

Online and pet stores as sources of trade for reptiles in South Africa

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Abstract

The ever-increasing human population, globalisation, and desire to keep pets have resulted in the translocation of many species into non-native environments. As a result, some of the non-native reptile species have been introduced to South Africa through the pet trade. However, little is known about the extent of trade in reptiles via online and physical pet stores in South Africa and their potential climatically suitable areas. We assessed the physical pet store and online trade of reptiles in South Africa. We found 69 physical pet stores and 18 online advertising websites selling 1,912 individuals of 66 species and 859 individuals of 50 reptile species, respectively. In total, we found 88 unique species representing 18 families from both sources, of which 86.4% were non-native species and 32 species were CITES-listed. Snakes were the most dominant (76.1%) traded group. Ball python *Python regius* (n = 601), corn snake *Pantherophis guttatus* (n = 553) and central bearded dragon *Pogona vitticeps* (n = 419) were the most-traded reptiles. Prices ranged from ZAR100.00 to ZAR6,000.00, with sharp-nosed viper *Deinagkistrodon acutus acutus* being the most expensive species. For present distributions, the red-eared slider *Trachemys scripta elegans*, *P. guttatus*, and Western diamondback rattlesnake *Crotalus atrox* had the largest predicted climatic suitability. The future predictions for the latter two species were predicted to increase while red-eared slider suitability shifted. Most popular species were available in large volumes, sold at relatively low prices and had high climatic suitability, representing a high potential invasion risk. We, therefore, propose that the existing pet trade regulations should be revised to include a more restricted trade on the trade of endangered, non-CITES listed and potential invasive pet species.

Keywords

Biological invasions
Species distribution modelling
Non-native species
Establishment success
CITES
Reptile trade

1. Introduction

The global illegal and legal trade in wildlife has increased immensely because of the increasing human population, globalisation, and desire to keep non-domesticated species as pets or companion animals (Kopecký et al., 2013, Siriwat and Nijman, 2018, Lockwood et al., 2019). These two forms of trade are regarded as significant threats to global biodiversity and species conservation (Nijman and Shepherd, 2007, Challender et al., 2015, Siriwat and Nijman, 2018). Many species are traded for food and medicines (Yen & Ro, 2013), ornamentation (Kopecký et al., 2013), research (Jojola et al., 2005), entertainment (Alves et al., 2010), and pets (van Wilgen et al., 2012). It has been reported that ~ 59 reptile species are critically endangered because of the global reptile trade (Marshall et al. 2020). Although there has not been any extinction case associated with the pet trade, it has been reported to be the cause for many declines of some species (Smith et al., 2009, Morton et al., 2021). For example, the wildlife population of green python *Morelia viridis* has declined significantly because of the illegal wildlife pet trade (Lyons and Natusch, 2011). The main contributing factor or driver of the global wildlife trade is the high demand for pets (Moorhouse et al., 2017).

The high demand of wildlife species for the pet trade has many inevitable implications such as population loss, zoonotic risks, welfare issues and the introduction of non-native species (Fong and Chen, 2010, Baker et al., 2013, Bush et al., 2014, McFadden et al., 2017, Siriwat and Nijman, 2018, Spee et al., 2019). Consequently, the pet trade has become an important pathway for introducing non-native species into new environments (van Wilgen et al., 2008, Reed et al., 2012, Faulkner et al., 2016, Measey et al., 2017, Siriwat and Nijman, 2018). Pet owners, stores or breeding facilities have contributed significantly to introducing non-native species through either intentional release or accidental escapes (Mazzotti and Harvey, 2012, Da Rosa et al., 2018). Some of these species have been reported to compete for resources with native species (Mori et al., 2017), cause biodiversity loss (Orzechowski et al., 2019), negatively impact agriculture (Gibson and Yong, 2017, Shivambu et al., 2020a) and introduce pathogens that threaten the public health (Travis et al., 2011). For example, the brown anole *Anolis sagrei* competes successfully with the green anole *A. carolinensis* for resources (Stuart et al., 2014), the corn snake *Pantherophis guttatus* was reported to be a major threat to vulnerable frogs such as the Cuban treefrogs *Osteopilus septentrionalis* (Meshaka, 2011), and the green iguana *Iguana iguana* damaged and destroyed crops in Puerto Rico (López-Torres et al., 2012). The international trade in amphibians has also facilitated the spread of the chytrid fungus (*Batrachochytrium salamandrivorans*), causing Chytridiomycosis (Spitzen-van der Sluijs et al., 2013, Richgels et al., 2016, Nguyen et al., 2017). Furthermore, some invasive species also influence the behaviour of native species (Falaschi et al., 2020).

Online trade and pet stores are the primary sources for pet trade by which many pet species are traded in different countries (Kikillus et al., 2012, Su et al., 2015, Nelufule et al., 2020, Shivambu et al., 2021c, Shivambu et al., 2021b). This has resulted in difficulties in tracking or monitoring species sold across these complex platforms, especially the online trade (Runhovde, 2018). As a result, some of the species that are sold in these platforms have now been reduced in the wild, while others are posing serious threats to native biodiversity, economy and human health in invaded areas (Meshaka, 2011, Marshall et al., 2020,

Shivambu et al., 2020a). In addition, some of the species may be sold illegally on these platforms, for example, native species are not allowed to be sold as pets in South Africa (DEA, 2016). The accessibility and exposure to the internet and physical pet stores have influenced the modern-day illegal wildlife trade (Lavorgna, 2015, Morgan and Chng, 2017, Bergin et al., 2018, Siriwat and Nijman, 2018). Consequently, many non-native species, e.g. small mammals (Shivambu et al., 2021a, Shivambu et al., 2021b), tarantulas (Hauke and Herzig, 2017, Shivambu et al., 2021c, Shivambu et al., 2021b), reptiles (van Wilgen et al., 2010), and birds (Su et al., 2015, Mori et al., 2017) are traded through these platforms. It is noteworthy that online platforms, including several national and local blogs or sites, and social media have become the most dominant and key modes of trade in live reptiles (Walker, 2011, Morgan and Chng, 2017). Social media has been used as a tool for sourcing and advertising live non-native animals (Derraik and Phillips, 2010, Spee et al., 2019). This has provided a suitable platform for illegal traders to advertise and sell reptiles, including critically endangered and prohibited specimens (Morgan & Chng, 2017). This verified that both platforms are highly complex and pose serious challenges for the management and regulation of wildlife trade (Maki and Galatowitsch, 2004, IFAW, 2008, Siriwat and Nijman, 2018).

In South Africa, the trade of wildlife as pets is relatively young but has increased as they have become a popular hobby (van Wilgen et al., 2010, Nelufule et al., 2020, Shivambu et al., 2021a, Shivambu et al., 2021b). The trade of wildlife in South Africa involves a range of taxa, including amphibians, reptiles, birds, fishes, invertebrates, small mammals, and birds (van Wilgen et al., 2008, Symes, 2014, Marr et al., 2017, Measey et al., 2017, Nelufule et al., 2020, Shivambu et al., 2021a, Shivambu et al., 2021b). Some of these animals have established, spread, and become invasive, for example, frogs (*Lithobates catesbeianus* and *Xenopus laevis*) (Measey et al., 2017), rose-ringed parakeets (*Psittacula krameri*) (Hart & Downs, 2015; Shivambu et al., 2020d), and red-claw crayfishes (*Cherax quadricarinatus*) (Nunes et al., 2017).

