Drivers of the live pet trade: the role of species traits, socioeconomic attributes and regulatory systems

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Abstract

The live 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. We used South Australia's native wildlife permit reporting system as a data-rich example of a live vertebrate pet market, spanning 590 species 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 bird and reptile captive keeping, breeding, trading, and escapes into the wild. Birds and reptiles with higher annual fecundity, as well as widely distributed reptiles with higher adult mass, were more likely to be kept in captivity and sold. Species with more stringent permit requirements were possessed, and escaped, in lower abundances. Pet keeping was weakly correlated with regions of lower population densities and higher unemployment rates, yet other socioeconomic variables were ultimately poor at explaining trade dynamics. More escapes occurred in regions which possessed larger quantities of pets, further emphasising the role of propagule pressure in the risk of pet escapes.

Synthesis and applications: Species traits are a strong determinant of pet trade dynamics, yet permit systems also play a key role in de-incentivising undesirable trade practices. While our research highlights the potential of trade regulatory systems, we recommend that consistent permit category criteria are established to reduce trade in threatened species, as well as alien species of high biosecurity risk. Implementation of such systems is broadly needed across a greater diversity of wildlife markets and jurisdictions.

Keywords

Biosecurity, exotic pets, pet trade, invasive alien species, threatened species, trade dynamics, wildlife trade

Introduction

The trade of live exotic (i.e., non-domesticated) pets is a major source of global conservation and biosecurity threats (Ribeiro *et al.* 2019; Gippet and Bertelsmeier 2021). While pet keeping can improve human mental and physical wellbeing (Pasmans *et al.* 2017; Peng and 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 and Lameter 2020; Marshall *et al.* 2020). International transport and the subsequent release or escape of pets also leads 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 and Lameter 2020; Marshall *et al.* 2020). We define pets herein as animals traded or housed 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). Contemporary research has aimed to characterise various live pet markets in terms of the rate of trade and diversity of traded taxa (e.g., Herrel and van der Meijden (2014)). However, to effectively anticipate negative impacts before they occur, an understanding of the drivers of trade and the motivations for keeping and trading wildlife are needed (Mohanty and Measey 2019). Current examples of such an approach include modelling trade as a function of species traits (Stringham and Lockwood 2018; Tedds *et al.* 2020), profiling pet owners (Alves *et al.* 2019), characterising owner desire for specific pets (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 species involved in 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 and 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 analysed the relationships between exotic pets, 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 the pet trade across multiple stages (from trade to escape), levels of regulation, diversity of taxa (105 families and 590 species 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 suffer from key reporting biases or not accurately reflect rate of trade for all taxa (e.g., Vall-Llosera and 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.

Materials & Methods

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' threat level (Department for Environment and Water 2018). Specialist species are considered fully protected, as the possession, breeding or trade of any number of individuals of said species is permit-regulated, whereas Basic species are only partially regulated (e.g., one individual may be possessed without a permit). South Australian permit holders are legally required to maintain a record of the species possessed and the total number of individuals acquired or transported, the method of acquisition or transportation (e.g., sale, interstate import), as well as the number of births, deaths, and escapes that occur during possession of wildlife. Highly popular pets that require little keeping experience, such as cockatiels (*Nymphhicus hollandicus*), are in the Unprotected and Exempt permit categories and therefore do not require a permit to trade. We omitted Unprotected and Exempt species from our analysis, as well as alien species, which are not regulated under a common licencing framework in Australia.

We obtained all DEW Basic and Specialist permits from 2015-01-01 to 2017-06-30 (n = 37 461 unique records pertaining to live animals). For each unique permit, the dataset included: (i) the species held; (ii) South Australian suburb of captivity; (iii) total number of individuals possessed; as well as the total reported (iv) births; (v) deaths; (vi) escapes and (vii) sales per species over the entire monitored period. The permit data was 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 species prior to analysis of socioeconomic attributes and species traits respectively. In total there were 590 native 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.

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 S1.2 for trait data sources and Appendix S1.3A for specified relationships). We also collated data for maximum longevity and age at sexual maturity, but omitted them from our analysis, as data was 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 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).

