Assessing the trade of reptile species in the South African pet trade

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GENERAL ABSTRACT

Despite the negative impacts that the pet trade has on the native and non-native biodiversity, economy and human health, the research suggests that the demand for pets and the extent of trade in live animals as pets has increased dramatically over the years. As a result, many species, including reptiles, have been translocated and introduced into new or non-native environments. Some of these have established feral populations, become invasive and are causing significant environmental and socio-economic impacts on non-native environments. Reptiles are among the most popular groups of animals in the pet trade industry globally. Trade in pet reptiles in South Africa is large and one of the major pathways through which non-native species, including invasive species, are introduced into the country. Despite this, little is known about the dynamics of the wildlife trade in pet reptiles globally. To understand the dynamics of the global trade in pet reptiles, we carried out a comprehensive literature search to gather relevant information from reptile pet trade-based publications. We further compiled a list of traded pet reptiles from all South African physical pet stores and online advertising websites to determine which species are traded, pose an invasion risk and have potential environmental and socio-economic impacts.

We found a total of 39 publications based on the reptile pet trade from 1994 – 2021 worldwide. Our analyses revealed that the research effort was not uniform globally, with the majority (63.6%) of all relevant studies originating from three continents (Asia, Europe, and North America). Moreover, the United States of America (North America) and Indonesia (Asia) produced the greatest research outputs (12.1% each) compared with other countries across the world. We found at least 1140 reptile species belonging to 60 families involved in the global pet trade, with invasive red-eared slider *Trachemys scripta elegans* being the most frequently studied species (number of studies = 23/39). Of the recorded species, at least 79 are invasive, 46 endangered, 29 critically endangered, while only 546 are CITES-listed.

In terms of reptile species sold in South Africa, we recorded a total of 2771 individuals representing 88 unique reptiles, 69 from physical pet stores and 18 from online advertising websites. KwaZulu-Natal, Gauteng and Western Cape Provinces had the highest number of pet stores and online advertising websites; therefore, they subsequently recorded the highest number of pet reptiles compared with other provinces. Physical pet stores were found to have the highest number of species compared to online trade. Of the recorded species, 76 are non-native, and 15 of these are invasive to South Africa. Moreover, only 32 pet reptiles are listed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). For current distributions, 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. Some species, such as Burmese pythons *Python bivittatus,* showed low invasion risk based on climatic suitability. However, given their large body size, history of invasion and their popularity in the pet trade, they are most likely to escape or be released from captivity and become invasive.

A total of 76 reptile species were assessed for environmental and socio-economic impacts using the Generic Impact Scoring System (GISS), Environmental Impact Classification for Alien Taxa (EICAT), and Socio-Economic Impact Classification for Alien Taxa (SEICAT). Using GISS, we found that 13 species had environmental impacts (E_GISS), while 11 species had socio-economic impacts (SE_GISS). For EICAT and SEICAT, 13 species had environmental impacts, and eight had socio-economic impacts, respectively. The most popular pet species, red-tailed boa *Boa constrictor*, green iguana *Iguana iguana*, *P. bivittatus*, *T. elegans*, and central bearded dragon *Pogona vitticeps* had impacts in all the three scoring schemes. The later species and corn snake (*Pantherophis guttatus*) scored the highest for all impact schemes. Species sold in high numbers, with large climatically suitability and potential impacts, are more likely to establish feral populations and become invasive should they escape or be released from captivity. We, therefore, recommended that the trade in pet reptiles should be constantly monitored to avoid new introductions and the implications that the pet trade may have to the country.

PREFACE

The data described in this thesis were collected from various online websites and physical pet shops around South Africa from January 2020 to December 2020. This work was carried out while registered at the School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, under the supervision of Prof Colleen T. Downs and Co-supervision of Dr Tinyiko C. Shivambu and Dr Ndivhuwo Shivambu.

