Check for updates

Received: 27 August 2021 | Accepted: 3 February 2022

DOI: 10.1111/1365-2664.14138

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

# Drivers of the Australian native pet trade: The role of species traits, socioeconomic attributes and regulatory systems

Adam Toomes[1] | Pablo García-Díaz[2] | Oliver C. Stringham[1] | Joshua V. Ross[3] | Lewis Mitchell[3] | Phillip Cassey[1]

[1]Invasion Science and Wildlife Ecology Group, The University of Adelaide, Adelaide, SA, Australia

[2]School of Biological Sciences, University of Aberdeen, Aberdeen, UK

[3]School of Mathematical Sciences, The University of Adelaide, North Terrace, Adelaide, SA, Australia

**Correspondence**
Adam Toomes
Email: adam.toomes@adelaide.edu.au

**Funding information**
Australian Research Council Discovery Grant, Grant/Award Number: DP210103050; Centre for Invasive Species Solutions, Grant/Award Number: Project P01-I-002; Newton LATAM Funding Programme, Grant/Award Number: NERC grant NE/S011641/1; Open access publishing facilitated by The University of Adelaide, as part of the Wiley - The University of Adelaide agreement via the Council of Australian University Librarians

**Handling Editor:** Margaret Stanley

## Abstract

1. The pet trade is a major driver of both biodiversity loss and the introduction of invasive alien species. Building a comprehensive understanding of the pet trade would improve prediction of conservation and biosecurity threats, with the aim to prevent further negative impacts.
2. We used South Australia's native wildlife permit reporting system as a data-rich example of a vertebrate pet market, spanning 590 distinct taxa across 105 families of terrestrial vertebrates (mammals, reptiles, birds and amphibians). Using a piecewise structural equation modelling (SEM) approach, we tested the influence of 11 a priori variables relating to pets (e.g. species traits), pet owners (e.g. socioeconomic metrics) and regulatory systems (e.g. permit requirements) on the quantities of captive pet keeping, breeding, trading and escapes into the wild.
3. Birds and reptiles with higher annual fecundity were more likely to be kept in captivity and birds with larger adult mass were more likely to be sold. Species with more stringent permit requirements were possessed and escaped, in lower abundances. Pet keeping was weakly correlated with regions of lower human population densities and higher unemployment rates, yet all socioeconomic variables were ultimately poor at explaining trade dynamics.
4. More escapes occurred in regions that possessed larger quantities of pets, further emphasising the role of propagule pressure in the risk of pet escapes.
5. *Synthesis and applications*. Species traits are a strong determinant of native pet trade dynamics, yet permit systems also play a key role in de-incentivising undesirable trade practices. While our research highlighted the positive potential of trade regulatory systems, we recommend that consistent permit category criteria are established to reduce trade in threatened species as well as invasive alien species of high biosecurity risk. Implementation of such systems is broadly needed across a greater diversity of wildlife markets and jurisdictions.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2022 The Authors. *Journal of Applied Ecology* published by John Wiley & Sons Ltd on behalf of British Ecological Society.

**KEYWORDS**
biosecurity, exotic pets, invasive alien species, pet trade, threatened species, trade dynamics, wildlife trade

## 1 | INTRODUCTION

The trade of non-domesticated pets is a major source of threats to global biodiversity conservation and environmental biosecurity (Gippet & Bertelsmeier, 2021; Ribeiro et al., 2019). While pet keeping can improve human mental and physical well-being (Pasmans et al., 2017; Peng & Broom, 2021), and pets can be traded as commodities that support businesses (Andersson et al., 2021), market demand for pets can also drive the unsustainable harvest of wild populations, which is of particular concern for threatened species (Altherr & Lameter, 2020; Marshall et al., 2020). International transport and the subsequent release or escape of pets also lead to higher rates of alien species introductions and their subsequent establishment (Lockwood et al., 2019). There is clear incentive to predict and mitigate negative trade-based impacts, which should first be underpinned by a thorough understanding of pet trade patterns and drivers.

The dynamic nature of pet demand is leading to an ever-increasing number of species being exploited, including species with no prior history of trade (Altherr & Lameter, 2020; Marshall et al., 2020). However, to effectively anticipate negative impacts before they occur, an understanding of the drivers of trade and the motivations for keeping and trading wildlife is needed (Mohanty & Measey, 2019). Current examples of such an approach include modelling trade as a function of species traits (Stringham & Lockwood, 2018; Tedds et al., 2020), profiling pet owners (Alves et al., 2019), characterising owner desire for specific pets (Measey et al., 2019; Siriwat et al., 2019; Toomes et al., 2020) and analysing pet ownership from a sociological perspective (Hergovich et al., 2011). While providing valuable insight into pet ownership behaviour and species' desirability, existing research has seldom considered the effects of regulatory systems, pet attributes and owner socioeconomic metrics on trade dynamics using a common data source, nor have multiple aspects of trade (e.g. pet keeping, breeding and trading) been investigated concurrently.

Here, we seek to identify relationships between non-domesticated species involved in the pet trade, the extent to which their trade is regulated, and the attributes of both the animal (at the species level) and the trade participant (i.e. owner/breeder/sellers). To date, investigation of these relationships has been hindered by a lack of unbiased data (i.e. biased by taxonomy or detection) related to trade dynamics, owner attributes and species traits in a combined context. For example, documentation of legal trade may be incomplete or contaminated by deliberate mislabelling (Janssen & Leupen, 2019), and few legal markets have any formal documentation process to track trade dynamics (Marshall et al., 2020). Fortunately, examples of legal trade, where detailed regulatory systems are implemented and thorough permit information is documented, provide a valuable context in which to study these dynamics (e.g. Elwin et al., 2020). We define pets herein as animals traded or possessed for reasons of companionship or ornament, and exclude animals used in cultural ceremonies, as gifts or status symbols, or used in recreational hunting (Phelps et al., 2016).

We analysed the relationships between non-domesticated pets, pet owners and trade dynamics (i.e. pet keeping, breeding, selling and escapes) using South Australia's domestic vertebrate permit system as a data-rich example of high-diversity trade at the resolution of individual trade participants. Critically, we provide a unique set of analyses of the drivers of pet trade across multiple stages (from trade to escape), levels of regulation, diversity of taxa (105 families, 590 species/subspecies of terrestrial vertebrates) and Australian socioeconomic metrics. Moreover, we used direct measures of pet keeping and trading quantities, rather than proxies such as market price or presence/absence records, which may not accurately reflect rate of trade for all taxa (e.g. Vall-llosera & Su, 2019). Using a structural equation modelling (SEM) framework, we identified a network of interrelationships and predict the effects of pet attributes and owner demographics on trade dynamics.