Table 1: Species trait variables (i.e., model covariates) and corresponding units. See Appendix S1.2 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 divided by annual clutch frequency.	249
Endemic status	Binary category (Endemic/non-endemic)	Whether a species is endemic or native 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

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 S1.3B for specified relationships). We used socioeconomic variable annual means from 2011–2017, as this period of time was most concurrent with the permit data. When a single suburb spanned multiple SA2 regions, we used the mean values of all socioeconomic variables in those regions.

Table 2: Socioeconomic variables (n = 163) 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

Structural Equation Modelling

To investigate the complex network of relationships between trade dynamics, species attributes, socioeconomic variables, and trade regulation, we used a Structural Equation Modelling (SEM) approach. 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 non-Gaussian distributed relationships and spatial lag models.

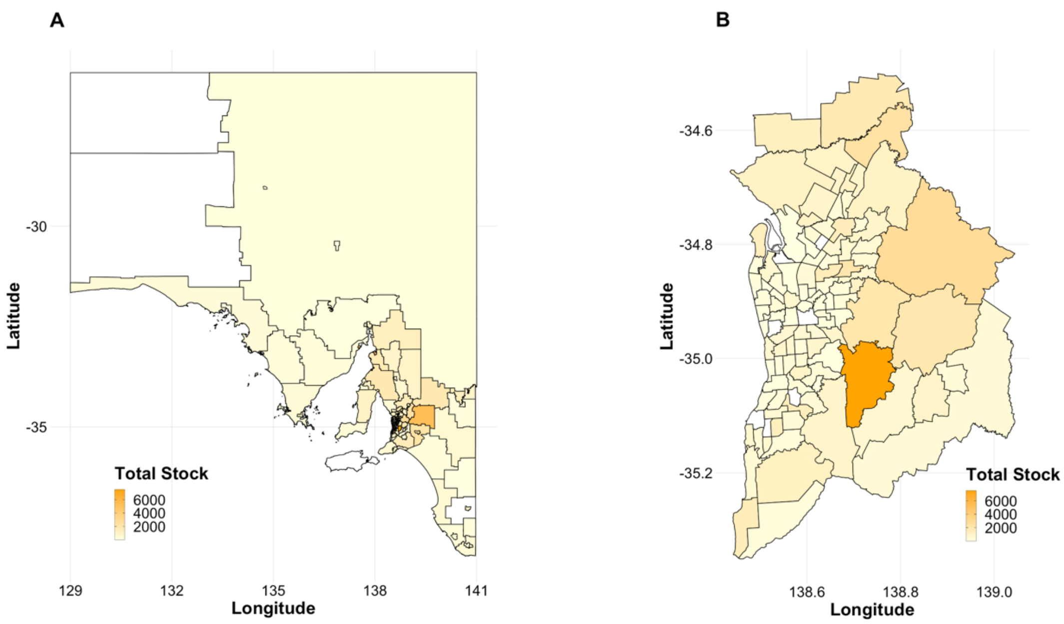
We generated initial path diagrams in a three-fold repeatable process, which we based on existing Piecewise SEM literature (e.g., Redmond *et al.* (2018); and Luo *et al.* (2019)): (1) collate *a priori* known univariate relationships; (2) validate relationships with model selection; and (3) construct initial multivariate path diagram from selected models (see Appendix S1.1 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 (Shipley 2013; Lefcheck 2016). This process is outlined fully in Appendix S1.4.

We generated separate SEMs to model species attribute and socioeconomic variable relationships, with trade dynamics (i.e., total animals possessed, sold, bred, and escaped) 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 overparameterising 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; Reptile SEM hereafter) to determine if different variable relationships exist amongst taxa. Due to the relative paucity of mammalian (60 species, 60 species and 3664 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 species (590 species, 105 families and 37461 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: (i) species attributes for reptiles, (ii) species attributes for bird, (iii) 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 S1.5. 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 and Weisberg 2018). If collinearity was detected, variables with the least explanatory power were excluded from the SEM (as determined by AIC comparison). 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 (summing to one) with a given response (Lindeman *et al.* 1980).