Reptiles are among the most popular animal taxa in the South African pet trade (van Wilgen et al., 2010, Shivambu et al., 2021c). However, little is known about the magnitude of the wildlife trade in reptile species in the South African online trade and physical pet stores. Some of the reptiles imported as pets to South Africa have been reported to be invasive elsewhere (van Wilgen et al., 2010). These include Burmese pythons *Python bivittatus* in south Florida (Willson et al., 2011, Lockwood et al., 2019) and red-eared sliders *Trachemys scripta elegans* in many countries worldwide (Lever, 2003). A study by van Wilgen et al. (2010) assessed the invasion risk of reptiles that are traded in South Africa; however, areas at risk of invasion are not known. Additionally, the reptile pet trade has not been assessed in the country since the study of van Wilgen et al. (2010). Considering the general increase in the wildlife trade at an international level (Siriwat and Nijman, 2018, Lockwood et al., 2019), it is possible to find new introductions to the South African reptile trade. Many studies have used rapid screening tools such as species distribution models and climate matching to determine which areas are at risk of invasion (Bomford, 2006, Jiménez-Valverde et al., 2011, Keller and Kumschick, 2017). The species distribution modelling (SDMs) uses the presence of occurrence records to predict organisms' climatic suitability (Elith & Leathwick, 2009; Di Febbrano et al., 2013).

We assessed the availability of live reptiles in physical stores and on online trade platforms. Our present study objectives were to (1) determine the trade volume of reptiles in the South African pet trade (physical and online); (2) determine which reptile species are most traded; (3) examine if the price is determined by species invasion status, IUCN (International Union for Conservation of Nature) conservation, CITES, and venomous status, and (4) determine the present and future potential distribution of non-native pet reptiles in South Africa. We predicted that physical pet stores would have more species available than online trade, given that pet stores are most likely to advertise different species in abundance, especially when they are in demand. Given the high popularity of snakes amongst the other groups of reptiles in the pet trade industry (Natusch and Lyons, 2012, Alves et al., 2019), we predicted to find more snakes compared with the other groups of reptiles. We further predicted that species with high availability in both sources of trade and large occurrence records would have wider climatic suitability distribution than species with relatively small occurrence records.

2. Methods

2.1. Pet trade survey

2.1.1. Data collection

In the present study, we considered the two most important platforms through which many reptile species are advertised and sold as part of the pet trade via the internet and physical pet stores. We surveyed a total of 69 pet stores and 18 websites in South Africa.

2.1.2. Online pet trade

We gathered a list of online pet stores using search terms such as “reptile pets for sale”, “exotic pets” in Google search engine (<https://www.google.com/>). The names of the pet shops are not included to protect their identity. We also surveyed advertising websites such as Gumtree (<http://www.gumtree.co.za>), Ananzi (<http://www.ananzi.co.za>), Junk mail (<http://www.junkmail.co.za>), OLX (<http://www.olx.co.za>), Public Ads (<http://www.publicads.co.za>) including open and closed Facebook groups (<http://www.facebook.com>) to generate a species list of reptiles in the South African online pet trade. Key terms such as “reptiles for sale in South Africa”, “reptiles in the South African pet trade”, or “reptile pets in South Africa” were used to search for species. We undertook searches from March to November 2020 to account for species turnover.

Cases of reptiles being re-advertised or resold may lead to data duplications, and thus to avoid this, all posts recorded were compiled and cross-checked for vendor’s username, date of post and the pictures included in the advertisement. We recorded the following, species names (common and scientific), number of individuals and prices for each reptile species. For advertisements without scientific names, we used personal experience and identification guides where necessary (O’Shea, 2007, Wallach et al., 2014, Spawls et al., 2018; Fig. 1).



Fig. 1. A photographic representation of some reptile species recorded, where (a) shows two Burmese pythons *Python bivittatus* (Alb = albino, Nrm = normal), (b) a ball python *Python regius*, (c) a false water cobra *Hydrodynastes gigas*, and (d) a red-tailed boa *Boa constrictor* (Photograph credits: A Mantintsilili).

2.1.3. Physical pet stores

We obtained a list of physical pet shops ($n = 114$) from Shivambu et al., 2021a, Shivambu et al., 2021b. All 114 pet stores were visited. However, we could only sample 69 pet stores since 45 pet stores closed during the COVID-19 pandemic. We visited the pet shops in Gauteng ($n = 29$), Western Cape ($n = 11$), KwaZulu-Natal ($n = 7$), Eastern Cape ($n = 5$), Free State ($n = 4$), North West ($n = 4$), Limpopo ($n = 4$), Mpumalanga ($n = 4$), and Northern Cape ($n = 1$), in March 2020 and November 2020 to document a list of reptiles for sale (Fig. 2). Each pet store was visited at least once during the sampling months. We spent at least three days in each province as most of the pet shops are relatively close to each other and clustered within the same city (Fig. 2). After getting the pet store owner's verbal consent to participate in our study, we conducted the sampling. We recorded species names, number of individuals and prices for each reptile species for each store. We also determined if the traded reptile originated from captive or wild populations by searching for information on the CITES website.

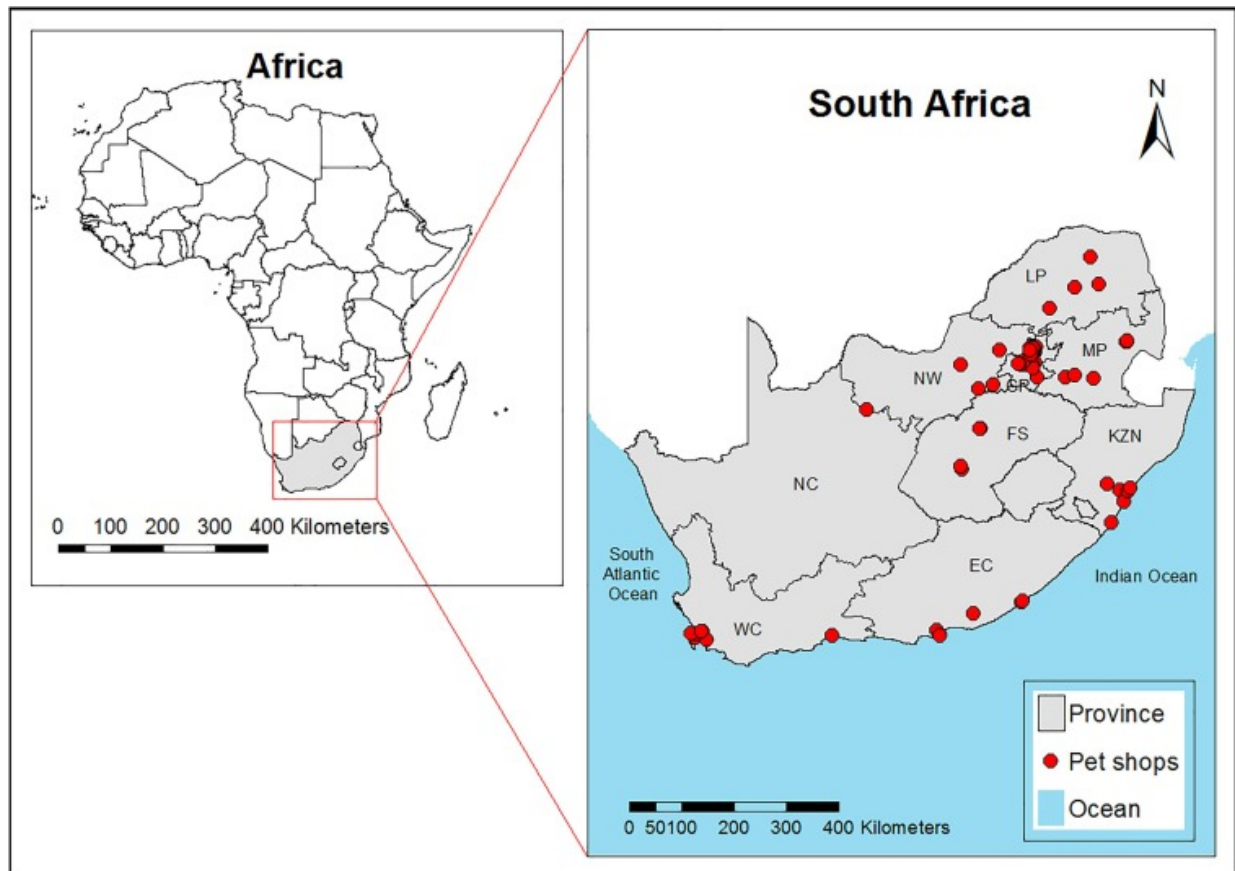


Fig. 2. The distribution of physical pet stores surveyed in March and November 2020 in South Africa. (Note: The abbreviations in the map represent names of provinces where LP: Limpopo, GP: Gauteng, MP: Mpumalanga, NW: North West, FS: Free State, KZN: KwaZulu-Natal, EC: Eastern Cape, NC: Northern Cape, and WC: Western Cape).