## 2 | MATERIALS AND METHODS

### 2.1 | Study context

In the Australian State of South Australia, the Department for Environment and Water (DEW) categorises all native terrestrial vertebrates (i.e. amphibians, birds, mammals and reptiles) into four tiered levels of increasing protection for wildlife keeping and trade: (i) Unprotected, (ii) Exempt, (iii) Basic and (iv) Specialist. The possession of wildlife in the Basic and Specialist categories requires respective permits, and reflects differences in animal husbandry and keeping requirements, as well as a species' IUCN threat status (Department for Environment and Water, 2018). Unique permits are required for different taxa, which are categorised at either the species or subspecies level by DEW. Specialist taxa are considered fully protected, as the possession, breeding or trade of any number of individuals of said taxa is permit-regulated, whereas Basic species are only partially regulated (e.g. one individual may be possessed without a permit). Highly popular pets that require little keeping experience, such as cockatiels (*Nymphicus hollandicus*), are in the Unprotected and Exempt permit categories and therefore do not require a permit to trade. There is a low proportion of Exempt and Unprotected taxa in our dataset (6.44% and 1.19%, respectively; see Appendix S1.1 for full descriptions of permit categories). Alien taxa (including highly popular domesticated animals such as cats, dogs, rabbits and non-native rodents), which are not regulated under a common licencing framework in Australia, are not included.

We obtained all DEW Basic and Specialist permits from January 1, 2015 to June 30, 2017 ($n$ = 37,461 unique records pertaining to live animals). For each unique permit, the dataset included: (a) the species/subspecies held; (b) South Australian suburb of captivity; (c) total number of individuals possessed; as well as the total reported (d) births; (e) deaths; (f) escapes and (g) sales per taxa over the entire monitored period. The permit data were de-identified to ensure no further personally identifiable information was accessed. We summarised variables of interest (total possession, sales, births and escapes) across each unique permit-holder suburb and across each taxon prior to analysis of socioeconomic attributes and species traits, respectively. In total, there were 590 native taxa (573 species and 17 subspecies; hereafter referred to as 'species') held across 592 suburbs (out of 1891) in South Australia. We excluded permits from eight suburbs known to contain zoos or wildlife parks, prior to all analysis, because there is no distinction in the DEW permit data between zoo or wildlife park permits and private keeping permits. Our research did not work directly with animals; therefore, the research did not require ethics approval.

## 2.2 | Explanatory variables

We selected a set of species attributes and socioeconomic variables to test for relationships with possession, breeding, trade and escapes of captive wildlife (hereafter referred to as trade dynamics). We selected the following species attributes based on availability of data, existing peer-reviewed evidence of relationships with trade dynamics and our own hypothesised relationships (Table 1): adult mass, threatened status, annual fecundity, endemic status and extent of occurrence (see Appendix S1.4 for trait data sources and Appendix S1.5A for specified relationships). We also collated data for maximum longevity and age at sexual maturity, but omitted them from our analysis, as data were missing for over 50% of species. We recorded whether a species is subject to full trade regulation (i.e. whether permits are required for possession, breeding and trade of any number of individual animals; 'Regulatory status' hereafter). We standardised scientific names according to the Catalogue of Life annual checklist (Roskov et al., 2019) and recorded the International Union for the Conservation of Nature (IUCN) conservation status of each species, using a precautionary approach where a species' IUCN status was superseded by the highest State-wise threat rating of any State in Australia (Atlas of Living Australia, 2019). We used Global Biodiversity Information Facility occurrence data to verify whether species are endemic to Australia, disregarding populations outside of Australia if they are introduced (GBIF, 2019).

We aggregated permit suburbs at the Australian Statistical Area 2 (SA2) level, and gathered the following SA2-resolution metrics from the Australian Bureau of Statistics (2019): population density, median household income, mean number of household inhabitants, median age, unemployment rate, education rate, proportion of Australian citizens and proportion of households with dependents (see Appendix S1.5B for specified relationships). We used socioeconomic variable annual means from 2011 to 2017, which was most concurrent with the permit data. When a single suburb spanned multiple SA2 regions, we used the mean values of all socioeconomic variables (Table 2) in those regions.

## 2.3 | Structural equation modelling

To investigate the complex network of relationships between and among trade dynamics, species attributes, socioeconomic variables and trade regulation, we used a structural equation modelling (SEM) approach. SEMs unite multiple statistical models, typically linear regressions or 'paths', to model multivariate direct and indirect relationships

**TABLE 1** Species trait variables (i.e. model covariates) and corresponding units. See Appendix S1.4 for further details

| Variable | Units | Description | Sample size |
|---|---|---|---|
| Adult mass | g | Mean adult body mass | 516 |
| Threatened status | Binary category (Threatened/ non-threatened) | State-wise Conservation Status condensed into a binary outcome: 'Threatened' is defined as IUCN Endangered, Critically Endangered or Vulnerable. 'Not threatened' is defined as Near Threatened, Least Concerned or Data Deficient. If species had a State-specific conservation status that differed from their IUCN status, the most severe (i.e. threatened) status was used | 590 |
| Annual fecundity | Offspring per year | The mean clutch size multiplied by annual clutch frequency | 249 |
| Endemic status | Binary category (Endemic/ non-endemic) | Whether a native species is endemic or non-endemic to Australia based on the Global Biodiversity Information Facility | 590 |
| Extent of occurrence | $km^2$ | Extent of occurrence, calculated from BirdLife International and IUCN spatial distribution data, using the 'EOO.computing' function in the *ConR* package (Dauby et al., 2017) with R software version 3.4.4 (R Core Development Team, 2019) | 513 |
| Regulatory status | Binary category (Specialist/ non-specialist) | Whether a species has 'Specialist' South Australian permit status | 590 |

TABLE 2 Socioeconomic variables (available for 163 suburbs) and corresponding units. See. Australian Bureau of Statistics (2019) for further details

| Variable | Units | Description |
|---|---|---|
| SA2 size | $km^2$ | Area of statistical area 2 |
| Median household income | AUD | Median equivalised total household weekly income |
| Mean number of household inhabitants | Count | Mean number of household inhabitants |
| Median age | Year | Median age of residents of a working age (15–64 years) |
| Population density | People per $km^2$ | Population density |
| Unemployment rate | Proportion | Proportion of unemployed residents of a working age (15–64 years) |
| Education rate | Proportion | Proportion of residents over 15 years of age with year 12 qualification or equivalent |
| Proportion of households with dependents (under 15) | Proportion | Couples and single-parent families with children under 15 years of age |
| Proportion of Australian citizens | Proportion | Proportion of Australian citizens |

by partitioning variable correlation between exogenous (explanatory) and endogenous (response) variables (Grace, 2006). Since some of our variable relationships were non-Gaussian distributed. (e.g. Poisson, binomial), we adopted the piecewise SEM approach developed by Lefcheck (2016). This approach constructs SEM path diagrams (i.e. networks of variable relationships) based on multiple local estimations of Generalised Linear Model coefficients and can incorporate both models with non-Gaussian distributed relationships and spatial lag models (see Appendix S1.2 for full details of SEM model choice).

