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A snapshot of online wildlife trade: Australian e-commerce trade of native and non-native pets

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ABSTRACT

The international trade of non-domesticated pets impacts both conservation and biosecurity via the harvest and release of live animals beyond their native distributions. The extent to which individual countries mitigate these impacts via regulation of trade is inconsistent, as is their capacity to monitor internet facilitated trade. We investigated the online trade of vertebrate pets within Australia, a country with a reputation for relatively stringent pet-importation regulations and world-class border biosecurity. Using semi-automated data mining (i.e., webscraping) techniques, we collected online pet trade data over the course of 14 weeks from 12 Australian e-commerce platforms selected using an a priori set of search terms. We analysed spatial, temporal and taxonomic biases in trade and identified instances of high rates of trade in: (i) threatened species, (ii) non-native species, (iii) and species not permissible for live import. We identified over 100,000 individual live animals across 1192 species, including: 667 non-native species for sale within Australia from 03/12/2019 to 20/03/2020 (mammals were excluded from our analysis). Our findings constitute a much greater scale (in terms of abundance and richness) of non-native species trade than previously recorded in Australia. Substantial changes to legislative control of domestically traded pets are needed at the national level to reduce the volume of non-native pets that may contribute to the establishment of invasive species in Australia. We suggest that contemporary examples of permit systems applied to native taxa may provide a valuable template for the implementation of such changes.

1. Introduction

The international wildlife trade, particularly the trade of live animals as non-domesticated pets, has garnered growing research interest across the last decade (e.g., Mohanty and Measey, 2019; Marshall et al., 2020); primarily due to the conservation, criminological and biosecurity threats posed by unsustainable trade practices (Warwick et al., 2018; Lockwood et al., 2019). Contemporary investigation of wildlife trade has largely focused on the cross-border movement and trade of species by utilising import/export permit recording systems such as for CITES-listed species or the US wildlife import-export recording system (Harfoot et al., 2018; Watters et al., 2022). Documentation of illegal components of the international pet trade have relied on seizure data compiled by various border-security agencies of a wide variety of nations (Ribeiro et al., 2019; Hitchens and Blakeslee, 2020), although this data is rarely collected on a consistent basis subject to an international standard (e.g., Nijman and Shepherd, 2021). Such sources of data have nonetheless provided substantial improvements in our understanding of pet trade trends and spatio-temporal dynamics (Harfoot et al., 2018; Andersson et al., 2021). However, a considerable (yet not fully quantified) proportion of trade of internationally-sourced species takes place within the domestic borders of individual nations (de Magalhães and

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São-Pedro, 2012; Papavlasopoulou et al., 2014; Janssen and Leupen, 2019). Regulation and documentation of such domestic trade is conducted on a case-by-case basis by individual nations (if at all) and is often subject to taxonomic biases (as identified in Fukushima et al., 2020).

Australia is a country widely regarded as having highly stringent border security policies, which strictly controls the importation (and exportation) of most live animals for commercial purposes (Whittington and Chong, 2007; Schneider et al., 2018). These regulations, implemented by the Commonwealth government, go far beyond Australia's obligations as a signatory to CITES (UNEP-WCMC, 2022). However, non-native species are nonetheless present in Australia, many of which were imported prior to the implementation of such policies. There is also a shortage of documentation for the domestic trade of both native and non-native species taking place within Australia (Vall-llosera and Cassey, 2017c; Woolnough et al., 2020; Millington et al., 2022a). Australia is federated into six States and eight Territories (two mainland and six external), and while Commonwealth-wide regulations are in place for some taxa (e.g., the trade and private possession of non-native reptiles is universally prohibited across Australia; see Toomes et al. (2019)), most regulations pertaining to the pet trade are managed and enforced at the individual State/Territory jurisdiction (see Toomes et al. (2022) and Woolnough et al. (2020) for specific examples). This jurisdiction-specific management ranges from simple prohibited lists to more complex permit systems that would-be traders need to acquire before buying specific taxa. As such, Australia does not consistently document the trade of live pets across all taxa and jurisdictions, allowing an unknown proportion of trade to occur without guarantee of sustainable or ethical practice.

Such lack of oversight in wildlife trade is concerning for several biosecurity and conservation-related reasons. From a biosecurity perspective, non-native species, including species that are invasive elsewhere in the world, are known to be illegally smuggled into Australia, held in private captivity and escape into Australian ecosystems (Toomes et al., 2019). There is also public desire to possess other highly invasive species as non-domesticated pets in Australia (Toomes et al., 2020), and non-native species that were brought into Australia prior to importation bans are known to be widely (and legally) traded and bred domestically (Woolnough et al., 2020). From a conservation perspective, Australian native species are highly desirable and valuable on the international pet market (Vall-llosera and Cassey, 2017a; Marshall et al., 2020; Heinrich et al., 2021) and there is a known domestic trade of threatened native species (Toomes et al., 2022). While the trade of some Australian species can be supplied by captive breeding, the slow life history traits and restricted distributions of many Australian native (particularly endemic) taxa leave them vulnerable to trade-incentivised harvesting of wild populations (e.g., *Holocephalus bungaroides*; Jolly et al. (2020)). When such biosecurity and conservation concerns are considered alongside additional threats such as the transmission of pathogens (Norval et al., 2020) and animal welfare concerns associated with captive keeping/breeding (Wyatt et al., 2022), there is a clear need to monitor and quantify the risk of domestic trade to ensure that wildlife trade occurs sustainably and ethically, Yet, to date, no systematic method of monitoring trade has been implemented by Australian Commonwealth and State/Territory governments.