2.2. Species distribution modelling

2.2.1. Species selection and distribution data

To develop species distribution models (present and future distribution models), we assembled species occurrence records (museum collections) for the 12 reptile species, which were selected based on the following criteria (1) species with extensive occurrence records, (2) species listed under the National Environmental Management: Biodiversity Act (NEMBA), (3) species with a history of invasion elsewhere, and (4) those with high numbers (high availability) in the pet trade. These occurrence records were assembled from the Global Biodiversity Information Facility database (GBIF; <http://www.gbif.org>; GBIF.org, 2021a, GBIF.org, 2021b, GBIF.org, 2021c, GBIF.org, 2021d, GBIF.org, 2021e, GBIF.org, 2021f, GBIF.org, 2021g, GBIF.org, 2021h, GBIF.org, 2021i, GBIF.org, 2021j, GBIF.org, 2021k, GBIF.org, 2021l) using the *rgbif* package (Chamberlain et al., 2014) in R statistical software (version 3.4.4, R Core Team, 2018). All records that overlapped or had either the latitude or longitude coordinates missing were cleaned and removed using the *Biogeo* package in R (Robertson et al., 2016) to preclude autocorrelation. The cleaned datasets were then converted into spatial points format readable in R statistical software. According to Naimi

and Araújo (2016) absence records of species are also crucial for the species distribution model fitting. Thus, in the present study pseudo-absence records ($n = 10,000$ at runs of 100 bootstrap replications) were drawn from the background of present records.

2.2.2. Climatic data and variable selection

The model included all 19 updated bioclimatic variables from WorldClim (<http://www.worldclim.org>) at 10-minute spatial resolution. Predictor variables that collinear with each other were removed from the model using the Variance Inflation Factor function in R (VIF; Marquardt, 1970) and Pearson correlation as they can affect the performance and prediction of the model (Dormann et al., 2013). A threshold value of $p = |0.7|$ was used as a benchmark to select the variables that were not highly collinear (i.e. all variables with p less than 0.7) (Dormann et al., 2013).

2.2.3. Climatic matching and model evaluation

We used eight methods to determine the predictor variable that best described the reptile species distribution suitability and the model performance. The methods we used included boosted regression tree (BRT: Friedman, 2001), classification and regression trees (CART: Breiman, 1984), multivariate adaptive regression spline (MARS: Friedman, 1991), generalised linear model (GLM: McCullagh, 1989), generalised additive model (GAM; Hastie & Tibshirani, 1990), random forest (RF: Breiman, 2001), support vector machine (SVM: Vapnik, 1995) and MaxEnt (Phillips et al., 2006). For each method, the variables performance figures were displayed to determine which predictor variable contributed most to the climatic suitability prediction. All models were assessed at 100 runs of bootstrap replications. We evaluated model performance using the independent-threshold statistic, area under the curve (AUC). We then used the mean independent AUC thresholds to obtain binary predictions (i.e. presence or absence output). The value of AUC ranges from 0 to 1, where values between 0.7 and 0.9 are considered good (Fielding & Bell, 1997). For this study, we used a threshold of 0.8 to define model performance.

2.2.4. Future predictions

We further obtained CMIP6 climate variables from the WorldClim v2.1 (<https://www.worldclim.org/data/cmip6/cmip6climate.html>) database to develop future (year 2070) distribution maps at 10 min spatial resolution. We used the representative concentration pathway (RCP) 8.5 scenario from the fifth Report of the International Panel on Climate Change (IPCC5) to build future models. The RCPs are used to predict potential climatic scenarios that depend on greenhouse emissions in the future (Coban et al., 2020). In future scenarios, the bioclimatic data for 2070 represents the mean values from 2061 to 2080 (Ramya et al., 2015; Çoban et al., 2020). We selected the “AC” model to predict the future climatic scenario for each species since the future predictions are influenced by the general circulation model (GCM) (Randal 2000; Ashrafzadeh & Haidarian, 2021). We determined whether if the modelled species will gain, lose or go extinct in the future years (year 2070) by subtracting the future suitability from the weighted mean of the present. The model was classified into three categories (red = extinction, gray = persistence, and dark

green = colonisation). A positive value represented gain, while loss had a negative value. The model outputs were displayed in R and later downloaded for our analyses.

2.3. Statistical analyses

All statistical analyses were performed with R statistical software (version 3.4.4, R Core Team, 2018). We counted the number of reptiles advertised for sale via South African online sites and physical pet stores to determine species abundance, richness and those that were most popular. We found that the data were not normally distributed when we tested for normality using the Kolmogorov-Smirnov normality test. We, therefore, used a Kruskal-Wallis to determine whether there was a significant difference in species abundance and richness in physical pet stores and online advertising websites across nine South African provinces. We also used a Mann-Whitney pairwise test with Bonferroni p values adjusted at 0.01 to determine if online and pet store trade differed in species abundance and richness. We examined the relationship between each explanatory variable (invasive status, IUCN status, CITES-listed, aggression status, and invasion status) against the selling price (dependent factor) using regression models. To determine the model with the greatest explanatory power, we used the Akaike Information Criterion (AIC).

3. Results

3.1. Volume of trade

We recorded a total of 1912 individuals representing 66 reptiles from 69 physical pet stores (Supplementary Material Table S1). We further recorded 859 individuals representing 50 reptiles from online advertising websites selling reptiles (Supplementary Material Table S1). In total, we recorded 88 unique reptiles representing 18 families across both sources combined, of which only 32 were CITES listed. Of those species, 76.1% (number of species (n) = 67) were snakes, 13.6% (n = 12) lizards, 9.0% (n = 8) turtles or tortoises and 1.1% (n = 1) alligators (Supplementary Material Table S1). Of the recorded species, 12 (13.6%) reptiles were native to South Africa, with the majority (6/12) recorded exclusively from the online pet trade. In addition, only three native species were CITES listed. There were only three native species recorded exclusively from the physical pet stores (Supplementary Material Table S1). Moreover, 76 (86.4%) of the recorded species are non-natives to South Africa (Supplementary Material Table S1).

For our online sampling, 12 new species were recorded during the follow-up searches (Supplementary Material Table S1). The species accumulation curve of the number of reptiles sold in the South African pet trade indicated that sampling from both websites and pet stores did not reach an asymptote (Fig. 3). We further found that at least 34.1% (30/88) of the recorded species originated from wild populations. Of these, four are declared vulnerable (the African spurred turtle *Centrochelys sulcata*, Indian star turtle *Geochelone elegans*, Indochinese spitting cobra *Naja siamensis* and Chinese water dragon *Physignathus cocincinus*), with the Indian star turtle being the CITES Appendix I species (Supplementary Material Table S1). In addition, from the observed species that originated from the wild, 19 species and 14 species were recorded from physical pet stores and online advertising websites, respectively (Supplementary Material Table S1). The remaining 65.9% (58/88) are

commonly kept and bred by private keepers around the world (Supplementary Material Table S1). These include two *Acrantophis* spp. (Dumeril's boa *A. dumerili* and the Madagascar ground boa *A. madagascariensis*), which are listed under CITES Appendix I (Supplementary Material Table S1).

