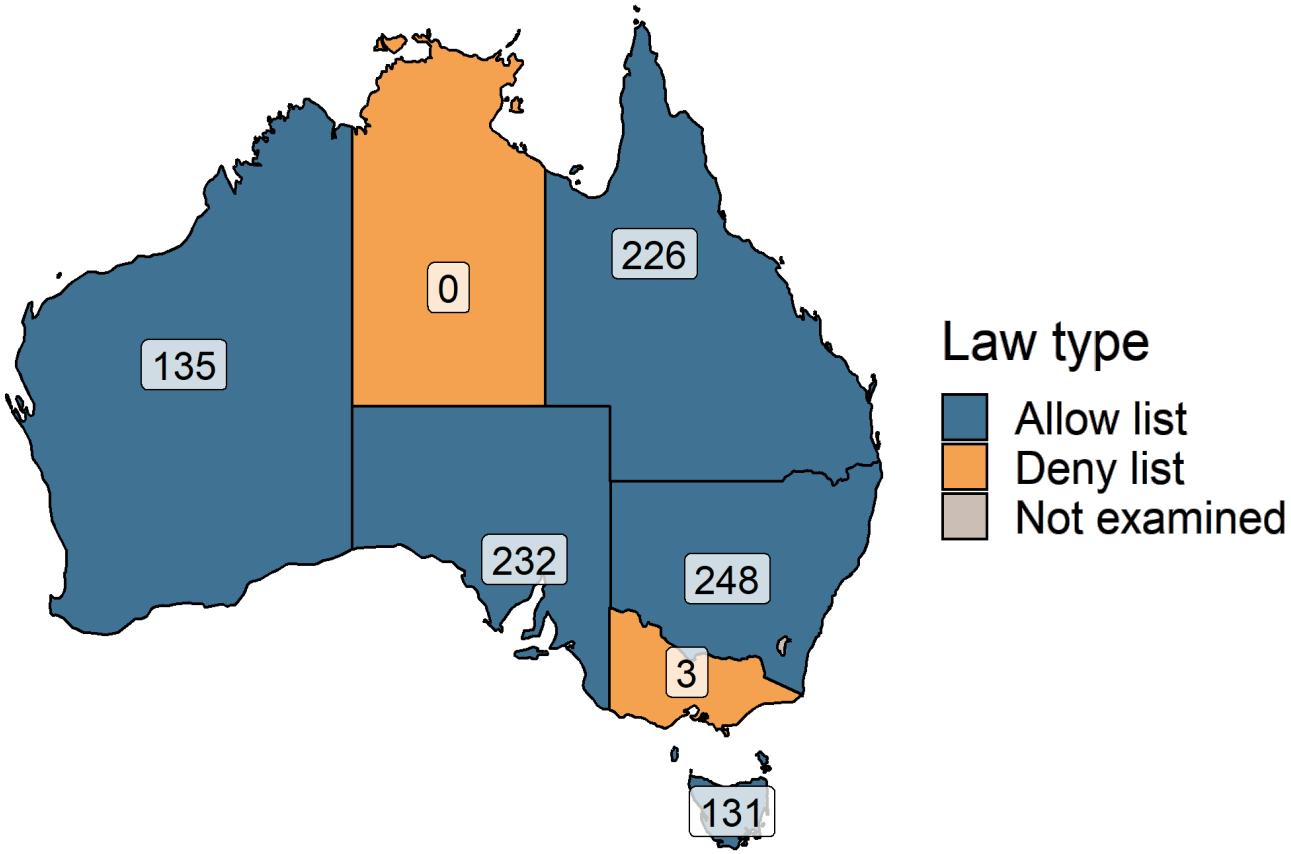


Figure 19. Numbers correspond to the number of bird species in each state's allow or deny list. Note: we did not examine the ACT's legislation about keeping alien wildlife.

For reptiles, federal legislation bans the import of alien reptiles as pets (Department of Agriculture, Water and the Environment 2022). Further, New South Wales, Tasmania, South Australia and Western Australia do not list any alien reptiles on their allow lists (i.e. all alien reptiles are illegal). Queensland lists one species of reptile on its allow list (i.e. legal): the Asian house gecko (*Hemidactylus frenatus*). Victoria and Northern Territory list all alien reptiles on their deny lists (i.e. illegal).

For amphibians, federal legislation bans the import of all alien amphibians as pets, except for the axolotl (Department of Agriculture, Water and the Environment 2022). Further, New South Wales, Queensland, South Australia and Western Australia list the axolotl on their allow lists (i.e. legal). Tasmania does not list any alien amphibian on its allow list (i.e. all alien amphibians are illegal). Northern Territory lists the axolotl on its deny list (i.e. illegal), while Victoria does not list any amphibian on its deny list (i.e. legal). New South Wales and Queensland list the cane toad (*Rhinella marina*) on their allow list (i.e. legal). Further, Northern Territory also bans the trade and keeping of all frog species that are not native to the Northern Territory.

For birds, federal legislation allows for the import of about 20 alien bird species as pets (Department of Agriculture, Water and the Environment 2022). However, unlike for reptiles and amphibians, most bird alien bird species in the modern-day Australian pet trade were present in the country prior to the

ban of their entry. Thus, state legislation around the keeping of alien birds accounts for the present composition of these species in trade, with some variation between states (Woolnough et al. 2020). Among the states with allow lists, New South Wales legislation allowed the most alien bird species (*n* = 248), followed by South Australia (*n* = 232), Queensland (*n* = 226), Western Australia (*n* = 135) then Tasmania (*n* = 131) (Figure 19). Among the states with deny lists, Victoria legislation banned the trading and keeping of three bird species, while the Northern Territory did not ban any species of alien birds. However, Northern Territory law specified that alien species brought into NT must be accompanied with proof of *legal* purchase in another state.

CASE STUDY 2: THE ABUNDANCE OF UNREGULATED ALIEN TERRESTRIAL VERTEBRATES TRADED ON THE AUSTRALIAN SURFACE WEB

This case study was led by Adam Toomes and is a condensed version of the manuscript 'A Snapshot of Online Wildlife Trade: Australian ecommerce trade of native and alien pets', which is currently being prepared for scientific peer review.

SUMMARY

We investigated the trade of alien fish and birds across 12 Australian ecommerce sites.

We found trade of 528 alien species of fish, including 266 that are not permissible for live import and 22 that are already established populations in Australia.

We found a further 112 species of alien birds, including species known to be invasive elsewhere in the world.

Almost all alien pet trade was taking place in an unregulated manner – without the need for permits or provenance testing.

There was a large (but unquantifiable) trade in taxa that are alien, though not yet taxonomically described – meaning their biosecurity threat is currently unknown.

Objectives

We expanded upon the objectives in Case Study 1 to expand our scope beyond species that are explicitly illegal. Through preliminary research we identified a large diversity of species being traded openly on the surface web despite being alien to Australia, and in some cases known to be invasive species elsewhere in the world. While such trade is not technically illegal, the lack of regulation of these species often stems from stakeholder resistance rather than a lack of biosecurity risk. Therefore, we sought to quantify the frequency and diversity of trade in alien species to better quantify trade-associated biosecurity threats.

Methods

We created and maintained fit-for-purpose web scrapers for 12 Australian ecommerce platforms and collected a 'pre-COVID-19' snapshot of data spanning 14 weeks. We adopted the library of scientific names generated in Case Study 1 in order to automate the identification of advertisements based on the presence of scientific, common or trade names. We expanded upon this list as we encountered new taxa, resulting in over 1,200 distinct native and alien taxa. Alien status for each species was determined using the Australian Faunal Directory and manual inspection of distribution data on the Global Biodiversity Information Facility.

For listings that matched multiple names, we manually inspected the text and recorded each unique taxon that was advertised for sale, ensuring that the unique listing identifier was recorded for each taxon. We omitted domesticated taxa from our analysis: namely, pigeons (*Columba livia*) and chickens (*Gallus gallus*).

Due to the considerable quantity of listings selling pets, we deemed it logistically infeasible to manually establish additional information such as the quantity of pets for sale. Consequently, we queried listing titles and text against a predefined set of strings to categorise listings based on the presence of information pertaining to pet quantity, captive-bred status and life stage. If listings specified a 'pair' or 'trio' of animals, quantity was assumed to be two or three respectively. Listings referring to animals using a plural term (e.g. dragons, parrots) were assumed to be advertising two individuals, noting that the actual number may be higher. Listings that referred to a 'colony' or other collective terms were assumed to be advertising five individuals.

We collated Global Invasive Species Database records of invasive species to categorise advertised pets based on their history of invasions. We also cross-referenced taxa against the Commonwealth List of Specimens Taken to be Suitable for Live Import ('Live Import List').

Results

We have recorded the highest known diversity of exotic pets traded in Australia to date. While species accumulation curves reveal a plateau in new bird species throughout our sampling period, fish species richness continued to rise without plateau, suggested that yet more alien species remain undetected (Figure 20). For pets identified to species level, there were almost 38,000 individual alien animals advertised for sale over 14 weeks.

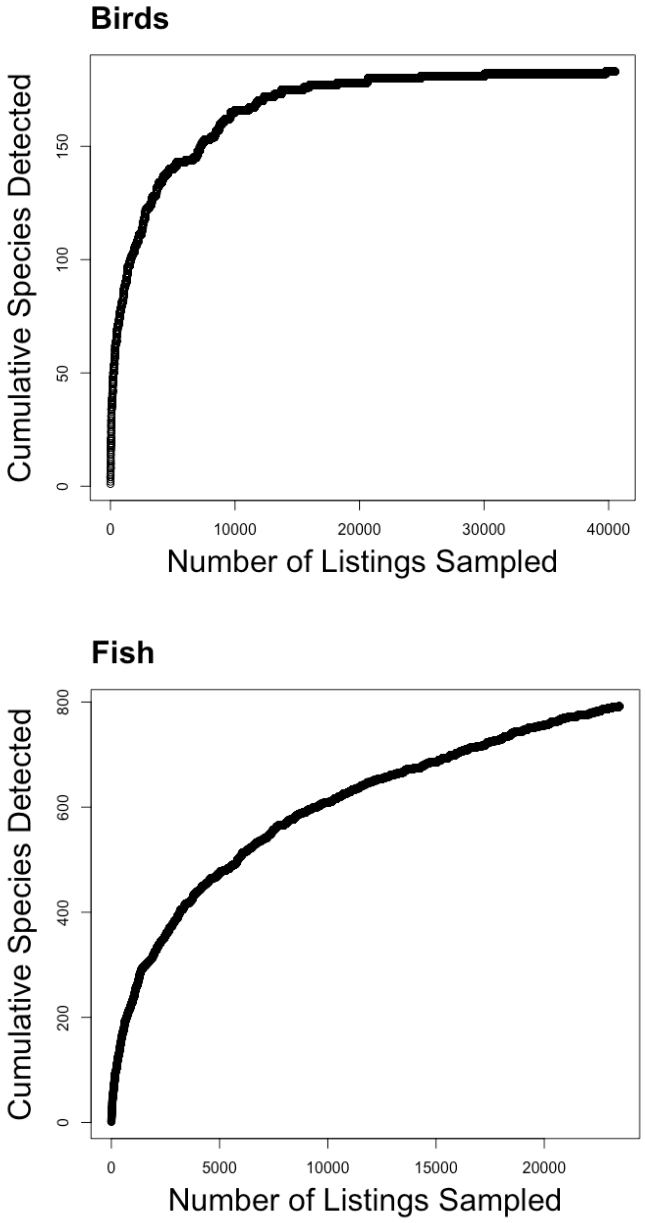


Figure 20. Species accumulation curve for native and alien bird and fish taxa detected in Australian ecommerce trade. Raw data is displayed after randomly sampling species without replacement from all listings.

The vast majority of trade took place on classifieds sites (66,158 listings; 96.6%), followed by pet stores (2,098 listings; 3.12%) and forums (193 listings; 0.28%). There was a high diversity of species

(619) found on only a single ecommerce platform, implying a high level of ecommerce specialisation catering to specific hobbies or consumer types.

One alien bird species, the Pacific parrotlet (*Forpus coelestis*), was not already listed on the 2007 inventory of known traded species in Australia, implying that they have been newly introduced into the trade since that inventory was created (DAWE 2021).

Fish were the most diverse taxon traded, with 885 distinct taxa (8 hybrids, 50 genera, 12 families, three orders) including 799 species, 528 of which are alien (constituting 11,308 listings). Perciformes were the most diverse order of fish (482 species, 521 distinct taxa), followed by siluriformes (88 species, 103 distinct taxa), characiformes (58 species, 59 distinct taxa) and cypriniformes (57 species, 59 distinct taxa), which collectively account for 83.8% of all identified fish taxa (Figure 21). A total of 266 alien fish species were not permitted for live import, yet were detected in our trade snapshot.

Thus far, only 13 of the traded alien species have become invasive elsewhere in the world. Twenty-two of the alien fish species have introduced populations in Australia, including species that are invasive elsewhere such as jaguar cichlids (*Parachromis managuensis*) (Holmes et al. 2020) and species whose invasion potential has yet to be realised, such as Siamese fighting fish (*Betta splendens*) (Hammer et al. 2019).

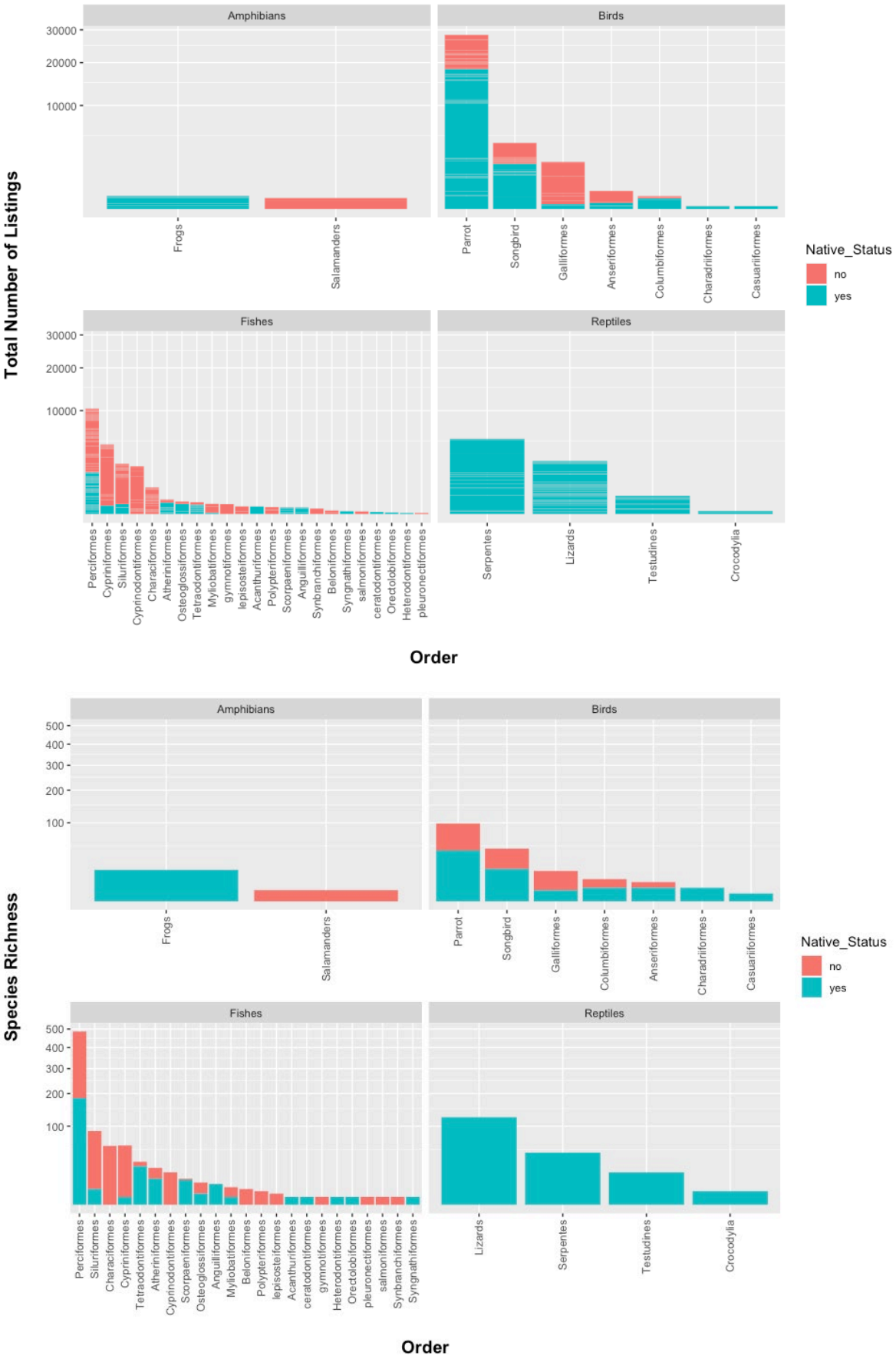


Figure 21. Total number of listings (A) and species richness (B) of ecommerce trade by taxonomic order for native and alien species, displayed on a square-root scale.

IMPLICATIONS

Our findings illustrate a much greater abundance and richness of alien species trade than previously recorded in Australia, implying that the biosecurity threat posed by the pet-release pathway continues to be underestimated. While there are existing audits of alien species such as the avicultural records compiled by Vall-llosera and Cassey (2017c) and the grey list of ornamental fish (Fredberg and McNeil 2010), our online surveillance reveals that contemporary understanding of the domestic alien pet trade is far from comprehensive. While our results contribute to such an understanding, the lack of saturation in the accumulation of new species (of some taxa) despite extensive sampling of thousands of advertisements suggests that the true diversity of alien taxa has yet to be determined.

The vast majority of the 641 traded alien species are not subject to any form of permit regulation. Even high-biosecurity-risk species that are regulated or prohibited, such as *P. krameri*, are not done so uniformly across all states and territories (Woolnough et al. 2020). Not only does such lack of regulation hinder the ability of Australian biosecurity authorities to control the trade of high-risk species, such as those already listed in Global Invasive Species Database, but it also deprives those authorities of a systematic means of recording alien escapes/release from captivity.

In contrast to the paucity of trade in nationally prohibited reptiles, species that are only prohibited in particular jurisdictions such as *P. krameri* in Western Australia and Tasmania were detected on the surface web (albeit in lower abundances than in permitted jurisdictions). This implies that jurisdiction-specific infringements are occurring unwittingly, and future communication with the traders responsible for infringements may reveal the extent to which taxa are traded knowingly. Regardless, our results show a clear parallel between Australia's policy regarding domestic trade of alien species and both the quantity and diversity of contemporary trade. Alien fish and birds, while mostly illegal to import via the *Biosecurity Act 2015* (DAWR 2019), are legal to trade without quota or documentation unless specifically declared as prohibited by a state or territory. In contrast, all alien reptiles are prohibited except for non-commercial purposes. This inconsistency in policy is worthy of further interrogation, because there is no evidence that the biosecurity threats posed by reptile and non-reptile vertebrate taxa are fundamentally different, as evidenced by the number of introduced and known invasive vertebrates currently present in Australia (Vall-llosera and Cassey 2017b; García-Díaz et al. 2018).

We detected a high volume of trade that could not be identified to species level; however, this was not entirely due to a lack of advertised information. Many hybrids are commonly traded, yet the origin species that constitute the hybrid are not always conclusively known. This is exemplified by the popular flowerhorn cichlid (see Figure 21), which is believed to originate from a multigeneration hybrid of several *Cichlasoma* species with *Vieja synspila* (Nico et al. 2007). Other examples include red Texas cichlids (cichlidae), lemon bristlenose catfish/pleco (*Ancistrus*) and pigeon blood discus (*Symphysodon*). Moreover, there were many ornamental fish that have not been formerly described, yet nonetheless are widely known and traded (Tan and Armbruster 2016). For example, there are several undescribed cichlid fish from Lake Malawi that are known only as captive-bred colour morphs (Msukwa et al. 2022). Similarly, there are a diversity of catfish that can only be identified to genus level, yet are partitioned into pseudo-taxonomic units by traders using so-called 'L numbers' (Glaser and Glaser 1995) that do not necessarily map to distinct species (Cardoso et al. 2016). The lack of taxonomic resolution stifles efforts to evaluate both the biosecurity threat posed by traded fish, as well as the risk that trade poses to their conservation. Undescribed and/or hybrid fish are nonetheless known to be introduced (Maciaszek et al. 2019) or invasive (Herder et al. 2012) elsewhere in the world.

CASE STUDY 3: FINDING SUBSTANTIAL ONLINE ILLEGAL TRADE OF WEEDS IN AUSTRALIA

This case study is based on the work of Jacob Maher (currently a PhD student at the University of Adelaide). All results and findings are preliminary; a paper is currently being drafted for submission to a peer-reviewed scientific journal.

SUMMARY

We investigated trade in declared plant species in Australia on a popular ecommerce website.

155 declared plant taxa were traded online in Australia from a sample of 10,000 advertisements.

