Who’s a pretty bird? Predicting the abundance of bird species in Australian online pet trade

Katherine GW Hill (katherine.hill@adelaide.edu.au)  
The University of Adelaide  https://orcid.org/0000-0002-6827-6770

Steven Delean  
The University of Adelaide School of Biological Sciences

Oliver C Stringham  
RU: Rutgers The State University of New Jersey

Stephanie Moncayo  
The University of Adelaide School of Biological Sciences

Adam Toomes  
The University of Adelaide School of Biological Sciences

Jonathan J Tyler  
The University of Adelaide

Phillip Cassey  
The University of Adelaide School of Biological Sciences

Research Article

Keywords: online trade, parrots, pet birds, phylogenetic cross-validation, songbirds, wildlife trade

Posted Date: December 17th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2360337/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Version of Record: A version of this preprint was published at Biological Invasions on December 16th, 2023. See the published version at https://doi.org/10.1007/s10530-023-03221-1.
Abstract

The exotic pet trade has largely shifted from traditional brick-and-mortar shops to online commerce. Understanding the dynamics of online pet trade, including relationships between species characteristics and a species’ relative popularity, can assist in informing trade regulation for conservation and biosecurity. Here, we identified the leading correlates behind the abundance in the Australian trade of parrot (Psittaciformes) and songbird (Passeriformes) species. We examined 14,000 online sales of parrots and songbirds collected from a popular online Australian marketplace in 2019 (representing 235 species) using an automated data collection method. We identified the characteristics that correlated with online species abundance (i.e., popularity); including (i) breeding and handling requirements; (ii) trade and availability; and (iii) appearance and behaviour. We found 55% of parrot species and 64% of songbird species traded online were non-native to Australia (i.e., alien species), most of which (81% and 85% respectively) have an extreme risk of establishing invasive populations. Species abundance of both orders was influenced by cheaper prices, which is associated with a higher invasion risk. Trade in parrots was also correlated with attractive birdsongs, being easy to care for, and a preference for native Australian species. Songbird abundance was correlated with attractive plumage colour and, to a lesser extent, the availability of colour mutations and smaller range sizes. These results, combined with an understanding of consumer behaviour and international trends, may help predict which species will become popular in domestic trade in the future, and identify current and future invasion risks to assist in environmental biosecurity efforts.

Introduction

The global exotic pet trade threatens both biosecurity and biodiversity conservation. The transport of species outside of their native ranges is a major pathway for new invasive alien species and diseases to establish and spread (Lockwood et al. 2019; Toomes et al. 2019; Vall-llosera and Cassey 2017b), while animals may be illegally or unsustainably harvested from the wild to meet increasing demand (Natusch and Lyons 2012; Shepherd et al. 2012). Despite these threats, the dynamics of pet trade, including species composition and abundance, are relatively unknown. Understanding the major correlates behind species abundance (i.e., popularity) in pet trade can help inform regulation policy and assist with improving conservation and biosecurity outcomes, such as predicting which new species may enter the market, where a species may be a future invasion risk (Stringham et al. 2021a; Vall-llosera and Cassey 2017b), or which species are most at risk of overharvesting (Shepherd et al. 2012).

The presence and popularity of a species in pet trade is a human-driven supply and demand process, which is strongly influenced by biological, cultural, and financial factors. The selection and popularity of certain species in trade over others in trade had been explored for several taxa and is highly dependent on species characteristics, such as their availability and attractiveness, as well as individual behaviours, such as temperament and sex (e.g., Banos-Villalba et al. 2021; Romero-Vidal et al. 2020). However, factors such as trade restrictions and networks, and different pet-keeping practices and cultures, mean
that the most desirable pet species characteristics are likely to greatly vary between different marketplaces and regions.