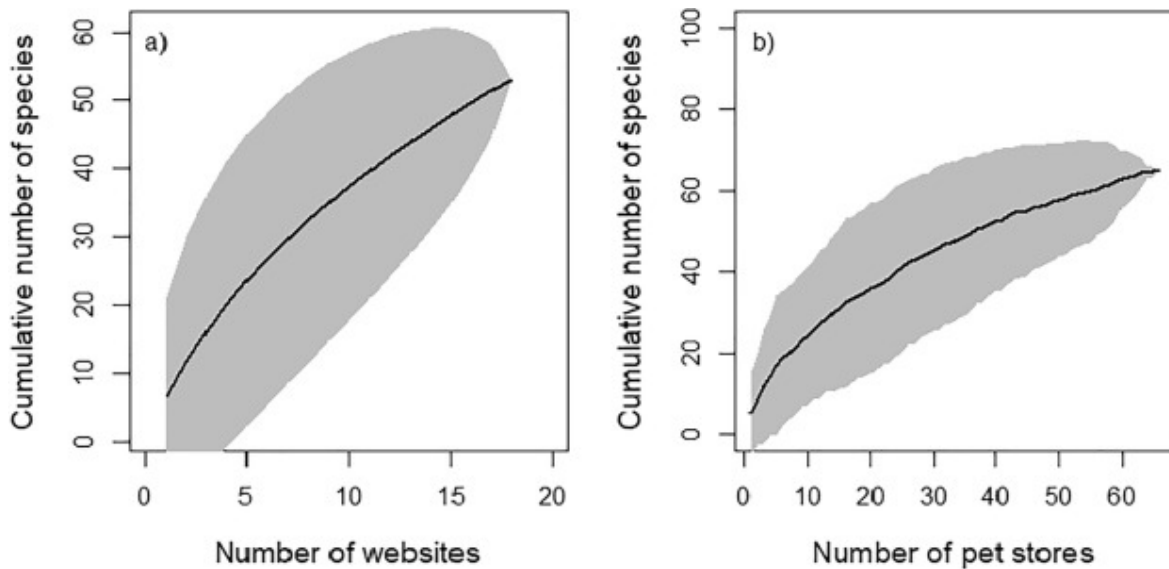


Fig. 3. Species accumulation curves estimating the number of reptiles present in the South African pet trade obtained from a) online searches and b) physical pet stores visits in the present study. (Note: A black line represents the mean accumulation curve, and the grey shaded area shows the standard deviation of the data from 100 random permutations using the “vegan” package in R (Oksanen et al., 2016)).

We found a significant difference in the number of individuals of each reptile species traded in the physical pet store across nine South African provinces (Kruskal-Wallis $\chi^2 = 34.79$; $df = 8$; $P = 1.288e-12$). The provinces of Gauteng, Eastern Cape and KwaZulu-Natal recorded more individuals than the other provinces, with each recording more than 250 individuals (Fig. 4a). We found a significant difference in species richness between the number of reptile species traded in pet stores across the nine South African provinces (Kruskal-Wallis $\chi^2 = 19.27$; $df = 8$; $P = 0.0021$). The provinces with high species diversity were KwaZulu-Natal and Gauteng, which each recorded more than 25 species (Fig. 4b). For online trade, we also found a significant difference in the number of individuals of each species sold via the online trade across all nine South African provinces (Kruskal-Wallis $\chi^2 = 28.54$; $df = 8$; $P = 1.019e-13$) with Gauteng and KwaZulu-Natal recording more than 250 individuals of reptile species each (Fig. 4a). Other provinces recorded less than 70 individuals (Fig. 4a). We also found a significant difference in species richness in the online trade across all nine South African provinces (Kruskal-Wallis $\chi^2 = 18.34$; $df = 8$; $P = 0.0002$). The provinces with high species diversity were also KwaZulu-Natal and Gauteng, which recorded 30 and 29 reptile species, respectively (Fig. 4b). Online advertising websites did not record any reptile species for sale in Limpopo and Northern Cape provinces (Fig. 4b).

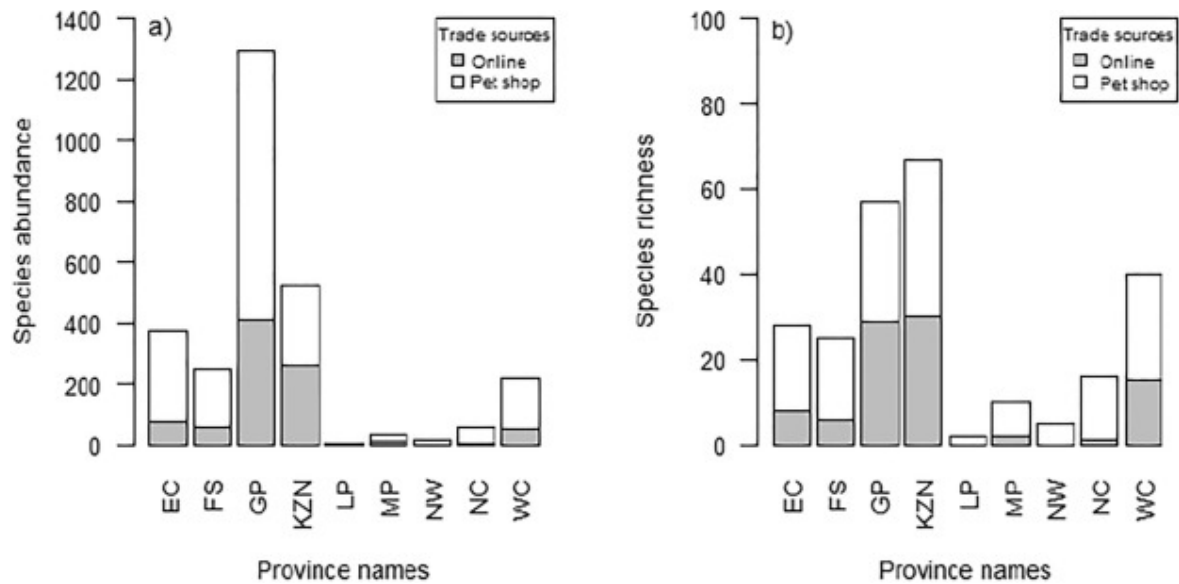


Fig. 4. Reptile species a) abundance and b) richness obtained from the two sources of trade (websites and pet stores) across nine South African provinces in the present study. (Note: see Fig. 2 for the abbreviations of provinces).

3.2. Most popular species

The availability of reptile species recorded differed between the two sources (Supplementary Material Table S1). Thirty-eight species were exclusively recorded from the physical pet stores, 22 from online searches and 28 species were shared amongst the two sources (Fig. 5).

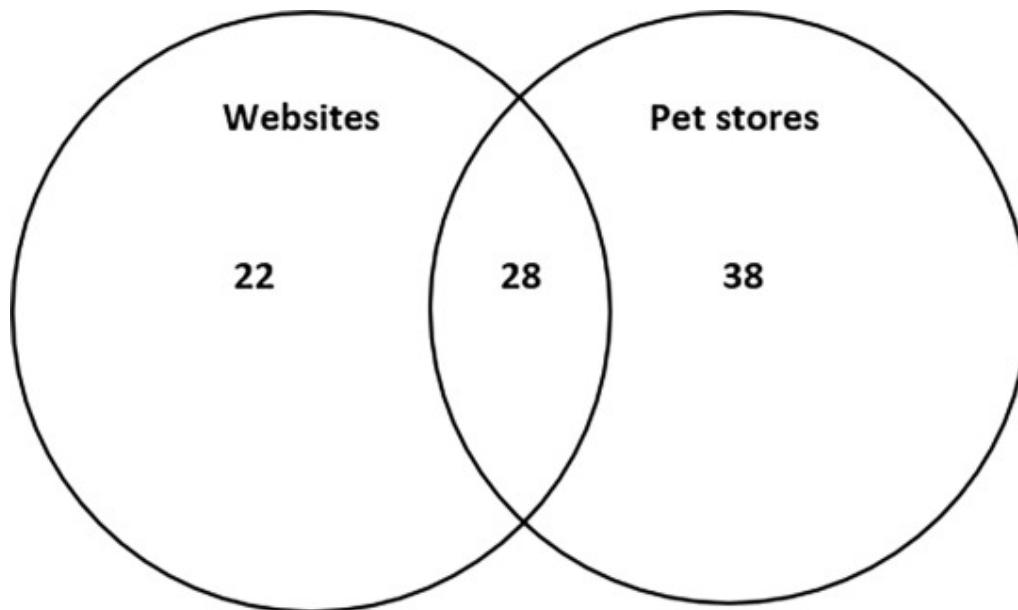


Fig. 5. Venn diagram demonstrating the total number of reptiles obtained from two sources (websites and physical pet stores) and those shared among sources in the present study.