We detected 1,418 declared plants traded, 413 of which were prohibited (the plant was declared in the state of sale).

Prickly pear (*Opuntia*) cacti, aquatic weeds and invasive garden plants were traded in the greatest quantities.

The trade in declared plants online in Australia is substantial, and should be considered a significant pathway for the incursion and spread of invasive plants.

OBJECTIVES

Our objective was to capture baseline data on the diversity and quantity of declared plants traded online in Australia. We defined declared plants as prohibited to trade in an Australian state or territory. We identified species of declared plants traded online and those which were traded illegally. We captured data on the quantity, location and price of declared plants traded.

METHODS

To investigate the trade of weeds online we compiled a list of plant species prohibited to trade in Australia (simply ‘declared plant’ hereafter). To assemble this list, we used relevant government sources, including websites, online databases, legislative acts and gazettes (Table 2). The list of declared plants and relevant legislation was verified with appropriate state and territory government biosecurity authorities. We standardised the taxonomy of the declared plants using the Global Biodiversity Information Facility taxonomic database (GBIF 2022). This finalised the list of declared plant species to 1,236 species across all states and territories.

Table 2. The relevant legislation for each state/territory in Australia

State/ territory	Relevant legislation	Category relating to ban of sale	Source of listing for declared plants	Corresponding branch of government
ACT	Pest Plants and Animals Act 2005	Pest Plant – Prohibited (4)	Pest Plants and Animals (Pest Plants) Declaration 2015 (No 1)	Environment, Planning and Sustainable Development Directorate
NSW	Biosecurity Act 2015	State and Regional Priority Weeds	NSW Department of Primary Industry website – 1 and 2	Department of Primary Industries
NT	Weeds Management Act 2001	Declared Weed – Class A, B and C	Declared Weeds in the Northern Territory [PDF, 598 KB]	Department of Environment, Parks and Water Security
Qld	Biosecurity Act 2014	Prohibited matter, Restricted matter – Category 3	Biosecurity Act 2014	Department of Agriculture and Fisheries
SA	Landscape South Australia Act 2019	Declared Plants to which section 188(1) applies	South Australian Government Gazette 60: 4024–4038, 23 July 2020 [PDF, 2,797 KB]	Department of Primary Industries and Regions
Tas	Weed Management Act 1999	Declared weed	Weeds Index	Department of Natural Resources and Environment
Vic	Catchment and Land Protection Act 1994	Noxious weeds – state prohibited, regionally prohibited, regionally controlled, and restricted	Victorian Noxious Weeds List [PDF, 186 KB]	Department of Jobs, Precincts and Regions
WA	Biosecurity and Agriculture Management Act 2007	Declared Pest, Prohibited – s12 and Declared Pest – s22(2)	Western Australian Organism List	Department of Primary Industries and Regional Development

We selected a popular Australian ecommerce website to investigate the trade of declared plants. We sampled 12 months of plant advertisements between 1 February 2020 and 31 January 2021. There were 235,162 advertisements for plants during this time. From this we took two samples: one targeted declared plants and the other did not. For the non-targeted sample, we randomly sampled 5,000 advertisements distributed evenly across the eight states and territories (625 ads each). For the targeted sample, we used declared plants' scientific and common names to search through the advertisements. This resulted in 12,751 advertisements that matched search terms for declared plants. From this, we took a sample of 5,000 advertisements.

Three states had substantially fewer advertisements: Australian Capital Territory, Northern Territory and Tasmania (Table 3). Their representation was too low to evenly sample across states and territories. Therefore, we used weighted random sampling to increase their representation in our dataset. Our rationale for this decision was to provide all states and territories with valuable insight into trade occurring in their jurisdiction.

For each advertisement we identified the species present using photos and text provided. We captured the price, quantity and location of the advertisement. We also captured more specific information when provided, including: plant hybrids or named cultivars, ads for seeds or bulbs, derived parts sold (e.g. fruit, flowers, leaves), uses for the plant, or if it had been harvested from the wild.

We quantified the trade of declared plants sold anywhere in Australia. We also cross-referenced detections against the dataset of declared plants to determine advertisements which were illegal (the plant was declared in the state of sale).

We now describe the most frequently traded declared species and characterise their price trends.

Table 3. The number of advertisements from each state/territory that matched search terms for declared species and that were manually cleaned

State/territory	Matched	Cleaned
Australian Capital Territory	510	420
New South Wales	3,261	1,031
Northern Territory	66	66
Queensland	2,893	948
South Australia	1,073	539
Tasmania	308	308
Victoria	2,567	921
Western Australia	2,073	767
Total	12,751	5,000

RESULTS

13,559 plant identifications were made from the 10,000 advertisements that were sampled; we identified 1,777 plant taxa; 155 of these were declared taxa (Figure 20). There were 1,296 advertisements that contained declared plants. Some ads contained multiple declared plants, which brought the total number of detections to 1,418. Based on the non-targeted sample, three per cent of plants advertised on the ecommerce website were declared weeds. Using targeted search terms increased the proportion of declared plants in the target sample to 23.66%. In other words, the chance of successful detection improved from approximately 1 in 30 to approximately 1 in 5 using targeted search terms.

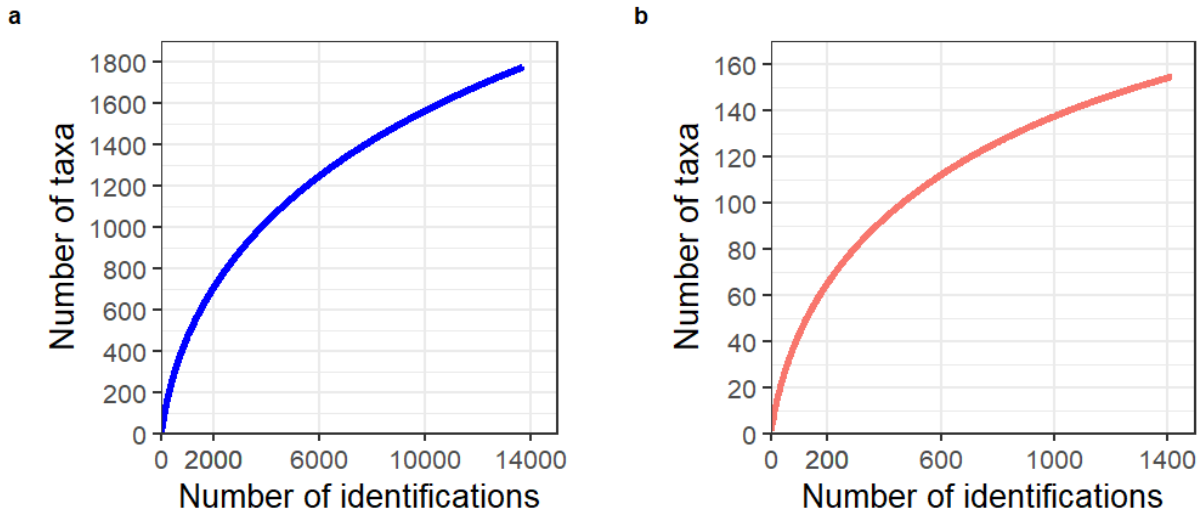


Figure 22. (a) Accumulation curve of plant taxa identified from online advertisements. There were 1,777 taxa observed from 13,671 identifications. (b) Accumulation curve of declared plant taxa detections from online advertisements. There were 155 taxa identified in 1,398 detections of declared plants.

Declared plants were advertised in every state and territory in Australia. There were more detections of declared plants advertised in states with higher populations. New South Wales had the highest number of detections (*n* = 331) and Northern Territory the fewest (*n* = 52) (Figure 21). Illegal advertisements were observed in all states and territories (413 total detections). Western Australia had the highest number of illegal ads (*n* = 108) and Northern Territory the fewest (*n* = 15).

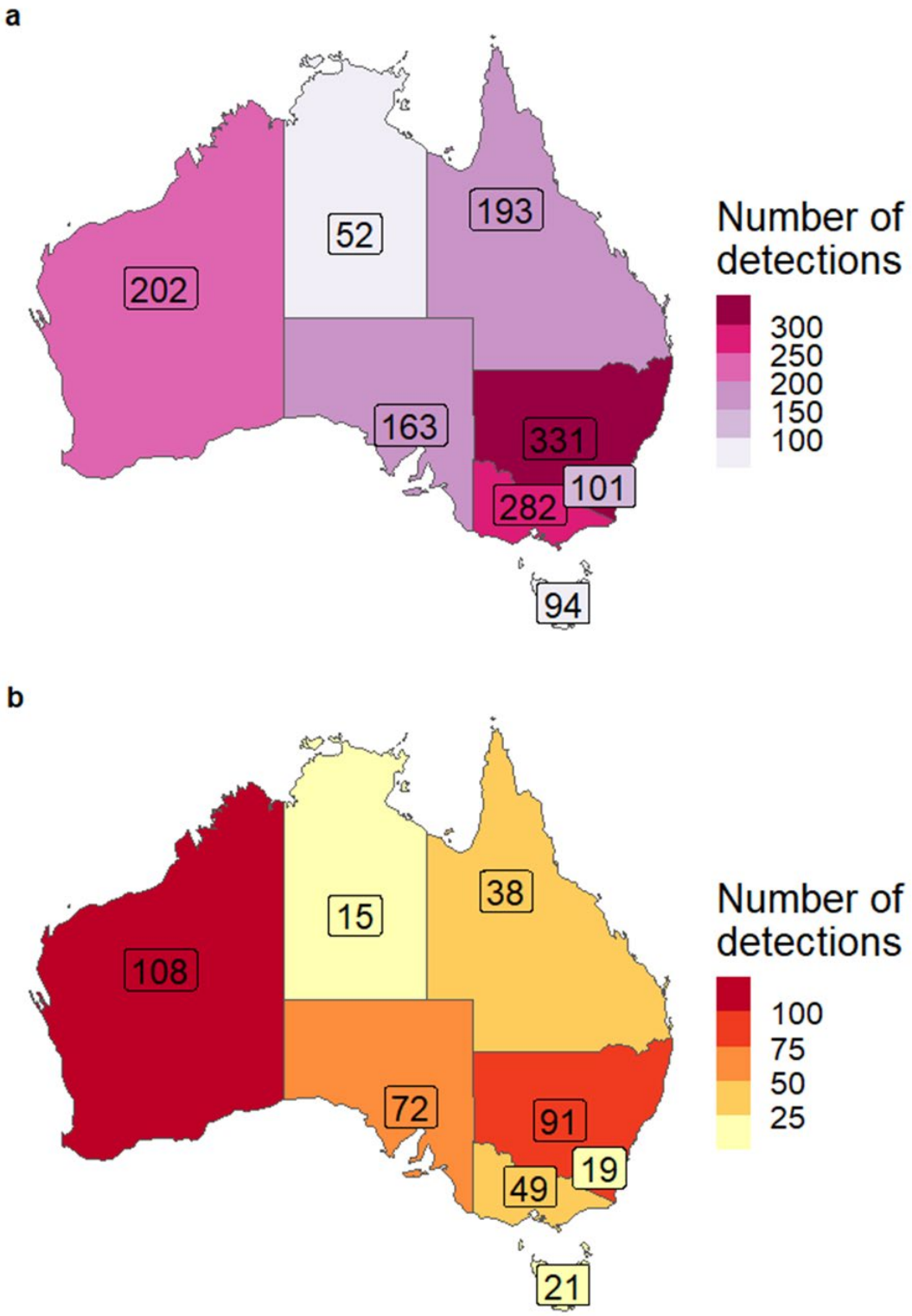


Figure 23. Detections of declared plants advertised online in Australia: (a) detections of plants declared in any state or territory, and (b) detections of plants declared within the state or territory of sale.

The most frequently advertised declared plants were *Opuntia* cacti, aquatic weeds and invasive 'backyard' garden plants. *Opuntia* cacti were often advertised illegally; the bunny ears cactus (*Opuntia microdasys*) was the most frequently illegally advertised plant (Figure 22). Frequently detected aquatic weeds were water hyacinth (*Eichhornia crassipes*) and Amazon frogbit (*Limnobium laevigatum*). The arum/calla lily (*Zantedeschia aethiopica*) was the most frequently advertised

declared plant and the second most frequently advertised illegally (Figure 22). Other invasive garden plants were gazania (*Gazania spp.*), English ivy (*Hedera helix*), topped lavender (*Lavandula stoechas*) and blackberries (*Rubus fruticosus* aggregate); noting that thornless varieties are often exempt from declaration. Four frequently detected declared plants were Weeds of National Significance[6]. These were blackberries, bunny ear cactus, drooping prickly pear (*Opuntia monacantha*) and water hyacinth.

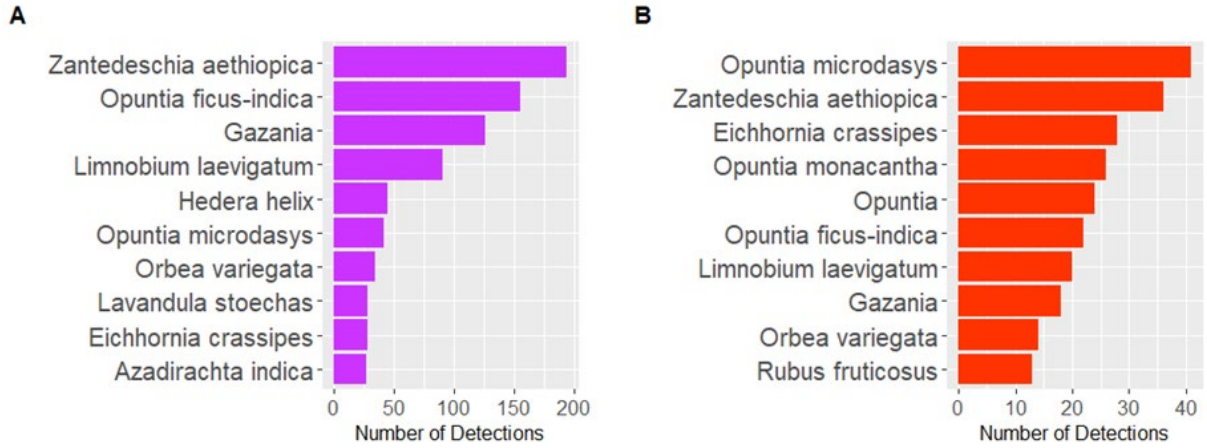


Figure 24. (a) The top-10 most frequently advertised plants declared anywhere in Australia. (b) Top-10 most frequently advertised declared plants prohibited in the state or territory of sale

Declared plants were advertised with relatively inexpensive prices. The price of the 10 most frequently advertised declared plants typically ranged from $5 to $30 (Figure 23). Indian fig (*Opuntia ficus-indica*) had the highest median price of the frequently sold declared plants. In some cases the cacti were advertised with exceptionally high prices – between $200 and $500.

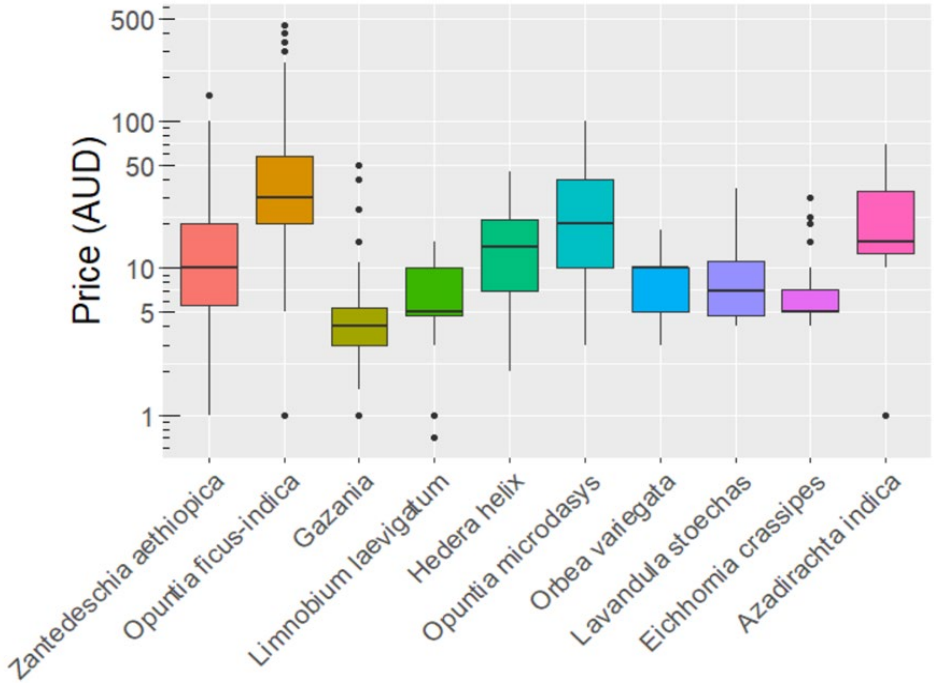


Figure 25. Prices of the 10 most frequently advertised declared plants

[6] Problematic plants because of their invasiveness, potential for spread and environmental, and social and economic impacts

CASE STUDY 4: DETAILED CASE STUDY ON THE TRADE OF POPULAR AQUATIC WEEDS IN AUSTRALIA

This case study is based on the work of Lisa Wood's University of Adelaide honours project ('The Australian Domestic Online Trade of Invasive Aquatic Plants' 2021). All results and findings are preliminary, and a paper is currently being drafted for submission to a peer-reviewed scientific journal.

SUMMARY

We examine the online trade of five common invasive aquatic plants, including: water hyacinth (*Eichhornia crassipes*), frogbit (*Limnobium laevigatum*), water lettuce (*Pistia stratiotes*), salvinias (*Salvinia molesta*, *Salvinia minima* and other *Salvinia* species).

We detected 525 illegal sales weeds from about 2,000 advertisements we examined.

There were illegal sales in every state and territory, with the exception of Tasmania. Western Australia had the most illegal sales (about 50 ads for frogbit and 30 ads for water hyacinth).

Our results clearly demonstrate the trade of illegal aquatic weeds is being facilitated over the internet; however, the scale of the illegal trade still needs to be examined (see Case Study 2).

OBJECTIVES

Our objective was to provide an in-depth analysis of the Australian online trade of invasive aquatic plants, with a focus on five species and one genus: water hyacinth (*Eichhornia crassipes*), frogbit (*Limnobium laevigatum*), water lettuce (*Pistia stratiotes*), *Salvinia molesta*, *Salvinia minima* and other *Salvinia* species. We use data extracted from a major Australian ecommerce website to answer the following questions: (i) What is the scale of the online trade of invasive aquatic species within Australia? (ii) Is there a relationship between the legality of species and the number and pricing of listings? (iii) How active are sellers in the trade, and do they correctly identify species within their listings?

METHODS

We used a web scraper to collect online listings (i.e. advertisements) from the 'plants' section of a major Australian classifieds website. We collected listings on a weekly basis over a 15-month period (30 January 2020 – 29 April 2021). After the data was collected, we used keyword searches to target listings that may contain the study taxa. Keywords included each species' scientific and common names, as well as trade names that were identified through a rapid literature review of each species. We also used non-specific terms such as "pond plant" and "water plant" to collect listings that did not explicitly name the target species within the listing title or description. From this process, we identified 2,083 listings.

We manually processed the listings to extract relevant information. Manual extraction of variables was required due to the 'open text' format of the listing titles and descriptions. Our manual cleaning process consisted of first identifying if (and what) relevant taxa were being advertised in each listing. If a relevant taxon was identified, we also extracted the following from the listing: the quantity traded, the price per plant, if the listing was a 'for sale' advertisement, and whether the species was correctly identified by the seller with a recognisable species/scientific/trade name.

To determine whether a listing was illegal (e.g. the listing had a plant advertised in a location where regulations restrict trade), we cross-referenced the location of each listing with state legislation.

RESULTS

We made a total of 525 detections of the studied water weeds being sold online across Australia over the 15-month period, including 194 illegal advertisements (Figure 24). Frogbit had the most advertisements (324), followed by water lettuce (79), water hyacinth (59), *Salvinia minima* (15), other *Salvinia* species (15), and *Salvinia molesta* (13). Illegal sales were recorded in all states and territories except Tasmania.