Here, we focus on the trade of pet birds in Australia; one of the most traded taxa within a unique domestic market. While previous studies have investigated some species characteristics as correlates in international bird trade (e.g., Chan et al. 2021, Vall-llosera and Cassey 2017c), they are unlikely to transfer to the Australian domestic market due to different pet-keeping cultures and Australia's unique regulatory landscape (Toomes et al. 2019). Australia implements a near complete ban on the import of live birds (Su et al. 2022), while simultaneously leaving the domestic trade largely unregulated, creating a closed system. For parrots, one of the most globally traded orders of birds, there is an international preference for species that are colourful, large-bodied, cheap, uncommon (i.e., “rare”), and can sing or imitate speech (Chan et al. 2021; Ribeiro et al. 2019; Romero-Vidal et al. 2020; Tella and Hiraldo 2014). While we expect some of these correlates to be shared in the domestic Australian market, the closed nature of the trade is likely to influence species availability and popularity. Furthermore, the Australian trade is unique in that many parrots native to Australia are also popular in the global pet trade (e.g., eastern rosella, Platycercus eximus; sulphur-crested cockatoo, Cacatua galerita; and rainbow lorikeet, Trichoglossus haematodus) (Vall-llosera and Cassey 2017a). A previous study has investigated correlations between species characteristics and abundance in Australian bird trade using data collected from pet stores, newspaper classifieds, and pet avifauna price guides (Vall-llosera and Cassey 2017c); however, the authors used price as a proxy for abundance, as actual abundance counts were unavailable.

Here, we investigated which biological and economic characteristics influence species popularity in trade. To measure popularity, we collected data from an internet marketplace, which provides unique opportunities to quantify and investigate the dynamics of the pet bird trade (Siriwat and Nijman 2020; Stringham et al. 2021b). We monitored a highly-used Australian bird trading website and determined the number of advertisements of each species traded. We fitted Generalized Linear Models (GLMs), using block cross-validation methods to account for the influence of phylogeny, to correlate biological species characteristics and trade variables, which we hypothesised to influence popularity. Finally, we used our unique online bird trade dataset to address two other secondary aims of potential biosecurity importance: (i) we compared the rate at which alien and native species are traded; and (ii) investigated the use of price as a proxy measure for abundance.

**Methods**

**Data collection**

**Online trade data**

We monitored a popular surface-web Australian classifieds website where the Australian domestic bird trade is prolific (Stringham et al. 2021c). Using an established automated data collection method specified in Stringham et al. (2021b), we collected listings (i.e., advertisements) over five months from
July to December 2019). Over this period, we collected 66,704 unique listings from the ‘bird’ subsection of the website (Supplementary File SI1 for list of species found). As this website used free text (i.e., traders type their listings individually), each listing needed information to be manually cleaned and extracted for species names and other attributes. Due to the large number of listings, we chose to clean a random subset accounting for 25% of all listings over this time (Supplementary File SI2). All data were collected according to established ethical standards for de-identifying e-commerce data, and we received ethics approval from the University of Adelaide (Semi-automated monitoring of international online wildlife trade; HREC no. H-2020-184).

From each listing, we used the listing text and photos (if provided) to identify the species traded to the most specific taxonomic rank possible, following BirdTree nomenclature (www.BirdTree.org). We recorded the quantity of individuals sold, and if the bird was a colour mutation or mentioned to be hand-raised or wild-caught. For our analyses, we only considered listings identified to species and subspecies, excluding hybrids of two species and listings only to genus or family level identifications. Our focus was on the orders Psittaciformes (parrots; 95 species, 9192 listings, 23121 individuals) and Passeriformes (songbirds; 48 species, 1245 listings, 4077 individuals). We excluded listings that included domesticated species, and species not commonly sold as pets, including species from the following orders: Anseriformes (waterfowl; 9 species, 313 listings), Casuariiformes (Cassowary; 1 species, 4 listings), Charadriiformes (shorebirds; 1 species, 2 listings), and Columbiformes (pigeons and doves; 9 species, 86 listings) (Supplementary File SI2). To identify potential biosecurity risk of alien species, we compared the proportion of sales of native and exotic species and identified the threat categories of all alien species using the Australian List of Threat Categories of Non-indigenous Vertebrates (Australian Intergovernmental Environment & Invasives Committee 2018). These threat categories incorporate the danger posed by an individual animal if it were to escape captivity, the likelihood of it establishing a wild population, and the consequences if it were to establish.