We found that the overall species abundance in online trade was significantly lower than the species abundance in pet stores (Mann-Whitney U test = 23546, P = 0.0034). The two sources also differed significantly in species richness (Mann-Whitney U test = 950, P = 1.265e-15), with physical pet stores recording more reptile species than online trade. The top ten most traded reptiles across both sources combined included six snakes, three lizards and one tortoise (Table 1). Two of these were native species that are not supposed to be traded (Table 1). The most expensive species recorded was a non-native species, the sharp-nosed viper *Deinagkistrodon acutus acutus* (with the mean price of ZAR6,000.00) and the cheapest species was a native species, the southern brown egg eater *Dasypeltis inornata* (ZAR100.00) (Supplementary Material Table S1). We further found that CITES-listed species (Appendix II) determined the selling price of reptile species in physical pet stores (Supplementary Material Table S2). For online trade, the model showed that invasion status determined reptile species' selling price (Supplementary Material Table S2).

Table 1. Summary of the top ten most traded reptiles advertised for sale in South African pet stores and online (detailed table in Supplementary Material Table S1).

Species names	Common names	Pet shops			Online		
		Species abundance	Mean price (ZAR)	No. of provinces	Species abundance	Mean price (ZAR)	No. of provinces
<i>Boa constrictor</i> *	Red-tailed boa	73	456.17	6	3	568.33	2
<i>Boaedon capensis</i> ¹	Cape house snake	26	256.63	4	12	200.00	2
<i>Correlophus ciliatus</i>	Crested gecko	52	456.25	5	53	260.54	4
<i>Eublepharis macularius</i>	Common leopard gecko	257	536.69	7	57	235.93	4
<i>Gongylophis colubrinus</i>	Kenyan sand boa	48	289.96	6	5	320.00	3
<i>Pantherophis guttatus</i> *	Corn snake	319	651.47	8	234	421.15	5
<i>Pogona vitticeps</i>	Central bearded dragon	349	277.87	7	70	240.00	5
<i>Python bivittatus</i> *	Burmese python	53	688.89	7	15	674.50	1
<i>Python regius</i>	Ball python	401	363.18	7	200	451.95	6
<i>Stigmochelys pardalis</i> ¹	Leopard tortoise	0	0	0	76	539.21	5

Species with an asterisk (*) are those known to be invasive elsewhere. Species with a 1 are native species.

3.3. Distribution modelling

3.3.1. Present distribution

The mean independent AUC threshold values indicated that the models performed well (AUC greater than 0.87) in predicting areas that are climatically suitable for all 12 non-native reptile species traded in South Africa (Table 2). The brown anole's predicted climatic suitability was particularly in coastal areas of KwaZulu-Natal, Eastern Cape and partly in the Western Cape Province (Fig. 6a). The predictor variables mean diurnal range (Bio 2) and precipitation of warmest quarter (Bio 18) contributed most to predicting the climatic suitability distribution for this species (Table 2). The predicted climatic suitability for *I. iguana* included the east-north coastal areas of South Africa (Limpopo, Mpumalanga and KwaZulu-Natal provinces), with the mean temperature of the driest quarter (Bio 9) and isothermality (Bio 3) being the most contributing predictor variables (Table 2; Fig. 6b). The corn snake's predicted climatic suitability was relatively large, covering almost all South African provinces besides the Western Cape Province (Fig. 6c). The climatic suitability for this species was best described by the mean temperature of the warmest quarter (Bio 10) and isothermality (Bio 3) (Table 2). The projected climatic suitability for red-tailed boa *Boa constrictor* and Colombian boa *B. constrictor imperator* occurred in similar areas to those reported for green iguana (Fig. 6d, e). However, the climatic suitability for red-tailed boa was best described by isothermality (Bio 3) and the mean temperature of the wettest quarter (Bio 8) (Table 2). Whereas for the Colombian boa, the climatic suitability was best described by isothermality (Bio 3) and precipitation of warmest quarter (Bio 18) (Table 2). The predicted climatic suitability for Burmese python, beauty rat snake *Orthriophis taeniurus*, ball python *Python regius* and veiled chameleon *Chamaeleo calypttratus* were relatively low (Fig. 6f & Fig. 7a, b, d).

The full names of predictor variable numbers are as follows: 1: BIO1 = annual mean temperature, 2: BIO2 = mean diurnal range (mean of monthly (max temp - min temp)), 3: BIO3 = isothermality (BIO2/BIO7) ($\times 100$), 4: BIO4 = temperature seasonality (standard deviation $\times 100$), 5: BIO5 = max temperature of warmest month, 8: BIO8 = mean temperature of wettest quarter, 9: BIO9 = mean temperature of driest quarter, 10: BIO10 = mean temperature of warmest quarter, 13: BIO13 = Precipitation of Wettest Month, 14: BIO14 = Precipitation of Driest Month, 15: BIO15 = Precipitation Seasonality (Coefficient of Variation), 18: BIO18 = Precipitation of Warmest Quarter, and 19: BIO19 = Precipitation of Coldest Quarter.

Table 2. A summary of the model performance of eight fitted methods generated using presence records for 12 reptile species in South Africa. The GBIF reference for each species is included in the reference section below.