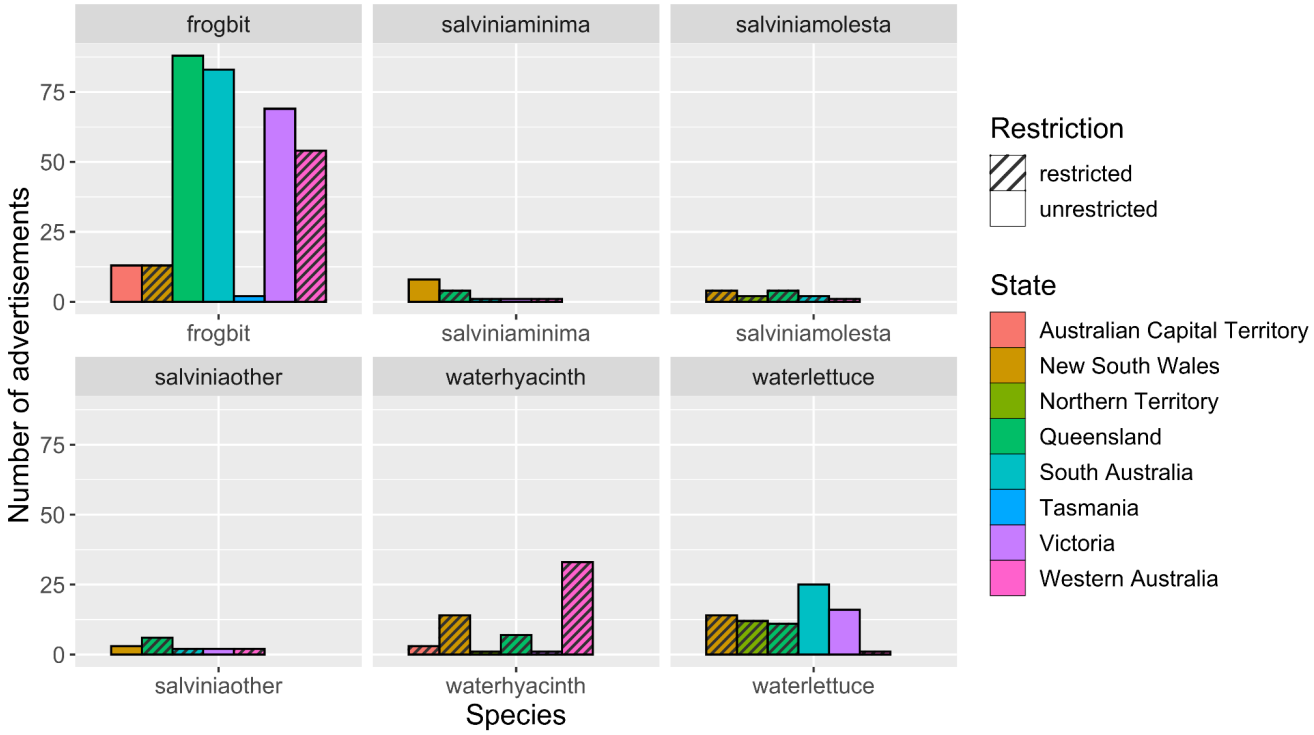


Figure 26. Number of advertisements listed in each state and territory for each species. Striping indicates that the species is restricted for sale in the relevant state/territory.

We found that the advertised species we examined were inexpensive – almost all individual plants were advertised for $10 or less. *Salvinia molesta* had the highest median price per plant ($6.66), followed by water hyacinth ($5), water lettuce ($2), *Salvinia minima* ($1.60) and frogbit ($1).

We found that, overall, these species were sold in significantly smaller quantities in states where they were restricted (i.e. where they are illegal), compared with in unrestricted states. Additionally, the price of species in restricted states were higher per unit than where they were unrestricted.

For all species, the majority of sellers (66.9%) listed only one advertisement (of that species) within the study period. Generally, for all species, both restricted and unrestricted, the number of sellers decreased as the number of advertisements per seller increased. There were however, two sellers that did not follow this trend, with one advertising frogbit 31 times, and the other advertising water hyacinth 28 times. Both sellers were advertising species restricted in their state.

Overall, the majority of advertisements correctly identified the applicable species that they were selling (68.5%). The other advertisements either misidentified the species (3.17%) or used generic terms; for example, pond plant, water plant or aquatic plant (28.3%). However, when grouped by restrictions (i.e. restricted or unrestricted), restricted species were much less likely to be identified within an advertisement compared with unrestricted species (estimated mean probability of 0.89, compared with 0.36).

CASE STUDY 5: EXAMINING THE DYNAMICS OF ONLINE TRADE OF INVERTEBRATES AS PETS IN AUSTRALIA

This case study is based on the work of Charlotte Lassaline's University of Adelaide honours project ('Untangling the Web: Dynamics of the Australian Online Terrestrial Invertebrate Trade' 2021). All results and findings are preliminary, and a paper is currently being drafted for submission to a peer-reviewed scientific journal.

SUMMARY

We examined the online trade of terrestrial invertebrates as pets in Australia by monitoring one popular classifieds website and 23 invertebrate pet stores.

We found 264 invertebrate species traded in about 2,900 advertisements. The most popular taxa – and with greatest species richness within the online trade – were spiders, ants, scorpions and stick insects.

Most species were native to Australia, but 37 species were alien, including three invasive species: Asian tramp snail (*Bradybaena similaris*), the Mediterranean coastal/white garden snail (*Theba pisana*) and the African big-headed ant (*Pheidole megacephala*).

Our research will help inform biosecurity and conservation management about the risks of invertebrate trade, and ideally provide impetus for addressing the unregulated transport of invertebrates between Australian states and the potential threat of over-exploiting wild invertebrate populations.

OBJECTIVES

Our objective was to characterise the diversity and scale of live terrestrial invertebrate trade online within Australia, and to identify associated conservation and biosecurity risks. We used data extracted from public online advertisements on ecommerce websites to develop a baseline understanding of the terrestrial invertebrate species traded online. Further, we identified trade of species with high conservation or biosecurity concern. Finally, we explored market-level trends by investigating how the abundance and location of traded invertebrates correlate with human population density and median annual income.

METHODS

We chose to collect ecommerce data from a popular Australian classifieds website and 23 systematically selected Australian online pet store websites. We web-scraped advertisements in an automated fashion from the classifieds website, collecting data over a one-year period (July 2019 to July 2020). We collected 24,984 advertisements from the 'other (pets)' section of the website. Through cleaning processes (e.g. viewing each advertisement and extracting the scientific name/s), we identified 2,205 advertisements that traded terrestrial invertebrates as pets. Additionally, we manually extracted data from 23 online pet store listings, once per website, over a one-month period (May 2021). We selected online pet stores using a systematic web search on Google. A total of 58 keyword search phrases were used, combining general invertebrate names and trade terms. We recorded 30 Australian online pet stores selling invertebrates and, from these, selected 23 target websites selling live invertebrate pets. We collected a total of 701 invertebrate advertisements from these websites.

We extracted the following information from each invertebrate advertisement: species name (or to highest identifiable taxonomic level), quantity traded, price and seller location. We identified the provenance of each species traded (i.e. native or alien) and recorded if the species is known to be an invasive species. To determine which traded invertebrate species were native or non-native to Australia, we collected species occurrence data from the Global Biodiversity Information Facility. A short literature review was then conducted for each non-native species to further investigate their provenance and impacts on the Australian environment. We used various statistical models to

compare the two ecommerce platform types and used a species-accumulation curve to verify the adequacy of the sample size used for this project.

For the 20 most popular species on each ecommerce platform type (i.e. featuring in the greatest number of advertisements), we conducted short literature reviews and further collected species-characteristic data including: if a species was not recommended for handling, if it was venomous to humans, if it was potentially lethal to humans, and if it was assessed by the International Union for Conservation of Nature.

We collected socio-economic information from the locations trading invertebrates online. Our aim was to identify underlying factors influencing the likeliness of trade to occur in a given suburb. Using data from the Australian Bureau of Statistics (www.abs.gov.au), we compared population density by km^2 using Australian Bureau of Statistic website information (population estimates by LGA 2019 to 2020), and average annual income (Total income by LGA, 2011–12 to 2017–18) at locations where invertebrate sellers were present and not present.

RESULTS

We collected a total of 2,906 advertisements: 701 from online pet stores and 2,205 from the classifieds website. We successfully identified the species traded in over two-thirds of all listings. Overall, we found 264 invertebrate species traded in the Australian online market. From the classifieds website, we identified 145 invertebrate species. From the online pet stores, we identified 201 species. Spiny leaf insects (*Extatosoma tiaratum*) were the most traded species, while arachnids (order Arachnidae) and insects (order Insecta) were the most traded invertebrate orders. The most popular taxa (i.e. largest number of advertisements) and with greatest species richness within the online trade were spiders (81 species), ants (20 species), scorpions (18 species), and stick insects (15 species).

The species-accumulation curve (Figure 25) shows no sign of reaching a plateau, indicating that we have not captured the entirety of the diversity of species traded online.

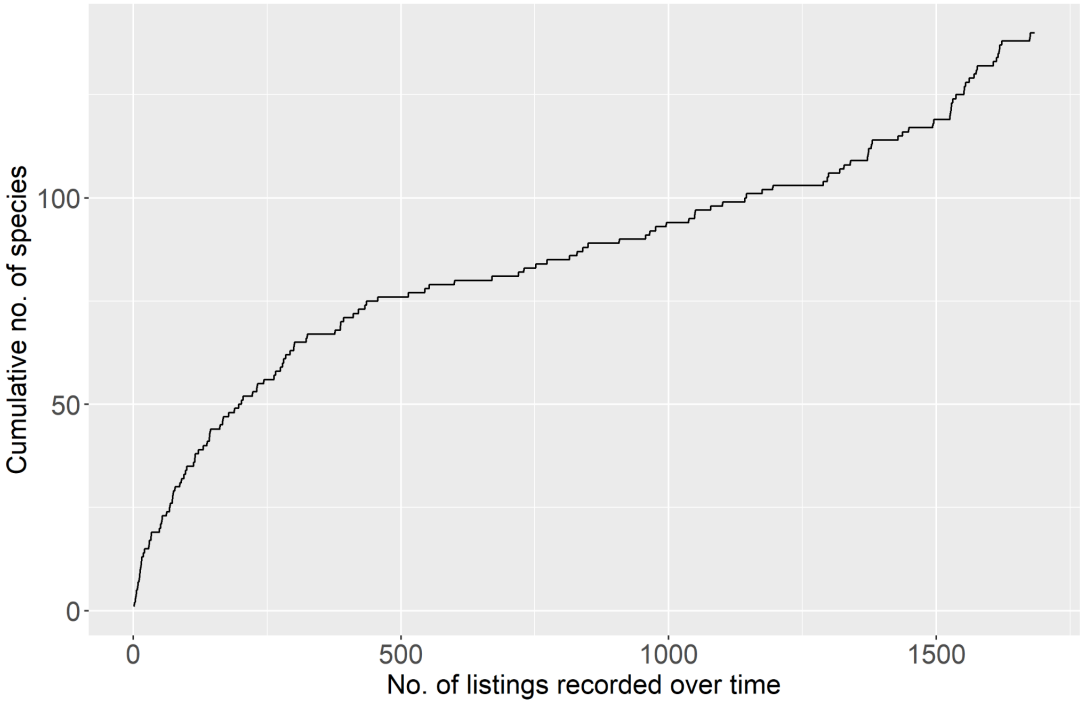


Figure 27. Species-accumulation curve for invertebrate listings collected from the classifieds website, representing the total cumulative number of species identified over time as listings were collected from the website

We found that 86% of traded species are native to Australia. The other 14% were alien species, three of which are known to be invasive in Australia (the Asian tramp snail, Mediterranean coastal/white garden snail and the African big-headed ant). There are current reports of all three of these invasive species having detrimental impacts on the Australian natural environment and on agriculture.

When comparing characteristics of the 20 most popular invertebrate species traded on both ecommerce platform types, over 80% of the species are not recommended for handling and over 70% have records of delivering a painful bite to humans. Four species were considered potentially lethal to humans (funnel-web spider and tarantula species). Only two species were evaluated by International Union for Conservation of Nature: goliath stick insect (*Eurycnema goliath)* and crowned stick insect (*Onchestus rentzi*); both were listed as 'least concern'. The other species remain unevaluated.

The distribution of invertebrate advertisements varied across Australian states and differed between online pet stores and the classifieds website. The majority of advertisements from the classifieds website came from New South Wales (30.11%). Victoria had the greatest number of online pet stores (n = 8); however, South Australian online stores had the greatest number of invertebrate advertisements (19.12%). There was a statistically significant correlation between the location of an invertebrate seller and human population (people/km^2). There was no significant relationship between median annual income and invertebrate seller locations.

CASE STUDY 6: LIVE REPTILE SMUGGLING IS PREDICTED BY TRENDS IN THE LEGAL EXOTIC PET TRADE

This case study has been published in a peer-reviewed journal (Stringham et al. 2021a). Here, we report a summary of this paper.

SUMMARY

We investigated the characteristics of illegal alien reptile species smuggled to Australia.

We found the following:

Of the 75 species illegally smuggled to Australia, 74 species are legally traded in the US.

Popular species in the US legal reptile trade (e.g. pet stores) were more likely to be smuggled to Australia than non-popular species.

It took an average of 5.6 years from first appearing in the US legally for a species to be first smuggled to Australia.

Our results can be used to predict future incursions of alien reptiles based on their popularity overseas and other characteristics.

OBJECTIVES

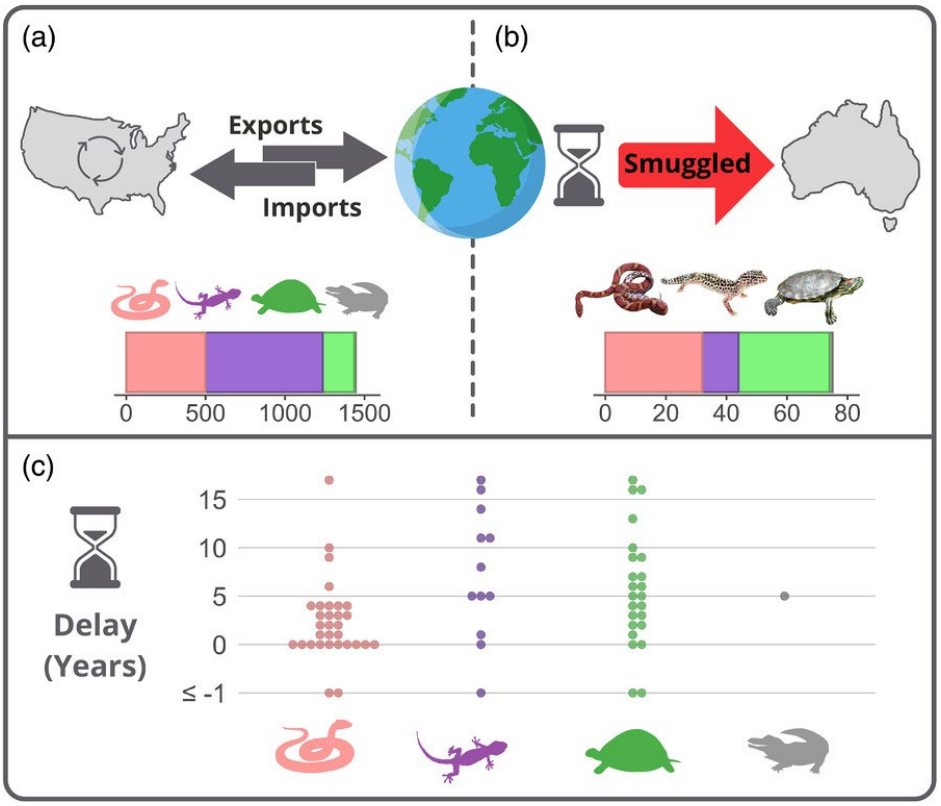
The smuggling of alien animal and plant species is a biosecurity risk in terms of invasive species and diseases. There is a lack of understanding why certain species are smuggled over others. To investigate this issue, we focused on reptiles, a popular group of species for the pet trade. We investigated which species of alien reptiles have been smuggled to Australia. We then explored the characteristics of these species to determine any commonalities among them.

METHODS

We used a dataset of all recorded alien reptile smuggling events into Australia from 1999 to 2016 (Toomes et al. 2020) to determine which alien species have been illegally smuggled to Australia. We collected other information on these species including: their popularity in the US market, gathered through online advertisements of US pet stores (Stringham and Lockwood 2018), their popularity in other overseas markets such as in Europe (Marshall et al. 2020), the number of imports and exports into/from the US (Eskew et al. 2020), and life history traits such as adult mass. We calculated the time lag for a species to first appear in the US trade (either in pet stores or in import/exports) to when they first are smuggled to Australia. We used a Bayesian regularised logistic regression to determine which characteristics were statistically important in relation to the species smuggled to Australia.

RESULTS

We found 75 species of alien reptiles illegally smuggled to Australia from 1999 to 2016. Of those, 74 species were found in the legal US trade. Overall, there were 1,445 species of reptiles being traded in the US (excluding Australian natives).



Smuggled species pictured in (b) include (left to right) the corn snake (Pantherophis guttatus), leopard gecko (Eublepharis macularius), and red-eared slider (Trachemys scripta elegans). Source: corn snake by Jthatt~enwiki, leopard gecko by Matt Reinbold, and red-eared slider by Massimo Lazzari.

CASE STUDY 7: EXISTING MODELS TO CLASSIFY TEXT CAN STREAMLINE ANALYSIS OF ONLINE WILDLIFE TRADE

This case study has been published in a peer-review journal (Stringham et al. 2021b). Here, we report a summary of this paper.

SUMMARY

We tested if existing natural language processing methods can be used to categorise wildlife advertisements based on the text of the advert.

We found that text classification models can predict with a high degree of accuracy if a wildlife advertisement is relevant or not (i.e. is trading a species of interest).

This method has the potential to streamline online wildlife trade analyses by removing non-target advertisements.

OBJECTIVES

Data collected from the internet is both numerous (i.e. many thousands of advertisements) and messy (i.e. not readily usable for analysis). Having methods to decrease the number of advertisements or categorise advertisements into different categories of relevance can help streamline analyses of wildlife trade occurring over the internet.

Here, our main objective was to determine if existing text-classification models commonly used in other fields can be applied to wildlife-trade data collected over the internet. Specifically, we tested these models' abilities to predict if an advertisement falls into one of three categories: (1) junk, not advertising wildlife (e.g. bird cage, bird food); (2) domestic poultry, advertising farm animals not of interest to us for research (e.g. ducks, geese, chickens); and (3) wanted advertisements where a user is requesting a certain species but does not currently own it. Each of these categories are very common in online data of the wildlife trade (specifically the pet bird trade) and being able to accurately predict which advertisements are not relevant can save researchers many hours of manual labour reading through them individually. Our second objective was to quantify how much data is needed to have a text-classification model with a high degree of accuracy.

METHODS

We monitored the online trade of birds on a popular Australian classifieds website over a five-month period from July 2019 to December 2019. We collected a total of 66,704 unique advertisements from the bird subsection of the website. Given the substantial effort required to manually label advertisements for attributes (e.g. species), we chose to manually label a random subset of 25% of this data (n = 16,509 advertisements). For each advertisement, we labelled the taxa being traded (e.g. species, genus). We used the advertisement title, description and any pictures provided to aid in identification. We used the Global Biodiversity Information Facility taxonomic database (GBIF 2022) to standardise taxonomic names. We labelled junk advertisements (e.g. seller is advertising non-wildlife products such as 'bird cage') and wanted advertisements (seller is requesting a certain species, not selling it). Further, from the species identified in the advertisement, we labelled if the species was 'domestic poultry': any species that is commonly sold as farm animals (e.g. domestic chickens).

We cleaned the text found in each advertisement using standard natural language processing cleaning procedures. This included: removing numbers, punctuation and special characters; converting words to lowercase; removing stop words found in the *SMART*, *snowball*, and *onix* lexicons; and stemming each word using the Snowball stemmer. Finally, we encoded text as one-word unigrams; these unigrams and their counts (i.e. frequency) became the features to be used in the text-classification models.

We used three common text-classification models (i.e. text classifiers): Logistic Regression, Naive Bayes, and Random Forest. We ran each model for each of these three categories, and used tenfold cross validation to train each model and evaluate predictions. We used commonly used model metrics

to evaluate the effectiveness of the text-classification models, including: receiver operating characteristic (ROC) curve and its area under the curve (ROC AUC), precision-recall curve and its area under the curve (PR ROC), and F1 score.

To determine the answer to the question “How much data is needed to have a text-classification model that predicts with a high degree of accuracy”, we performed sensitivity analyses. In short, we re-implemented the model, but systematically decreased the amount of data supplied to the model. We evaluated the F1 score of the models with each new sample size to measure any reduction in model performance.

RESULTS

Of the 16,509 listings we manually cleaned, we labelled 15.0% (*n* = 2,473) as junk, 21.9% (*n* = 3,615) as domestic poultry, and 4.8% (*n* = 787) as wanted. The remaining advertisements (about 58%) represented the trade of bird taxa of relevance.

We found that text-classification models worked exceptionally well to predict the category of online bird advertisements. Specifically, the classifiers worked extremely well for the domestic poultry category, with an ROC AUC of > 0.99, precision-recall AUC of ≥ 0.97, and F1 score of > 0.95 for all text classifiers. The junk classifiers performed similarly with slightly lower metric values. The text classifiers for the wanted category did not perform as well; however, the models were still much better than chance (with a ROC AUC > 0.98, precision-recall AUC > 0.88, and F1 score > 0.77).