This thesis, submitted for the degree of Master of Science in Ecological Sciences in the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, School of Life Sciences, Pietermaritzburg campus, represents original work by the author and has not [illegible]nitted in any form for any degree or diploma to any University. Where use [illegible]e work of others, it is duly acknowledged in the text.

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Asekho Mantintsilili

November 2021

We certify that the above statement is correct, and as the candidate's supervisors, we have approved this thesis for submission.

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DECLARATION 1 – PLAGIARISM

I, Asekho Mantintsilili, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a. Their words have been re-written, but the general information attributed to them has been referenced
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DECLARATION 2 - PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis.

Publication 1: Provisionally accepted in Conservation Biology

A review of the global reptile species trade

Asekho Mantintsilili, Ndivhuwo Shivambu, Tinyiko C. Shivambu & Colleen T. Downs

Author contributions: AM conceived paper with TCS, NS, and CTD. AM collected and analysed the data. AM wrote the paper, while TCS, NS and CTD contributed valuable comments to the manuscripts.

Publication 2: Published in Journal of Nature Conservation (https://doi.org/10.1016/j.jnc.2022.126154)

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

Asekho Mantintsilili, Ndivhuwo Shivambu, Tinyiko C. Shivambu & Colleen T. Downs

Author contributions: AM conceived paper with TCS, NS, and CTD. AM, TCS and NS collected and analysed the data. AM wrote the paper, while TCS, NS and CTD contributed valuable comments to the manuscripts.

Publication 3: In review (Biological Invasions)

Assessing the potential impacts of exotic reptile species advertised for sale in the South African pet trade

Asekho Mantintsilili, Tinyiko C. Shivambu, Ndivhuwo Shivambu & Colleen T. Downs

Author contributions: AM conceived paper with TCS, NS, and CTD. AM collected the data and analysed the data with TCS and NS. AM wrote the paper, while TCS, NS and CTD [illegible] comments to the manuscripts.

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Lastly, I would like to thank the Lord, my saviour, for the strength, courage and ability to complete this work. If it was not for His mercies, I would not have completed this thesis. To God, be the glory!

“*The wolf shall dwell with the lamb, and the leopard shall lie down with the kid, and the calf and the young lion and the fatling together; and a little child shall lead them. They shall not hurt nor destroy in all my holy mountain: for the Earth shall be full of the knowledge of the Lord.*” (*Isaiah 11: 6*)

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CHAPTER 1

General introduction

1.1 Introduction

1.1.1 Global pet trade

The ever-increasing human population, globalisation, and the desire to keep pets have resulted in the translocation of many wildlife species into new or non-native environments through illegal and legal trade (Hulme, 2009; Fong and Chen, 2010; Siriwat and Nijman, 2018; Lockwood et al., 2019). Keeping live animals as household companions, ornaments or for entertainment is extremely widespread and is continuously growing in popularity worldwide as the living standards improve (Bush et al., 2014; Measey et al., 2017; Lockwood et al., 2019). It is argued that even if the demand for pets remains stable globally, the growing human population and expanding middle class will result in the growing demand for pets (Lockwood et al., 2019).

The legal and illegal pet trade is a multimillion-dollar industry estimated at US$300 billion per annum (Smith et al., 2017). As a result of this, the desire to sell, breed and own pets have increased across the world (Lockwood et al., 2019). It is suspected that the general increase in the demand for these pets can be explained by the fact that they are diverse, colourful, charismatic, and relatively cheap to maintain (Bauer, 1998; Gupta et al., 2007; van Wilgen et al., 2008; Monvises et al., 2009; Pinthong et al., 2013). The global pet trade involves many species of fishes, mammals, amphibians, birds, invertebrates, and reptiles (van Wilgen et al., 2010; Su et al., 2016; Chucholl and Wendler, 2017; Maligana et al., 2020; Shivambu et al., 2020a, b; Nelufule et al., 2020). Amongst these, birds, fishes, and reptiles dominate the global pet trade (Green et al., 2020; Gippet and Bertelsmeier, 2021). The global pet trade industry involves approximately 350 million live animals per annum (Karesh et al., 2005). It is further estimated that at least 43 of the non-native reptiles have established feral populations in Florida as a result of pet trade release and escapes (Meshaka, 2011; Prestridge et al., 2011).