We generated initial path diagrams in a threefold repeatable process, which we based on existing Piecewise SEM literature: (a) collate a priori known univariate relationships; (b) validate relationships with model selection and (c) construct initial multivariate path diagram from selected models (see Appendix S1.3 for further details). To test whether missing paths should be included or current paths should be omitted (i.e. to select a final path diagram), we used directional tests of separation (d-Sep) to add or remove paths based on the probability of two variables being independent, conditional on the existing causal relationships specified (Lefcheck, 2016; Shipley, 2013). This process is outlined fully in Appendix S1.6.

We generated separate SEMs to model species attributes (including whether a species was fully regulated) and socioeconomic variable relationships, with the quantity of possession, breeding, sales and escapes included as response variables in all SEMs. While this approach implies that attributes of pets and pet-keepers influence trade dynamics independently, which may not be fully representative of the system, preliminary analysis indicated this approach was necessary to avoid overfitting and over-parameterising the SEM, thus losing information due to lack of model convergence. Specifically, separate species attribute SEMs were generated for birds (297 species, 65 families and 18,707 permits; Bird SEM hereafter) and reptiles (224 species, 16 families and 15,063 permits; Reptile SEM hereafter) to determine whether different variable relationships exist among these taxa. Due to the relative paucity of mammalian (60 species, 21 families and 3,664 permits) and amphibian (nine species, three families and 27 permits) permit data, we did not generate SEMs specific to these taxa. The relationships between socioeconomic variables and trade dynamics were modelled in a single SEM using permit data for all taxa (590 species, 105 families and 37,461 permits; Socioeconomic SEM hereafter). We did not partition socioeconomic data by taxonomic class because the resulting sample sizes and zero inflation are unlikely to be adequate for suitable model fit. Thus, in total, we constructed three separate SEMs: (a) species attributes for reptiles, (b) species attributes for bird and (c) socioeconomic variables for all four vertebrate classes.

All data analyses were conducted in the R software version 3.4.4 (R Core Development Team, 2019) and we used the PiecewiseSEM package to generate and evaluate SEMs (Lefcheck, 2016). Our choice of statistical distribution and model type for each SEM path is outlined in Appendix S1.2. All explanatory variables were investigated for collinearity prior to their final inclusion in the initial SEM path diagram using a variance inflation factor test in the car package (Fox & Weisberg, 2018). If collinearity was detected, variables with the least explanatory power were excluded from the SEM (as determined by AIC comparison; Shipley, 2013). Model fit was reported using trigamma pseudo-$R^2$ for the Bird and Reptile SEMs, and Nagelkerke's pseudo-$R^2$ for the Socioeconomic SEM. Relative variable importance (RVI) scores were calculated for each explanatory variable to evaluate the relative strength of each variable relationship with a given response (summing to one for each response) (Lindeman & Merenda, 1980).

## 3 | RESULTS

We recorded 150,242 individual native animals across the 590 distinct taxa being kept under permits in South Australia, during our 2.5-year study period. The majority of species ($n$ = 400) had an IUCN status of Least Concern, including five species of amphibian (55.6%), 201 species of bird (67.7%), 14 species of mammal (23.3%) and 180 species of reptile (80.4%). A high proportion of mammal (43.3%) and bird (12.5%) taxa were classified as Endangered by the IUCN, and a total of 116 taxa classified as threatened by the IUCN were kept as pets ($n$ = 41,672 animals). All other taxa were Near Threatened ($n$ = 73) or Data Deficient ($n$ = 2). Most taxa (62.4%) were held under a Specialist licence, yet Basic licences accounted for a higher number of individual pets (74.5% of all animals; see Appendix S2 for full descriptive statistics). A lower proportion of mammal (58.3%) and reptile (59.8%) taxa were listed under Specialist permits compared to bird (64.3%) and amphibian (88.8%) taxa. Pets were kept in higher quantities in urban and peri-urban regions, namely eastern parts of Greater Adelaide (Figure 1). In total, there were 722 birds, 202 reptiles, 202 mammals and no amphibian escapes.

Our SEM analyses yielded convergent final path diagrams for Reptile (Fisher's $C = 40.6$, $p$-value = 0.202), Bird (Fisher's $C = 58.5$, $p = 0.102$) and Socioeconomic (Fisher's $C$ =55.042, $p = 0.573$) SEMs (see Appendices S1.6, S3.1 and S3.2 for further details of initial SEM path diagrams and d-Sep analysis).

Pet reptiles were possessed in greater quantities ($R^2$ = 0.42; Figure 2) if they have higher annual fecundity (RVI = 0.469); are larger bodied (RVI = 0.275) and not fully regulated (RVI = 0.180; Figure 3a; see Appendix S4 for all path coefficients, significance values and RVI scores).

Reptiles that are kept in larger quantities have higher annual fecundity (RVI = 0.732), are not fully regulated (RVI = 0.171) and were sold in larger quantities (possession and sales covaried; $R^2$ = 0.24). Reptiles were bred in higher quantities ($R^2$ = 0.12) if they have higher fecundity (RVI = 0.893). Escapes ($R^2$ = 0.29) occurred in greater quantities for reptile species that were possessed in higher numbers (i.e. possession quantity and escapes covaried), have high annual fecundity (RVI = 0.517), are not fully regulated (RVI = 0.364) and have higher adult mass (RVI = 0.110).

Pet birds were possessed in greater quantities ($R^2$ = 0.30; Figure 3b) if they are not fully regulated (RVI = 0.801) and have higher annual fecundity (RVI = 0.199). Birds with larger adult mass (RVI = 0.474) and higher annual fecundity (RVI = 0.440) were sold in greater quantities ($R^2$ = 0.68). More birds were bred ($R^2$ = 0.11) if they are not fully regulated (RVI = 100). Escapes ($R^2$ = 0.21) occurred more for species that were kept in higher quantities (i.e. possession quantity and escapes covaried), are not fully regulated (RVI = 0.891) and have higher annual fecundity (RVI = 0.109).

Overall, socioeconomic attributes did not strongly determine trade dynamics. Regions were possessed more pets ($R^2$ = 0.560) if they bred pets in greater quantities (RVI = 0.776), had higher unemployment rates (RVI = 0.0937) and lower population densities (RVI = 0.0810). Breeding quantity ($R^2$ = 0.0393) was poorly explained by socioeconomic metrics. Regions with higher quantities of pet breeding (RVI = 0.899) sold pets in greater quantities ($R^2$ = 0.705). Escapes ($R^2$ = 0.376) occurred more for regions that kept a greater quantity of pets (RVI = 0.952).

## 4 | DISCUSSION

Here we demonstrate the role of a trade regulatory system as a key determinant of trade dynamics, alongside species attributes and (to a lesser degree) socioeconomic metrics. Specifically, whether a species was fully regulated (reflective of greater husbandry demands, and with higher associated costs/difficulty of acquiring a permit) had a significant impact on the quantity of pet keeping, breeding, trading and escapes, even after accounting for all other species-level attributes. Although this process explains only a proportion of the overall variation in pet keeping, our result indicates that South Australia's wildlife permit system is, in part, influencing trade dynamics, and may provide a valuable regulatory tool to shift trade away from undesirable or otherwise detrimental aspects of the trade. For example, while we reported 1,126 escapes in total, our findings also indicate that escapes would have been higher in the absence of regulation (Figure 3).