**Species characteristics**

To investigate correlates of species abundance in trade, we collected species characteristics that we predicted may contribute to a species’ desirability. We grouped these characteristics into three categories: (i) breeding and handling; (ii) trade and availability; and (iii) appearance and behaviour (Table 1). Where characteristic data was missing for a species, we used the average for the genus, if available. If this information was not available, the species was excluded from the correlates of abundance analysis. We excluded 12 species where price was not advertised, and the median price could not be calculated (Supplementary File SI2), and excluded one species (Pictorella mannikin, *Heteromunia pectoralis*) that was missing values for some of the below characteristics in Table 1, where genus-level data was not available. We checked for correlations between characteristics by assessing variance inflation factors (VIF), removing characteristics if they were highly correlated with another (VIF > 10). We found no instances of high correlations between species characteristics, where the highest correlation for parrots was median price (VIF = 5.13), and for songbirds was level of care (VIF = 3.01).
Table 1
Species characteristics we hypothesised are related to species abundant in online trade. These characteristics were identified in previous studies on different wildlife trade markets.

<table>
<thead>
<tr>
<th>Character</th>
<th>Source</th>
<th>Unit</th>
<th>Description</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breeding &amp; handling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual fecundity</td>
<td>Birdcare</td>
<td>total eggs</td>
<td>Average number of eggs produced each year in captivity, according to an online birdkeeping guide Birdcare.</td>
<td>Species with a higher reproductive output may have more individuals available for sale, increasing total abundance (Toomes et al. 2022).</td>
</tr>
<tr>
<td>Body mass</td>
<td>Myhrvold et al. (2015)</td>
<td>grams</td>
<td>Average mass of species for males and females.</td>
<td>Birds with higher body mass are often described as more attractive, suggesting they will be more abundant (Romero-Vidal et al. 2020; Siriwat and Nijman 2020).</td>
</tr>
<tr>
<td>Level of care</td>
<td>Birdcare</td>
<td>1 (beginner) to 4 (specialist)</td>
<td>Level of experience recommended for keeping species, according to the online birdkeeping guide.</td>
<td>Birds that require more experience to keep may be less accessible to the public, and therefore less abundant (Vall-llosera and Cassey 2017c).</td>
</tr>
<tr>
<td>Mutations</td>
<td>Birdcare</td>
<td>presence</td>
<td>If colour mutations are present in Australian trade, according to the online birdkeeping guide.</td>
<td>Species which can have colour mutations available may be viewed as “collectable”, making the species more abundant (Chan et al. 2021).</td>
</tr>
<tr>
<td>Hand-raised</td>
<td>Calculated</td>
<td>presence</td>
<td>If hand-raised birds were present in the dataset.</td>
<td>Species which can be hand-raised may be seen as more desirable companion animals, and more abundant. No songbirds were handraised.</td>
</tr>
<tr>
<td>Trade &amp; availability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provenance</td>
<td>BirdLife Working List of Australian Birds</td>
<td>native or alien</td>
<td>If the species has a native range within Australia.</td>
<td>Alien species may be perceived as “rare” and more abundant.</td>
</tr>
<tr>
<td>Range size</td>
<td>Handbook of the Birds of the World</td>
<td>km²</td>
<td>Total geographic range size for the species, including invasive populations.</td>
<td>Species with smaller range sizes may be perceived as “rarer” and more desirable and abundant (Toomes et al. 2022).</td>
</tr>
<tr>
<td>Median price</td>
<td>Calculated</td>
<td>$AUD</td>
<td>Median price of all sales for each species in dataset.</td>
<td>Cheaper species may be more accessible to the public, and therefore more abundant.</td>
</tr>
</tbody>
</table>
### Data analysis

#### Relationships between abundance and species characteristics

Our analysis of relationships of abundance with species characteristics involved three steps. First, we identified candidate statistical models each containing various combinations of the species characteristics as explanatory variables. Second, we identified which models best predicted the data using a cross-validation method that accounted for phylogenetic autocorrelation. Finally, we ran the ‘best’ models on the full dataset using a model averaging approach and reported on covariates of interest and model performance metrics.