From our sensitivity analyses, we found that the text-classification models required a minimum of 5,500 advertisements to perform as well as the model with the full dataset (about 16,500). Thus, in this context, only 33% of the data we cleaned was needed to have a highly accurate text-classification model.

DISCUSSION

Australia's current biosecurity surveillance and management systems are insufficient to keep abreast of the growing demand and novel market for trade in new wildlife species (Toomes et al. 2020). Most of the domestic Australian trade in exotic pets and ornamental plants occurs without regulation or documentation. With the rapid and massive increase in internet ecommerce, we expect novel environmental biosecurity threats to emerge that will require substantial surveillance and enforcement efforts. Developing DIWT, producing research and obtaining baseline information are vital foundational steps in detailing the risks to Australian environmental and economic wellbeing. Regardless of the factors associated with the internet trade of alien pets and declared plants, it is clear that the diversity and scale of the trade is much greater than previously realised (see also Toomes 2022).

NEW ALIEN ARRIVALS WILL LIKELY CONTINUE IF SURVEILLANCE AND REGULATION DOES NOT INCREASE

New alien species continue to arrive in Australia despite not being permissible for commercial live import. For both fish and plant taxa it appears that new species are arriving illegally, yet the possession of new 'unlisted' species is not deemed an offence unless they are declared as noxious pests or weeds in the jurisdiction of their possession and/or trade. Given that these species are newly arrived, they are unlikely to have undergone any biosecurity risk assessment, which allows people to exploit a legislative loophole if illegally arriving species evade border detection.

We recommend two main priorities for Australian government authorities to pursue to reduce new alien species invasion risk: (i) increasing investment in new surveillance technology (including risk assessments for import profiling) and methods for improving the detection of incoming alien wildlife; and (ii) reforming legislation pertaining to the domestic trade of alien species and importation of wildlife, particularly of fish (see Case Study 2).

TAXONOMY CHANGES AND TRADE NAMES CAN STIFLE BIOSECURITY EFFORTS

Traders often stay abreast of contemporary taxonomy; however, there are inevitably instances of outdated taxonomy used when advertising plants and pets for sale. There are also instances where a trade/hobby community acknowledge a taxonomic revision yet continue to use a longstanding yet outdated scientific name. Such instances need to be considered during future efforts to monitor online trade, and synonyms should be considered wherever possible when querying character strings against large volumes of trade data.

We detected a high volume of trade that could not be identified to species level; however, this was not entirely due to a lack of advertised information. Many hybrids are commonly traded, yet their species of origin are not always conclusively known. This is exemplified by the popular flowerhorn cichlid, which is believed to originate from a multigeneration hybrid of several *Cichlasoma* species with *Vieja synspila* (Nico et al. 2007). Moreover, there were many ornamental fish that have not been formally described, yet are widely known and traded (Tan and Armbruster 2016). For example, there is a range of catfish that can only be identified to genus level yet are partitioned into 'pseudo' taxonomic units by traders using so-called 'L-numbers' (Glaser and Glaser 1995), which do not necessarily map to distinct species (Cardoso et al. 2016).

The lack of taxonomic resolution stifles efforts to evaluate both the biosecurity threat posed by traded fish, as well as the risk trade poses to their conservation. Undescribed and/or hybrid fish are nonetheless known to be introduced (Maciaszek et al. 2019) or invasive (Herder et al. 2012) elsewhere in the world. Considerable effort is therefore required to keep abreast of hobbyist naming conventions, particularly if future taxonomic resolution occurs. To this end, the work conducted by

Novák et al. (2022) provides a useful template of how hobbyist pseudo-taxonomic units such as L-numbers can be matched (in some cases) to current taxonomy.

ILLEGAL IMPORTS CONTINUE TO RISE BUT INTERNET SURVEILLANCE, E-DNA AND VOLATILOMICS MAY HELP

Australian native wildlife, particularly reptiles, are known to be smuggled internationally via the post (Heinrich et al. 2022). Conversely, inbound live plants and animals traded via the post are often identified and intercepted by Australian authorities (Wyatt 2016; Thompson 2018). It is clear that detection methods for postal surveillance are imperfect due to the methods used by smugglers to conceal items (e.g. evading x-rays using foil (Utermohlen and Baine 2018) and the fact that more commodities are imported than can feasibly be screened (Australian Customs 2010), as is the case for shipping containers (García-Díaz et al. 2017b).

Clearly there is a need for continued investment in border security with an increased emphasis on incoming postal commodities; emergent technologies are currently being developed to address this issue. Recent advances in volatile compound analysis (i.e. volatilomics) are facilitating forensic detection of both derived wildlife products (Ueland et al. 2020) and live animals (Brown et al. 2021). Environmental DNA (e-DNA) detection methods are also being considered for the border screening of ornamental fish and their associated pathogens (Roy et al. 2018; Trujillo-González et al. 2019), although false-negative and false-positive results pose challenges to current applicability (Trujillo-González et al. 2020). Ebner et al. (2020) also call for improving taxonomic identification (both at border and postborder levels) with the assistance of museum, research, hobbyist and industry expertise.

While such progress adds welcome additions to the border-detection repertoire, these tools are often taxon-specific and therefore unable to assist in the detection of entirely new taxa – particularly with difficulties around seeds and plant material. Efforts should be made to broaden the applicability of such tools; for example, e-DNA might be able to detect wildlife at coarser taxonomic resolutions to encompass new taxa (e.g. detect any undescribed ‘L-number’ catfish from Loricariidae). The Australian Government is investing in the use of innovative 3D X-ray technology as a means of automatically detecting smuggled imported and exported wildlife in both mail and luggage pathways (Dr Vanessa Pirotta, Rapiscan Systems, personal communication, 2022. Advances in technologies will enable this work – conducted in collaboration with Rapiscan Systems and the Taronga Conservation Society Australia – to adapt to changes in trafficking behaviour and concealment that traffickers may use in the future.

As our recent research has revealed (Stringham et al. 2021a), the arrival of new smuggled reptile species can be partially predicted by the rate of their legal trade elsewhere in the world. Therefore, a broader adoption of ecommerce surveillance of trade trends beyond Australia (e.g. Marshall et al. 2020) may assist in anticipating new arrivals of other wildlife and preparing appropriate detection techniques to target their demand.

LEGAL ALIEN PETS REQUIRE FURTHER DOMESTIC REGULATION AND POSSIBLY PERMITS

Regardless of current detection capabilities, the Department of Agriculture, Fisheries and Forestry (DAFF; formerly the Department of Agriculture, Water and the Environment) allows a very large range of alien fishes (over 4,000 species) to be imported live for commercial purposes (Trujillo-González and Militz 2019), which is vastly different to its approach for reptiles (zero species permitted). This is possibly because a larger number of alien fish were already present within Australia prior to implementing border restrictions beginning in 1982 under the *Wildlife Protection (Regulation of Exports and Imports) Act 1982*, now superseded by the *Environment Protection and Biodiversity Conservation Act 1999*, which is noted by DAFF as a legacy issue. Some unknown proportion of the fishes already present are neither declared as noxious pests nor explicitly approved for trade following risk assessment (Beyer and Fredberg 2010), giving rise to ambiguity in the legality of so-called

'greylisted' species. Despite previous research highlighting the threat of such species (Fredberg and McNeil 2010; Ebner et al. 2020), stakeholder resistance appears to be a barrier to implementing research recommendations (Moore 2010; Millington et al. 2022) and trade is evidently still prolific.

Considering the shortcomings of Australia's Live Import List, we recommend that new national legislation is developed concerning possessing and trading alien pets. A list of species, hybrids and pseudo-taxonomic units (e.g. L-numbers) should be drafted based on: (i) the current Live Import List, (ii) species known to pre-date importation regulations of 1982 (such as the list of alien birds known to be in Australia (DAWE 2021)), and (iii) the additional taxa identified in our online surveillance. The trade and possession of species not included in this list should be explicitly prohibited wherever feasible, and seized in the same manner as alien reptiles (McFadden et al. 2017; Toomes et al. 2019); however, there will inevitably be cases (such as for the invasive flowerhorn cichlid) where an animal or plant is already possessed in quantities that would render prohibition infeasible.

In such cases, the use of a permit system may be more appropriate as it could: (i) provide quotas to limit potential propagule pressure,[7] (ii) trace current trade to inform future management, and (iii) provide a general disincentive to trade high-risk species via permit fees or strict eligibility criteria (Toomes et al. 2022). These principles could equally be applied to species that are currently permitted, yet known to pose a biosecurity risk such as the rose-ringed parakeet (*Psittacula krameri*).

Substantial investment would be necessary for DAFF to establish domestic regulation, though preventative costs of managing invasive species are often much lower than the costs of eradication, control or invasion impacts (Hoffmann and Broadhurst 2016; Jardine and Sanchirico 2018).

ECOMMERCE SITES MUST TAKE MORE RESPONSIBILITY FOR TRADE COMPLIANCE

The responsibility of ensuring the sustainability of trade in exotic pets and ornamental plants should not rest solely with national and local government. In the majority of the ecommerce platforms we surveyed, traders could advertise wildlife for sale without providing scientific names or any proof of legal provenance. This applies to both unregulated trade and trade for which permits are required (Toomes et al. 2021). Instances of illegal trade were also detected on the most commonly used ecommerce classifieds sites, including requests to buy corn snakes (*Pantherophis guttatus*) and advertisements of rose-ringed parakeets (*Psittacula krameri*) in Western Australia. The illegal trade in declared plants is prolific, with thousands of detections of more than 150 declared plant taxa, including Weeds of National Significance, traded on a single popular ecommerce website.

Platforms should implement measures to prevent illegal or unsustainable trade (Macdonald et al. 2021) – such as automatic removal of listings containing the common or scientific names of prohibited species – and further obligate traders to comply with the provision of species and permit information. Previous attempts to engage with large commerce businesses and encourage self-regulation – such as by the Coalition to End Wildlife Trafficking Online – have had some success at removing non-compliant wildlife trade (WWF 2020; Grein 2021), yet have met with substantial criticism (Paul et al. 2020) and appear to fall short of their purported goals. Moreover, the use of a 'negative list' approach by such platforms (e.g. specifying prohibited species) implies that all other wildlife trade is permissible. By contrast, the use of 'positive lists' – where only named taxa are permissible – has been demonstrated to provide a better regulatory framework and remove ambiguity (Warwick and Steedman 2021). Onus should be placed upon platforms that profit from and, in some cases, encourage the sale of wildlife to provide the digital infrastructure that ensures trade is complying with laws of relevant jurisdictions.

DEEP WEB TRADE IS RAPIDLY INCREASING AND CHANGING, AND REQUIRES MONITORING

More stringent enforcement of online surface web trade is urgently needed, yet researchers, biosecurity and conservation practitioners should be prepared for the possibility that this may stimulate an increased use of deep web platforms. There is a growing body of evidence to suggest

that wildlife trade – both of live animals and plants – is becoming increasingly widespread on the deep web, particularly through social media (Martin et al. 2018; Sung and Fong 2018; Siriwat and Nijman 2020; Sardari et al. 2022). In some cases, the scale of social media trade is already larger than that of surface web and physical markets (Sung et al. 2021), owing to the ability to coordinate among large numbers of potential traders and the use of private and/or encrypted messaging functionality (e.g. Messenger, WhatsApp) (Sanchez-Mercado et al. 2020).

Our methodology is currently being applied to social media with a methodology drafted for surveillance of Facebook groups and plans to expand this to Instagram, MeWe and WeChat. However, notable procedural differences would need to be accounted for. Firstly, social media platforms typically require creating a user account that would necessitate the use of fake information, lest researchers reveal their personal information. Secondly, the account would require access to private groups within social media platforms where trade is likely to take place. There is no guarantee of acceptance within private groups and it is often not possible to determine whether trade is taking place without first gaining access.

Traders are also known to adapt their behaviour to avoid detection techniques. For example, shortly after Facebook enforced a removal of posts selling wildlife, users quickly began evading detection algorithms by omitting mention of price or the phrase ‘for sale’ (Paul et al. 2020), instead implying that wildlife featured in an image may be for sale (e.g. ‘looking for a new home’) and inviting fellow users to continue communication using private messaging. In fact, Xin and Xiao (2019) and Davies et al. (2022) found that the majority of social media advertisements do not explicitly declare that wildlife is for sale, but that the instance of an advertisement is inferred through additional information such as images, videos, post comments or the user’s previous social media activity (Davies et al. 2022).

To keep abreast of changing trader behaviour, methods are needed that can identify the occurrence of wildlife trade through cues other than the presence of scientific, common and trade names. Machine-learning tools may be implemented to semi-automatically detect advertisements based on co-occurrence of key character strings (Xu et al. 2019) or based on images (Di Minin et al. 2019). The use of such tools often requires a wealth of manually labelled data to train a machine-learning algorithm and determine model precision (e.g. Stringham et al. 2021b). The data-mining framework outlined in this report may assist efforts to train machine-learning tools by providing large datasets in a timely manner.

However, there are some barriers to the realistic adoption of such tools, such as the lack of generalisability of models trained on specific types of data (e.g. a model trained to identify images of snakes may not perform well when applied to images of pets stored in terrariums) (Lamba et al. 2019). We have noted a high degree of variation in the quality and number of images accompanying advertisements, which may pose a challenge for machine-learning models attempting to identify plants and pets based on image recognition. To mitigate this shortcoming, models should be trained using data that is as representative of real-world circumstances as possible.

INVERTEBRATE TRADE ALSO DESERVES SCRUTINY

We have focused on vertebrate pets and invasive plants (declared weeds); however, we included a case study on invertebrate trade. Global studies are bringing to light the scale of trade in other invertebrates; Marshall et al. (2022) identified over 1,200 species of tarantula for sale and noted a high proportion (67%) of advertised pets as wild caught. International examples exist for molluscs (Ng et al. 2016), crustaceans (Chucholl and Wendler 2017), myriapods (Wojcieszek et al. 2011) and cniderians (Duarte et al. 2022) – and the invertebrate trade is similarly known to be a pathway for alien introductions (Nelufule et al. 2020). The extent to which invertebrate pet demand is prominent in Australia is not yet fully understood, though our methodology could be readily applied to monitor online trade. Recent advances in nomenclature-matching tools such as Package ‘arakno’ (Cardoso and Pekar 2022) make the study of invertebrate trade more feasible than previously thought possible.

AUSTRALIA IN THE GLOBAL CONTEXT: A MODEL OR A WARNING?

There are both benefits and shortcomings of Australia's approach to alien species management that may inform other nations seeking to control previously unregulated trade. For example, Australian Government and its state/territory governments invest heavily in enforcing trade bans (e.g. of alien reptiles; Toomes et al. 2019), often collaborating and sharing resources and intelligence in the process. As a result, the biosecurity risk of reptile pets – while far from negligible (McFadden et al. 2017) – is evidently lower than that of other nations that do not enforce such regulations (Engeman et al. 2011). The efforts of the Australian Government are commendable. Nonetheless, the use of negative lists, even when strongly enforced, has been widely criticised (Warwick and Steedman 2021) because evidence is first required of detrimental impacts, by which point traders have already had the opportunity to establish a market for a particular high-risk pet. Stakeholder resistance is consequently often a barrier to the evidence-based addition of taxa to negative lists, as has been noted in Australia (Moore 2010; Woolnough et al. 2020).

A positive list–approach is recommended in instances where the criteria for inclusion are not confounded by stakeholder opinion (Toland et al. 2020). However, Australia exemplifies a nation which has dramatically changed its approach to managing exotic pets in the recent past, and therefore adopts elements of both positive and negative list approaches. Prior to the *Wildlife Protection (Regulation of Exports and Imports) Act 1982*, most species present in global trade could be imported to Australia, which is in stark contrast to current import regulations (albeit less so for ornamental fish). Consequently, Australian regulatory bodies are now tasked with managing the legacy of existing alien species that were imported before current-day regulations. In summary, a positive list is adopted when considering imports, yet state/territory-specific negative lists are adopted when considering pet possession within Australia, allowing for the exploitation of aforementioned loopholes.

Pre-border screening is mandated by the *Biosecurity Act 2015* to control the import of plants into Australia. DAFF's Weed Risk Assessment process is regarded as somewhat of a gold standard worldwide and has substantially improved plant quarantine through the adoption of a positive list rather than a negative list (Virtue et al. 2004; Invasive Species Council 2009). However, these policies are not free from the influence of stakeholder interests; and only apply to importation, not possession, within the country (Black and Bartlett 2020). Therefore, traders who mail seeds, bulbs or plant material undeclared into the country and who avoid detection cannot be prosecuted unless the plant is specifically prohibited in the relevant jurisdiction.

Differences in state-based declarations in conjunction with prevalent trade in invasive plants within the country reveals problematic conditions. For example, Amazon frogbit (*Limnobium laevigatum*) is traded in every mainland state and territory but is only prohibited in WA, NT and NSW. This creates a situation where NSW is surrounded by jurisdictions that do not declare the species. As an aquatic plant, there is a present risk that natural dispersal events such as floods could transfer *L. laevigatum* across state boundaries. New South Wales shares two river boundaries – the Dumaresq River with Queensland and the Murray River with Victoria – both of which do not currently declare the species. Human-mediated dispersal is also a risk; aquatic plants are known to be mailed long distances across state boundaries (Maki and Galatowitsch 2004). Southern states may consider *L. laevigatum* unlikely to naturalise in the cooler climates. However, warming temperatures due to climate change mean this species is considered a future risk in Poland – which experiences colder winters than south-eastern Australia (Pliszko and Górecki 2021). If these legal disparities between states are not resolved, particularly with highly traded invasive species, then circulation of the species will continue and interstate biosecurity will be compromised.

Studies of international trading sites (Marshall, Strine and Hughes 2020), and trade within individual nations (e.g. Borzée et al. 2020) emphasise that the ever-increasing arrival of exotic pets is not unique to Australia. Increased regulation and surveillance are therefore, unsurprisingly, recommended across a variety of global jurisdictions (Auliya et al. 2016; Green et al. 2020b; Andersson et al. 2021). As such, the legacy issues identified in Australia may be present in other countries that are seeking to create and enforce more stringent trade controls despite the historic presence of an undoubtably large

diversity of alien taxa. These nations should ensure that the taxa permitted for domestic possession are aligned with those permissible for import, and that positive lists are adopted with appropriately fine taxonomic resolution to remove the potential for import of undescribed species and novel hybrids.

CONCLUSION

Wildlife trade dynamics are extremely complex and ever-changing (Hughes, Marshall and Strine 2021). The exotic pet and ornamental plant trades have major implications for conservation and biosecurity because Australia is extremely vulnerable to introduction of new pests, weeds and diseases due to its geographic isolation and unique biodiversity. Australia's approach to managing domestic trade is not aligned with its purported biosecurity priorities. We have outlined a series of recommendations to mitigate the risk of alien species; namely, using permit systems to drive long-term reduction in the quantity of wildlife possessed and traded, and using finer taxonomic resolution when specifying which specimens are suitable for live import. Greater onus should also be placed on the ecommerce platforms that facilitate trade to ensure that they do not encourage an unnecessary level of risk or illegal activities.

We believe these recommendations, while necessitating time and resource investments, are feasible and within the capabilities of relevant platforms and government departments. We strongly advocate for the continued support and development of DIWT as a necessary surveillance tool for understanding and combating future waves of illegal wildlife trade. The extent to which globalised desire and trade in invasive species compromises Australian biosecurity will be determined by how trade is managed in the immediate future and on an ongoing basis.

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APPENDICES

APPENDIX 1. TABLE OF SEARCH PHRASES

These are the search keywords used to generate search phrases for our case study (Table 4). The taxa column refers to the taxa of interest, the location refers to our target locations, and website type refers to the website types of interest. We stopped each search after 50 search results (e.g. five pages of 10 URLs per page) before moving on to the next search.

We obtained the search phrases by performing all combinations of “taxa”, “location”, and “website type”, using the follow search phrase templates:

1. Buy {taxa} {location}
2. {taxa} for sale OR purchase {location}
3. {taxa} {website type} {location}

Table 4. Search keywords used to generate search phrases for our case study

Taxa	Location	Website Type
freshwater aquarium fish	United States	Forum
marine aquarium fish	United Kingdom	Store
pet birds	Australia	Breeder
exotic pet reptiles		Adoption
exotic pet amphibians		Classifieds

APPENDIX 2. TABLE OF SHORT-LISTED INVASIVE PLANTS

This is our short list of invasive plants used for surveying candidate Australian websites (Table 5). These species are prohibited to trade in at least one state/territory and are present on the Grow Me Instead website (Nursery & Garden Industry Australia 2009).