Our results supported our prediction that bird and reptile trade dynamics would have idiosyncratic relationships with species attributes. The most prominent difference we detected was the lack of direct significant effects of species attributes on bird keeping and trading, such as the effect of adult mass that was present for reptiles. Additionally, endemic reptiles were sold in greater quantities, yet endemism had no impact on the trade of birds (see Appendix S4). It is possible that bird trade dynamics are driven by more specific attributes for which data were not available on a sufficiently broad scale for our analysis. Examples include bird temperament (i.e. aggressiveness) or attractiveness (Vall-llosera & Cassey, 2017). Our results did support species-attribute relationships reported in previous reports of pet trade dynamics. The significant positive effect of adult mass on reptile escapes and the positive (though non-significant) effect of annual fecundity on reptile and bird escapes are concurrent with trends in the U.S. vertebrate trade (Stringham & Lockwood, 2018) and the South African alien reptile trade (Van Wilgen et al., 2010). The prevalence of the aforementioned relationships across multiple countries with different strategies for managing trade (e.g. complete prohibition of alien reptiles in Australia contrasted with South African prohibition of native reptiles) suggests that they may represent ubiquitous drivers of trade dynamics.

Other known attribute–dynamic relationships only partially support, or even contrast with, our findings. For example, birds traded in Taiwan tend to be smaller in size (Su et al., 2014), and a study of both native and alien cagebird trade in Australia found that larger birds had higher market value, which is negatively correlated with abundance (Vall-llosera & Cassey, 2017). These discrepancies may be due to differing dynamics between markets with different use types (e.g. companion versus ceremonial animals), as well as between native and alien pet markets. It is also noteworthy that Vall-llosera and Cassey (2017) used proxies for trade quantity (i.e. price), whereas we analysed trade abundance directly.

We found no direct relationship between household income and trade dynamics. While our results are correlative and do not necessarily represent causal relationships, the lack of an income–trade relationship suggests that associated costs are not a limiting factor for the acquisition of pets in Australia. There are many known benefits of pet ownership (e.g. Smith, 2012) that are likely evaluated alongside the economic costs by prospective pet keepers. We also found that population density and unemployment rate had very low

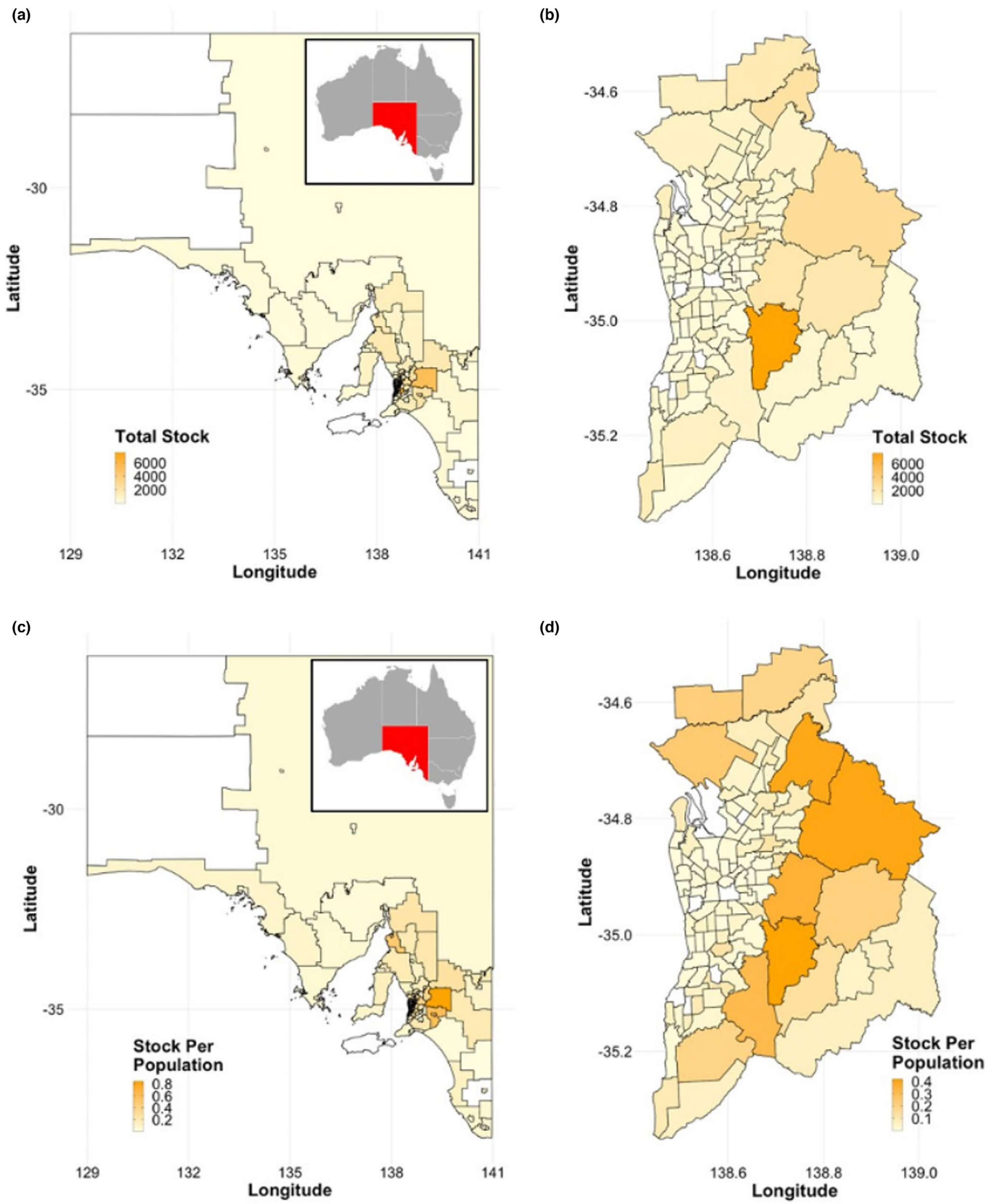


**FIGURE 1** Total number of pet permits (a, b) and number of pet permits per person (c, d) for each SA2 in South Australia (a, c) and greater Adelaide (b, d)