To identify the correlates of species abundance in trade, we used a model selection method with phylogenetic cross-validation to account for the non-independence caused by phylogenetic autocorrelation, investigating parrots and songbird trade separately. Due to the large number of characteristic covariates (n = 11) compared to the number of species in trade (83 parrots, 48 songbirds), we constrained the complexity of individual models to avoid overfitting by limiting the number of covariates used in each model. To do so, we created univariate models containing each explanatory variable from Table 1, as well as models with one variable from each model grouping: (i) breeding & handling; (ii) trade & availability; (iii) appearance & behavior. This resulted in 95 candidate models for parrots and 79 for songbirds (Supplementary File SI4). The dynamics of the trade in budgerigars (*Melopsittacus undulatus*) are very different to other parrots (e.g., often sold as a “starter bird” for children) (Vall-llosera and Cassey 2017a). Consequently, their abundance in online trade was four orders
of magnitude larger than the next most abundant species. Due to the magnitude of the difference and specific characteristics of this species, they were not considered further in any statistical analysis.

We checked for phylogenetic correlations in the data and found a high correlation for parrot abundance (Pagel's $\lambda = 0.99$, $p < 0.0001$), although not for songbirds ($\lambda = 0$, $p = 1$). Therefore, the linear regression assumption of independence of the observations was violated for parrots, and we needed to correct for phylogenetic autocorrelation. We used block cross-validation (Roberts et al. 2017), which takes “blocks” of species (i.e., phylogenetic clades) based on their phylogenetic distance to create training and test datasets and assess model predictive performance. The cross-validation procedure iterates over the phylogenetic blocks to build the model with training data and predict for the held-out test block of species (i.e., remaining species which were not in the “block”). Models were then ranked by their average predictive performance (i.e., root-mean-squared error (RMSE)) to identify the highest ranked models for inference. For consistency, we used this block method to evaluate candidate models for both parrots and songbirds separately.

Using methods from Roberts et al. (2017), we ran negative binomial Generalised Linear Models (GLMs) for all candidate models. As the phylogenetic distance that would ensure independence among species was unknown, we repeated the model selection with increasing numbers of phylogenetic “blocks” (i.e., reducing the number of held-out species) to assess the sensitivity of the model chosen for inference under different amounts of phylogenetic relatedness. Using a phylogenetic consensus tree using 1000 trees from BirdTree (Rubolini et al. 2015), we estimated an ideal block size (i.e., number of blocks/clades) of five for songbirds and four for parrots (Supplementary File SI4), from which we selected the best-performing models based on the lowest root-mean-square-error (RMSE).

To obtain final model estimates and to visualize relationships for count data with no zeros, we constructed negative binomial GLMs on the full dataset for all cross-validated models with $\Delta$RMSE < 10 and assessed model performance using marginal $R^2$ (Nakagawa et al. 2017). We used conditional model averaging, where models were weighted using RMSE, and the relative importance (RI) of each variable was calculated using the sum of model weights for models that included the variable. We used the results of model averaging to: (i) identify the average model estimates of each characteristic; (ii) identify which characteristics were most influential (i.e., greatest relative importance) on species abundance; and (iii) to interpret characteristics whose 95% confidence intervals do not overlap with zero.

**Testing the use of price as a proxy**

Finally, we tested price as a proxy for actual abundance in our database of Australian online trade, to investigate the validity of a common assumption made in previous wildlife trade studies (e.g., Vall-llosera and Cassey 2017c, Harris et al. 2017). To do so, we compared the abundance (i.e., number of individuals traded online) per species to their median per-unit price and calculated the Pearson's correlation statistic to quantify the relationships between abundance and price. We performed this analysis separately for parrots and songbirds.
All analysis was conducted using R 4.1.3 software for statistical and graphical computing (R Core Team 2022). Variance inflation factors and marginal $R^2$ values were calculated using package ‘performance’ (version 0.9.2, Lüdecke et al. 2021) and phylogenetic correlation calculated using ‘phytools’ (version 1.2.0, Revell 2012). GLMM models were fitted using ‘glmmTMB’ (version 1.1.4, Brooks 2017), and ‘MuMIn’ for model averaging (version 1.47.1, Barton 2022).

Results

Species composition and abundance

Native parrots were more abundant (73% of individual parrots) than alien parrots; however, most species were alien (53 species, 55% of all parrot species). Three native species dominated trade: budgerigar (*Melopsittacus undulatus*, 10,022 individuals), cockatiels (*Nymphicus hollandicus*, 2,457 individuals), and rainbow lorikeets (*Trichoglossus haematodus*, 1,889 individuals). Popular alien species included rose-ringed parakeets (*Psittacula krameri*, 1,971 individuals), green-cheeked parakeets (*Pyrrhura molinae*, 820 individuals), and rosy-faced lovebirds (*Agapornis roseicollis*, 805 individuals). On the Australian List of Threat Categories of Non-indigenous Vertebrates, 43 alien parrot species in the trade are listed as an extreme risk, two as a serious risk, five as a moderate risk, one as a low risk, and two species are not listed.