Throughout a complex legal landscape, the pet trade (and wildlife trade more broadly) has undergone a rapid transition from traditional brick-and-mortar marketplaces (e.g., pet stores) to online e-commerce platforms over the last decade (Siriwat and Nijman, 2018, 2020; Fink et al., 2021). Such online platforms include direct business-to-consumer sites (e.g., online pet stores) as well as more centralised community-based sites (e.g., large classifieds) (Stringham et al., 2021). The ease-of-access, potential anonymity and large consumer base afforded by e-commerce has increased both the scale and diversity of pet trade (Paul et al., 2020; Atoussi et al., 2022). Fortunately, this also provides researchers with an opportunity for large-scale surveillance of trade activity, assisted by the development of open-source data mining (a.k.a. webscraping) resources. Such tools have recently been used to rapidly collect large quantities of trade data beyond the capabilities of traditional manual surveillance (e.g., Marshall et al., 2020; Hughes et al., 2021; Marshall et al., 2022) and can facilitate the analysis of taxonomic, spatial and temporal wildlife trade dynamics in lieu of formal trade monitoring and regulation.

Here, we took advantage of the increasing abundance of online data to glean insights into the Australian vertebrate pet trade. We identified Australia as a suitable candidate for the implementation of data mining-based surveillance of the online pet trade due to the aforementioned lack of consistent monitoring and the clear biosecurity and conservation concerns. We developed fit-for-purpose data mining tools to provide a near-comprehensive snapshot of advertised pets for sale across major Australian surface-web e-commerce platforms (see Stringham et al. (2021) for descriptions of surface and deep web). Our objective was to simultaneously use Australia as a case study to highlight domestic trade as a crucial yet understudied facet of international pet trade, while also assisting relevant Australian biosecurity and conservation stakeholders by identifying trade of key species. Specifically, we aimed to quantify not only the diversity of pets traded in Australia but also the relative quantity of individuals possessed, in order to examine the proportion of trade that involves non-native and threatened taxa.

2. Methods

2.1. Surface web E-commerce

To identify relevant surface web e-commerce platforms (i.e., websites) that trade live animals as pets, we followed the framework developed in Stringham et al. (2021). Specifically, we defined a series of search phrases centred around our taxa of interest (freshwater aquarium fishes, marine aquarium fishes, pet reptiles, pet amphibians, and pet birds) and type of websites (pet stores, classifieds or forums) within Australia. We limited the taxonomic scope of our study to vertebrates as they are the most commonly recorded taxa in trade, and because there are (relatively) strongly resolved taxonomic databases that would facilitate identification of advertised pets on a sufficiently large scale for the quantity of data collected. We did not search for mammalian pets due to the very high quantity of e-commerce sites dedicated to the trade of highly domesticated mammals (e.g., dogs, cats, rabbits, hamsters). In total, we created 105 search phrases (see Appendix A for full list), which we used to search for candidate websites using the Google search engine during August 2019. For each search, we recorded the first 50 results (i.e., 5 pages of results with 10 URLs per page) and retrieved Alexa web ranking, the number of page visits per month and the number of new listings posted in August 2019 (if available; see Stringham et al. (2021) for further details of web traffic statistics). In total this resulted in the selection of 12 websites (eight pet stores, three classifieds and one forum).

2.2. Webscraping trade data

Once candidate websites were identified, we developed fit-for-purpose webscraping code in the Python programming language (Sheridan, 2016) using the Selenium Webdriver, Beautiful Soup and Requests modules (Patel, 2020), to acquire pet trade data (i.e., instances of pets being advertised for sale online). Further details of this procedure are provided in Appendix B. We recorded the following attributes, where available, from each listing of all platforms (see Appendix C): scientific name, common/trade names, quantity, price, location (at either State/Territory or suburb level), listing date. We also collected image URLs to assist with species identification in cases where scientific names were not present and taxa could not be reasonably derived from free-form listing text. We generated unique identification codes for each listing based on a combination of the listing text and website-specific identifier, where available. If platforms did not provide a date of listing creation, we assumed this to be the first date that data was collected. Webscrapers were constructed in a manner that did not unduly impact the selected platforms and were compliant with the University of Adelaide HREC approval (Projects H-2020-184 and H-2020-256). We determined the frequency of sampling (daily, weekly or fortnightly) based on the frequency of trade occurring on each individual platform to ensure we did not miss new advertisements. Although our webscrapers also recorded 'wanted ads' i.e., listings where potential buyers express an interest in a product, we limited our analysis to advertisements where pets were being offered for sale. We identified wanted ads based on the presence of the text strings 'wanted' or 'wtb' (meaning wanted to buy) in listing descriptions, as most websites did not distinguish between wanted ads and normal advertisements.