1.1.2 Sources of pet trade

Online trade and physical pet stores are two of the pathways by which many species are traded in different countries (Kikillus et al., 2012; Su et al., 2016; Nelufule et al., 2020). Until recently, online has become the most dominant source of many wildlife species trade, including reptiles (Lavorgna, 2015; La Laina et al., 2021). Among the most obvious reasons for this is that the online platform offers many advantages to sellers and buyers, such as reducing advertising costs and allowing people to hide their identities, especially when selling illegal specimens (La Laina et al., 2021). This has resulted in difficulties in tracking or monitoring species advertised on online platforms (Runhovde, 2018). Poor monitoring of the pet trade often leads to the establishment success of several non-native species and the decline of native biodiversity (Shiau et al., 2006; Jeschke et al., 2014; Lockwood et al., 2019). For example, the invasive Burmese python *Python bivittatus* was introduced through pet trade in Florida and has become the most disastrous invasive species causing significant environmental and socio-economic impacts on the native biodiversity and humans (Willson et al., 2011).

1.1.3 Pet trade and its associated impacts

1.1.3.1 Biodiversity loss

The pet trade is presently regarded as one of the major causes of the decline of many wildlife populations (Symes et al., 2018; Morton et al., 2021). Of most concern, the global pet trade involves many specimens, including threatened species that may subsequently go extinct if heavily traded (Flecks et al., 2012; Siriwat and Nijman, 2018; Frank and Wilcove, 2019). 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 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). Furthermore, the critically endangered spider tortoise *Pyxis arachnoides brygooi* endemic to Madagascar has also been reported to be declining in numbers as a result of the illegal pet trade (Walker, 2010).

1.1.3.2 Introduction of invasive species

Several species have accidentally escaped or deliberately released by humans from captivity into the wild, where they have caused severe economic and socio-economic impacts (Mazzotti and Harvey, 2012; Pearson et al., 2015; Burgos-Rodríguez et al., 2016; Shivambu et al., 2020c, d). Possible reasons for pet owners to abandon their pets in the wild include lack of proper housing, high maintenance in medication and food (Grant et al., 2017; Harrington et al., 2019). Other reasons include aggressive temperaments, fear of zoonotic diseases, and species growing into larger sizes (e.g. Burmese python and yellow anaconda *Eunectes notaeus*) (Benning, 2002; Reaser and Meyers, 2007; Stringham and Lockwood, 2018). Once some of these species become invasive, they compete for resources with native species, e.g. invasive brown anole *Anolis sagrei* has been reported to compete with native green anole *A. carolinensis* for resources (Stuart et al., 2014). The corn snake *Pantherophis guttatus* has been reported to heavily predate on the vulnerable Cuban treefrogs *Osteopilus septentrionalis*, while the Burmese python has been responsible for the decline of native birds and mammals in Florida through predation (Benning, 2002; Meshaka, 2011; Hoyer et al., 2017). In addition, some of the reptile species have been cited in the outbreak of zoonotic diseases; for example, the outbreak of Salmonella has been linked to pet reptiles (Fuller et al., 2008; Centers for Disease

Control and Prevention, 2018; Vrbova et al., 2018; Can et al., 2019). The invasive green iguana *Iguana iguana* has been reported to be damaging and destroying crops, infrastructure (e.g. seawalls, canals, etc.), and gardens (Krysko et al., 2007; Merrick et al., 2016; Rivera-Milán and Haakonsson, 2020).