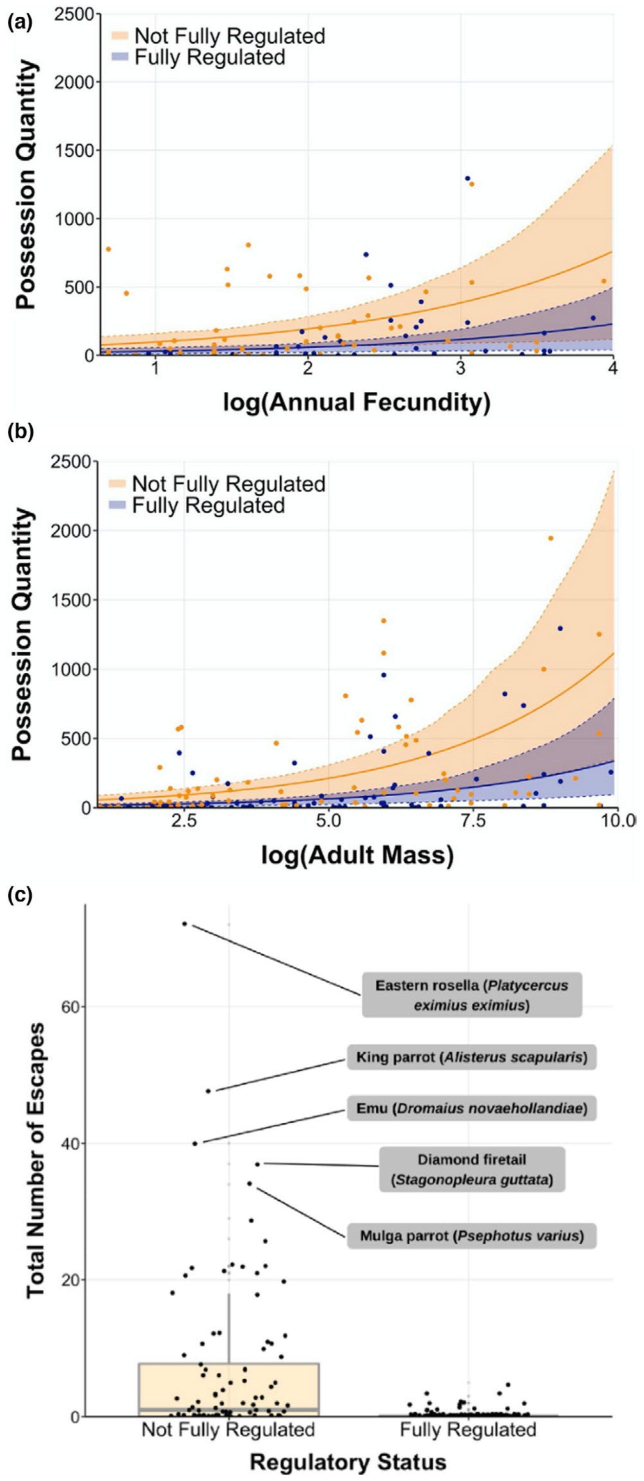


**FIGURE 2** Model predictions for native reptile possession quantity against (a) adult mass and (b) annual fecundity (see Appendix S1.1 for details of model choice). Shaded areas represent 95% confidence intervals derived from parametric bootstrapping and points represent raw data. Raw data points with possession quantity above 2000 are not displayed ($N = 3$; *Intellagama lesuerii*, *Morelia spilota*, *pogona vitticeps*). (c) Raw number of escaped birds for fully regulated (i.e. specialist) and not fully regulated (i.e. non-specialist) birds. Species with more than 30 total escapes are labelled. While emus are known to be bred for commercial purposes in Australia, 91.9% of permit holders in our dataset possessed 10 or fewer individuals

explanatory power and are therefore likely to have less influence on trade dynamics compared to species traits and trade regulation. By contrast, pet keepers in other pet markets are known to either have higher disposable incomes compared with people who do not keep pets (Alves et al., 2019), or associate pet ownership with wealthy status (Reuter et al., 2018). Norconk et al. (2020) and Bennett et al. (2021) suggest that wealth inequality (i.e. relative wealth), rather than absolute wealth, is a driver for both the harvesting and consumption of wildlife, including live pets.

Australia's comparably low rates of income inequality and high absolute wealth per capita (Ortiz & Cummins, 2011) may partially explain the lack of any universal trade–income relationship across nations with idiosyncratic cultural and socioeconomic backgrounds.

While our findings contribute to a correlative understanding of pet trade dynamics, they also have key biosecurity implications. For both reptile and birds, more animals escaped when possessed in higher quantities (also observed in zoos, see Cassey & Hogg, 2015). Therefore, it appears that pet popularity (i.e. possession) is partly proportional to propagule pressure, a major determinant of alien population establishment (Cassey et al., 2018). Moreover, we found that escaped pets had higher annual fecundity, which is a trait associated with successful establishment of new populations (Allen et al., 2017; Howeth et al., 2016). It is possible that high pet fecundity itself contributes to the probability of release from captivity, especially considering the increased space and financial requirements of resultant offspring (Lockwood et al., 2019). DEW have a process of inquiry when unusually high instances of deaths/escapes are reported by permit holders during annual data collection. It is therefore possible that escapes were underreported by permit holders if they perceive that escapes might negatively influence their eligibility to retain permits.

While our analysis pertains to species native to Australia, many Australian species are nonetheless held in domestic captivity outside of their native range and therefore still pose biosecurity risks via the potential establishment of the so-called 'domestic alien' species (e.g. Australian King parrots [*Alisterus scapularis*] are not native to South Australia yet escape in large abundances; Figure 2c). Not only is there a risk that new populations will establish to the detriment of native ecosystems (Lockwood et al., 2019), but released pets, regardless of whether they are outside their native range or whether they successfully establish, pose a biosecurity risk through the potential transmission of pet-borne pathogens and parasites (e.g. Norval et al. 2020). Additional risks include the release on non-native subspecies or captive breeding morphs that may hybridise with native populations (e.g. Fox & Hogan, 2020).

The desire for alien pets in Australia is substantially biased towards threatened species (Toomes et al. 2020), and increased trade demand for threatened species is a known component of international wildlife trade (Courchamp et al., 2006; Holden & McDonald-Madden, 2017). Yet, we found no such preference towards threatened species in the keeping of native species in South