2.3. Generating a list of taxa names

We compiled a list of the scientific names of advertised pets and manually standardised them to the Global Biodiversity Information Facility (GBIF, 2021). Where a hybrid was advertised for sale, we recorded the hybrid status and GBIF identification of both parent taxa, if known. Additionally, we included as synonyms for each unique GBIF record any terms frequently used by the community of online pet traders and keepers that are context specific, including common names, incorrect/outdated scientific names and 'trade names'. Outdated scientific names were matched to current scientific names by manually cross referencing advertised names against GBIF. Informal trade names were matched to scientific names using hobby-specific knowledge from naturalist and trade forums, as well as the authors own knowledge of Australian trade. For example, 'IRN' is used in trade to refer to the Indian ringneck parrot (*Psittacula krameri*).

Although we did not use data from 'wanted ads' in our analysis, we did inspect the text of these listings in order to assist with the compilation of standardised taxa names and synonyms used to search for taxa that may be advertised for sale. In total we generated a library of 1583 scientific names, 1408 common names and 2743 trade names for a total of 1381 species, 42 subspecies and 44 hybrids, with additional taxa only identifiable to genus (n = 79), family (n = 25) or higher (n = 8) level. While we have taken every effort to reduce the chances of non-target character string matches occurring, we do acknowledge that this may occur and lead to an overestimation of the frequency of trade in some species. However, scientific, common and trade names were only included in our library and used in string matching if they had been encountered for sale or in wanted ads at least once during our preliminary analysis. As such, we anticipate false matches to be infrequent.

2.4. Curation and analysis of advertised listings

All data curation and analyses were conducted in the R statistical software version 4.0.3 (R Core Team, 2022), using base functions unless otherwise specified. All data visualisation was generated using the ggplot2 package (Wickham, 2016). We extracted webscraped data for a 14-week snapshot: 3rd December 2019–20th March 2020. This study period was selected based on the date at which all our webscrapers became operational until the date that Australia closed its borders to non-resident human travel. Australia was not entirely unaffected by COVID prior to 20th March 2020 (e.g., air traffic was reduced when other nations closed their borders earlier in 2020) and therefore it is impossible to capture circumstances that entirely represent pre-COVID trade conditions. However, to the best of our knowledge, no other research or government entity was systematically collecting online trade data in Australia across this many platforms prior to Australia closing its borders. Therefore, we believe our dataset to be the best available representation of pre-COVID conditions and is referred to as a pre-COVID snapshot hereafter.

We used literal character string (i.e., letter and number) matching with the stringr package (Wickham, 2022) to identify listing titles or text that contained scientific, common and trade names (in that respective order of priority) from our reference library, at the taxonomic resolution of species and subspecies. For the remaining unmatched listings, we performed fuzzy string matching with the same list of names using a Levenshtein edit distance of two (i.e., matches any string within any combination of two-character additions, deletions or substitutions), excluding names of six or fewer characters in length. We also manually inspected cases where a fuzzy-string match yielded a notably higher number of listings and excluded this string if matches did not contain the target taxa. Finally, we repeated this process for unmatched listings against names at the resolution of family and genera. For listings that failed to match any literal or fuzzy string, we omitted them based on a pre-defined list of exclusion terms (Appendix D) and manually inspected the remaining unidentified listing text to determine if any pet was advertised for sale. If one or more pets were advertised for sale, we manually assigned them to the most specific taxonomic rank possible. In some instances, a pet was advertised that had not yet been taxonomically described yet is present in trade and referred to using hobby-specific terms/jargon (e.g., undescribed catfish). In such instances, we recorded taxonomy at a coarser level (genus, family or order, where possible).

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 highly domesticated taxa from our analysis, namely pigeons (*Columba livia*) and chickens (*Gallus gallus*). We generated species accumulation curves by randomly sampling listings without replacement and plotted the number of species detected against sampling effort.

For websites that provided a unique listing identifier, we used this to distinguish between unique listings, otherwise we used the unique combination of listing title and text to distinguish between unique listings. However, this does not account for the possibility that the same product may be advertised multiple times in different listings that have small differences in text description. Due to the considerable quantity of listings selling pets (62,584, not including listings selling pet products), we deemed it logistically infeasible to manually verify the uniqueness of listings or to manually establish additional information such as the quantity of pets for sale. 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 conservatively assumed to be advertising five individuals. We did not determine listing quantity based on the presence of numerical character strings (i.e., digits) due to the prevalence of information in free form text that contained digits yet was unrelated to quantity (e.g., addresses, phone numbers). Given the diversity of platforms, taxa and locations covered by our online surveillance, as well as human ethical considerations of contacting pet traders directly, we were unable to manually verify the veracity of advertisements.