Songbird trade was predominantly alien species in both composition (33 species, 65% of songbird species) and abundance (59%). The most popular native species were zebra finches (*Taeniopygia guttata*, 698 individuals), Gouldian finches (*Erythrura gouldiae*, 598 individuals), and painted finches (*Emblema pictum*, 94 individuals). Popular alien species included domestic canaries (*Serinus canaria*, 1,667 individuals), java finches (*Lonchura oryzivora*, 130 individuals), and European goldfinches (*Carduelis carduelis*, 86 individuals). Of the alien songbird species, 28 are listed as an extreme risk and five as a serious risk.

Relationships between between abundance and species characteristics

For parrot trade, four models were selected, with high marginal $R^2$ (0.62 to 0.66; Supplementary File SI4). The most important correlate with species abundance was song complexity (i.e., the variety of songs and ability to mimic speech). This variable was in all top-performing models (relative importance (RI) = 1.00), with a positive correlation between more complex songs and abundance in trade (slope ($M$) and 95% confidence interval = $1.97 \pm 0.57$; Supplementary File SI4). The level of care was the next most important characteristic (RI = 0.91), where higher levels of care were negatively correlated with abundance ($M = -0.91 \pm 0.32$). Provenance was an important characteristic (RI = 0.60), where native Australian species were positively correlated with abundance ($M = 0.48 \pm 0.53$); however, its confidence interval included zero. Median price had low relative importance (RI = 0.15) and a negative correlation with abundance in
trade \( (M = -1.29 \pm 0.77) \), while the presence of colour mutations was the least important characteristic of those selected \( (RI = 0.09) \), with a positive correlation \( (M = 0.96 \pm 0.68) \) and preference towards species with mutations available in trade.

For songbird trade, eight models were selected, with high marginal \( R^2 \) (0.60 to 0.74) the most important correlate with species abundance was the median price \( (RI = 0.96) \), where lower prices were correlated with higher abundances \( (M = -3.15 \pm 1.32) \). Plumage colour was the next most important characteristic \( (RI = 0.84) \); however, its small negative correlation \( (M = -0.05 \pm 0.05) \) included zero. The presence of colour mutations had low relative importance \( (RI = 0.17) \) a positive correlation \( (M = 1.26 \pm 0.92) \) with preference towards birds with mutations available in trade. Range size had a low relative importance \( (RI = 0.04) \), with a negative correlation with abundance \( (M = -0.77 \pm 0.41) \). The remaining characteristics had confidence intervals overlapping zero, including annual fecundity \( (RI = 0.09; M = -0.08 \pm 0.12) \), intelligence \( (RI = 0.08; M = -2.77 \pm 5.24) \), level of care \( (RI = 0.05; M = -0.61 \pm 1.11) \), and song complexity \( (RI = 0.01; M = 0.16 \pm 0.51) \).

**Testing price as a proxy for abundance**

Median price has a very weak, although significant, negative relationship with total abundance of parrots \( (R^2 = 0.14, F_{1,82} = 14.03, p < 0.001) \) and songbirds \( (R^2 = 0.36, F_{1,47} = 28.47, p < 0.001) \) (Supplementary File SI5).

**Discussion**

As the bird trade in Australia continues to be an emerging source of new invasive species, continued monitoring of pet sales is crucial for early prevention and effective biosecurity (Vall-llosera and Cassey 2017b). Here, we have found that a number of characteristics which influence species abundance in trade are also characteristics associated with successful invasive species.