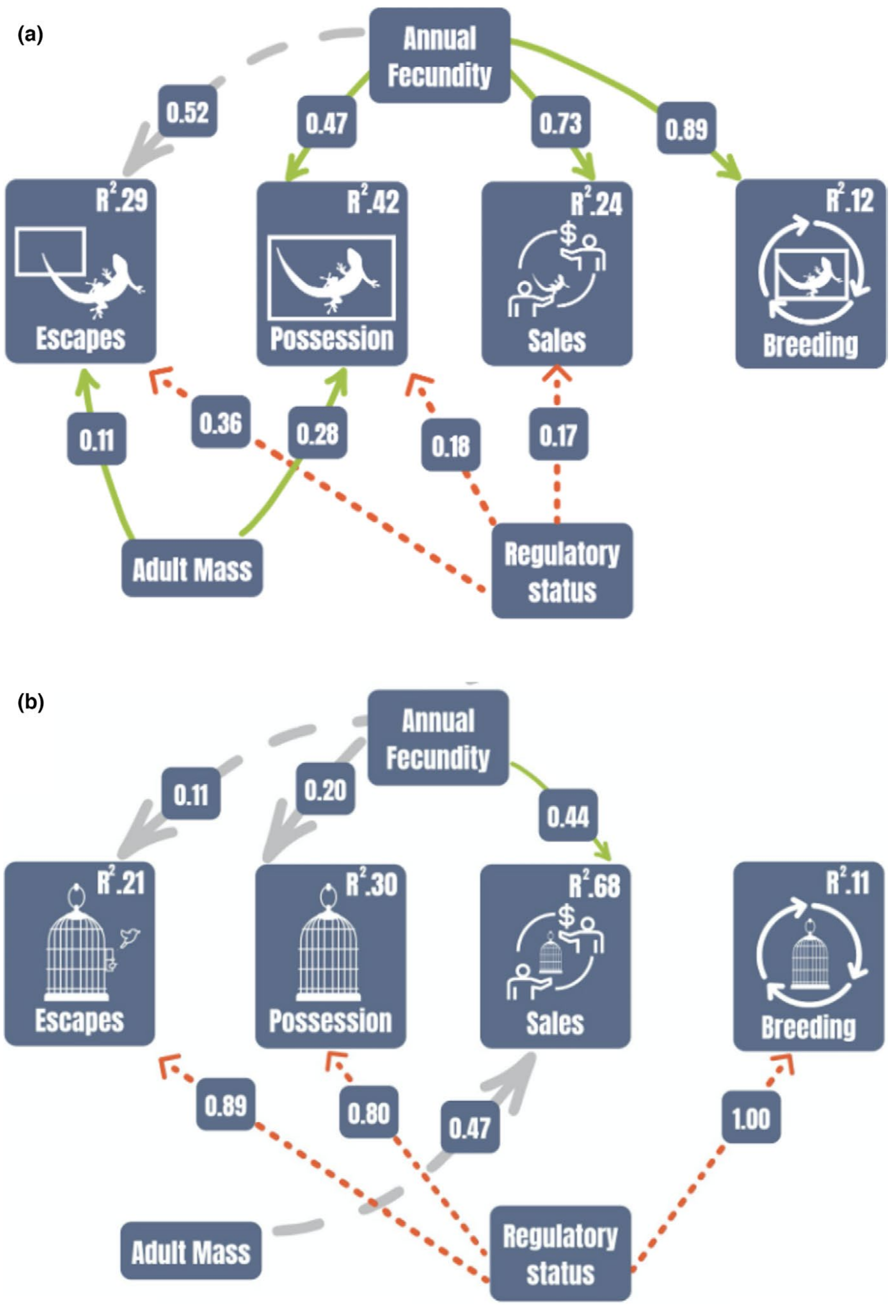


FIGURE 3 Final SEM path of south Australian native (a) reptile and (b) trade dynamics and species attributes. Only direct relationships with trade dynamics (i.e. total number of individuals possessed, bred, sold and escaped) are displayed, with relative variable importance (RVI) >0.1 displayed on corresponding arrows. Covariation paths are omitted. Grey (long dash) paths represent those with non-significant effect sizes ($p > 0.05$). Green (no dash) and orange (short dash) paths represent those with significantly positive and negative effect sizes, respectively

Australia. Furthermore, this finding is even more meaningful considering our data source omitted some of the most common non-threatened pets that would undeniably be kept in high quantities (as well as an undocumented number of instances where pet keepers possess only one individual of a Basic species). This finding implies that the potential conservation threat posed by permit-regulated pet trade, as a driver of unsustainable harvest of wild populations, is minimal. However, it is important to note that our analysis did not quantify the rate of permit non-compliance; rapid changes in trade demand can lead to population declines even for species that were not previously threatened or known to be traded (Marshall et al., 2020; Nijman et al., 2019); and incidents of illegal wild harvest of reptiles have been documented in Australia (e.g. Heinrich et al. (2021)). Our study system may be unique in that desire for threatened species does not appear to directly translate into acquisition, at least through legal means.

## 4.1 | Recommendations and conclusions

We conclude that the use of a permit system with multiple tiers of regulation has, in part, shaped patterns of pet keeping in the South Australian pet trade. Such regulatory systems can be used to effectively manage the trade of species that are (a) threatened by trade activities such as demand-induced harvesting; (b) aggressive, dangerous or otherwise difficult to ethically house in captivity; (c) traded outside their native range; and (d) known to be a biosecurity risk such as potential invasive species or vector for high-risk pathogens.

We recommend that contemporary tiered permit systems, such as those used to regulate the alien bird trade in Victoria, Australia (Woolnough et al., 2020), be used to regulate a greater diversity of native and alien taxa elsewhere. However, different jurisdictions are likely to vary in their willingness to adopt such regulatory systems (e.g. Harris et al., 2019). As such, we recommend that relevant government agencies evaluate both their own enforcement capacity and the anticipated level of compliance from affected hobbyists and businesses, before proceeding with implementation. We recommend exploring the relevance of our findings to broader market contexts such as illegal/unregulated trade, and trade across broader cultures and use-types, given the future availability of suitable data.

There are a number of species, particularly alien cagebirds and ornamental fish, that are not consistently regulated in Australia despite posing clear environmental threats (e.g. DAWE (2021)). Prohibition of the trade of these species is not feasible due to the large number of domestic keepers and breeders already in operation (Vall-llosera et al., 2017). However, implementation of a permit system, with ease of acquisition and trade of pets proportional to the associated risks, may lead to long-term positive shifts in trade participation if sufficient resources are allocated for enforcement. We also recommend the development of consistent criteria across Australian State/Territory jurisdictions, which currently use disjointed regulatory systems, to select which category a species should be allocated based on animal welfare, conservation and biosecurity risks. Such criteria could incorporate information from pre-existing data sources or assessment tools, such as animal husbandry requirements (e.g. Warwick et al., 2018), threatened status, life-history traits, invasion risk (e.g. Environment and Invasives Committee 2019), rate of e-commerce trade (Stringham et al., 2020) and the presence/absence of a species in Australian seizure records (Heinrich et al., 2021; Toomes et al., 2019).

In summary, our findings highlight the roles and relative contributions of regulatory systems, as well as owner and (particularly) species-level attributes to wildlife trade dynamics, many of which follow previously observed patterns. By contributing to a growing understanding of these relationships, our research can help predict the susceptibility of species to high rates of trade or high escape probability based on life-history traits, regulatory control and owner demographics. We hope to encourage a wider implementation of trade regulatory systems by emphasising the key role of fully enforced permits in de-incentivising undesirable trade practices.

## ACKNOWLEDGEMENTS

We acknowledge that the land on which we conducted our research is the traditional land of the Kaurna people of the Adelaide Plains. We pay our respects to Kaurna elders past, present and emerging. We thank the South Australian Department for the Environment and Water for recording and facilitating access to all permit data used in our analysis. This research was funded by the Centre for Invasive Species Solutions (Project P01-I-002). P.C. was supported by an Australian Research Council Discovery grant (DP210103050). PG-D was supported by the NERC grant NE/S011641/1 under the Newton LATAM funding programme. Open access publishing facilitated by The University of Adelaide, as part of the Wiley - The University of Adelaide agreement via the Council of Australian University Librarians.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHORS' CONTRIBUTIONS

A.T. contributed to the project conceptualisation and led the data curation, analysis, manuscript writing and data visualisations. P.G.-D. contributed to the project conceptualisation, data analysis and manuscript editing. O.S. contributed to the data curation, data analysis, manuscript editing and data visualisation editing. J.V.R. contributed to the project conceptualisation and manuscript editing. L.M. contributed to the project conceptualisation and manuscript editing and provided co-supervision to A.T.; and P.C. contributed to the project conceptualisation, manuscript editing and data visualisation editing, and provided lead supervision to A.T. All authors approved this manuscript to be submitted for publication.