We collated International Union for Conservation of Nature (IUCN) threat status of all traded species, and Global Invasive Species Database (GISD) records of invasive species, to categorise advertised pets based on their conservation status and history of invasions respectively. For birds we also compared the species identified for sale with the offline aviculture records previously collated by Vall-llosera and Cassey (2017c). We cross referenced scientific names and, where necessary, upstream taxonomy against the Australian Commonwealth 'List of Specimens Taken to be Suitable for Live Import' (Live Import List hereafter). For the subset of listings that were identified to species level and contained a specified location, we determined the rate of trade per region (i.e., city, town or municipality). The native/non-native status of reptile and bird species were determined by visually inspecting the distribution records listed in GBIF (2021), excluding introduced populations. Due to the large diversity of fish taxa detected, we cross-referenced scientific names against the Australian Faunal Directory (AFD) list of native species, including scientific name synonyms, in order to determine native/non-native status (Australian Faunal Directory, 2021). Similarly, we also identified non-native species that are known to be introduced using the AFD list.

3. Results

We have recorded a notable diversity of non-domesticated pets traded online in Australia, with 1192 species detected, including 667 non-native species (56.0 %). Species accumulation curves reveal a plateau in new bird species throughout our 14-week sampling period. Notably, fish and reptile species continued to accumulate without plateaux (Fig. 1). We detected a total of 62,584 listings advertising at least 109,056 live animals (52,409 non-native; 47.6 %) at the species level, including a minimum of 66,894 individual birds (24,899 non-native; 37.2 %), 30,343 fish (27,455 non-native; 90.5 %), 11,603 reptiles (all native), and 216 amphibians (55 non-native; 25.5 %). For listings that contained location information, most trade occurred in highly populous cities, namely Sydney (22,797 animals), Melbourne (13,866 animals), Brisbane (10,424 animals) and Perth (9854 animals). The highest volume of trade was concentrated in the most populous Australian States, namely New South Wales (35,181 animals), Queensland (26,781 animals), and Victoria (17,188 animals) (see Appendix E for summaries of trade frequency per region). The vast majority of trade took place on classifieds sites (60,306 listings; 96.4 %), followed by pet stores (2089 listings; 3.34 %) and forums (189 listings; 0.302 %). There was a high diversity of species that were not found on more than one website (600 species, 50.3 %), implying a high level of e-commerce specialisation catering to specific hobbies or consumer types.

Fish were the most species-rich taxon traded with 885 distinct taxa — 805 species, one subspecies and eight hybrids, including taxa that could only be identified at the level of genus (n = 53), family (n = 15), and order (n = 3). 553 of identified species are non-native (62.5 %; constituting 18,850 listings). A total of 279 non-native fish species are illegal to import into Australia based on the Live Import List yet were detected in our trade snapshot. Perciformes were the most species-rich order of fish in trade (perch and relatives, 483 species), followed by Siluriformes (catfishes, 88 species), Characiformes (characins, 57 species) and Cypriniformes (carp and relatives, 56 species), which collectively account for 85.0 % of identified fish species richness (Fig. 2).

We detected 228 distinct taxa of birds — 184 species, 11 subspecies, nine hybrids and two domesticated breeds, including taxa that could only be identified at the level of genus (n = 18) and family (n = 4). 113 of identified species are non-native species (61.4 %; constituting 16,345 listings). The most species-rich bird order in trade was Psittaciformes (parrots, 99 species), followed by Passeriformes (passerines, 48 species) and Galliformes (fowl and relatives, 16 species). The native red-collared lorikeet (*Trichoglossus rubritorquis*) and four species of non-native birds were not already listed on the 2007 inventory of known bird species traded in Australia, implying that they have been newly introduced into the trade since this inventory was created (DAWE, 2021). While the updated classification of *T. rubritorquis* (previously the rainbow lorikeet (*Trichoglossus moluccanus*)), may have obscured their trade in this earlier inventory, there is no such explanation for the non-native Pacific parrotlet (*Forpus coelestis*), olive-headed lorikeet (*Trichoglossus euteles*), yellow-fronted canary (*Crithagra mozambica*) or orange-breasted waxbill (*Amandava subflava*). Of the 197 non-native bird species previously identified by Vall-llosera and Cassey (2017c), 91 species were not detected in our online surveillance.