In our study, the price of a given bird species was a correlate of abundance, where cheaper species were more abundant. This has implications for biosecurity, as price is also a major correlate for species escapes from captivity in Australia (Vall-llosera and Cassey 2017b). Simultaneously, cheaper species are also correlated with captive escapes which, combined with the higher abundances in trade identified here, increases the propagule pressure of alien species in trade (Cassey et al. 2018). The two most commonly traded alien parrots, the rose-ringed parakeet \( (Psittacula krameri) \) and the green-cheeked parakeet \( (Pyrrhura molinae) \), and two of the most commonly traded alien songbirds, the domestic canary \( (Serinus canaria) \) and European goldfinches \( (Carduelis carduelis) \) are identified as extreme biosecurity risks (Australian Intergovernmental Environment & Invasives Committee 2018). In particular, wild incursions of rose-ringed parakeets are increasing in Australia due to increasing pet trade, and are likely to establish as an invasive species without ongoing control (Vall-llosera et al. 2016). This species possesses the most important correlates with abundance for parrots: it is relatively cheap (approximately AUD$120), is easy to care for (often sold for “beginners”), has a wide variety of songs and is available in many colour
mutations. This is consistent with other studies where the characteristics which make a species popular in trade also makes them successful invasive species (Gippet and Bertelsmeier 2021). Concerningly, 81% of alien parrot species and 85% of alien songbird species listed as an extreme biosecurity risk on the Australian List of Threat Categories of Non-indigenous Vertebrates, which suggests that these species should not be kept unless there is sufficient management to reduce the potential of these species to establish. With the current lack of regulation around bird-keeping in Australia, we recommend these extreme risk species be closely monitored by environmental agencies and birdkeeping societies to reduce their potential for establishing invasive populations.

Although there were more alien species present in trade, native species were sold in far greater abundances. For native species, it is likely that many of these species are being sold outside of their native ranges, potentially in large numbers, which is an unexplored biosecurity risk. For example, the third most abundant native parrot species, the rainbow lorikeet (*Trichoglossus haematodus*), is native to the eastern coast of Australia, but has established invasive populations in Western Australia and Tasmania due to their popularity in trade (Chapman, 2005; Robinson 2020). With the high number of native species sold, there is potential for another ‘domestic non-native’ species to establish.

Most species characteristics we explored differed in their importance between parrot and songbird abundance. The most influential species characteristic on parrot abundance in trade was song complexity, the measure of how attractive people find the species’ call measured by unique uploads to a birdcall website (Xeno-Canto.org). While this may be a traditionally desirable characteristic in parrots due to their association with repeating phrases, it may also be driven by modern media, as videos of parrots mimicking songs and speech are popular online (e.g. Moloney et al. 2021; Siriwat et al. 2020). We also found that species which are easy to care for (i.e., “beginner” species) were more popular, which encapsulates species that are hardy, have generalist diets and do not need specialist housing or attention. Characteristics associated with easy care are also correlates of successful invasive species; where they are able to readily adapt to new environments (Vall-llosesa and Sol D, 2009).

Alternately, songbird trade abundance is driven by characteristics more associated with aviary birds, where cheaper, more colourful species were more abundant. Plumage colour (here, for the “natural” colour, not colour mutations) was the next most important factor explaining abundance after median price; however, the direction of which is unclear. Similarly, the presence of colour mutations had some effect on species’ abundance, where pet owners may wish to have unusual colours or forms, collect a variety of different mutations, or attempt to breed new mutations. However, this might not have a direct influence on abundance, as the more a species is captive bred, the higher the chance of a colour mutation arising (Chan et al. 2021). The most abundant native and alien species, zebra finches (*Taeniopygia guttata*) and domestic canaries (*Serinus canaria*) respectively, have some of the most diverse colour mutations available, and are highly desired for use in birdkeeping competitions.

Interestingly, body mass was not identified as a significant correlate for either order, which has previously been identified as a major driver of species abundance in international bird trade (Romero-Vidal et al.
While being potentially more attractive, this may counteracted by their higher ongoing costs to keep. Annual fecundity did not correlate with species abundance for parrots, and very weakly for songbirds, indicating that the abundance in trade is not necessarily influenced by reproductive output (i.e., supply), but by consumer demand for certain species and its species characteristics.

Despite the high relative importance of median price on species abundance, it was not an appropriate proxy for abundance in Australian online trade. The correlation is far too weak and varied to make assumptions on the abundance of a single species. We recommend that the median price on its own is not used as a proxy for Australian online trade; however, the combination of other covariates, such as the influential species characteristics identified here, can be used to predict abundances.