Results

We recorded 150 242 individual native animals across 590 species being kept under permits in South Australia during our 2.5-year study period. The majority of species (n = 400) had an IUCN State-wise 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%) species were Endangered and a total of 116 threatened species were kept as pets (n = 41 672 animals). Most species (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%) species were listed under Specialist permits compared to bird (64.3%) and amphibian (88.8%) species. Pets were kept in higher quantities in urban and peri-urban regions, namely eastern parts of Greater Adelaide (Figure 1).



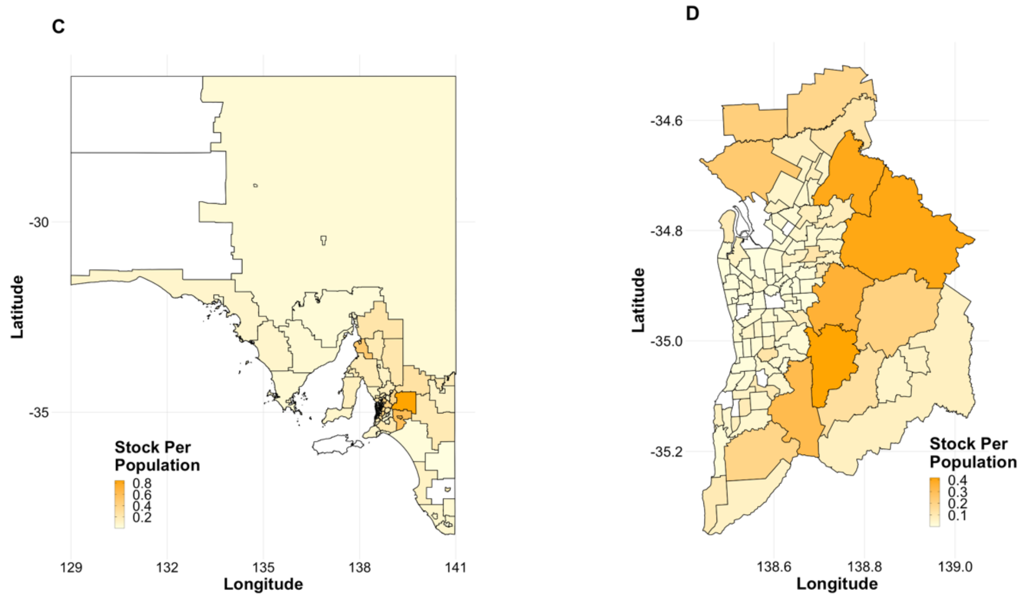


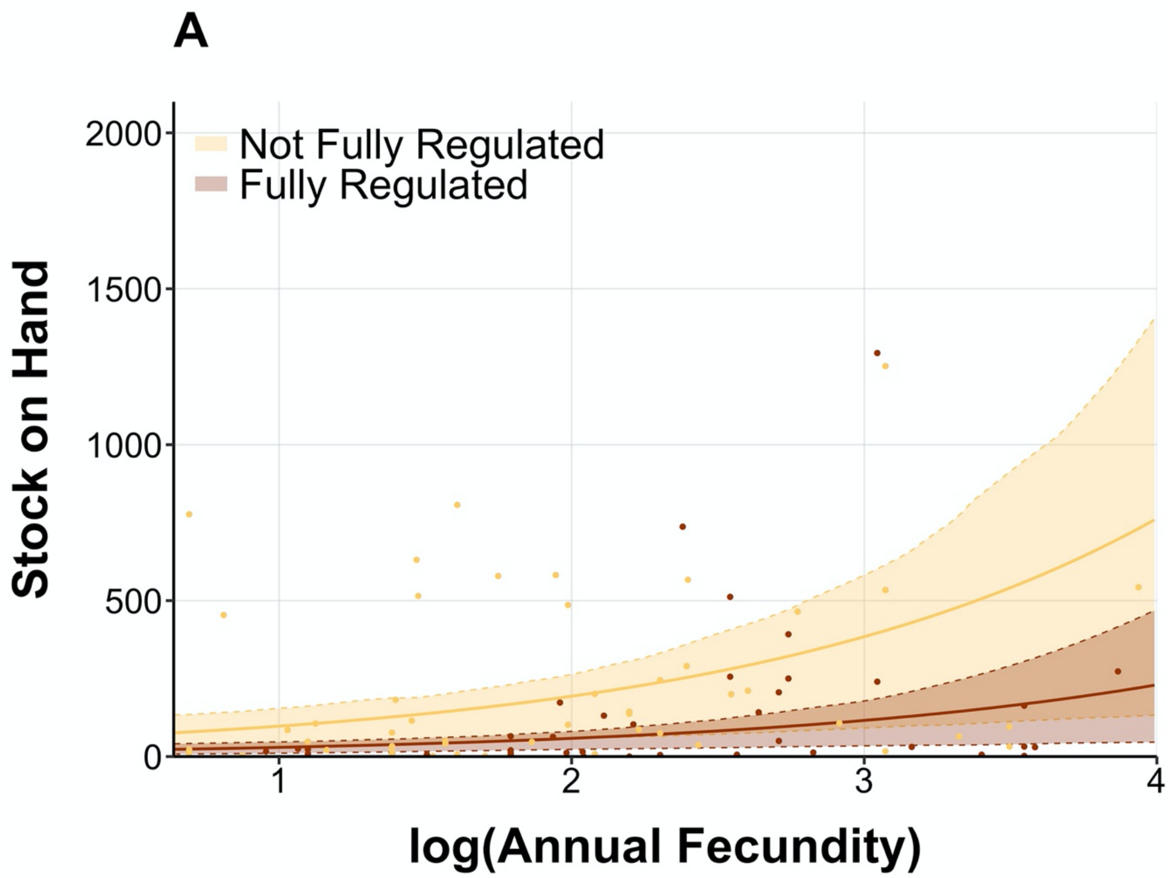
Figure 1

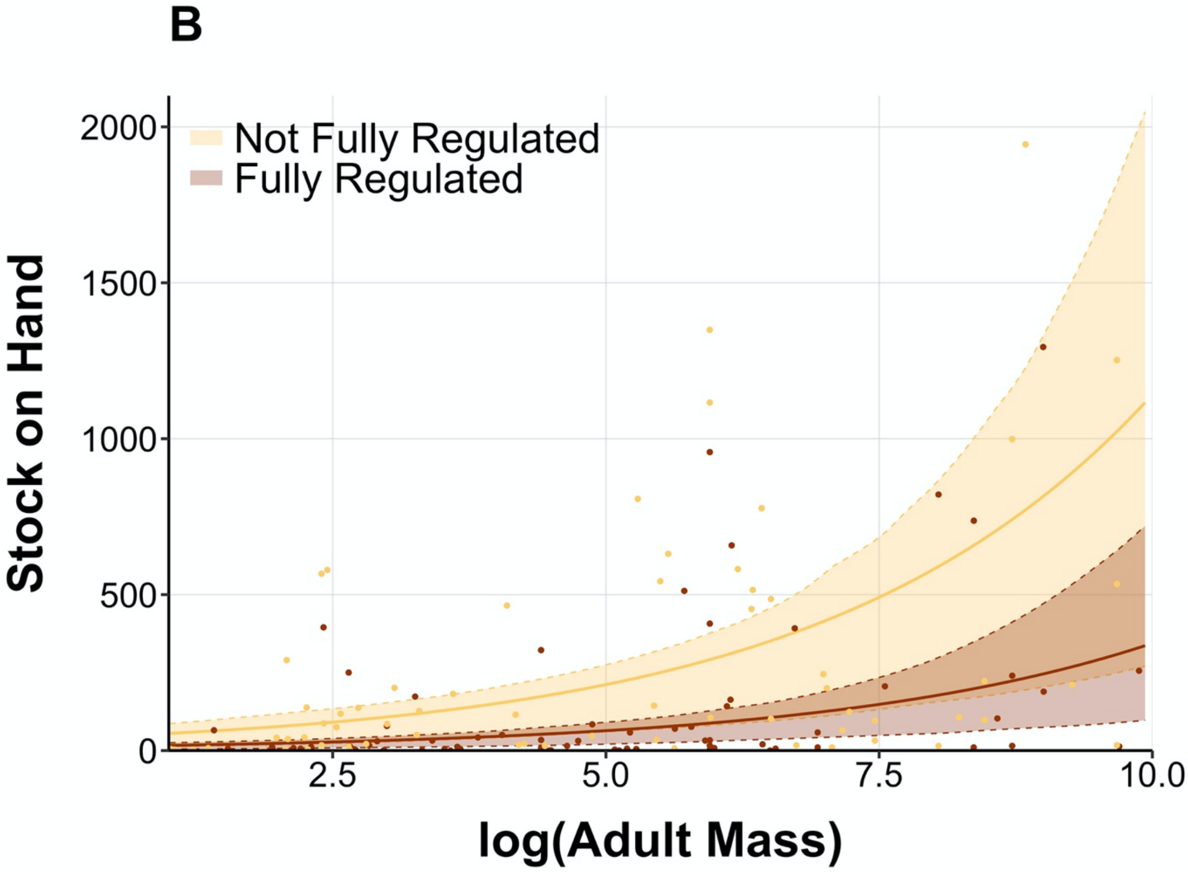
Pet total stock per Statistical Area 2 (SA2) region for **(A)** South Australia and **(B)** Greater Adelaide, as well as pet total stock per SA2 human population size for **(C)** South Australia and **(D)** Greater Adelaide.