Species names	Common names	BRT		CART		MARS		GLM		GAM		RF		SVM		Maxent	
		AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables
<i>Anolis sagrei</i>	Brown anole	1	18, 15	0.97	18, 2, 15	1	2, 8, 9	0.98	18, 2, 8	0.98	14, 2, 3	1	18, 2, 9	1	18, 2, 15	0.96	18, 8, 15
<i>Boa constrictor</i>	Red-tailed boa	0.96	3, 13, 8	0.92	3, 8, 19	0.95	3, 15, 14	0.92	8, 3, 18	0.95	3, 8, 9	0.99	3, 8, 13	0.95	3, 18, 8	0.93	3, 13, 8
<i>Boa constrictor imperator</i>	Colombian boa	0.97	3, 18, 19	0.92	3, 9, 18	0.97	3, 15, 14	0.92	9, 3, 18	0.97	15, 3, 8	1	3, 9, 18	0.98	3, 15, 19	0.92	3, 18, 15
<i>Chamaeleo calyptratus</i>	Veiled chameleon	0.98	18, 8, 13	0.89	8, 18, 2	0.99	3, 14, 15	0.92	18, 9, 2	0.96	18, 8, 2	1	8, 18, 14	0.97	18, 14, 8	0.99	13, 8, 18
<i>Eunectes notaeus</i>	Yellow anaconda	0.99	18, 4, 2	0.97	4, 18, 2	0.98	3, 10, 2	0.98	4, 3, 15	0.99	3, 18, 15	1	18, 4, 2	0.99	18, 10, 3	0.9	8, 4, 18
<i>Iguana iguana</i>	Green iguana	0.96	9, 13, 3	0.89	9, 8, 13	0.95	15, 3, 9	0.94	18, 9, 2	0.96	3, 15, 8	1	3, 9, 8	0.98	3, 9, 8	0.95	3, 9, 15
<i>Orthriophis taeniurus</i>	Beauty rat snake	0.99	19, 13, 8	0.98	3, 13, 19	0.99	3, 2, 4	0.98	4, 18, 3	0.98	3, 2, 4	1	9, 10, 8	0.99	15, 3, 13	0.99	3, 13, 18
Species names	Common names	BRT		CART		MARS		GLM		GAM		RF		SVM		Maxent	
		AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables	AUC	Variables
<i>Pantherophis guttatus</i>	Corn snake	0.98	14, 10, 4	0.96	14, 10, 8	0.98	14, 10, 3	0.95	4, 18, 3	0.98	4, 3, 13	0.99	10, 14, 18	0.99	10, 15, 3	0.9	10, 4, 3
<i>Python bivittatus</i>	Burmese python	1	18, 10, 8	1	18, 10, 4	1	4, 8, 3	1	4, 8, 3	0.99	4, 8, 19	1	8, 18, 4	1	18, 3, 13	1	10, 4, 8
<i>Python regius</i>	Ball python	0.98	10, 19, 13	0.96	13, 10, 19	0.98	4, 8, 19	0.93	4, 10, 3	0.95	3, 13, 2	0.99	19, 10, 13	0.97	19, 2, 8	0.9	13, 10, 19
<i>Crotalus atrox</i>	Western diamondback rattlesnake	0.98	3, 4, 18	0.96	3, 4, 19	0.99	3, 4, 15	0.95	2, 4, 3	0.99	3, 4, 18	1	3, 4, 8	0.99	3, 15, 14	0.96	18, 4, 8
<i>Trachemys scripta elegans</i>	Red-eared slider	0.95	19, 4, 10	0.88	19, 4, 10	0.95	3, 19, 10	0.87	4, 3, 15	0.96	4, 3, 2	1	4, 3, 10	0.97	4, 15, 10	0.95	4, 19, 10

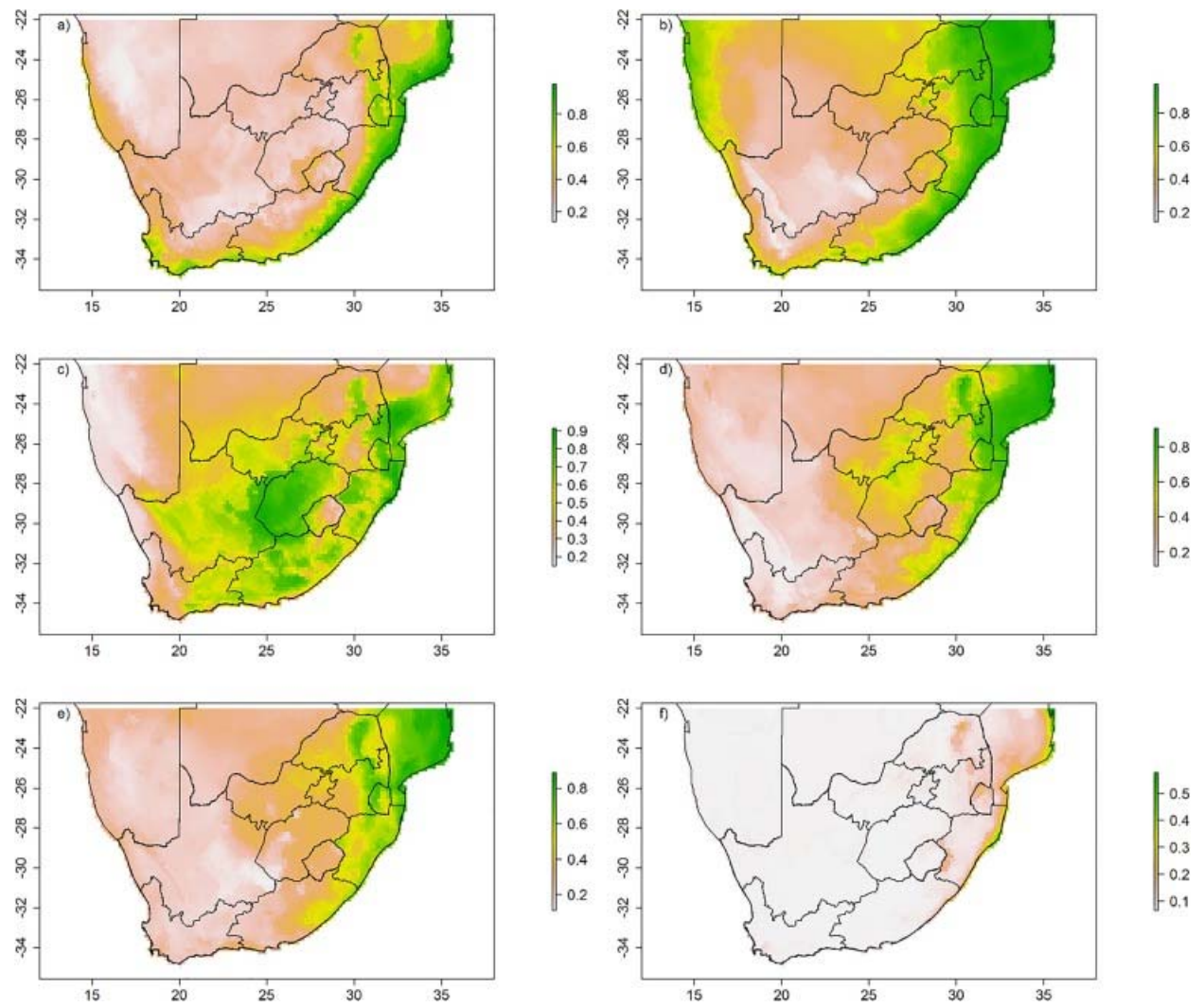


Fig. 6. The species distribution modelling showing predicted climatically suitable areas for a) *Anolis sagrei*, b) *Iguana iguanas*, c) *Pantherophis guttatus*, d) *Boa constrictor*, e) *Boa constrictor imperator*, and f) *Python bivittatus* in South Africa. (Note: The climatic suitability is shown by a colour ramp threshold on the right of each map; the strong green colour denotes more suitable areas).