## DATA AVAILABILITY STATEMENT

The raw data used in our analysis were collected by the South Australia Department for Environment and Water and contain potentially confidential information. Therefore, these data have not been archived. We have published a summary dataset used in our statistical analysis, which contains the total possessions, breeding, sales and escapes for each species/subspecies, as well as collated species attributes and regulatory status, in Figshare. https://doi.org/10.6084/m9.figshare.16436379.v2 (Toomes et al., 2021).

## ORCID

*Adam Toomes* https://orcid.org/0000-0003-4845-1073
*Pablo García-Díaz* https://orcid.org/0000-0001-5402-0611

## REFERENCES

Allen, W. L., Street, S. E., & Capellini, I. (2017). Fast life history traits promote invasion success in amphibians and reptiles. *Ecology Letters*, *20*, 222–230.

Altherr, S., & Lameter, K. (2020). The rush for the rare: Reptiles and amphibians in the European pet trade. *Animals*, *10*, 2085.

Alves, R. R. N., de Araújo, B. M. C., da Silva Policarpo, I., Pereira, H. M., Borges, A. K. M., da Silva Vieira, W. L., & Vasconcellos, A. (2019). Keeping reptiles as pets in Brazil: Ethnozoological and conservation aspects. *Journal for Nature Conservation*, *49*, 9–21.

Andersson, A. A., Lau, W., Tilley, H. B., Dudgeon, D., Bonebrake, T. C., & Dingle, C. (2021). CITES and beyond: Illuminating 20-years of global, legal wildlife trade. *Global Ecology and Conservation*, *26*, e01455.

Atlas of Living Australia. (2019) Conservation Status. Retrieved from http://www.ala.org.au

Australian Bureau of Statistics. (2019) 'Data by Region.' Retrieved from https://dbr.abs.gov.au.

Bennett, E. L., Underwood, F. M., & Milner-Gulland, E. (2021). To trade or not to trade? Using Bayesian belief networks to assess how to manage commercial wildlife trade in a complex world. *Frontiers in Ecology and Evolution*, *9*, 123.

Cassey, P., Delean, S., Lockwood, J. L., Sadowski, J. S., & Blackburn, T. M. (2018). Dissecting the null model for biological invasions: A meta-analysis of the propagule pressure effect. *PLoS Biology*, *16*, e2005987.

Cassey, P., & Hogg, C. J. (2015). Escaping captivity: The biological invasion risk from vertebrate species in zoos. *Biological Conservation*, *181*, 18–26.

Courchamp, F., Angulo, E., Rivalan, P., Hall, R. J., Signoret, L., Bull, L., & Meinard, Y. (2006). Rarity value and species extinction: The anthropogenic Allee effect. *PLoS Biology*, *4*, e415.

Dauby, G., Stévart, T., Droissart, V., Cosiaux, A., Deblauwe, V., Simo-Droissart, M., Sosef, M. S., Lowry, P. P., Schatz, G. E., & Gereau, R. E. (2017). ConR: An R package to assist large-scale multispecies preliminary conservation assessments using distribution data. *Ecology and Evolution*, *7*, 11292–11303.

DAWE, 2021. 2007 inventory of exotic (non-native) bird species known to be in Australia.

Department for Environment and Water. 2018. Species codes & permit status.

Elwin, A., Green, J., & D'Cruze, N. (2020). On the record: An analysis of exotic pet Licences in the UK. *Animals*, *10*, 2373.

Environment and Invasives Committee (2019). Australian list of threat categories of nonindigenous vertebrates.

Fox, BC, Hogan, S (2020) Hypopigmentation as the cause for the neurological disorder "Spider Wobble" in Python regius.

Fox, J., & Weisberg, S. (2018). *An R companion to applied regression*. Sage Publications.

Gippet, J. M., & Bertelsmeier, C. (2021). Invasiveness is linked to greater commercial success in the global pet trade. *Proceedings of the National Academy of Sciences of the USA*, *118*, e2016337118.

Global Biodiversity Information Facility. (2019) GBIF Home Page. Retrieved from https://www.gbif.org/en/citation-guidelines.

Grace, J. B. (2006). *Structural equation modeling and natural systems*. Cambridge University Press.

Harris, L., Gore, M., & Mills, M. (2019). Compliance with ivory trade regulations in the United Kingdom among traders. *Conservation Biology*, *33*, 906–916.

Heinrich, S., Toomes, A., Shepherd, C., Stringham, O., Swan, M., & Cassey, P. (2021). Strengthening protection of endemic wildlife threatened by the international pet trade: The case of the Australian shingleback lizard. *Animal Conservation*, *35*(4), 1130–1139. https://doi.org/10.1111/acv.12721

Hergovich, A., Mauerer, I., & Riemer, V. (2011). Exotic animal companions and the personality of their owners. *Anthrozoös*, *24*, 317–327.

Holden, M. H., & McDonald-Madden, E. (2017). High prices for rare species can drive large populations extinct: The anthropogenic Allee effect revisited. *Journal of Theoretical Biology*, *429*, 170–180.

Howeth, J. G., Gantz, C. A., Angermeier, P. L., Frimpong, E. A., Hoff, M. H., Keller, R. P., Mandrak, N. E., Marchetti, M. P., Olden, J. D., & Romagosa, C. M. (2016). Predicting invasiveness of species in trade: Climate match, trophic guild and fecundity influence establishment and impact of non-native freshwater fishes. *Diversity and Distributions*, *22*, 148–160.

Janssen, J., & Leupen, B. T. (2019). Traded under the radar: Poor documentation of trade in nationally-protected non-CITES species can cause fraudulent trade to go undetected. *Biodiversity and Conservation*, *28*, 2797–2804.

Lefcheck, J. S. (2016). piecewiseSEM: Piecewise structural equation modelling in r for ecology, evolution, and systematics. *Methods in Ecology and Evolution*, *7*, 573–579.

Lindeman, R. H., & Merenda, P. F. (1980). *Introduction to bivariate and multivariate analysis*. Scott Foresman.

Lockwood, J. L., Welbourne, D. J., Romagosa, C. M., Cassey, P., Mandrak, N. E., Strecker, A., Leung, B., Stringham, O. C., Udell, B., & Episcopio-Sturgeon, D. J. (2019). When pets become pests: The role of the exotic pet trade in producing invasive vertebrate animals. *Frontiers in Ecology and the Environment*, *17*, 323–330.

Marshall, B. M., Strine, C., & Hughes, A. C. (2020). Thousands of reptile species threatened by underregulated global trade. *Nature Communications*, *11*, 1–12.