We detected 237 distinct taxa of reptiles — 186 species, 25 subspecies and 14 hybrids, including taxa that could only be identified at the level of genus (n = 7), family (n = 3), suborder (n = 1), and order (n = 1). All detected species were native, although we did detect two expressions of interest (i.e., 'wanted' advertisements) for the prohibited non-native corn snake (*Pantherophis guttatus*). Lizards (122 species) were

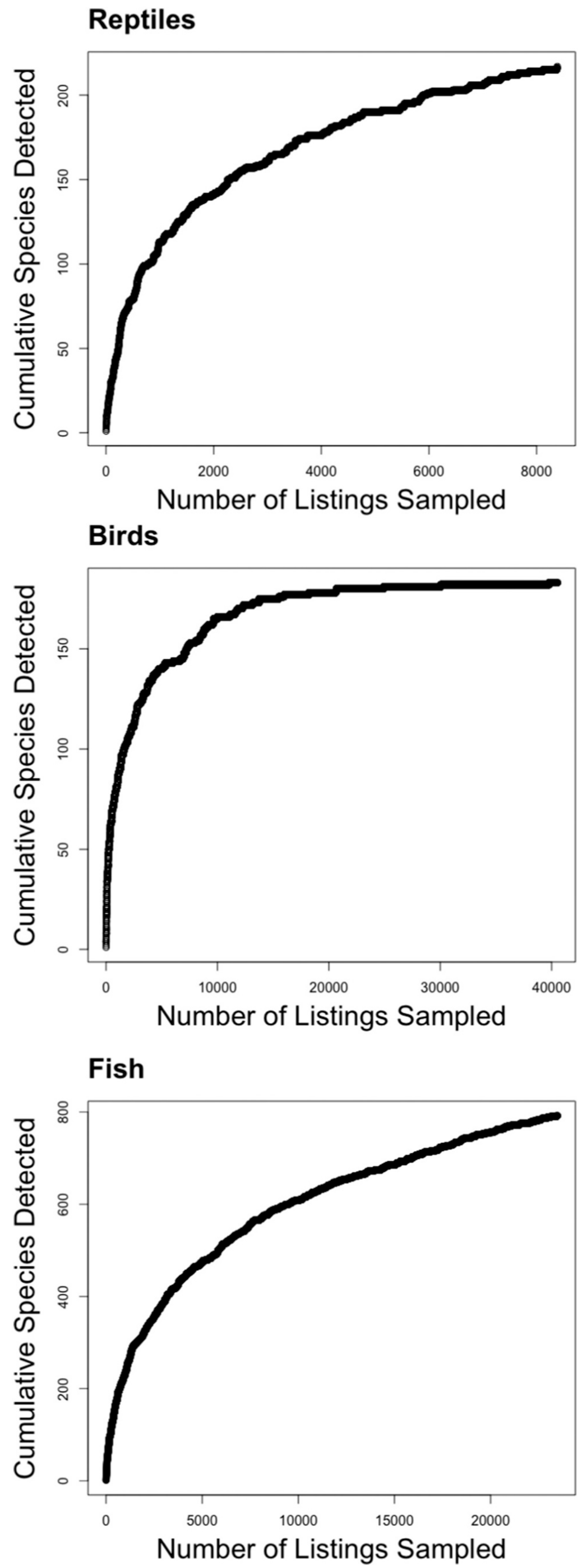
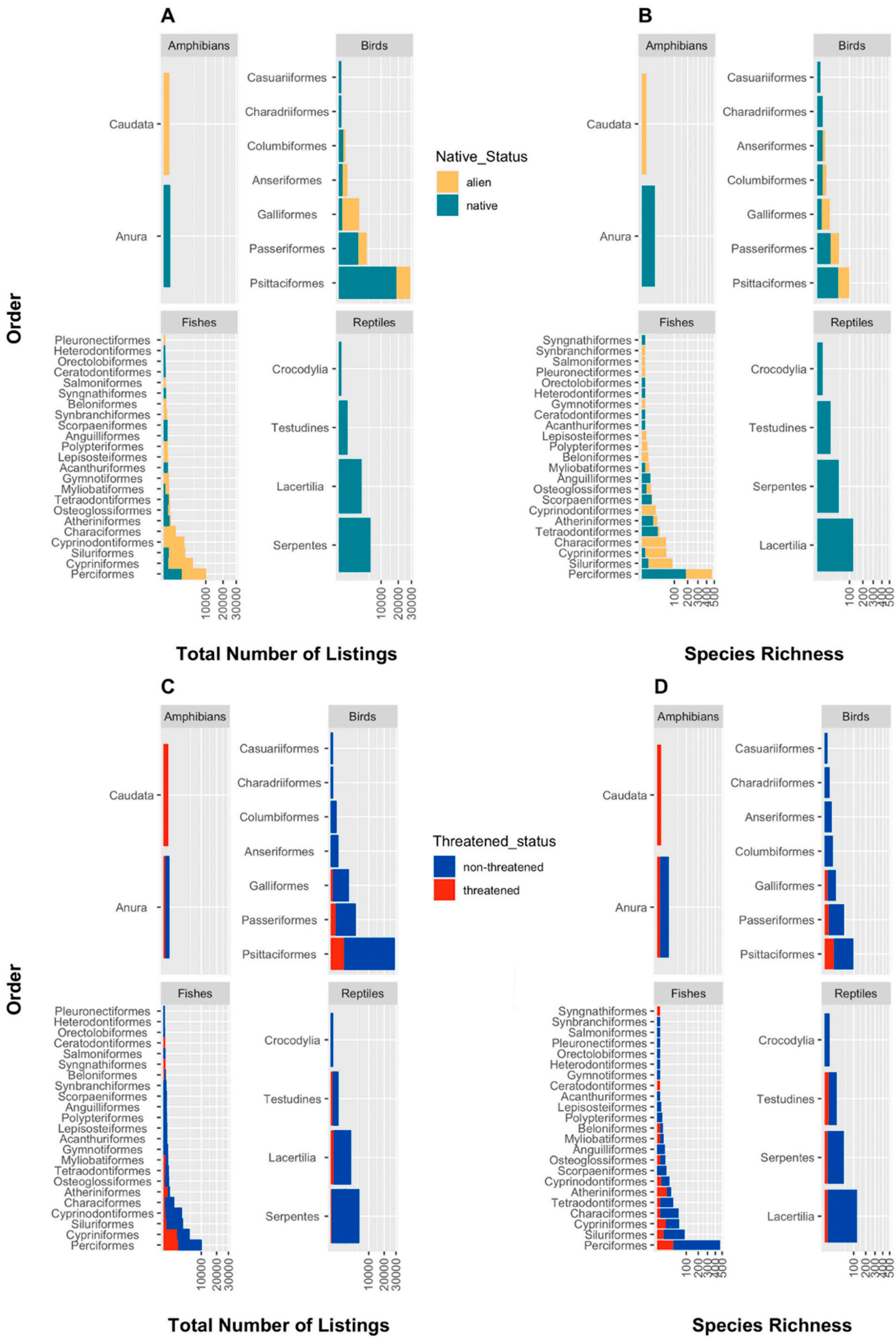