Table 5. Short list of invasive plants used for surveying candidate Australian websites

Scientific name	Common name
Acacia baileyana	Cootamundra wattle
Acer negundo	Box elder
Ardisia elliptica	Shoebutton ardisia
Arundo donax	Giant reed
Asparagus aethiopicus	Ground asparagus fern
Asparagus densiflorus	Foxtail fern
Asparagus plumosus	Climbing asparagus fern
Asparagus scandens	Asparagus fern
Asystasia gangetica	Chinese violet
Austrocylindropuntia	Coral cacti
Azadirachta indica	Neem
Billardiera heterophylla	Bluebell creeeper
Cabomba caroliniana	Cabomba
Callisia repens	Creeping inchplant
Cascabela thevetia	Yellow oleander

Celtis australis	Nettle tree
Cinnamomum camphora	Camphor laurel
Coprosma repens	Mirror bush
Cortaderia	Pampas grass
Cortaderia jubata	Pampas grass
Cotoneaster pannosus	Cotoneaster
Crataegus monogyna	Hawthorn
Crataegus sinaica	Azarola
Cylindropuntia	Pear cacti
Cytisus scoparius	Scotch broom
Dalbergia sissoo	Dalbergia
Dipogon lignosus	Dolichos pea
Egeria densa	Leafy elodea
Eichhornia crassipes	Water hyacinth
Equisetum	Horsetails
Erica arborea	Tree heath
Erica baccans	Berry heath
Erica lusitanica	Spanish heath
Fraxinus angustifolia	Desert ash

Gleditsia triacanthos	Honey locust
Gloriosa superba	Glory lily
Hedera helix	English ivy
Hedychium gardnerianum	Kahili ginger
Hyparrhenia hirta	Coolatai grass
Lantana camara	Lantana
Lantana montevidensis	Creeping lantana
Lavandula stoechas	Topped lavender
Leptospermum laevigatum	Coastal teatree
Leucaena leucocephala	Leucaena
Leycesteria formosa	Elisha’s tears
Ligustrum lucidum	Broad-leaf privet
Ligustrum sinense	Narrow-leaf privet
Lilium formosanum	Tai wan bai he
Lonicera japonica	Japanese honeysuckle
Muntingia calabura	Calabur
Myriophyllum aquaticum	Parrot’s feather
Nasella tenuissima	Mexican feather grass
Olea europaea	Olive

Opuntia	Prickly pears
Orbea variegata	Carrion flower
Phyllostachys aurea	Yellow bamboo
Pinus halepensis	Aleppo pine
Pittosporum undulatum	Sweet pittosporum
Polygala myrtifolia	Polygala
Populus alba	White poplar
Populus nigra	Lombardy poplar
Retama monosperma	White weeping broom
Rhamnus alaternus	Italian buckthorn
Robinia pseudoacacia	False acacia
Salix cinerea	Grey sallow
Salix nigra	Black willow
Salix rubens	Hybrid crack willow
Spathodea campanulata	African tulip tree
Sphagneticola trilobata	Singapore daisy
Tecoma stans	Yellow bells
Thunbergia grandiflora	thunbergia
Vinca major	Periwinkle

Watsonia meriana	Wild watsonia
Watsonia meriana var. bulbillifera	Bulbil watsonia
Zantedeschia aethiopica	Arum lily

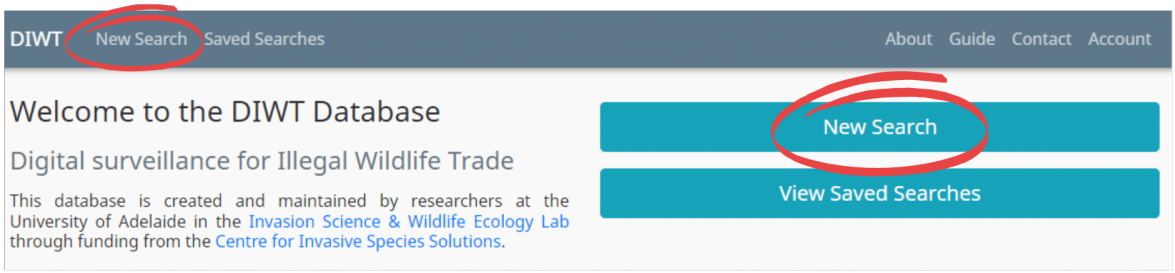
APPENDIX 3. DIWT USER GUIDE

SEARCHING DIWT

You can access the DIWT database by creating a search. For each search, you must define several options, such as the websites to search through, the keywords to search, the search words to match, and email alert options.

This page describes, in detail, the process of creating a search and the specifics of each search option. You can adjust all search options after the search is created.

You can initiate a new search by selecting the “New Search” option from the homepage or from the top navigation bar (login required). Every new search requires you to put in several pieces of information.

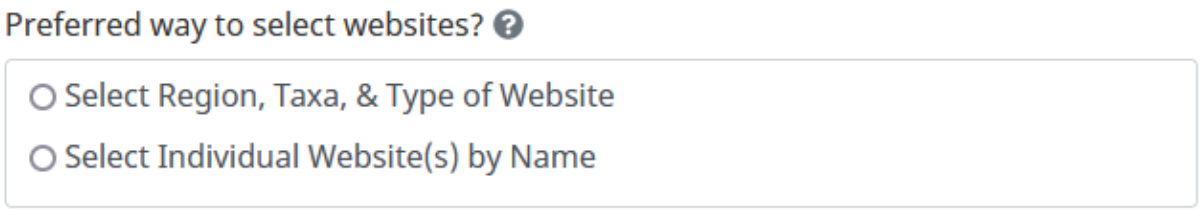


Home screen of DIWT where you can select to create a new search (circled in red).

SEARCH OPTIONS

SELECT WEBSITES

The first step is to decide which websites you would like to search through. There are two options to select websites: (1) Select Region, Taxa, & Type of Website or (2) Select Individual Website(s) by Name:



Two options on how you can select which websites to search through

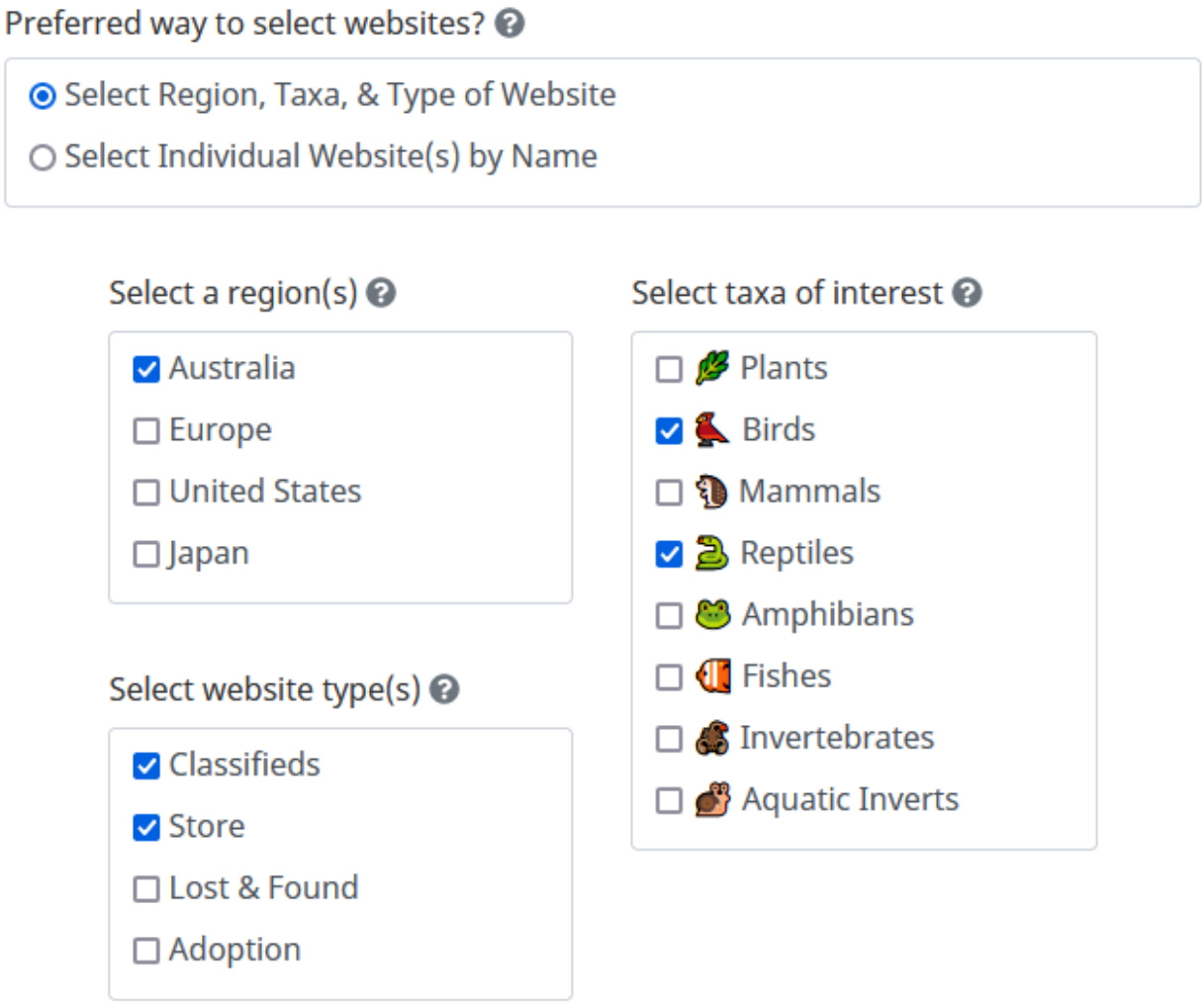
SELECT REGION, TAXA AND TYPE OF WEBSITE

Option 1 simplifies the selection of websites for you, so that you do not need to pick specific websites by name. You only need to select which region a website belongs to, the taxa of interest and the type of website. Behind the scenes, DIWT converts that selection into a list of websites to search through the database. For each option, you can select multiple checkboxes.

The region denotes the country/countries which the website ‘services’. Another example is pet stores or plant nurseries which (usually) only service one country.

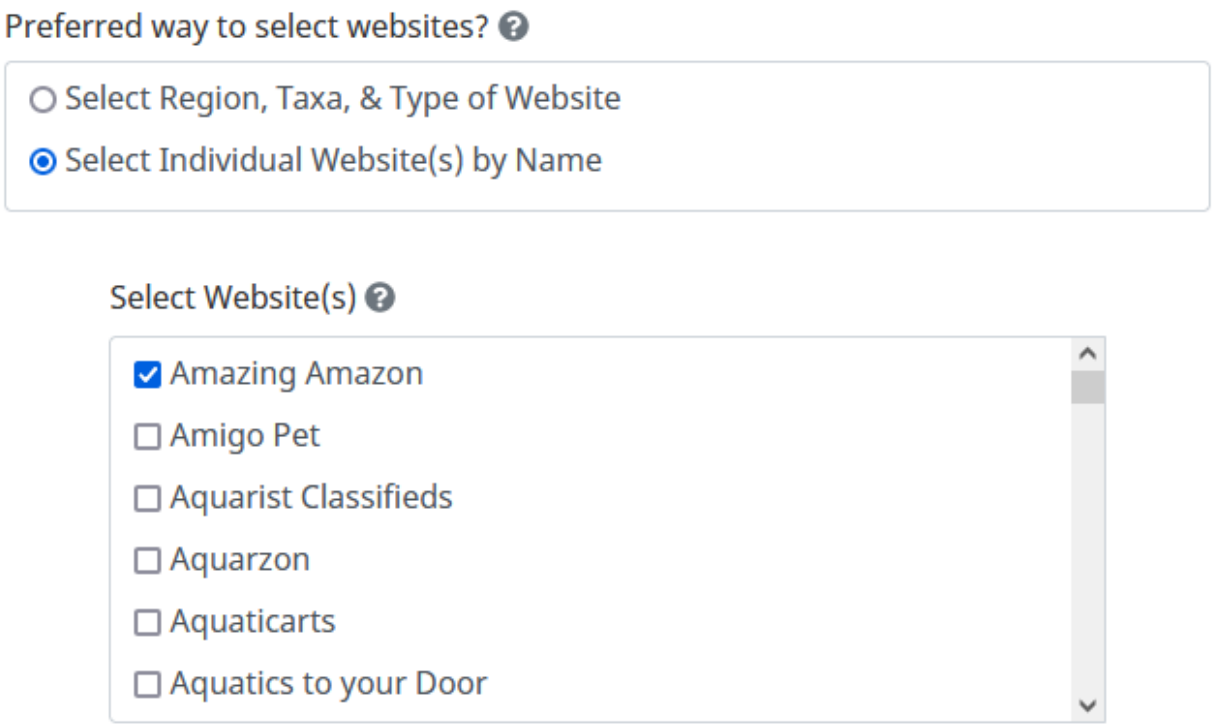
The taxa option refers to which specific flora or fauna you are interested in. Some websites only trade a specific subset of taxa. Thus, the filter will narrow down the websites searched to only include websites that trade the desired taxa. For example, some pet stores only sell reptiles. Thus, if only reptiles are checked, then websites that trade reptiles will be searched and not websites that trade fish (or other taxa).

The “type” of website option refers to either how the website operates or the type of business the website is. Classifieds are websites where many different people can advertise wildlife. Stores are websites of individual pet stores or plant nurseries. Lost & Found websites advertise lost and found pets. Adoption websites advertise pets up for adoption (note: we are only monitoring one adoption site based in the US).



In this example, DIWT will select all the websites that are: (i) based in Australia, (ii) trade birds or reptiles, and (iii) are either classifieds or stores.

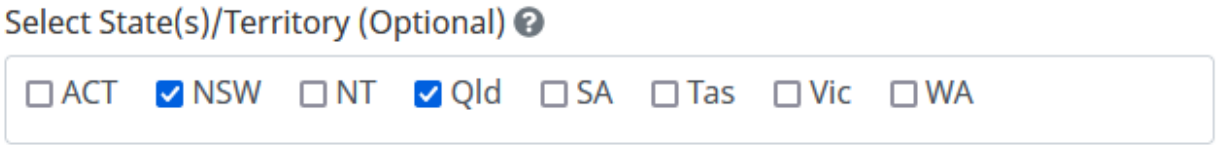
Option 2 involves you explicitly choosing the website(s) you would like to search.



In this example, DIWT will search through one website: Website #1 (name redacted). Note: you can select more than one website.

SELECT AUSTRALIAN STATE(S)/TERRITORIES

If you would like to restrict the search to certain Australian states, the state(s) should be selected under "Select State(s)/Territory". To search all Australian states, select nothing. Location filtering will only work for websites that display the location of advertisement. Advertisements of unknown locations will be returned regardless of what state(s) are chosen (if advertisement is in Australia). DIWT considers pet stores to be 'located' only in the state/territory you are physically located. DIWT considers plant nurseries to be 'located' in the state/territory you are physically located and wherever you mention you are able to post plants or seeds.



In this example, DIWT will search for advertisements that are located in NSW and Qld (assuming Region selected is Australia or website(s) selected is Australian). Advertisements located in NSW and Qld will be returned, along with any matching advertisements in Australia that do not have a specified location.

SEARCH WORDS

DIWT returns advertisements only if they match your specific search words. The input word(s) or phrase(s) are matched to the text found in the advertisements of the chosen website(s). You can separate search words by either a new line or by a comma.

Search is case insensitive (i.e. case of words do not matter).

Wildcard operators * are allowed. For example, `parrot*` will match ads with the words: parrot, parrots, parrotlet, parrotlets.

Using the NOT operator is allowed. For example, `parrot NOT conure` will match ads with the word parrot but not ads with both the words parrot and conure.

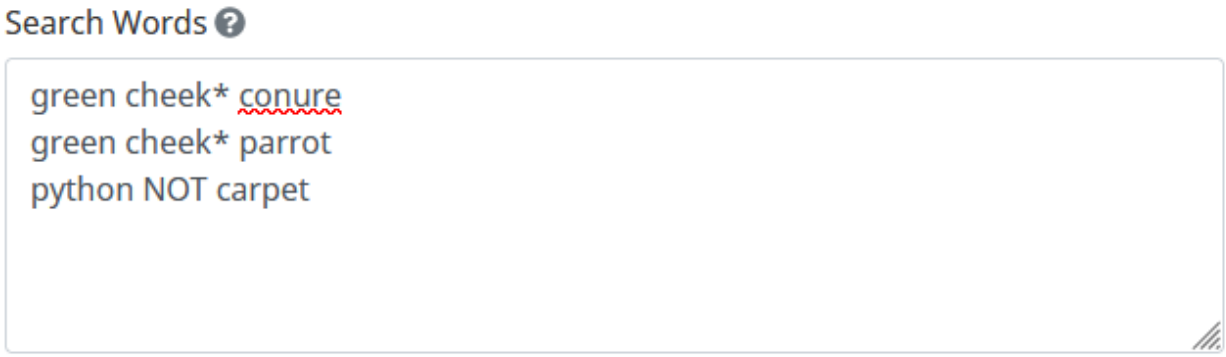
Using multiple NOT operators per search term is allowed. For example: `parrot NOT conure NOT african`.

Word boundaries are allowed using double quotes. For example, if one would like to find ads with the word ant, searching `“ant”` will return ads with the word ant but not ads with the word plant. Alternatively, one could use this search: `ant NOT plant`.

This search does not account for typos or alternative names.

If searching many names, we recommend instead keeping track of the names in a spreadsheet or text document and copying/pasting the names into the search box.

To search through all advertisements (in chosen websites), type * into the search box.



In this example, you have put in three search phrases. Two phrases are related to the green-cheek conure. The third is for advertisements that contain the word ‘python’ but don’t contain the word ‘carpet’.

TIME FRAME

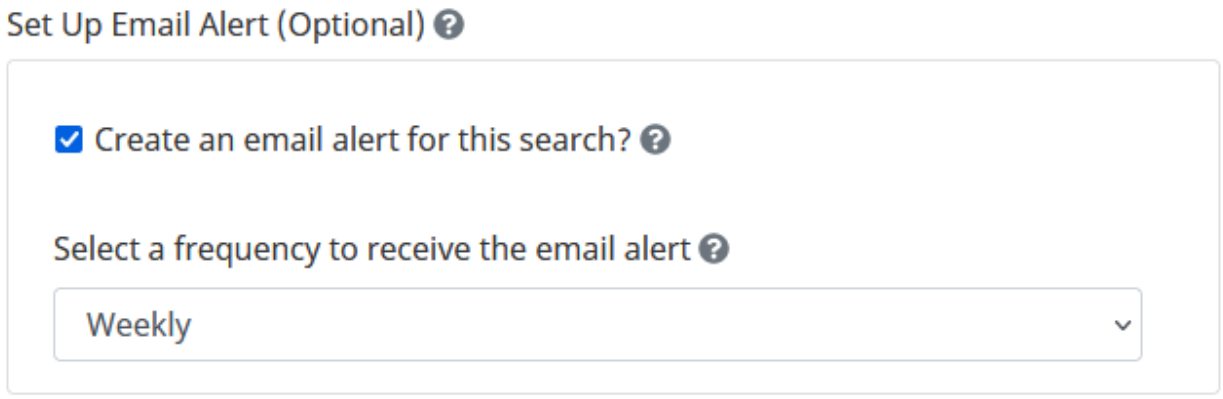
You can specify searching for advertisements from a certain number of days ago OR from a range of dates. DIWT will filter results by either the date the advertisement was posted or the date we found the advertisement. Currently, only 30 days prior OR a 30-day range is supported in this platform. If you’d like access to historical data, please contact us.

In this example, you restricted the search to the last 7 days.

EMAIL ALERTS

You can specify if you would like to receive scheduled email alerts for the search you are creating. You can specify the frequency to receive scheduled email alerts: daily, weekly (once a week), biweekly (once every other week) or monthly (once a month). You can change the frequency, and opt in or out of email alerts at any time in the future.

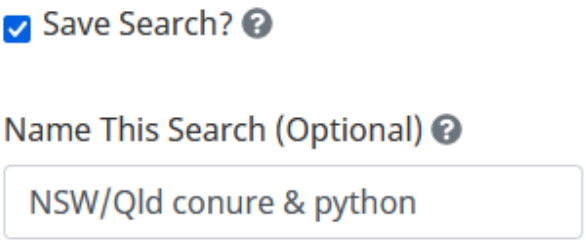
Note: the email frequency does not affect the chosen time frame of the search. For example, if you choose to search five days ago and choose to receive email alerts daily, you will receive email results every day from the prior five days. Thus you most likely will want to match your search time frame with the email frequency.



In this example, you have opted to receive email alerts once a week for this search.

SAVE SEARCH

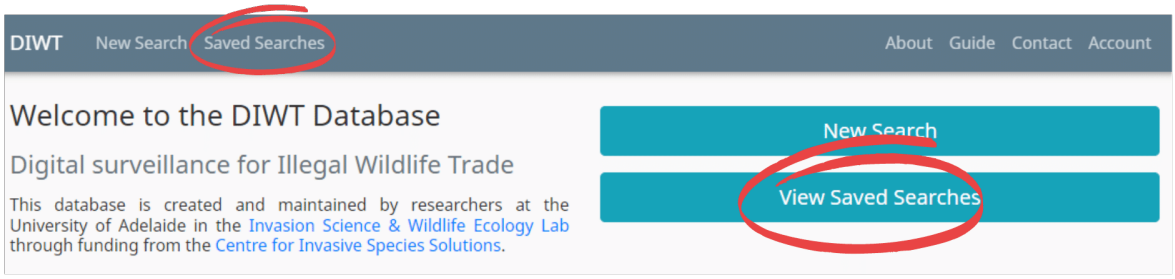
You can choose to save your search so that it can be accessed in the future. For instance, if you would like to run the search on the website at a later date, then choosing to save it avoids the need to create a new search. Also, you can choose to adjust the options of a saved search at a later date (such as the search words or email frequency). We recommend you save all meaningful searches and give them descriptive names.