Measey, J., Basson, A., Rebelo, A. D., Nunes, A. L., Vimercati, G., Louw, M., & Mohanty, N. P. (2019). Why have a pet amphibian? Insights from YouTube. *Frontiers in Ecology and Evolution*, *7*, 52.

Mohanty, N. P., & Measey, J. (2019). The global pet trade in amphibians: Species traits, taxonomic bias, and future directions. *Biodiversity and Conservation*, *28*, 3915–3923.

Nijman, V., Nekaris, K., & Imron, M. A. (2019). Asian songbird crisis also affects unprotected species. *Oryx*, *53*, 13–13.

Norconk, M. A., Atsalis, S., Tully, G., Santillán, A. M., Waters, S., Knott, C. D., Ross, S. R., Shanee, S., & Stiles, D. (2020). Reducing the primate pet trade: Actions for primatologists. *American Journal of Primatology*, *82*, e23079.

Norval, G., Halliday, B., Sih, A., Sharrad, R. D., & Gardner, M. G. (2020). Occurrence of the introduced snake mite, Ophionyssus natricis (Gervais, 1844), in the wild in Australia. *Acarologia*, *60*, 559–565.

Ortiz, I, Cummins, M (2011) Global inequality: Beyond the bottom billion–a rapid review of income distribution in 141 countries. Available at SSRN 1805046

Pasmans, F., Bogaerts, S., Braeckman, J., Cunningham, A. A., Hellebuyck, T., Griffiths, R. A., Sparreboom, M., Schmidt, B., & Martel, A. (2017). Future of keeping pet reptiles and amphibians: Towards integrating animal welfare, human health and environmental sustainability. *Veterinary Record*, *181*, 450.

Peng, S., & Broom, D. M. (2021). The sustainability of keeping birds as pets: Should any be kept? *Animals*, *11*, 582.

Phelps, J., Biggs, D., & Webb, E. L. (2016). Tools and terms for understanding illegal wildlife trade. *Frontiers in Ecology and the Environment*, *14*, 479–489.

R Core Development Team. (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

Reuter, K. E., Clarke, T. A., LaFleur, M., Ratsimbazafy, J., Kjeldgaard, F. H., Rodriguez, L., Schaeffer, T., & Schaefer, M. S. (2018). Exploring the role of wealth and religion on the ownership of captive lemurs in Madagascar using qualitative and quantitative data. *Folia Primatologica*, *89*, 81–96.

Ribeiro, J., Reino, L., Schindler, S., Strubbe, D., Vall-llosera, M., Araújo, M. B., Capinha, C., Carrete, M., Mazzoni, S., & Monteiro, M. (2019). Trends in legal and illegal trade of wild birds: A global assessment based on expert knowledge. *Biodiversity and Conservation*, *28*, 3343–3369.

Roskov, Y, Ower, G, Orrell, T, Nicolson, D, Bailly, N, Kirk, P, Bourgoin, T, DeWalt, R, Decock, W, van Nieukerken, E, Zarucchi, J, Penev, L. (2019). Species 2000 & ITIS catalogue of life, 2019 annual checklist.

Shipley, B. (2013). The AIC model selection method applied to path analytic models compared using ad-separation test. *Ecology*, *94*, 560–564.

Siriwat, P., Nekaris, K., & Nijman, V. (2019). The role of the anthropogenic Allee effect in the exotic pet trade on Facebook in Thailand. *Journal for Nature Conservation*, *51*, 125726.

Smith, B. (2012). The 'pet effect': Health related aspects of companion animal ownership. *Australian Family Physician*, *41*, 439–442.

Stringham, O. C., & Lockwood, J. L. (2018). Pet problems: Biological and economic factors that influence the release of alien reptiles and amphibians by pet owners. *Journal of Applied Ecology*, *55*, 2632–2640.

Stringham, O., Toomes, A., Kanishka, A. M., Mitchell, L., Heinrich, S., Ross, J. V., & Cassey, P. (2020). A guide to using the internet to monitor and quantify the wildlife trade. *Conservation Biology*, *35*, 1130–1139.

Su, S., Cassey, P., & Blackburn, T. M. (2014). Patterns of non-randomness in the composition and characteristics of the Taiwanese bird trade. *Biological Invasions*, *16*, 2563–2575.

Tedds, H, McCormick, W, Sneddon, S, Ollerton, J, Clubb, R (2020) Herps across England: Investigating the scale of reptile and amphibian trade, UFAW: Recent advances in animal welfare science VII

Toomes, A, García-Díaz, P, Stringham, OC, Ross, JV, Mitchell, L, Cassey, P (2021) Data from: Drivers of the Australian native pet trade: The role of species traits, socioeconomic attributes, and regulatory systems. Figshare Dataset. https://doi.org/10.6084/m9.figshare.16436379.v2.

Toomes, A., García-Díaz, P., Wittmann, T. A., Virtue, J., & Cassey, P. (2019). New aliens in Australia: 18 years of vertebrate interceptions. *Wildlife Research*, *47*, 55–67.

Toomes, A., Stringham, O. C., Mitchell, L., Ross, J. V., & Cassey, P. (2020). Australia's wish list of exotic pets: Biosecurity and conservation implications of desired alien and illegal pet species. *NeoBiota*, *60*, 43–59.

Vall-llosera, M., & Cassey, P. (2017). Physical attractiveness, constraints to the trade and handling requirements drive the variation in species availability in the Australian cagebird trade. *Ecological Economics*, *131*, 407–413.

Vall-llosera, M., & Su, S. (2019). Trends and characteristics of imports of live CITES-listed bird species into Japan. *Ibis*, *161*, 590–604.

Vall-llosera, M., Woolnough, A. P., Anderson, D., & Cassey, P. (2017). Improved surveillance for early detection of a potential invasive species: The alien rose-ringed parakeet *Psittacula krameri* in Australia. *Biological Invasions*, *19*, 1273–1284.

Van Wilgen, N., Wilson, J., Elith, J., Wintle, B., & Richardson, D. (2010). Alien invaders and reptile traders: What drives the live animal trade in South Africa? *Animal Conservation*, *13*, 24–32.

Warwick, C., Steedman, C., Jessop, M., Arena, P., Pilny, A., & Nicholas, E. (2018). Exotic pet suitability: Understanding some problems and utilizing a labeling system to aid animal welfare, environment, and consumer protection. *Journal of Veterinary Behavior*, *26*, 1726–1726.

Woolnough, A. P., de Milliano, J. W., Petel, T. P., & Cassey, P. (2020). A policy approach to nonindigenous bird management in Victoria: Managing potential threats to biodiversity, social amenity and economic values. *The Victorian Naturalist*, *137*, 203–209.

## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

**How to cite this article:** Toomes, A., García-Díaz, P., Stringham, O. C., Ross, J. V., Mitchell, L., & Cassey, P. (2022). Drivers of the Australian native pet trade: The role of species traits, socioeconomic attributes and regulatory systems. *Journal of Applied Ecology*, 59, 1268–1278. https://doi.org/10.1111/1365-2664.14138