1.1.4 Impact assessment for non-native species

Despite the well-known negative impacts that are associated with non-native species, the global trade in wildlife species, including invasive species, continues to grow at an alarming rate (Brunel et al., 2013; Patoka et al., 2018; Lockwood et al., 2019). The demand for pets is no exception to this growing trend which will further facilitate the spread of invasive species to invade new environments (Bush et al., 2014; Moorhouse et al., 2017; Gippet and Bertelsmeier, 2021; Olden et al., 2021). To prevent the introduction and spread of invasive species, many countries have adopted impact assessment and species distribution modelling as preventive measures for potentially invasive species (van Wilgen et al., 2008; Lodge et al., 2016; Shivambu et al., 2020c). Impact assessment protocols have been recently developed, successfully used for many species, and proved useful when identifying and prioritising species that should be prevented (Kumschick and Nentwig, 2010; Patoka et al., 2014; Marr et al., 2017; Shivambu et al., 2020c). Several studies have used species distribution modelling as a rapid screening tool to determine areas that are at risk of invasion (Thuiller et al., 2004; Giovanelli et al., 2008; Jiménez-Valverde et al., 2011; Keller and Kumschick, 2017; Shivambu et al., 2020c). The species distribution modelling (SDMs) uses the present occurrence records to predict organism’s climatic suitability (Elith and Leathwick, 2009; Di Febbrano et al., 2013). Combining impact assessment and SDM is vital in identifying and prioritising introduced species with the potential of becoming invasive.

1.1.5 Pet trade in South Africa

South Africa is one of the African countries involved in the wildlife trade, although its pet trade is still young and growing (van Wilgen et al., 2010). There is a growing number of non-native species in the South African pet trade, for example, amphibians (Measey et al., 2017), reptiles (van Wilgen, 2010), small mammals (Maligana et al., 2020; Shivambu et al., 2021e), invertebrates (Nelufule et al., 2020; Shivambu et al., 2020b), and gastropods (Shivambu et al., 2020a). Native species are also traded in the country and exported, for example, rodents such as the southern multimammate mouse *Mastomys coucha*, several bird species, and reptiles (Warchol, 2007; Shivambu et al., 2021e, f). Some of these species are prohibited from trade and are listed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES, 2021), suggesting that their trade should be strictly regulated. In South Africa, the trade in wildlife species is regulated by the National Environmental Management: Biodiversity Act (NEM: BA) of 2004 (DEA, 2016). This act prohibits the sale of both native and non-native species, e.g. Southern African python x Burmese python *Python natalensis* x *Python molurus*, common boa *Boa constrictor* and European pond turtle *Emys orbicularis* (DEA, 2016). Reptiles are among the most popular animal taxa in the South African pet trade industry (van Wilgen et al., 2010; Shivambu et al., 2021f). These species are traded for various reasons, including profit, breeding, and fun.

1.2 Study motivation

The overexploitation of reptile species from the wild and the impacts caused by the global illegal and legal trade to the native biodiversity, economy and human health are the motivation for the present study. There are approximately 295 records of reptile species present in the South African trade industry (van Wilgen et al., 2010). Some of these are known to be invasive and cause significant environmental and socio-economic impacts elsewhere. For example, Burmese python in Florida and red-eared slider *Trachemys scripta elegans* in many parts of the world (Lever, 2003; Willson et al., 2011; Lockwood et al., 2019). Moreover, some non-native reptile species involved in the pet trade have been associated with the spread of zoonotic diseases to other species and human (Sanyal et al., 1997; Nagano et al., 2006). Furthermore, research has also shown that the global pet trade involves many species, including those protected under CITES, because of their declining numbers in the wild (Walker, 2010; Lyons and Natusch, 2011). It is possible that some of the traded species may go extinct in future as the global trade in pet reptiles is growing at an alarming rate. Therefore, there is an urgent need to assess the global and national (South Africa) trade in reptiles to avoid the aforementioned consequences of the pet trade.

1.2 Study aims and objectives

The main aim of this study was to determine the extent of trade in reptile species globally, and their potential distribution in South Africa, environmental and socio-economic impacts. The study had four main objectives:

1. Review the global literature on the reptile pet trade industry to understand the research effort globally and the magnitude of the global pet trade. We predicted that there will be an increase in the number of studies focusing on the reptile pet trade in the present decade as the reptile pet trade is increasingly becoming a popular hobby worldwide (Lockwood et al., 2019).
2. Survey the two sources of pet trade (physical pet shops and online websites) to understand the extent of trade in reptile species in South Africa. Describe the reptile trade market in terms of species availability and prices. We predicted that physical pet stores would have more species available than online trade, and popular species will be available on both platforms than less available species.