In this example, you have opted to save the search and call it 'NSW/Qld conure & python'.

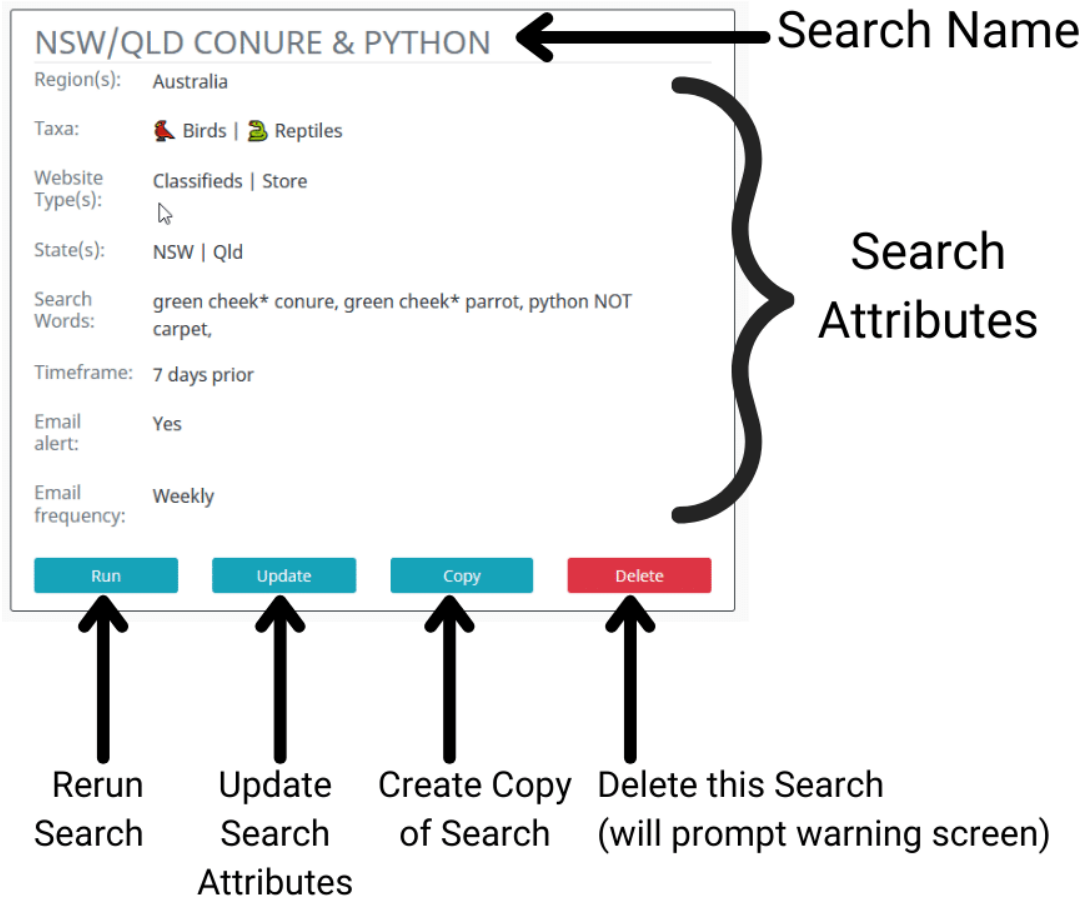
SAVED SEARCHES

You can edit searches that have been saved. First, to view saved searches, select ‘Saved Searches’ from the homepage or from the top navigation bar (login required).



Viewing saved searches

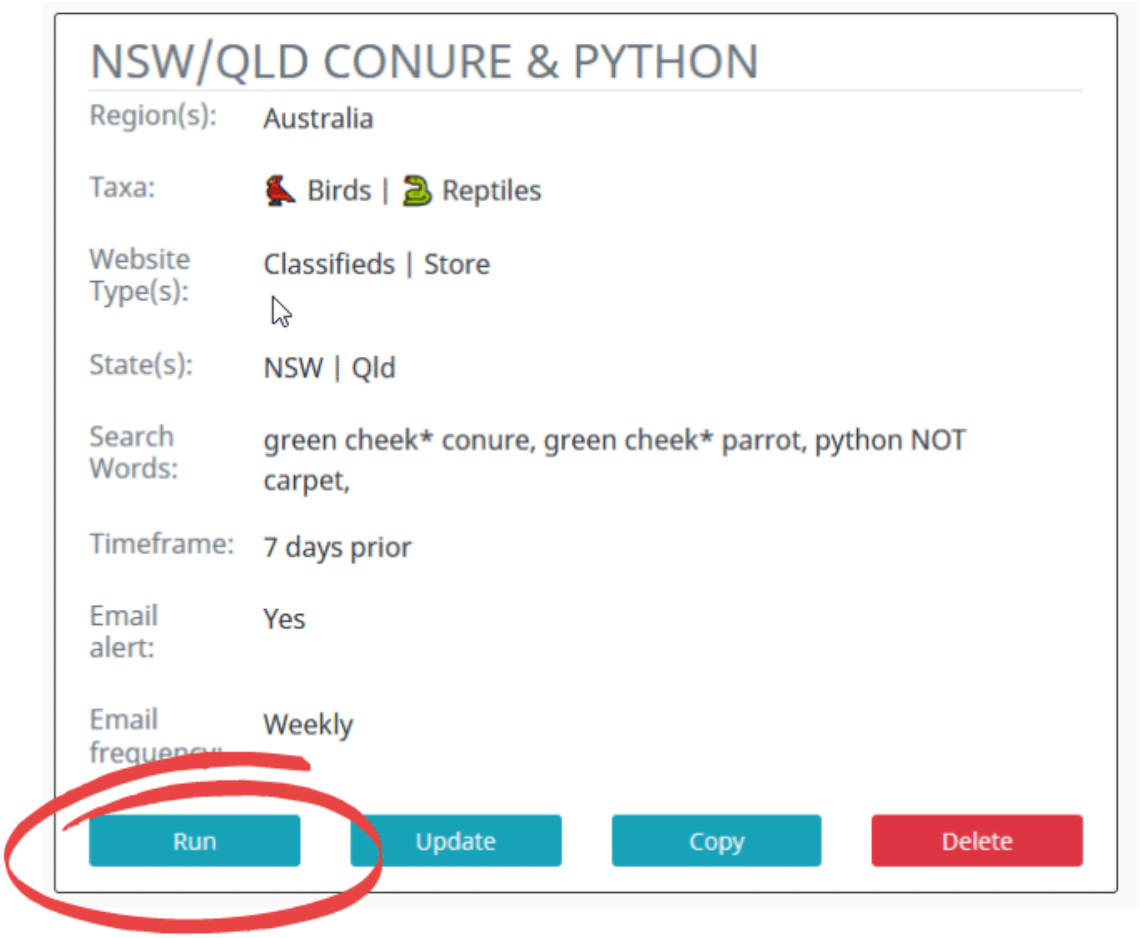
On this page, you will see all of your saved searches. There are several actions you can take for each saved search.



Actions you can take about your saved searches

RERUN SEARCH

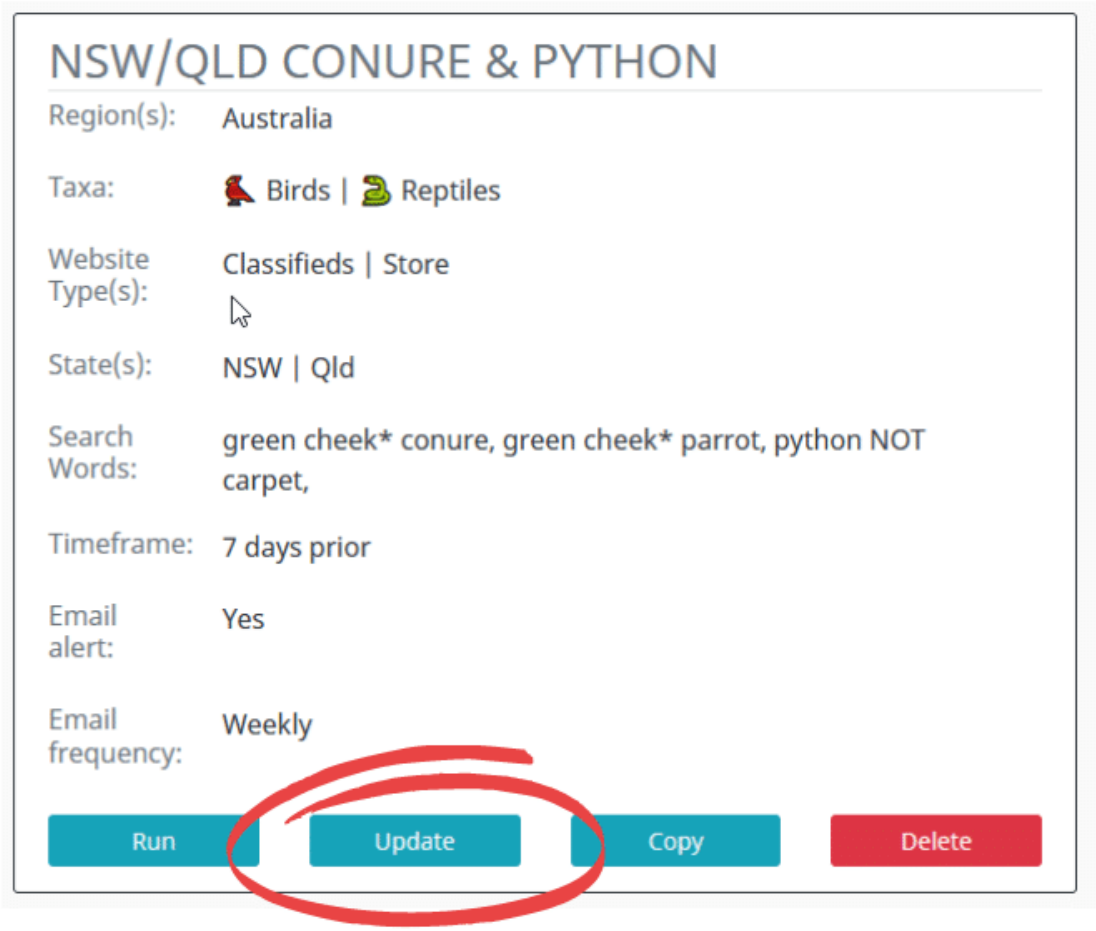
To rerun a search and view the results, select “Run” in the desired saved search.



Rerunning a saved search

UPDATE SEARCH

To update the attributes of a search, select “Update” in the desired saved search.

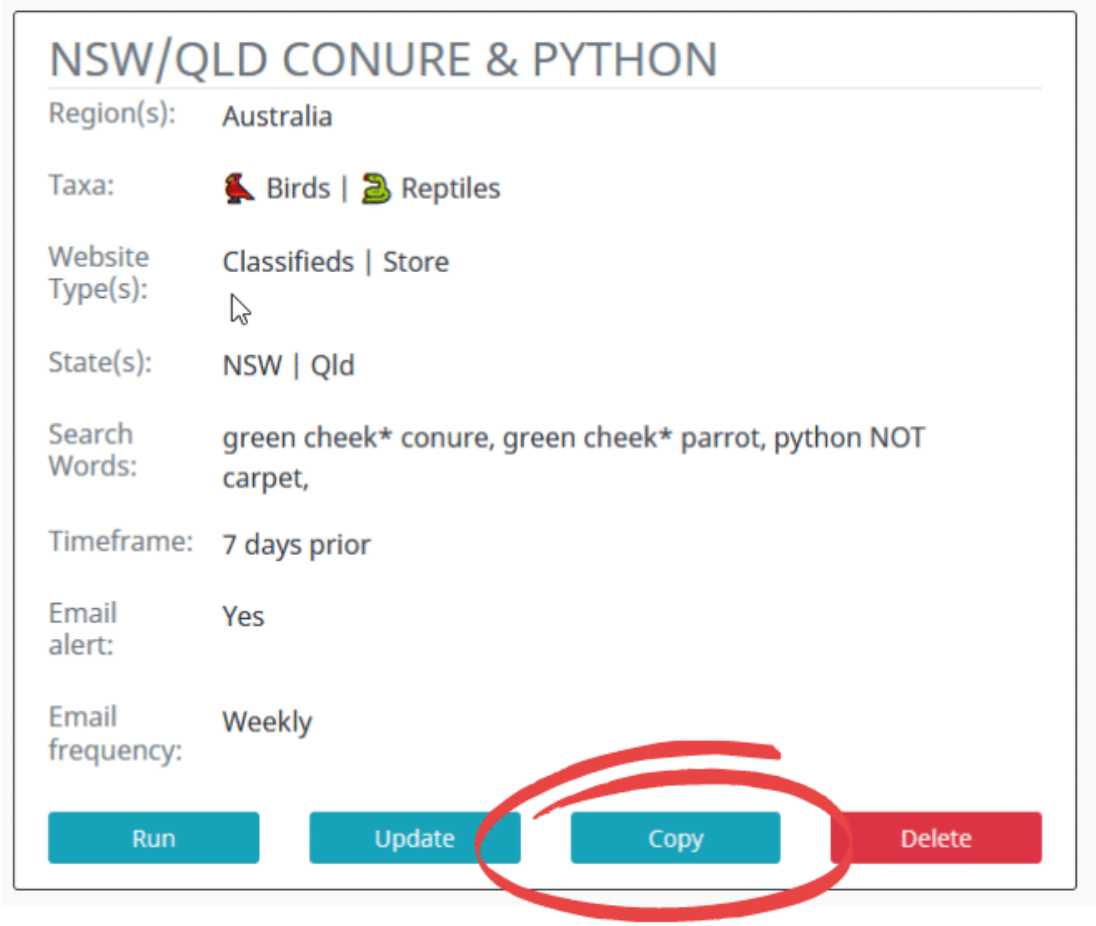


Updating a saved search

This will bring up the search and you can edit any/all attributes of the search. Any component of the search can be modified, including email alerts. To save changes, select “Save Updated Search” at the bottom of the page.

COPY SEARCH

To make a copy of a search, select “Copy” in the desired saved search. A pop-up screen will appear to confirm the creation of a copy.

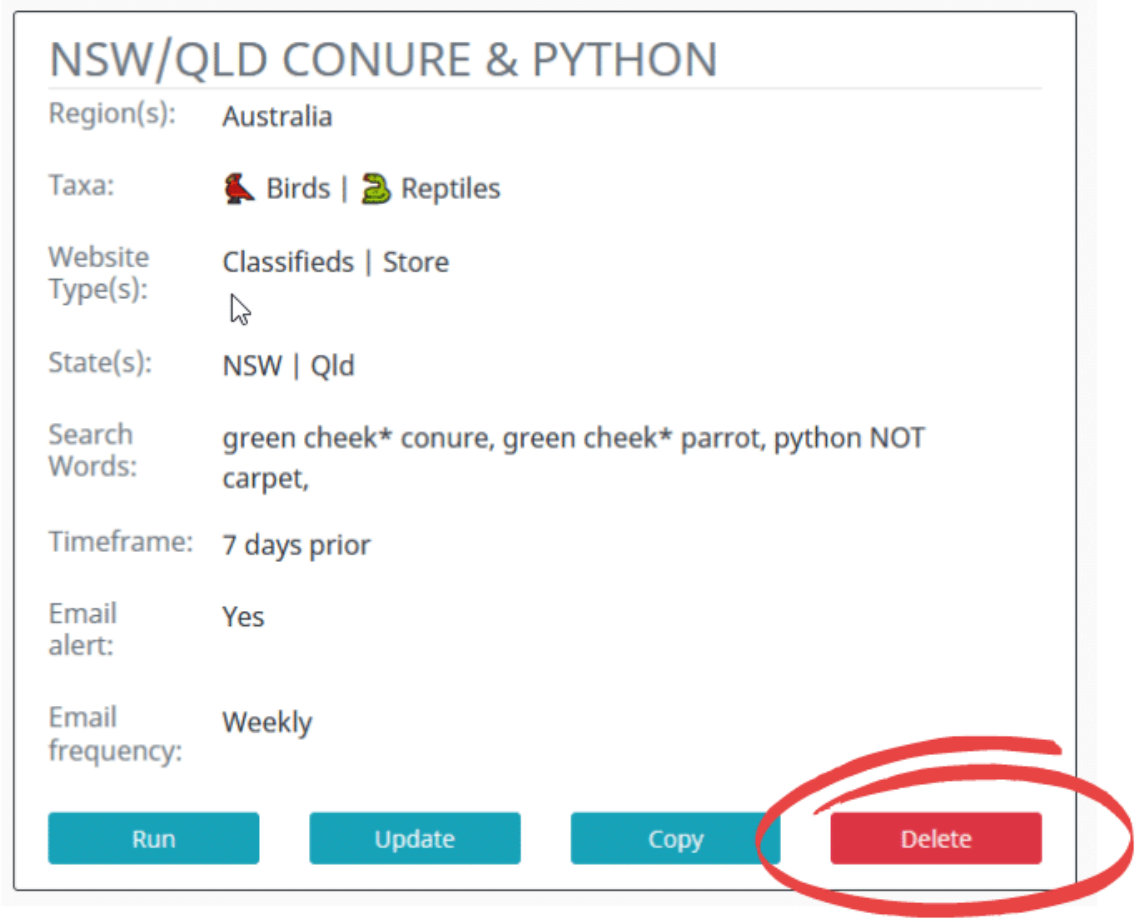


Copying your saved search

This “Copy” feature creates a new search named “Copy of [old name]”. The main likely application of “Copy” is for you to create similar searches without having to start from scratch. The attributes (including name) of the copied search can be edited using the “Update” button.

DELETE SEARCH

To delete a search, select “Delete” in the desired saved search. A pop-up screen will appear to confirm the irreversible deletion of a copy.

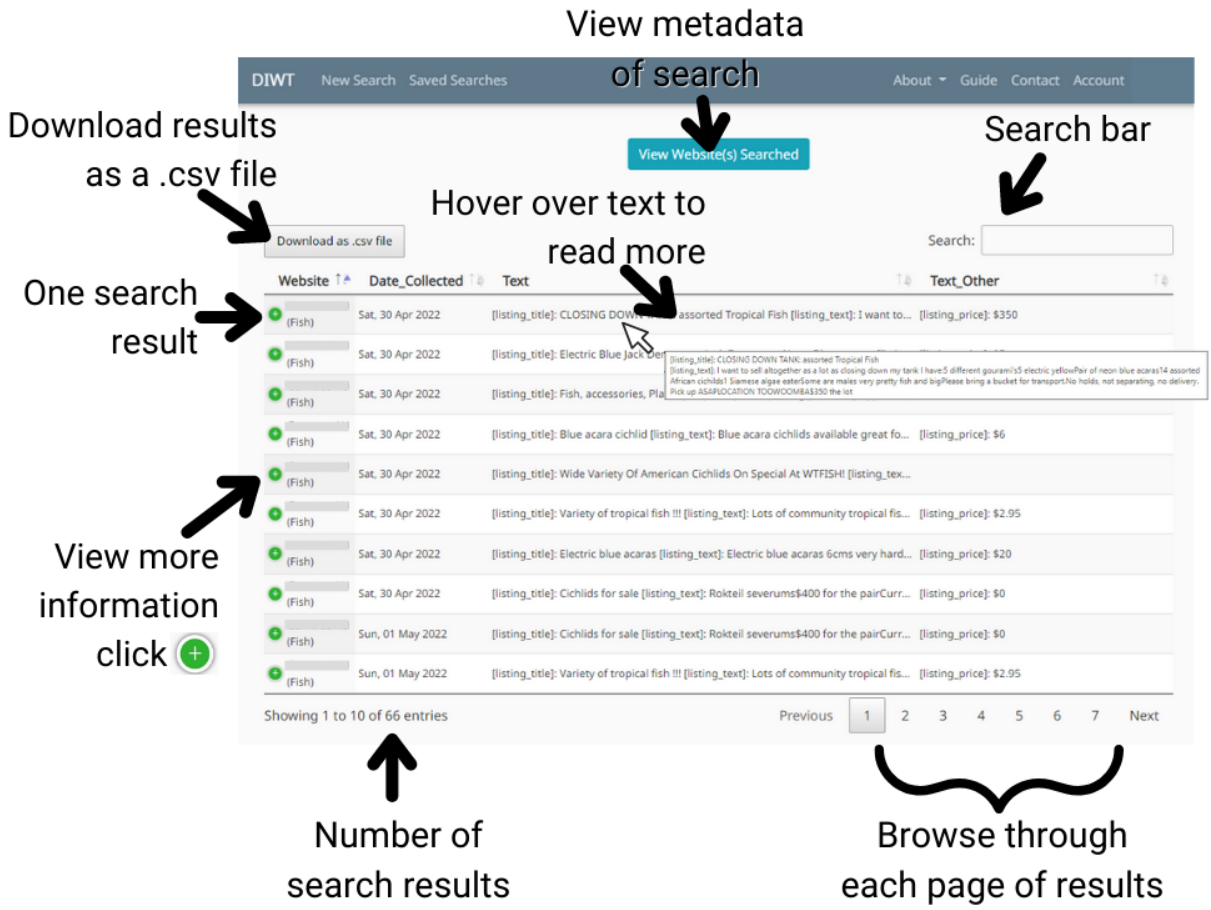


Deleting your saved search

This “Delete” feature completely removes the search from our system and we cannot recover it.