Fig. 1. Species accumulation curve for reptile, bird and fish taxa detected in Australian e-commerce trade. Raw data is displayed after randomly sampling species without replacement from all listings.



(caption on next page)

Fig. 2. Total number of listings (A and C) and species richness (B and D) of e-commerce trade by taxonomic order for native and non-native species (A and B), and for threatened and non-threatened species (C and D), displayed on a square-root scale. Threat status was determined based on the IUCN Red List, with the Endangered, Critically Endangered and Vulnerable categories being classed as threatened. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the most species-rich reptile taxa in trade, followed by Serpentes (snakes, 44 species), Testudines (turtles, 18 species) and Crocodilians (crocodiles, 2 species).

Amphibian trade was relatively sparse, with 18 distinct taxa detected, including 17 species, one of which is non-native (5.88 %; constituting 55 listings). Frogs (Anura) were most species-rich taxa in trade, with 16 species. The only other amphibian species was the axolotl (*Ambystoma mexicanum*), the sole non-native amphibian. There was a low diversity and abundance of native amphibians relative to reptiles in Australia, with the magnitude of the disparity between taxa not represented in other studies (Hughes et al., 2021). This may be due to the low diversity of Australian amphibian fauna (247 species of anurans compared to 1034 species of reptile; AmphibiaWeb, 2023; Melville et al., 2021).

Twenty of the traded non-native pet species identified here are invasive elsewhere in the world, according to GISD (Appendix F). In addition, a total of 22 traded non-native 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). Of the 1192 species identified in our trade snapshot, 81 were classified by the IUCN as threatened (12 Critically Endangered, 35 Endangered, 34 Vulnerable), and 35 classified as Near Threatened. Most taxa were classified as Least Concern (797), with the remaining taxa classified as Data Deficient (38) or simply Not Listed (241). Many examples of species not listed, such as *Peckoltia compta* and *Symphysodon discus*, have highly restricted known range sizes and it is possible that their eventual assessment will categorise them as Threatened.

4. Discussion

4.1. Scale of the non-native pet trade

Our online surveillance has captured a considerable richness of traded non-native pets (667 species) and, to the best of our knowledge, provided the only contemporary and systematic survey of online pet trade frequency in Australia. While there are existing audits of non-native species such as compiled avicultural records (197 bird species; Vall-llosera and Cassey, 2017c) and a species inventory compiled by the Australian government in collaboration with the ornamental fish industry (447 fish species; Millington et al., 2022b), our online surveillance reveals that contemporary understanding of the domestic non-native pet trade is far from comprehensive. The lack of saturation in the accumulation of new species (for fish and reptiles) despite extensive sampling of tens of thousands of advertisements suggests that the true diversity of non-native taxa traded in Australia has yet to be determined and implies that the biosecurity threat posed by the pet-release pathway continues to be underestimated. This is further evidenced by our surveillance failing to detect 91 species identified from offline aviculture records (Vall-llosera and Cassey, 2017c). Additional trade may be taking place across the deep web, namely social media platforms (see Appendix G for considerations of Deep Web surveillance).