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-value = 0.102) and Socioeconomic (Fisher's C = 55.042, P-value = 0.573) SEMs (see Appendix S3.1 & S3.2 for further details of initial SEM path diagrams and d-Sep analysis).

Pet reptiles were more likely to be stocked in captivity (R^2 = 0.42; Figure 2) if they are larger bodied (RVI = 0.275), not fully regulated (RVI = 0.180) and higher annual fecundity (RVI = 0.469; Figure 4; see Appendix S4 for all path coefficients, significance values and RVI scores). Reptiles that are not full regulated (RVI = 0.171), stocked in large quantities, and have high annual fecundity (RVI = 0.732) were sold in larger quantities (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) were more likely for reptile species that were stocked in higher numbers, not fully regulated (RVI = 0.364), have higher adult mass (RVI = 0.110) and annual fecundity (RVI = 0.517).




B
Not Fully Regulated
Fully Regulated
Stock on Hand
2000
1500
1000
500
0
2.5
5.0
7.5
10.0
log(Adult Mass)

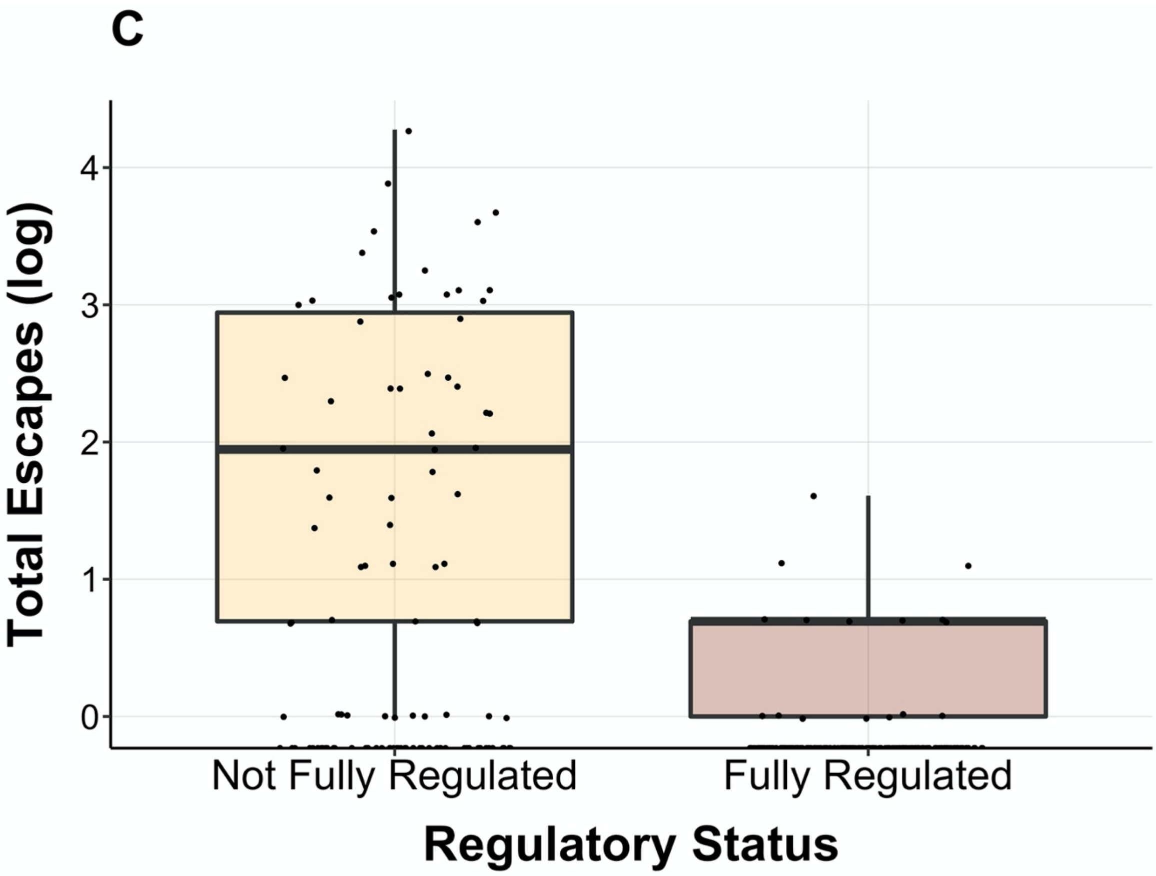

C
Total Escapes (log)
4
3
2
1
0
Not Fully Regulated
Fully Regulated
Regulatory Status

Figure 2: Model predictions for native reptile stock on hand against (**A**) adult mass and (**B**) annual fecundity (from Negative Binomial Generalised Linear Mixed Model; see Appendix S1.5 for details of model choice). Shaded areas represent 95% confidence intervals derived from parametric bootstrapping and points represent raw data. Raw data points with stock on hand above 2000 are not displayed. Number of escaped birds for Specialist (fully regulated) and non-Specialist (not fully regulated) birds (**C**).