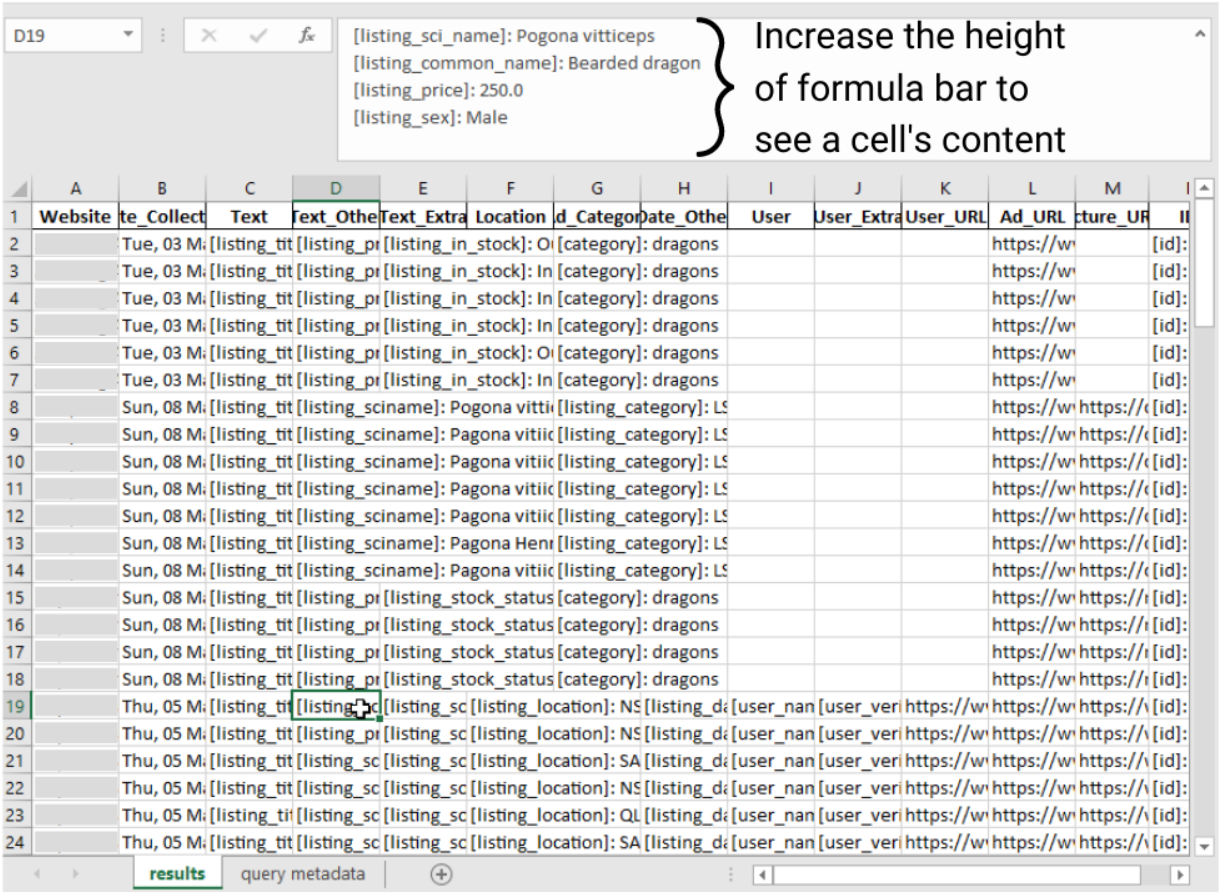
UNDERSTANDING DIWT SEARCH RESULTS

When you submit a search, DIWT examines relevant advertisements and returns all matching advertisements in the form of a table. Each row in the table is a matching advertisement. When searching on the DIWT website itself, the table appears as a webpage. When receiving email alerts, the table is in the form of an attached spreadsheet. If no matching advertisements are found, a message will be displayed indicating no matches were found.



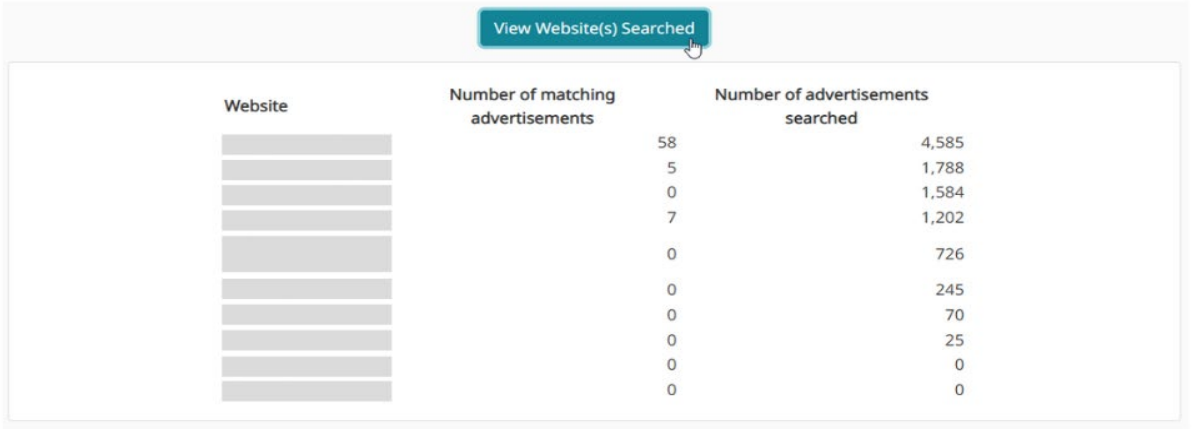
Screenshot of search results on the DIWT website. Website names are redacted.

The search results in the spreadsheet attachment from email alerts appear similar to the table of the website. However, the spreadsheet interface is not as visually friendly as the DIWT website table. A key difference is that URLs are not clickable in the spreadsheet. You must copy and paste the URL into a web browser to visit the site. Further, sometimes, it is difficult to read the entirety of a cell's content because there is a lot of text. A workaround is to increase the height of the 'formula bar' to see the entirety of a cell's content, now displayed in the formula bar.



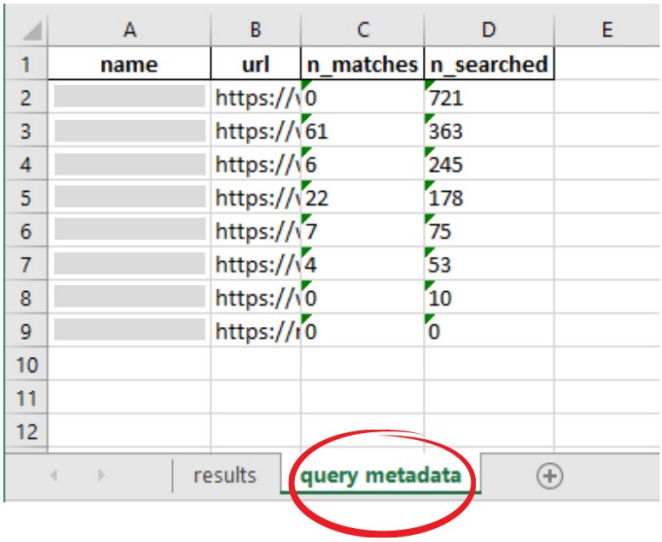
Screenshot of search results in an attached spreadsheet. Website names are redacted.

The search results also contain metadata about the search, including which websites were searched and how many advertisements were examined. To view this information on the DIWT website, select the “View Website(s) Searched” button on top of the table.



Viewing the website(s) searched on the DIWT website. Website names redacted.

To view this information when receiving an email alert, you must download the spreadsheet attachment and click the “query metadata” sheet tab near the bottom left of the spreadsheet.



Viewing the website(s) searched in an attached spreadsheet. Website names redacted.

Sometimes the metadata will indicate that zero advertisements were searched for a given website. There can be two reasons for this: (1) the time period search is too short (for instance, some websites are ‘scraped’ once a week so if you searched in the last two days, there may have not been a data-collection event and thus no advertisements), or (2) the web scraper that collects the data may have stopped working and has not successfully collected data within the time period of the search.

Each search results table contains 14 columns of data (Table 6). The information given in each column will depend on what was provided by the website at the time the web scraper collected the data. Some websites provide more information than others. Oftentimes, no information will be available for certain columns (e.g. location).

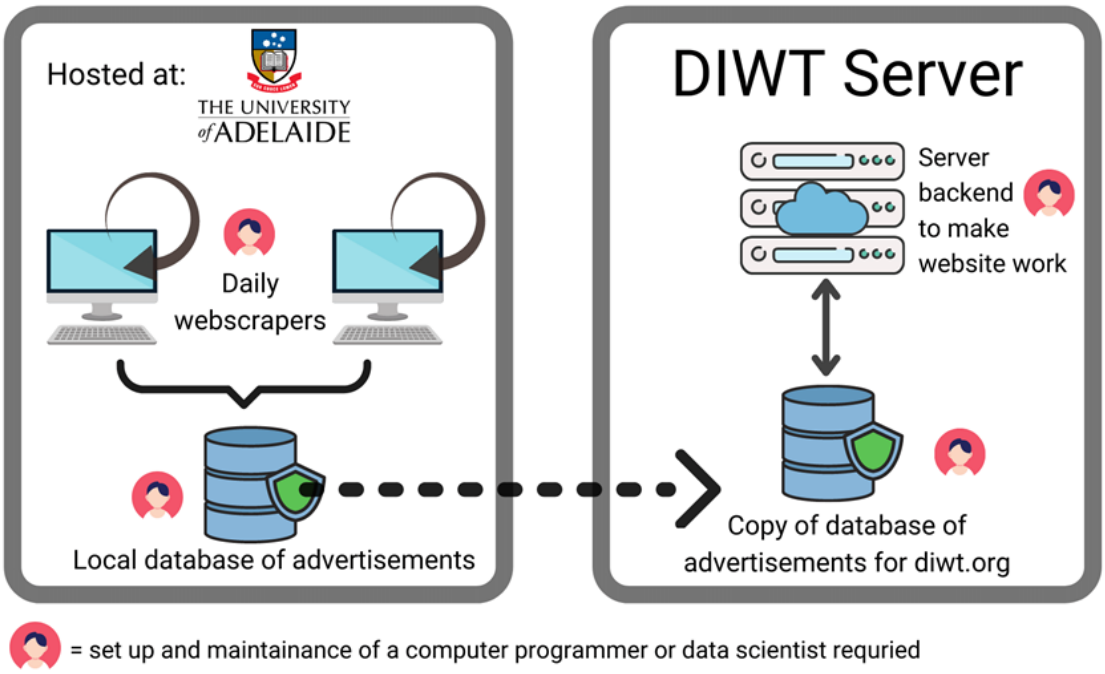
Table 6. Search results given from a DIWT search

Column name	Meaning
Website	The name of the website the advertisement comes from.
Date_Collected	The date the web scraper collected the advertisement.
Text	The main text of the advertisement, including the title and description.
Text_Other	Other text found in the advertisement. May include scientific name, common name, price, comments or shipping information.
Text_Extra	Other text found in the advertisement not related to the previous text columns. May include the availability (in/out of stock), inventory, further shipping information or number of views advertisement has received.

Column name	Meaning
Location	The location of the advertisement as specified by the website.
Ad_Category	The category of the advertisement as specified by the website.
Date_Other	Other dates associated with the advertisement such as the date the ad was posted or last updated.
User	The username of the seller.
User_Extra	Other attributes about the seller. May include contact information, ‘age’ of user or email of user.
User_URL	The URL of the user’s subpage on the website.
Ad_URL	The URL of the advertisement. Note: this URL may become unavailable if the seller or website removes the advertisement.
Picture_URLs	The URL(s) of the pictures found in the advertisement. Often these URLs will work even when the advertisement is no longer available to view online.
IDs	Assortment of unique identifiers; some are generated by the website itself and others are generated by DIWT.

APPENDIX 4. ESTIMATED MAINTENANCE AND/OR TRANSFER OF ECOMMERCE SURVEILLANCE PROJECT

SCHEMATIC OF E-SURVEILLANCE SYSTEM



Schematic of e-surveillance system

DETAILS OF EACH COMPONENT

WEB SCRAPERS

Web scrapers extract the attributes of the advertisements found on the ecommerce sites. Since each ecommerce website differs in its format and underlying structure (i.e. HTML), a custom web scraper is required for each website. Each web scraper is composed of several hundreds to thousands of lines of computer code. Our research team created all the web scraper code in use. We used the computer programming language Python. Currently, our web scrapers are run daily on two computers at the University of Adelaide.

CURRENT DEPLOYMENT

Currently all web scrapers are hosted on University of Adelaide computers. Adapting to a new location would require two desktop computers with good specifications (> 16 GB RAM, > 8 cores, > 1 terabytes of SSD), a 24/7 power supply and a hardwired internet connection. The web scraper computer code currently being used will need to be copied to these computers and set up to run at regularly timed intervals.

MAINTENANCE

Web scrapers stop working when a website changes its format. When this occurs, the web scraper code requires updating. If the code is not updated, then the web scraper can no longer collect data from that website. The amount of work required to change the code depends on the website update. If the update is minimal, then the fix should be fast. Sometimes, websites completely overhaul their design and an entirely new web scraper is required. It will require the technical expertise and labour of a computer programmer or data scientist to fix these web scrapers.

FUTURE DEVELOPMENT

If new websites emerge or new sites are identified as important, end users may wish to incorporate them into our e-surveillance system. This will require creating new web scrapers designed to capture the advertisements on those websites. Further, developing web scrapers for social media sites may be desired. Likewise, more sophisticated web scrapers will need to be developed and trialled to collect data from social media.

DATABASE SYSTEM

When a web scraper completes a 'scrape', the data collected is stored in a database. We use a SQL RMDS (Structured Query Language Relational Database Management System) for our database with the software MySQL. There is also a copy of this database stored in 'the cloud' for the diwt.org website to access (because the University computers cannot be accessed by any outside sources). The website database copy is updated daily as new data comes in. The local MySQL database is largely self-sufficient once set up. The set-up requires some time and technical expertise. There are some maintenance tasks required, including performing regular backups and adjusting table fields, data types, and indices as web scraper and website requirements change. The costs involved are storage (on local computer and website server), and labour costs of the maintenance tasks outlined. All of these technical set-up and maintenance tasks can be performed by a skilled computer programmer or data scientist.

WEBSITE

The DIWT website (https://diwt.org/) was created by our research team at the University of Adelaide. The website is a 'web application', meaning that it takes user input and returns dynamically produced information. In this case, the inputs are the specifications of the queries (location, species, websites) and output is matching advertisements. The web application is coded in the computer program language Python using the Flask framework. The web application is deployed on a Linux virtual machine hosted by cloud-computing company Linode (https://www.linode.com/).

For all facets of the website, the technical expertise and labour of a computer programmer or data scientist will be required. Regular tasks needed for the website include: updating website functionality as flaws are exposed, making sure all existing features are running properly (e.g. email alerts, search functionality), and the implementing any new features desired by end users.

If our payment to Linode lapses, then diwt.org will be immediately unavailable on the internet. The website can be restored using the computer code for the web application alongside the technical expertise to set up/initialise the website.

APPENDIX 5. A COMPARISON OF THE ECOMMERCE SURVEILLANCE CAPABILITIES BETWEEN THE DIGITAL SURVEILLANCE FOR ILLEGAL WILDLIFE TRADE (DIWT) SYSTEM AND THE INTERNATIONAL BIOSECURITY INTELLIGENCE SYSTEM (IBIS)

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3 March 2022

EXECUTIVE SUMMARY

The Digital surveillance for Illegal Wildlife Trade (DIWT) system and the International Biosecurity Intelligence System (IBIS) are both internet scanning tools for providing relevant user-ready information on various aspects of environmental health and security. Both systems specialise in different areas of environmental security:

- IBIS is comprehensive in its data collection and processing of global news articles related to any desired aspect of the environment.
- DIWT specialises in collecting detailed information on wildlife sold on ecommerce websites. While IBIS does have some ecommerce search capabilities, DIWT is (currently) more comprehensive and user-ready to monitor species and people involved in the illegal wildlife trade.

The purpose of this appendix is to elucidate these specific differences between DIWT and IBIS regarding their ecommerce surveillance capabilities.

BACKGROUND

Developed and maintained by the researchers at the University of Adelaide through funding from the Centre for Invasive Species Solutions (CISS), DIWT strictly focuses on the automated data-collection of advertisements of wildlife traded via ecommerce websites. DIWT uses specialised data-mining technology to store *all* ecommerce advertisements, extract species-specific details, filter by location of interest (e.g. an Australian state), extract user information and filter out irrelevant advertisements. Developed and maintained by the Department of Agriculture, Water and the Environment, IBIS is primarily focused on collating relevant global news articles related to any desired environmental security topic. IBIS undertakes recurring searches of the internet based on searches created by its users. These defined searches bring in news articles, journals, blogs, social-media posts and ecommerce posts that are then read, reviewed, kept and disseminated to a broader community of subscribed users in the form of ‘Daily Digest’ emails. IBIS does have some capabilities to source information from ecommerce websites, an area with slight overlap with DIWT. However, in relation to ecommerce, DIWT provides a much more detailed and comprehensive specialised system.

SPECIFIC ECOMMERCE CAPABILITIES OF DIWT AND IBIS

Here, we detail the differences in capabilities of DIWT and IBIS specifically about monitoring. For IBIS, the user is responsible for telling the system what information to collect, based on individual searches created by the user. Users are alerted about only the advertisements that match their specific search. DIWT has selected about 90 websites to monitor *all* advertisements from daily ecommerce trade. DIWT automatically collects all ecommerce advertisements and the user simply creates queries to access this data. Further, DIWT collects specific, detailed information on each advertisement, such as the species traded, the location of the advertisement and user information.

Currently, **DIWT has collected about 6,300,000 wildlife trade–related advertisements**, while **IBIS has collected about 56,000 advertisements**.

HOW DATA IS COLLECTED?

- IBIS can collect on various ecommerce platforms via its Vertical Search Engine (VSE). A user can define one website at a time, with up to four keywords to search. IBIS will then collect all matching advertisements from the search. This collection will occur daily, starting from the date the search was created. Currently, only ecommerce sites are supported; pet stores or plant stores are not.
- DIWT has selected about 90 websites (based on end-user feedback) to monitor. These websites include ecommerce, pet/plant stores, and lost & found websites. Advertisements are automatically collected for each site daily and stored in a local, secure database. All advertisements from the selected website are collected and therefore are retrievable at any time by end users.

WHAT KIND OF INFORMATION IS COLLECTED?

- IBIS collects the text of the advertisement, photos and link to source.
- DIWT collects the following for each advertisement: name of species, text description, price, quantity, location, date, user information, photos and link to source. Since DIWT collects location of the advertisement, users can filter their searches by state to retrieve only advertisements in a given state.

HOW MUCH DATA HAS BEEN COLLECTED TO DATE?

- IBIS has collected 56,000 VSE (advertisements) search results.
- DIWT has collected 6.3 million unique advertisements at a rate of about 40,000 new advertisements per week.

HOW CAN USERS ACCESS DATA?

- Users of IBIS can create a search that will result in one daily email alert.
- User of DIWT can access the entire database through the DIWT website (diwt.org). Users can directly query the database on the website and sign up for email alerts.