Further temporal sampling is underway to facilitate analysis of greater quantities of data taking place across multiple years. However, the immediate and long-term effects of COVID-19 on the Australian pet trade have yet to be investigated, which may frustrate efforts to exhaustively quantify the full suite of traded taxa if online trade is occurring less frequently than previously. Most e-commerce platforms provide user feedback metrics as a proxy for online reputation, meaning there is incentive for traders to advertise pets accurately (Bojang et al., 2017). Nonetheless, we acknowledge that the advertised information does not necessary accurately reflect the attributes of the pet for sale, and that some fake/misleading advertisements may be present within our dataset.

Although our research focused on the trade and regulation of non-native species nationally in Australia, we also note that the majority of the 667 traded non-native species are not regulated at a State/Territory level. Even high-risk species that are regulated or prohibited are not done so uniformly across jurisdictions. For example, *P. krameri* is prohibited in Tasmania and Western Australia yet can be traded without regulation or permits in other States (Woolnough et al., 2020). Such inconsistent regulation is rarely successful; rather creating opportunities for subversion of trade via other jurisdictions (e.g., Raghavan et al., 2013). We recommend that State/Territory governments use our collected data to cross-reference against their jurisdiction-specific regulations and identify non-compliant trade. Alternatively, we recommend that research and government authorities work collaboratively to collate all legislation pertaining to the domestic keeping and trading of pets across all Australian jurisdictions, in order to provide a resource that can be readily cross-examined against trade data analogous to the data collected in our research.

The lack of regulation not only hinders the ability of Australian biosecurity authorities to control the trade of high-risk species, such as well-known invasive species listed in GISD, but it also deprives those authorities of a systematic means of recording data pertaining to trade and escapes. For example, South Australia's permit system for the keeping of native species obligates permit holders to keep a record of the number of individuals that have been sold, bred and escaped over a given reporting period, yet no equivalent system is in place for non-native species. As such, the trade-related propagule pressure remains unquantified for hundreds of non-native species. The findings of Toomes et al. (2022) suggest that, for native pets, propagule pressure is proportional to the quantity of possession. Assuming this pattern extends to non-native species, our surveillance data provides a proxy measure of relative propagule pressure and may assist with the creation of priority lists for future management strategies/interventions.

4.2. Comparison with illegal seizures

The 111 species of non-native reptile detected during smuggling attempts or from illegal captivity in Australia (Toomes et al., 2019) were not detected in our surface web surveillance. Recent investigation of illicit e-commerce suggest that illegal pet trade is similarly rare on dark web platforms (Harrison et al., 2016; Stringham et al., 2022), though deep web (i.e., social media) trade warrants further investigation (see Section 4.3).

In contrast to the paucity of nationally prohibited species recorded here, non-uniformly prohibited species (e.g., *P. krameri* in Western Australia and Tasmania) were routinely recorded in prohibited jurisdictions, albeit in lower abundances than permitted jurisdictions. While part of this trade may be due to a lack of awareness surrounding the specific and varying trade regulations in different jurisdictions, their availability may instead illustrate the blatant disregard for trade regulations. 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 non-native species and both the quantity and diversity of contemporary trade. Non-native fish and birds, while mostly illegal to import, are legal to trade without quota or documentation unless specifically declared as prohibited (usually via the Biosecurity Act 2015 (DAWR, 2019)) by a State or Territory. In contrast, all non-native reptiles are prohibited except for non-commercial purposes. This inconsistency in policy is worthy of further interrogation because there is no evidence that biosecurity threat posed by reptile and non-reptile taxa are fundamentally different, as evidenced by the number of introduced and known invasive vertebrates currently present in Australia (Vall-llosera and Cassey, 2017b). Additionally, educating the public and the pet supply chain on trade regulations specific to each State and Territory may aid in reducing the incidence of non-uniformly prohibited species advertisements in prohibited jurisdictions.

4.3. Trade of threatened taxa

The impacts of wildlife trade, be they biosecurity, animal welfare or conservation related, are often difficult to identify (Morton et al., 2021). Many threatened taxa are traded globally, yet trade is not a threatening process if conducted sustainably (i.e., via captive breeding (Tensen, 2016)). We found examples of both native and non-native species in our analysis that are known to be threatened by wild harvest, including the broad-headed snake (*Hoplocephalus bungaroides*; Jolly et al., 2020) and Lake Malawi cichlids (Cichlidae; Msukwa et al., 2021). However, we cannot estimate the proportion of trade recorded in our analysis that was captive-bred versus wild-caught, as most traders did not provide this information. Indeed, there is no onus to provide traded pet species origin information in Australia despite calls for green certification (Millington et al., 2022a), which would simultaneously educate the general public and allow potential consumers to make an informed decision to purchase pets based on sustainability. One measure to ensure that the pet trade is not a driver of unsustainable trade is the use of a permit system to regulate the trade of threatened taxa (e.g., by issuing permit quotas or by requiring proof of captive-bred provenance). Currently, permit systems only exist in some Australian jurisdictions for certain taxa, such as in South Australia (Toomes et al., 2022). Various State and Territory departments tasked with wildlife management could use South Australia's system as a template, with the decision to control or reduce trade based on species' life history traits and rate-of-trade data.