3. Conduct species distribution modelling to determine climatically suitable areas for non-native reptile species sold as pets in South Africa. We predicted that species with high availability in both sources of trade and large occurrence records would have wider climatic suitability distribution compared with species with relatively small occurrence records.
4. Use the Generic Impact Scoring System (GISS), Environmental Impact Classification for Alien Taxa (EICAT), and Socio-Economic Impact Classification for Alien Taxa (SEICAT) to assess the potential environmental and socio-economic impacts associated with non-native reptile species sold as pets in South Africa. We predicted that there would be a variation between the impact mechanisms of non-native reptile species sold as pets. We also predicted that there would be a relationship between species popularity and impact magnitude.

1.3 Thesis outline

This study consists of five chapters. Of these, three chapters are data chapters (2, 3 and 4) that can be read independently. Each data chapter is formatted according to the peer-reviewed journal it has been submitted to and in review. One data chapter has been provisionally accepted, while the other two are under review. Because of the format of this thesis, there are some overlaps and repetitions that were unavoidable. The chapters are as follows:

1. Chapter 1: General introduction
2. Chapter 2: A review of the global reptile species trade
3. Chapter 3: Online and pet stores as sources of trade for reptilian species in South Africa
4. Chapter 4: Assessing the potential impacts of exotic reptile species advertised for sale in the South African pet trade
5. Chapter 5: General discussions and conclusions.

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CHAPTER 2

A review of the global reptile species trade

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Running header: Global reptile species trade

Article impact statement: Globally, there are concerns about the impacts of trade in species, and here we highlight reptiles traded in the pet industry and online.

2.1 Abstract

Wildlife trade has increased significantly and is listed among the greatest threat to biodiversity. The reptile pet trade is no exception to this increasing trend. Although the reptile pet trade has been relatively studied in many parts of the world, the sparsity of this research, more especially in developing countries, remains the biggest challenge in understanding important dynamics of the global reptile pet trade. To understand this, we carried out a comprehensive literature search to gather relevant information from reptile pet trade-based publications. We evaluated reptile pet trade-based studies from 1994 – 2021 to examine the trends in the taxonomic and geographical focus of peer-reviewed publications worldwide. Our results revealed that studies focusing on the reptile pet trade had increased enormously in recent decades. Reptile pet trade-based studies published in the last decade have doubled the number published from 2000 – 2010. We found research effort was not uniform globally, with the majority (63.6%) of all relevant studies originating from three continents (Asia, Europe, and North America). Moreover, the United States of America (North America) and Indonesia (Asia) produced the greatest research outputs (12.1% each) compared with other countries across the world. We further found that at least 1140 reptile species belonging to 60 families are involved in the global pet trade, with invasive red-eared slider *Trachemys scripta elegans* being the most frequently studied species (number of studies = 23/39). Our study illustrates that the research effort is not uniform globally and that most are concentrated in developed countries. Therefore, we recommend that more studies be conducted, especially in understudied regions, to give a complete picture of the global reptile pet trade and its extent.