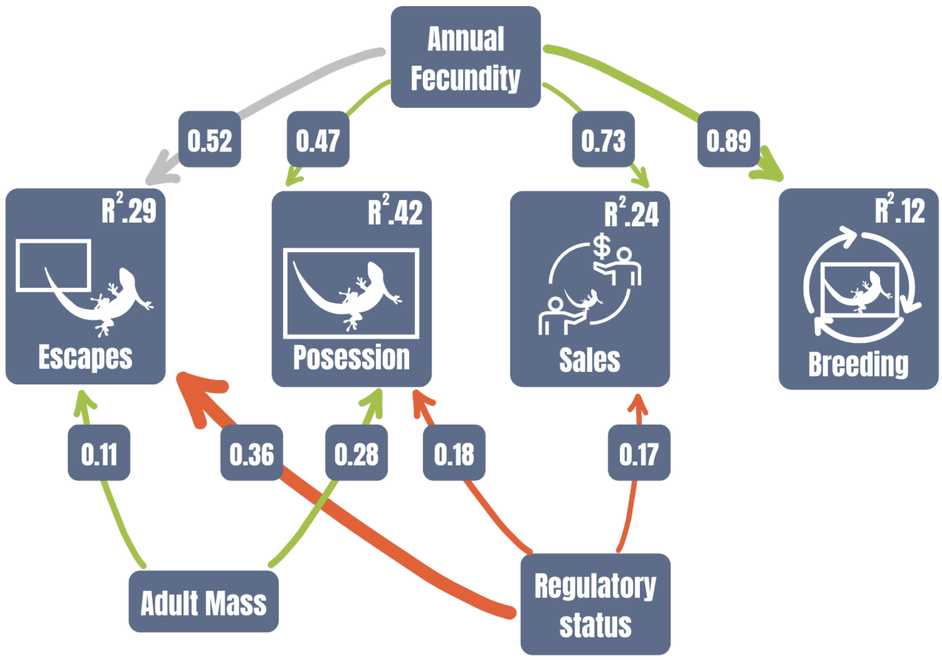


Figure 3

Final SEM path based on d-Sep piecewise SEM analysis of the South Australian native reptile trade dynamics and species attributes. Only direct relationships with trade dynamics are displayed, with relative variable importance (RVI) > 0.1. Covariation paths are omitted. Grey paths represent those with non-significant effect sizes (P-value > 0.05). Green and orange paths represent those with significantly positive and negative effect sizes respectively.

Pet birds were more likely to be kept in captivity (R^2 = 0.30; Figure 4) if they are not fully regulated (RVI = 0.801) and have high annual fecundity (RVI = 0.199). Birds with high annual fecundity (RVI = 0.440) and high adult mass (RVI = 0.474) were more likely to be 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, are not fully regulated (RVI = 0.891) and have high annual fecundity (RVI = 0.109).

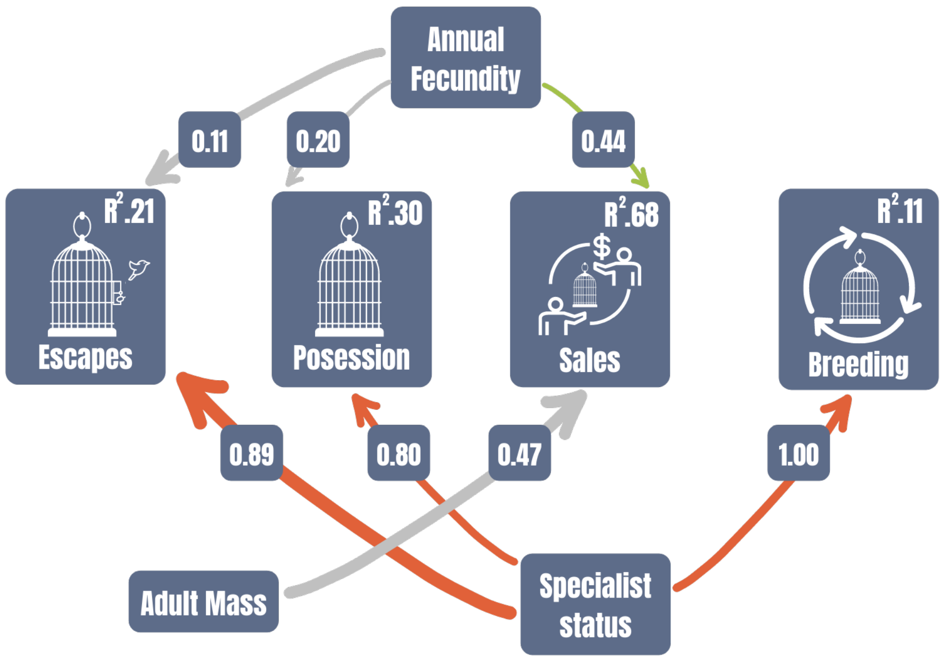


Figure 4

Final SEM path based on d-Sep piecewise SEM analysis native bird trade dynamics and species attributes. Only direct relationships with trade dynamics are displayed, with relative variable importance (RVI) > 0.1. Covariation paths are omitted. Grey paths represent those with non-significant effect sizes (P-value > 0.05). Green and orange paths represent those with significantly positive and negative effect sizes respectively.

Overall, socioeconomic attributes did not strongly determine trade dynamics. Suburbs were more likely to contain more pets ($R^2 = 0.560$) if they had lower population densities (RVI = 0.0810), higher unemployment rates (RVI = 0.0937) and bred pets in greater quantities (RVI = 0.776). Breeding quantity ($R^2 = 0.0393$) was poorly explained by socioeconomic metrics. Suburbs 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 suburbs that kept greater pet stocks (RVI = 0.952).