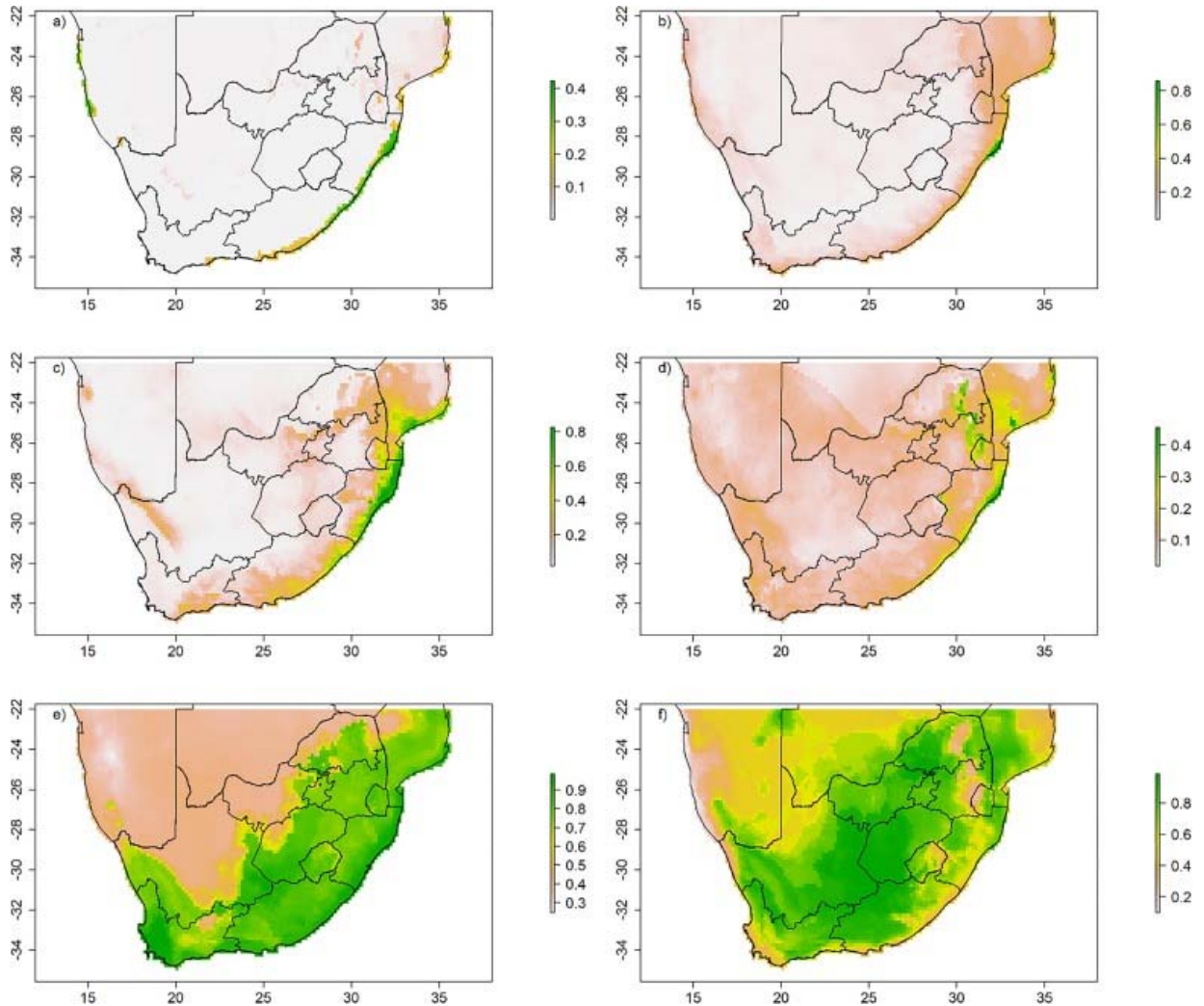


Fig. 7. The species distribution modelling showing predicted climatically suitable areas for a) *Orthriophis taeniurus*, b) *Python regius*, c) *Eunectes notaeus*, d) *Chamaeleo calyptratus*, e) *Trachemys scripta elegans*, f) *Crotales atrox* in South Africa. (Note: The climatic suitability is shown by a colour ramp threshold on the right of each map; the strong green colour denotes more suitable areas).

The projected climatic suitability areas for the yellow anaconda *Eunectes notaeus* were relatively low and occurred partly in the coastal areas of KwaZulu-Natal (Fig. 7c). The climatic suitability of this species was best described by the mean temperature of the warmest quarter (Bio 10) and precipitation of the coldest quarter (Bio 19) (Table 2). The predicted climatic suitability areas for the red-eared slider and western diamondback rattlesnake were relatively large, covering all South African provinces (Fig. 7e, f). The temperature seasonality (Bio 4), the mean temperature of warmest quarter (Bio 10) and isothermality (Bio 3) best described the suitability for these species (Table 2).

3.3.2. Future distribution

The results of this study showed that the present distribution of nine species would increase in the future, with the green iguana, corn snake, red-tailed boa, and red-eared slider predicted to gain more suitable areas in future (Supplementary Material Fig. S1 & S2). Our

analyses further revealed that some of these species would lose large areas of distribution, although they have gained suitability, e.g. red-eared slider and western diamondback rattlesnake. However, species such as the Colombian boa and ball python were predicted to lose the largest areas of distribution, while the beauty rat snake (*Orthriophis taeniurus*) showed no change in distribution in the future (Supplementary Material Fig. S3 & S4).

4. Discussion

4.1 vol. of trade

A study done by van Wilgen et al. (2010) recorded 275 species of reptiles imported to South Africa. This is far more than the number of pet reptiles recorded in this study. Our results recorded at least 88 reptiles sold as pets in South African online trade and pet stores. Although the number of species recorded by van Wilgen et al. (2010) was large, our study found 33 unique species not previously observed, suggesting new introductions to the reptile pet trade market. This may be explained by the fact that most species are poorly regulated; hence we found 22 species not listed on CITES, and van Wilgen et al. (2010) may have missed some of the species given the number of pet shops visited. It is noteworthy that the accumulation curve for reptiles showed no sign of reaching an asymptote for the two sources. This suggests that there might probably be many more species that we could have missed during our survey, given that some of the pet shops closed during the outbreak of the COVID-19 pandemic. In addition, species reported by van Wilgen et al. (2010) were recorded from other sources, including zoos, private traders, and government institutions such as the Department of Environment, Forestry and Fisheries (DEFF), Compliance and Enforcement Branches.

We found that KwaZulu-Natal, Gauteng, and Western Cape provinces had the highest number of pet stores and online advertising websites selling reptiles and subsequently recorded the highest number of reptiles sold than other provinces. Shivambu et al. (2021a) also found these provinces to have higher species abundance and richness of non-native small mammal species traded as pets. This suggests that the non-native trade in these provinces is dynamic. These provinces have international airports and excellent road access to all parts of South Africa and other countries such as Botswana, Mozambique, and Zimbabwe. In addition, the Western Cape (Cape Town, Mossel Bay and Saldanha Bay) and KwaZulu-Natal (Richards Bay and Durban) also have commercial seaports (harbours). All the aforementioned varied routes are more likely to promote the importation, transportation and subsequently, the trade of reptiles in South Africa (Edmunds et al., 2011). Additionally, the high diversity of reptile species recorded in these three provinces could also be attributed to these provinces' relatively high economic status and population rate (STAT SA, 2019). Previous studies have linked non-native species' trade to economic status and human population growth (Edmunds et al., 2011, Shepherd et al., 2007, Smith et al., 2017). It is known that some cultural factors often influence how people interact with reptiles (Alves and Rosa, 2010, Alves et al., 2019). For example, some cultures hate snakes and often associate them with evil. We suspect that this might be among the reasons for the fewer pet stores and reptiles recorded in some provinces such as the Northern Cape and Limpopo. Of most concern, the high demand for pets because of the ever-growing human population (Lockwood et al., 2019) and as living standards improve (Ding et al., 2008, Alves et al., 2010)

may increase the likelihood of non-native species becoming established and subsequently invasive. This is concerning for species with a history of invasion elsewhere and/or popular in the pet trade, e.g. corn snakes and Burmese pythons.

Many studies, such as for invertebrates (Nelufule et al., 2020), small mammals (Shivambu et al., 2021a), and tarantulas (Shivambu et al., 2020b), found that the online trade had the highest number of species compared with physical pet stores. However, we predicted that more reptile species would be recorded in physical pet stores when compared with online sales since pet stores are more likely to sell different species and in high abundance. Our prediction was supported as we found that physical pet stores had higher reptile species richness and abundance than online advertising websites selling pet reptiles. The relatively low reptile species abundance and richness of the online trade could be explained by the fact that private owners or hobbyists are likely to own one or two species while breeders and pet shops sell different species in abundance, especially when they are in demand. We found that there were differences in species composition between the two sources. A total of 10 reptile species were only found in pet stores and not online. In addition, most of the recorded native species were sold or advertised for sale on online advertising websites, while most non-native species were recorded in physical pet stores. This could be explained by many of the traders in the online trade likely sell or advertise species that they had caught in the wild (e.g. people trying to sell an animal they find in their garden or a natural area), while pet stores generally specialise in non-native species that are imported. This explains the necessity to record species from numerous sources to understand the pet trade's extent comprehensively.