4.4. Taxonomy and trade

Pet traders are often abreast of contemporary taxonomy, however there are inevitably instances whereby outdated taxonomy is used when advertising 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 synonyms, for example '*Nephrurus milii*' is often used to refer to barking geckos (*Underwoodisaurus milii*). Many hybrids are also commonly traded, yet the origin species that constitute the hybrid are not always conclusively known. This is exemplified by the popular flowerhorn cichlid (see Fig. 3), which is believed to originate from a multi-generation hybrid of several *Cichlasoma* species with *Vieja synspila* (Nico et al., 2007). Other examples include red Texas cichlids (Cichlidae sp.), lemon bristlenose catfish (Ancistrus sp.) and pigeon blood discus (Symphysodon sp.). 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.

There were many ornamental fish that have not been formerly described and yet are nonetheless widely known and traded both in previous research and during our surveillance (Tan and Armbruster, 2016). This lack of taxonomic resolution stifles efforts to evaluate both the biosecurity threat of traded fish, as well as the risk trade poses to their conservation. 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), representing as-yet undescribed taxa within the family Loricariidae that do not necessarily map to distinct species (Cardoso et al., 2016).

Fig. 3. Examples of traded pet fish that are difficult to taxonomically identify yet are nonetheless referred to by traders using pseudo-taxonomic units. Clockwise from top-left: flowerhorn cichlid (multi-species hybrid of *Cichlasoma* species with *Vieja synspila*); hongi (undescribed *Labidochromis* sp. erroneously referred to as *Labidochromis hongi*); pigeon blood discus (captive-bred colour morph of unknown *Symphysodon* sp.); gold nugget pleco (*Baryancistrus xanthellus*, previously referred to as L018 and L085 before being formerly described in 2011 (Py-Daniel et al., 2011)). Image credit, clockwise from top-left: patanasak (Getty Images); ArtEvent ET (Getty Images); vojce (Getty Images); Mirko_Rosenau (Getty Images). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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. Similarly, undescribed species can still face conservation threats: approximately 28,000 individual fish are harvested from Lake Malawi each year to supply the ornamental trade, the majority of which are undescribed, which limits capacity to understand whether overharvesting is occurring (Msukwa et al., 2021). Considerable effort is therefore required to keep abreast of hobbyist naming conventions, particularly if future taxonomic resolution occurs (e.g., recent scientific description of Geophagus sp. "Tapajos Red head" as *Geophagus pyrocephalus* (Chuctaya et al., 2022)). 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.

5. Conclusion

Australia's biosecurity priorities are commendable, yet its management of non-native pets falls short of a system that comprehensively reduces known and/or identifiable risks. We have provided the first instance of a systematic survey identifying a large diversity of non-native taxa including the first known systematic record of the frequency of online trade in Australia. Our results include undescribed taxa as well as hybrids with poorly documented provenance. A high diversity of threatened taxa are also traded, though the sustainability of trade is difficult to verify considering the paucity of information regarding captive-bred status. We recommend continued online surveillance in lieu of the lack of the saturation in species accumulation, as well as an expansion of this methodology to deep web platforms, as we likely did not detect all species in the trade. Ultimately such surveillance can support evidence-informed policy changes to more closely align the trade of non-native pets with a nation's biosecurity priorities.

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CRediT authorship contribution statement

Adam Toomes: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft. **Stephanie Moncayo:** Methodology, Validation, Data curation, Writing – review & editing. **Oliver C. Stringham:** Conceptualization, Methodology, Software, Data curation, Writing – review & editing. **Charlotte Lassaline:** Validation, Data curation, Writing – review & editing. **Lisa Wood:** Data curation, Writing – review & editing. **Mariah Millington:** Data curation, Writing – review & editing. **Charlotte Drake:** Data curation, Writing – review & editing. **Charlotte Jense:** Data curation, Writing – review & editing. **Ashley Allen:** Data curation, Writing – review & editing. **Katherine G.W. Hill:** Validation, Data curation, Writing – review & editing. **Pablo García-Díaz:** Conceptualization, Writing – review & editing, Supervision. **Lewis Mitchell:** Conceptualization, Writing – review & editing, Supervision. **Phillip Cassey:** Conceptualization, Resources, Funding acquisition, Writing – review & editing, Supervision.

Declaration of competing interest

We declare no conflicts of interest.

Data availability

As our data contains potentially identifiable or re-identifiable information, we have chosen not to publish it in any publicly available archive. However, we have published a dataset summarising the rate of trade for native and non-native species within Australia, which can be found at: https://doi.org/10.6084/m9.figshare.20956339.v1.

Supplementary Data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110040.

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