Discussion

Unregulated trade in live non-domesticated pets is a known driver of biosecurity, conservation, and animal welfare threats. We demonstrate the role of a trade regulatory system as a valuable 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. Owners kept and traded fewer pets that were fully regulated, even when 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. However, these results must be considered alongside the existing pet and owner-level attributes that otherwise drive trade.

We detected many species attribute relationships that are well supported in other studies of pet trade dynamics. The significant positive effect of adult mass on reptile escapes, as well as the positive (though non-significant) effect of annual fecundity on the number of reptile and bird escapes, are concurrent with trends in the U.S. vertebrate trade (Stringham and Lockwood 2018) and the South African alien reptile trade (Van Wilgen *et al.* 2010). Van Wilgen *et al.* (2010) also found, based on pet permits and estimates of trade, that dangerous (i.e., venomous or aggressive) reptiles tended to be kept in lower abundances. The significant negative effect of Specialist permit status on reptile stock (see Appendix S4) is mostly aligned with these findings, as almost all venomous native reptiles are listed as Specialist due to the increased demand of care. The prevalence of the aforementioned relationships across multiple countries with different legislative strategies for managing trade (e.g., Australian prohibition of alien reptiles 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 and 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.

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. 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 (e.g., song complexity or colour diversity; Vall-llosera and Cassey (2017)). Endemic reptiles were sold in greater quantities, yet endemism had no impact on the trade of birds (see Appendix S4). Australia has a high proportion of endemic reptiles (Long 2017), many of which are morphologically unique; therefore, it is possible that reptile traders are selecting endemic species due to their unique phenotypes (i.e., endemism is a proxy for physical uniqueness).

We found no evidence that owner decisions to acquire and trade pets in South Australia are motivated by financial opportunity or gain. While our results are correlative and do not necessarily represent causal relationships, the lack of any direct relationship between household income and trade dynamics may suggest that the benefits of pet ownership outweigh the economic cost (e.g., Langfield and James (2009); Smith (2012); Clements *et al.* (2019)). We also found that, while population density and unemployment rate significantly correlated with trade dynamics, they had very low explanatory power and are therefore likely to have less influence on trade dynamics compared to species traits and trade regulation. By contrast, consumers in other pet markets are known to either have higher disposable incomes compared with non-consumers (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 and 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 bird species, more animals escaped when stocked in higher quantities. 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 (Howeth *et al.* 2016; Allen *et al.* 2017). While our analysis pertains to species native to Australia, many species are held in captivity outside of their native range and therefore still pose biosecurity risks via the potential establishment of 'domestic alien' species (García-Díaz *et al.* 2017; Lockwood *et al.* 2019). Not only is there a risk that new populations will establish to the detriment of native ecosystems, 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., through the spread of deleterious captive-bred traits (Fox and Hogan 2020)).

Australian desire for alien pets 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 and McDonald-Madden 2017). Yet, we found no such preference in the keeping of native species in South Australia, despite our data omitting some of the most common non-threatened pets that would undeniably be kept in high quantities. This 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 rapid changes in trade demand can lead to population declines even for species that were not previously threatened or known to be traded (Nijman *et al.* 2019; Marshall *et al.* 2020) and that 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.

Recommendations and Conclusions

We have concluded 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 partially de-incentivise trade of species that are: (i) threatened by trade activities such as demand-induced harvesting; (ii) aggressive, dangerous or otherwise difficult to ethically house in captivity; (iii) traded outside their native range; and (iv) known to be host to high-risk pathogens. We recommend that contemporary tiered permit systems, such as those used to regulate the alien bird trade in Victoria (Woolnough *et al.* 2020), be used to regulate a greater diversity of native and alien taxa elsewhere. To support such implementation, and to investigate the remaining unexplained variation in trade dynamics, there is further potential to explore 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 threats (e.g., High Interest - Class 1 parrots species (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., EMODE (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 (Toomes *et al.* 2019; Heinrich *et al.* 2021).

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.

Data Availability Statement

The raw data used in our analysis was collected by the South Australia Department for Environment and Water and contains potentially confidential information. Therefore, this data has 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, as well as collated species attributes and regulatory status, in Figshare (doi: https://doi.org/10.6084/m9.figshare.16436379.v1).

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