While we quantified biological and economic correlates driving the abundances of traded bird species, it is important that this information is combined with consumer behaviour research on the reasons why people purchase pet birds. Biological species characteristics do not affect trade on their own, and where additional factors such as cultural preference or legislation may change the abundance of a species in trade. For example, wildlife trade is heavily influenced by regulation, which we did not consider in our analyses. While domestic bird trade in Australia is relatively unregulated, some jurisdictions require the pet owner to have a permit to keep or wild harvest a species, and others do not (Woolnough et al. 2020). This is likely to greatly influence the abundance of a species in trade, for both native and alien species, as species which require a permit would be available to a smaller market (Toomes et al. 2022). We found evidence of two illegally wild-caught individuals (Australian ringneck: *Barnardius zonarius*; and pink cockatoo: *Lophochroa leadbeateri*), which may be an indication of laws sufficiently protecting wild populations, or sellers purposefully concealing their origins. More detail on the trade or cultural factors which make a bird more likely to be purchased and kept as a pet, such as using surveys or choice experiments, would assist in further explaining trends in the bird pet trade (Krishna et al. 2019; Marshall et al. 2020). These, in combination with our findings, may assist in identifying key species requiring greater regulation to manage biosecurity and conservation priorities.

In conclusion, characteristics that correlate with a species’ abundance varied between songbirds and parrots, differed from international markets, and were synonymous with characteristics which predict successful invasive species. With actual abundance counts of species, and an understanding of drivers behind the online trade, this information will continue to assist policy makers and birdkeeping societies in identifying invasion risks of alien species and further aid in biosecurity efforts.

**Declarations**

**Funding**

This project was partly funded by the Centre for Invasive Species Solutions Project ‘Understanding and intervening in illegal trade in non-native species’ (P01-I-002) and University of Adelaide Postgraduate
Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

The project was conceptualised by KGWH, OSC and PC, and supervised by OSC, JJT and PC. Data collection methodology was developed by OSC, and data curation by KGWH, OSC, SM and AT. Data analysis methodology was developed by SD, and performed by KGWH, SD and OSC. The first draft of the manuscript was written by KGWH and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Acknowledgements

The authors acknowledge the Kaurna people of the Adelaide Plains, the Indigenous Traditional Owners of the land on which this research was conducted. This project was partly funded by the Centre for Invasive Species Solutions Project ‘Understanding and intervening in illegal trade in non-native species’ (P01-I-002) and University of Adelaide Postgraduate Research Awards to KGWH and AT.

References


32. Shepherd C, Stengel C, Nijman V (2012) The export and re-export of CITES-listed birds from the Solomon Islands


Figures
Abundances of species in Australian online tree, and their phylogenetic relationships using a consensus tree of 1000 trees from BirdTree. Bar height indicates the total abundance and are coloured by their risk of establishing wild populations according to the Australian List of Threat Categories of Non-indigenous Vertebrates (Australian Intergovernmental Environment & Invasives Committee 2018). The top three most abundant alien and native species are shown for both parrots and songbirds. Clockwise from top: Java sparrow (Lonchura oryzivora), Gouldian finch (Erythrura gouldiae), canary (Serinus canaria), European
goldfinch (*Carduelis carduelis*), rainbow lorikeet (*Trichoglossus haematodus*), budgerigar (*Melopsittacus undulatus*), rosy-faced lovebird (*Agapornis roseicollis*), rose-winged parakeet (*Psittacula krameri*), green-cheeked parakeet (*Pyrrhura molinae*), cockatiel (*Nymphicus hollandicus*), zebra finch (*Taeniopygia guttata*), and painted finch (*Emblema pictum*). Illustrations were produced with permission of Lynx Edicions.

**Figure 2**

Slopes and 95% confidence intervals for the correlations of species characteristics with species abundance in online trade for parrots (squares) and songbirds (circles). Characteristics are coloured by their relative importance (RI; 0 = light grey, 1 = black). The closer to 1, the more influential the characteristic on abundance.

**Supplementary Files**

This is a list of supplementary files associated with this preprint. Click to download.

- SI1Listofspeciestradedonline.pdf
- SI2Preparingonlinetradedata.pdf
• SI3Omittedcharacteristics.pdf
• SI4Crossvalidationmethodsandresults.pdf
• SI5Priceasabundanceproxy.pdf