Table 7. Method and function of DIWT versus IBIS

	DIWT	IBIS
Main purpose	Specialised software to monitor and record online advertisements of wildlife	Broad surveillance system to detect relevant new articles and websites related to wildlife trade and biosecurity/conservation
Monitors online news articles?	No	Yes, from 20 different types of search streams

Monitors advertisements on ecommerce websites?	Yes, 88 ecommerce websites from four different categories: classifieds, pet stores, and lost & found	IBIS's VSE is limited to user-defined searches. Specially, IBIS will only track advertisements found from specific user-specified websites and keywords. Current capabilities extend to classifieds ecommerce sites only (no pet stores or lost & found sites)
Search feature	User can search all websites monitored at once using unlimited keywords (i.e. species names)	User can create a search for one website at a time; four keywords max per search
Data-collection method	Daily. Collects and stores all advertisements from all monitored websites	Daily. Once a user defines a search for a website with specific keywords, IBIS will collect and store advertisements from the website that match the keywords
Taxa currently monitored	Birds, reptiles, amphibians, fish, mammals and plants	Any taxa that have been mentioned in user-defined search keywords
Regions	Australia, United States, Europe, Japan	Global
Location based-filtering	Yes, can filter to state of interest or even suburb	Limited to country-level location (i.e. Australia)
Data collected	For each advertisement, the following is collected (when available): name of species, text description, price, quantity, location, date, user information, photos, link to source	Text of news articles or advertisement, location (i.e. country) date, photo, link to source
Amount of data collected (to date)	6.3 million unique advertisements	2.8 million news articles, 56,000 VSE (advertisements) search results
Rate of collection	About 40,000 new advertisements per week	About 28,000 new articles sent through emails per week
Email alert system	Yes; sent in daily to monthly reports as requested by user	Yes; sent in daily digests

The following diagrams illustrate the methodology and functionality underpinning each system.

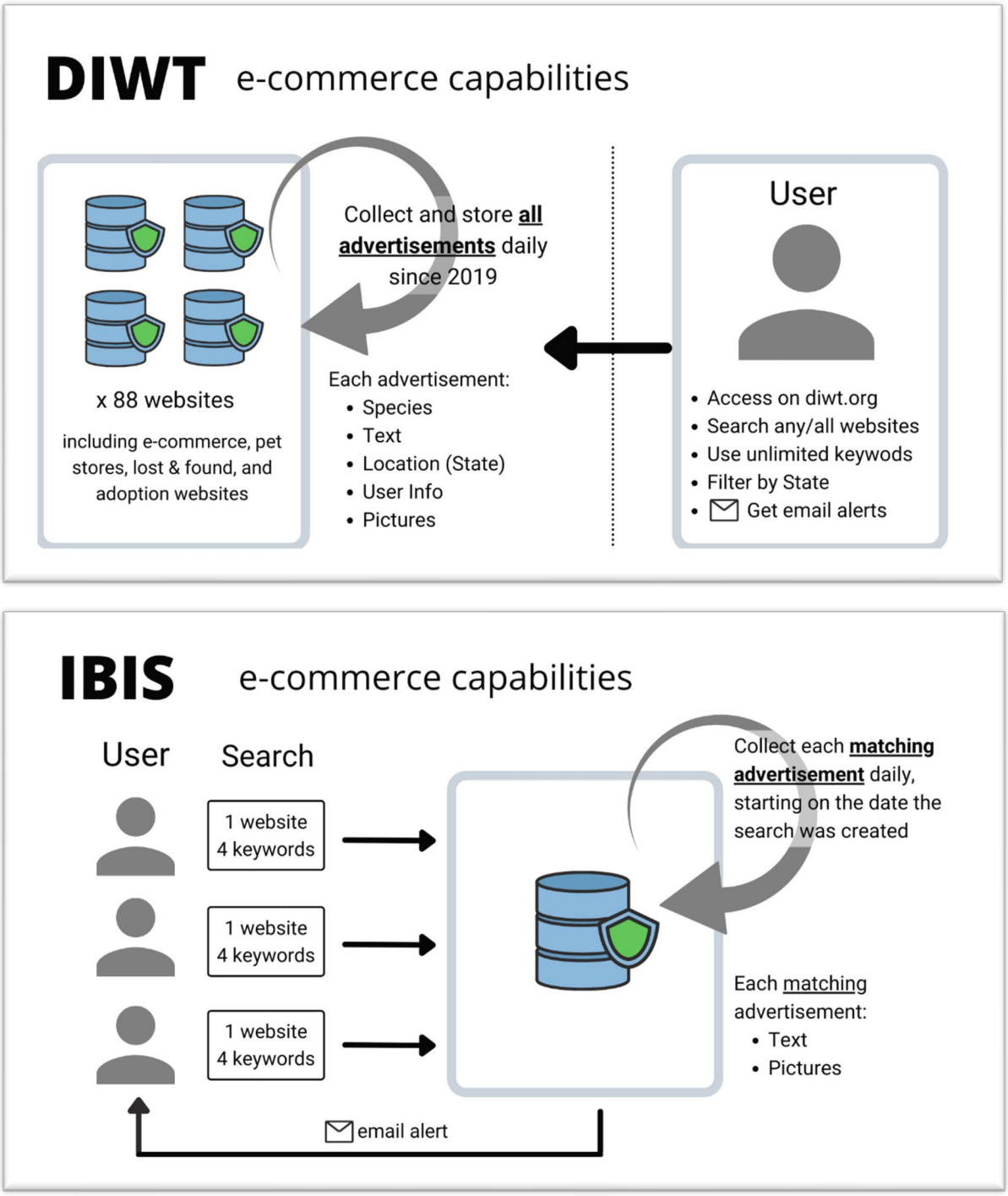


Figure 28. Diagrammatic comparison of the method and function of DIWT versus IBIS

DETAILED DESCRIPTION OF IBIS ECOMMERCE CAPABILITIES

Intelliriver Source, also known as the International Biosecurity Intelligence System (IBIS), is an automated internet-scanning tool for open-source intelligence (OSINT). It sets recurring searches of the internet based on searches created by its users. These defined searches bring in news articles, journals, blogs, social-media posts and ecommerce posts that are then read, reviewed, kept and disseminated to a broader community of subscribed users in the form of ‘daily digest’ emails.

Source has the following core functions:

1. Automate information collection: Articles in Intelliriver Source are brought in by searching through our partner news sources. IBIS automatically launches saved searches according to schedule every day unless a user or moderator deactivates the search. These articles are collated into the NewsFeed page for users to review, keep and/or add to the daily digest newsletter.

2. Collate information into relevant issues: Searches created can be added to a user-created issue (e.g. “Ebola Outbreak: Congo”). When a user adds an article to be part of the daily digest, the article is automatically added to the issue it is related to unless a moderator rejects it.

3. Produce a daily digest: The daily digest is a newsletter compilation of reviewed, relevant articles associated with the issues users follow. All users of Source can add an article to the digest. Group moderators review these articles and decide whether they are approved to be added to the daily digest email or not.

IBIS ECOMMERCE FUNCTIONALITY

IBIS can collect on various ecommerce platforms via the VSE option when a user selects a new search. VSE allows the user to conduct a word/phrase or username search across a specified domain or platform, and IBIS will pull back information on posts found using the search criteria entered by the user using a web scrape of that particular domain.

For example:

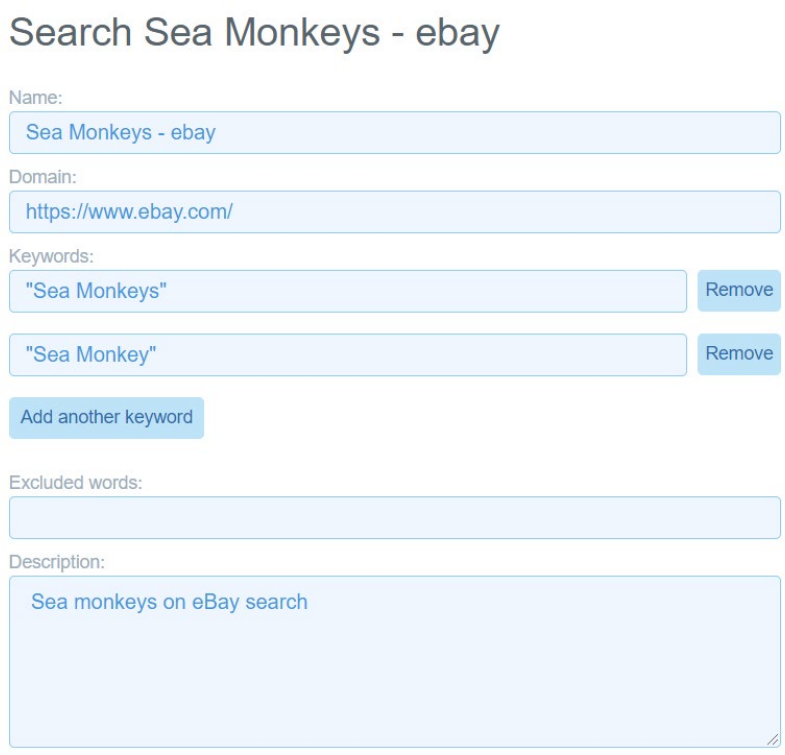


Figure 29. Example of a VSE search

Retrieved information can contain listing details such as title, item number (i.e. eBay item number), description details of the item from the listing, date posted (if possible) and any associated username. IBIS will also retrieve the originating URL so the end user may also visit the listing directly on the web, and also extract any listed locations into the internal map field and geolocation function within IBIS.

Figure 30. Example of an eBay retrieval

IBIS will then save these listing details into the text field – with the exception of date listed/found and any locations also listed, which have their own separate fields within IBIS that can be queried from within the system. As IBIS is primarily a collection tool rather than a data-analysis tool, users may query the data held for keywords within a listing to return historical results; look for articles/listings saved against issues; or find listings based on location, posting time/date or found using a specific search. Any other reporting or database queries need to be done on the 'back end' or though data-analysis tools.

DETAILED DESCRIPTION OF DIWT ECOMMERCE CAPABILITIES

OVERVIEW

The DIWT (2022) is a prototype web-tool project developed in collaboration between the University of Adelaide, the Centre for Invasive Species Solutions, and the Australian governments' Environment and Invasives Committee. In consultation with end users (personnel in state governments and Australian Government), and following a rigorous scientific methodology (Stringham et al. 2020), a set of 88 websites were chosen to collect advertisements. The types of websites varied from ecommerce (e.g. Gumtree, eBay), pet stores, plant stores, lost and found sites, speciality forums, and pet adoption websites. Researchers at the University of Adelaide then developed specialised web-scraping software to monitor and collect advertisements from these websites – starting from July 2019. Each website required a specific and custom web scraper in order to extract all available information into fields that were able to be queried (species, location, user, etc.). Users can access advertisements in this database through the DIWT website (diwt.org). Users can search through any/all websites using an unlimited amount of keyword (e.g. species names). Further, users can receive alert emails when new advertisements are recorded that match their specified keywords.

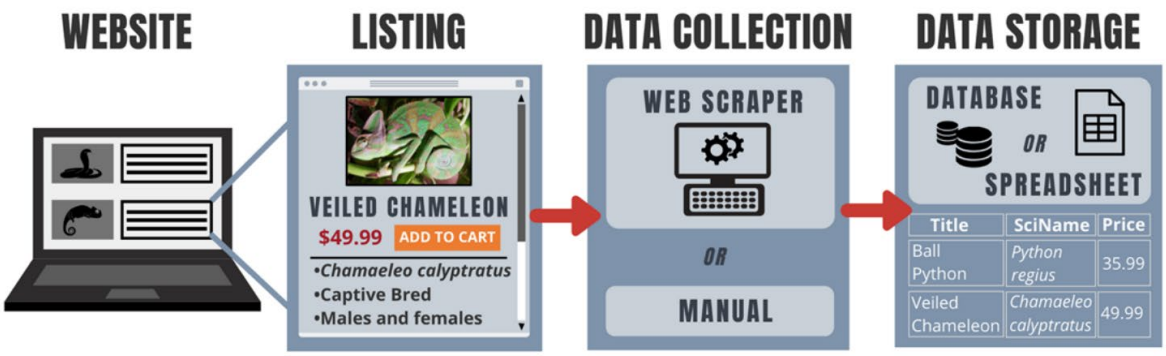


Figure 31. Illustration of DIWT's function

DIWT's key features include:

1. full coverage of a large number of ecommerce classifieds, online pet stores, and lost and found sites (currently 88 sites)
2. international coverage of Australian trade in alien and native species (currently Australia, United States, Europe and Japan)
3. broad taxonomic coverage (vertebrates, invertebrates and plants) with standardised nomenclature and capability to match and collapse synonyms and trade names
4. historical data collection since July 2019 (currently 6.3 million unique advertisements), with about 40,000 new advertisements per week
5. targeted collection of key fields including: species name, text description, price, quantity, location, date, username and photographs
6. user-friendly, secure website interface for search functions and automated email alerts.

DIWT's user interface:

Users can request access to DIWT via diwt.org.

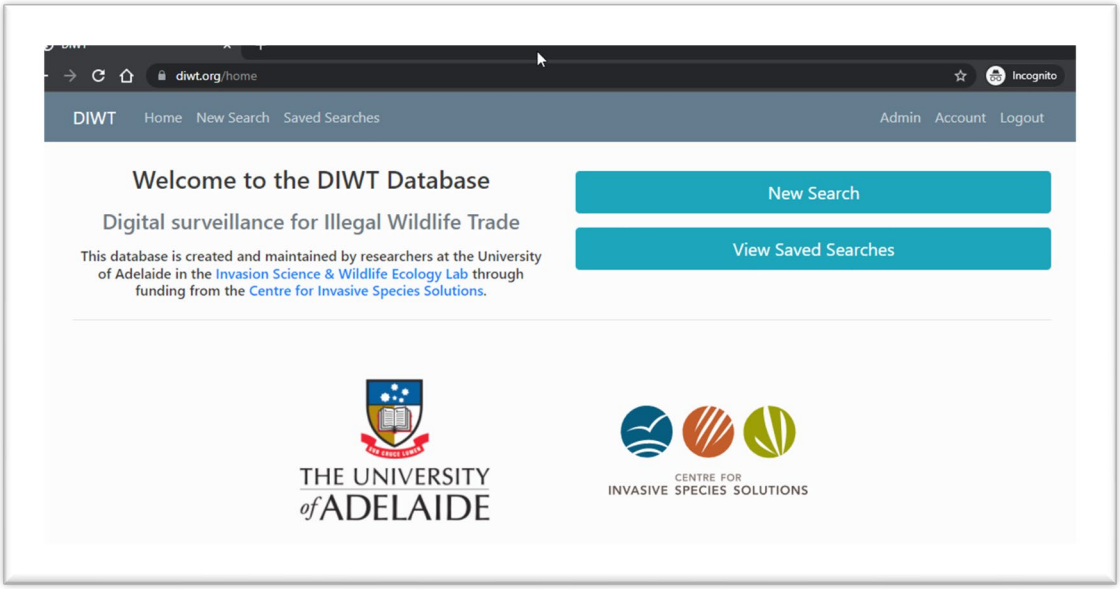
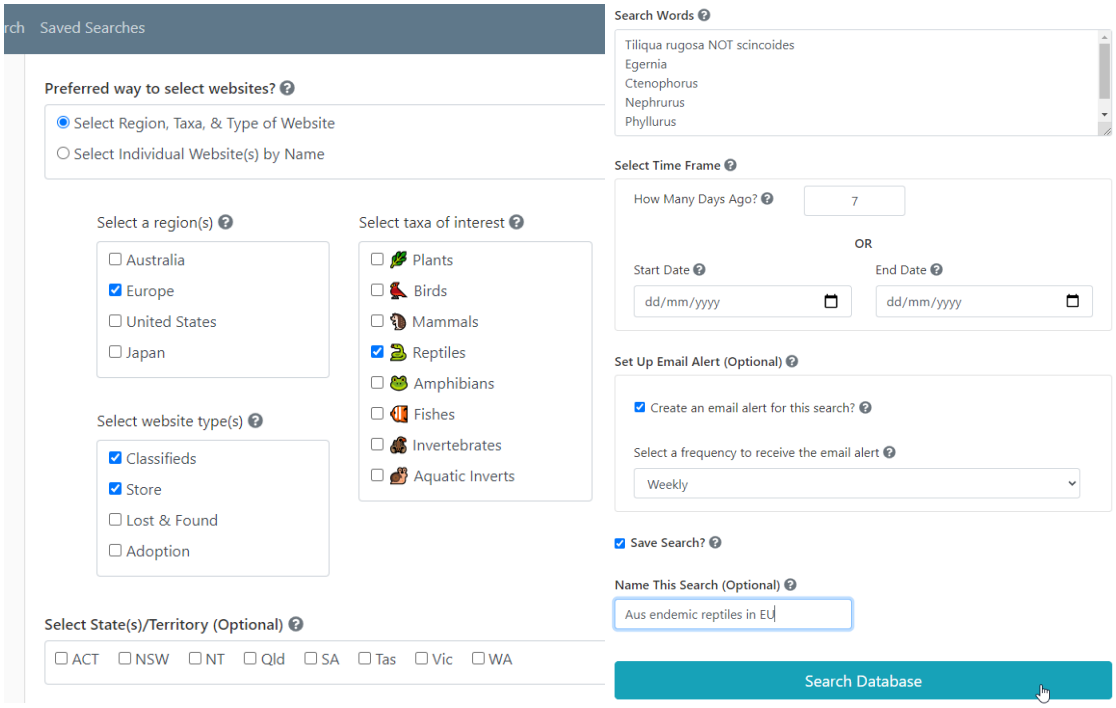


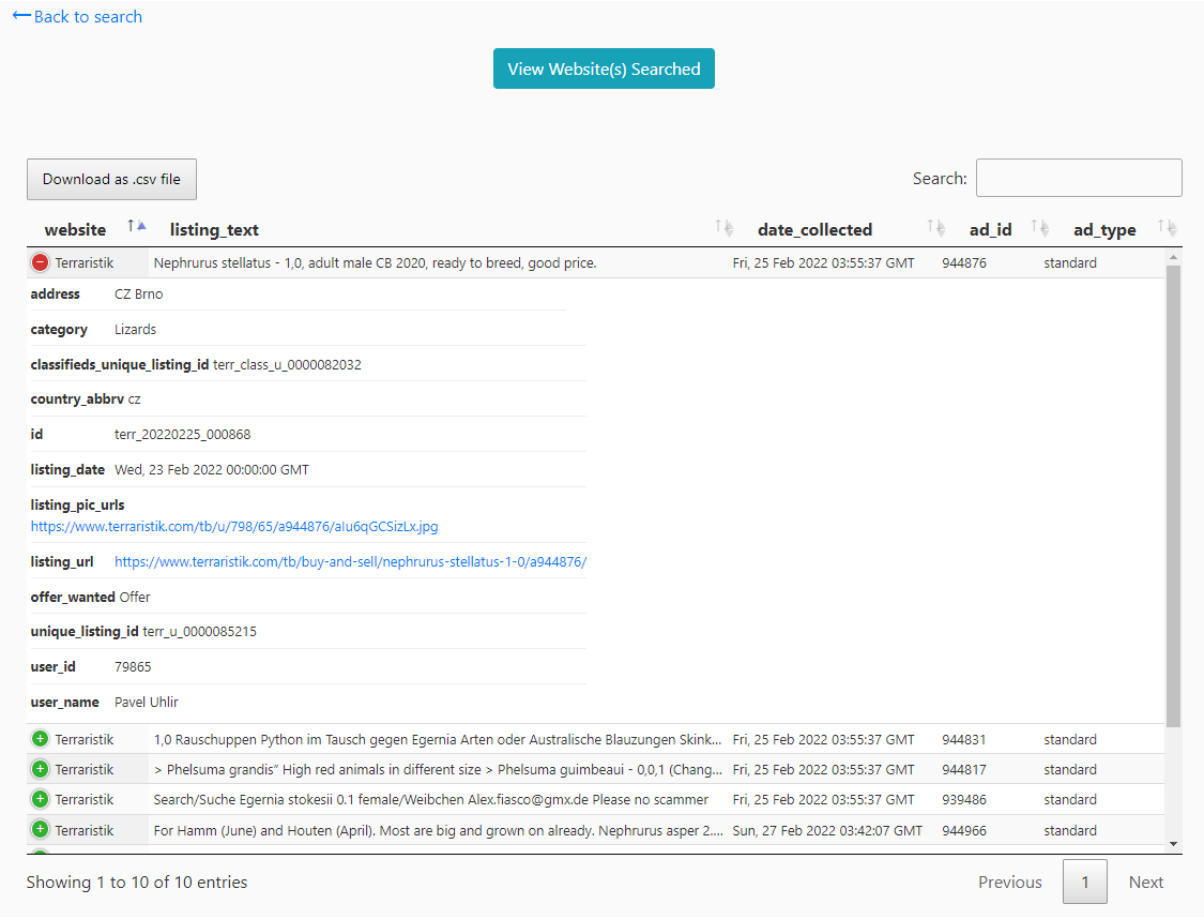
Figure 32. DIWT's landing page

Each search requires the following user input (screenshots follow):

- region
- type of website
- taxa of interest (e.g. reptiles)
- state/territory of interest (optional)
- search words
- date range
- option to set up email alert and at what frequency
- option to save search for the future.



The output is an interactive table that the user view and download. Links to the advertisement and pictures are provided.



If email alerts are enabled, the matching advertisements will be sent in an email to the user at the frequency of their desire (e.g., daily).

APPENDIX 6. 2019 ILLEGAL WILDLIFE TRADE WORKSHOP POST-MEETING REPORT

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