4.2. Most popular species

Considering the number of pet reptiles recorded in this study, our results revealed that snakes were the most preferred reptilian taxon as pets, followed by lizards and turtles or tortoises. The popularity of snakes in the pet trade industry has also been reported in other countries such as Indonesia (Natusch & Lyons, 2012), Japan (Wakao et al., 2018) and Brazil (Alves et al., 2019). Our results were comparable to other studies where it was found that the most traded species were available in large volumes and often available for purchase (Shivambu et al., 2021a, Siriwat et al., 2019, Su et al., 2015, Vall-llosera and Cassey, 2017). We also noted that the most traded pet reptiles were sold at relatively lower prices than other species. It is known that species with high availability and sold at low prices are more likely to be released or escape into the wild than expensive and rare species (Stringham and Lockwood, 2018, Lockwood et al., 2019). We also found that one of our native species, the leopard tortoise *Stigmochelys pardalis*, is among the country's most traded reptiles. To find this species in high numbers in the South African pet trade is highly concerning as it is amongst those that are easy to collect, profitable, require less specialised care (Lockwood et al., 2019) and is of high interest in the international trade (Auliya et al., 2016). All these may lead to an increased level of collection or poaching of this species in the wild, which may lead to a reduced population or local extinctions of this species. In addition, the trade regulation in each of the South African provinces prohibits the sale of native species (van Wilgen et al. 2010; <https://cer.org.za/virtual-library/legislation/provincial>). The Burmese python and two other species (red-eared slider and green iguana) that were recorded in our study are listed amongst the world's worst invasive species (Herrel & van der Meijden,

2014), yet the Department of Environmental Affairs in South Africa continue issuing permits for breeding, selling, transporting, and keeping these species as pets (van Wilgen et al., 2010, Moshobane et al., 2020). This outlines the importance of monitoring the trade of reptiles in South Africa to ensure compliance after permits are issued.

It is noteworthy that we recorded only 32 CITES-listed species representing 36% of all reptiles recorded in this study. Consequently, most species (64%) present in the South African reptile pet trade are not protected by international trade regulations. We further found that amongst the 12 South African native species recorded, nine were non-CITES, and six of those were not evaluated by the IUCN. Despite the prohibition of trade in native species by the National Environmental Management: Biodiversity Act (NEM: BA) of 2004 (<https://cer.org.za/virtual-library/legislation/provincial>), some of the native species recorded in this study, including wild-caught animals such as the leopard tortoise, are in high demand in the international trade and have been exported outside the country as live animals (Auliya et al., 2016). This may threaten many of South Africa's native wild reptile populations, as it has already been observed in other regions. For example, at least 21 species have had their wild populations destroyed by collectors or poachers to support the pet trade industry in Europe (Auliya et al., 2016, Marshall et al., 2020), while many other species' wild populations have declined significantly (Schlaepfer et al., 2005). Exporting South African native species to other countries may also pose serious conservation, health, and social challenges to those countries as some of these species are highly venomous, e.g. eastern green mamba *Dendroaspis angusticeps*. Moreover, some South African native reptiles may also pose an invasion risk to other countries as accidental escapes, and intentional releases are possible. The Burmese python may also pose a hybridisation risk for South African native python species if it should establish feral populations. For example, the Burmese python has been reported to breed with Indian python *Python moralus* in Florida (Nifong 2008). Again, NEMBA listed the hybrids of South African python *Python natalensis* and Indian python (DEA, 2016), and this may pose a threat to the gene pool of native python species. Therefore, the presence of these species in the South African pet trade industry outlines the gaps that exist in conservation assessments and the South African legal system. In addition, non-CITES and species not evaluated by the IUCN can be easily traded within and outside the country without producing any permit, given that no population data and trade regulations protect them (Marshall et al., 2020). This is further fueling the trade in these reptile species and may threaten their survival and wild populations.

4.3. Climatic suitability

We predicted that reptile species with high availability in the pet trade and extensive occurrence records would have wider climatic suitability distribution than rare species with relatively small occurrence records. In our study, the corn snake (high availability in the trade), red-eared slider, and western diamondback rattlesnake with extensive occurrence records had larger climatic suitability distribution ranges. These species represent the most serious threat to South African wildlife as they showed a wider potential distribution in South Africa. In addition to an extensive climatic suitability distribution range, the corn snake was the second most traded species and recorded in eight provinces of South Africa. Consequently, our future predictions suggest that this species will potentially gain a large suitable area in the future. Additionally, this species has been observed outside captivity in

the Bellville and Durbanville suburbs of Cape Town, Western Cape Province (W. Schmidt pers. comm.). This is highly concerning as this species has been declared a major threat to vulnerable Cuban treefrogs *Osteopilus septentrionalis* (Meshaka, 2011). We suspect that this species may also threaten some of South Africa's native frog species. Furthermore, the present geographical distribution of the invasive red-eared slider and western diamondback rattlesnake will increase significantly in the future, covering most parts of South Africa. The invasive red-eared slider and red-tailed boa present high risks of colonising many parts of South Africa in the future. These species have colonised many parts of the world, including the USA (Florida), China (Beijing), and three localities (Doñana, Acebuche, and Portil) in southwestern Spain (Hidalgo-Vila et al., 2011, Reed et al., 2012, Sinclair et al., 2020, Zhang et al., 2020), and have caused significant impacts in those areas after they have successfully colonised them. In addition, the latter species have a history of invasion elsewhere and are causing significant environmental and socio-economic impacts in invaded environments (Perry et al., 2003, Burger, 2009, Willson et al., 2011). This further suggests that these reptile species have a relatively high potential of establishing, becoming invasive and causing environmental and socio-economic impacts in South Africa should they be released or escape into the wild.

Some species, such as Burmese pythons and ball pythons, had the lowest climatic suitability despite extensive occurrence records. This is because the present distribution of these species does not fully cover relatively large extents and thus might have limited the distribution predictions for these species. It is worth noting that the AUC values for the models of these species were very high, indicating that the distribution patterns for these species are explained by climatic variables. Therefore, based on our predictive models, these species' invasion risk is relatively low in South Africa. However, although the Burmese python was amongst the most traded species, it can grow into a larger body size, and many studies have linked these with increased chances of being introduced (van Wilgen et al., 2010, Stringham and Lockwood, 2018). When predicting their future geographical distribution, we found that there were finer differences in comparison with the present distribution. Additionally, our model suggests that the Colombian boa and ball python present a high potential risk of suitability in many parts of South Africa in the future.

Our analysis further revealed that most of the species modelled in this study might persist in the future. These include two of the world's worst invasive species, the green iguana and Burmese python. We suspect that this is because some of these species can tolerate a wide range of environmental conditions and thus may quickly adapt and persist in new environments (Bodensteiner et al., 2021). Additionally, some species have high reproductive output, opportunists (they feed on everything available), large body sizes, aggressive behaviour and inhabit a wide range of habitats (van Wilgen et al., 2010, Reed et al., 2012, Orzechowski et al., 2019). All these could influence the persistence of these species in South Africa in the future.

4.4. Conclusions and recommendations

Our results revealed that the trade in live reptiles in South Africa involves many species, including endangered, native, non-CITES listed and invasive species with high risks of posing serious impacts on the native biodiversity, economy and human health. We, therefore,

recommend strict legislation and enforcement from a national level to a provincial level. Moreover, existing pet trade regulations should be revised accordingly by policymakers working with pet owners, breeders, and the pet trade industry to include a more restricted trade of invasive pet species with high potential impacts and invasion risk. For example, the red-eared slider, western diamondback rattlesnake and corn snake. Our results suggest that we could have missed some reptile species during our survey, given the list of reptiles reported by van Wilgen et al. (2010) and the impact of the COVID-19 regulations. Therefore, we recommend that the reptile pet trade be constantly monitored to get a complete picture of the extent of this trade in South Africa. This could be achieved by microchipping all pet species and keeping an online registry at the Department of Environment, Forestry and Fisheries, which would help monitor the number of individuals and species bred and sold as pets and their causes of death.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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