Keywords: Literature review, reptiles, wildlife trade, continents, impacts

2.2 Introduction

Globally, the wildlife pet trade has substantially increased over the years and is regarded as one of the major threats to many of the world's wildlife ecosystems (La Laina et al., 2021; Pragatheesh et al., 2021). The wildlife trade in reptiles is no exception to this increasing trend (Auliya et al., 2016; Hierink et al., 2020; Pragatheesh et al., 2021). This has allowed many exotic species to be translocated for purposes such as food sources, medicinal purposes, ornamentals and pet trade (van Wilgen et al., 2012; Kopecký et al., 2013; Yen & Ro, 2013; Marshall et al., 2020). Consequently, some of these introduced species have become established in many parts of the world, where they have caused significant impacts on native ecosystems and have led to the extinction of many native species around the world (Su et al., 2016; Lockwood et al., 2019; Mohanty & Measey, 2019). For example, the Burmese python *Python bivittatus* has been reported to negatively impact native biodiversity in Florida, United States of America (USA) (Dove et al., 2011; Reed et al., 2012). In addition, some of the reptile species have become threatened because of the increased under-regulated global trade (Altherr & Lameter, 2020; Marshall et al., 2020; Toomes et al., 2021). It has been reported that ~59 reptile species are critically endangered because of the global reptile trade (Marshall et al. 2020).

Physical pet stores and the internet are the two major platforms through which many of the world's species are advertised and sold as pets (Su et al., 2016; Nelufule et al., 2020). Until recently, the internet and other online advertising websites have become the most dominant source of many traded species, including reptile species (Lavorgna, 2015; La Laina et al., 2021). This is because online platforms provide many advantages to sellers and buyers, such as reducing advertising costs and allowing people to hide their identities, especially when dealing with illegal specimens (La Laina et al., 2021). As a result, online trade has been identified as an important platform to document the magnitude of the trade industry (Vaglica et al., 2017; Jensen et al., 2018; Pragatheesh et al., 2021).

Although the wildlife trade industry contributes enormously to the global economy, many studies have illustrated an inverse relationship between the trade of wildlife species and species diversity (Rao et al., 20211; Symes et al., 2018; Morton et al., 2021). This is caused by an intense extraction of live animals from the wild to support the ongoing trade and the translocation of species into new or non-native environments (Lockwood et al., 2019; Marshall et al., 2020; Harrington et al., 2021). In addition, the wildlife trade, in particular, has been highly linked with the introduction of new infectious diseases and viruses in humans and native biodiversity (Falcón et al., 2013; Mendoza-Roldan et al., 2020; Pragatheesh et al., 2021). For example, the green iguana *Iguana iguana* was reported to be the source of infection in many cases of human salmonellosis in Japan (Nakadai et al., 2005).

The research focused on the dynamics of the reptile trade industry has been fundamental to policymakers, conservation strategies, and broadening the scope of understanding the reptilian trade. However, the sparsity of this research, especially in developing countries, remains the biggest challenge. This, therefore, reveals an existing gap in understanding the research effort and magnitude of the global reptile trade industry. To fully understand these gaps, we assessed the existing literature on reptile trade worldwide to understand the trends of the taxonomic and geographical focus of peer-reviewed publications around the world. We expected a dramatic increase in the number of studies focusing on the reptile pet trade in the present decade as the reptile pet trade is increasingly becoming a popular hobby worldwide (Lockwood et al., 2019).

2.3 Methods

We conducted a comprehensive literature search to gather existing information on the reptile pet trade worldwide. In addition to the list of reptile species we compiled from South African pet shops, we compiled data from relevant peer-reviewed published using Thomson Reuters' Web of Science database (https://apps.webofknowledge.com), Google (https://www.google.com/), Google Scholar (https://scholar.google.com/), Web of Science (https://clarivate.com/), Wiley Online Library (https://onlinelibrary.wiley.com/), the Global Invasive Species Database (GISD: www.iucngisd.org/gisd), and the Centre for Agriculture and Biosciences International (CABI: www.cabi.org/isc). We used search phrases such as "*reptilian pet trade*", "*reptile species sold as pets*", "*reptiles for sale*", and "*global trade in reptiles*". In addition, country names in combination with reptile trade (e.g. "*reptile trade in South Africa*", "*reptile trade in Germany*", etc.) were also used to search for reptile pet trade-based studies. Publications were incorporated in the analysis if they represented a reptile pet trade-based research. Comments, editorials, letters, and book reviews were excluded from the analysis while the review papers were incorporated (Magle et al., 2012).

We refined searches on Google Scholar and Web of Science by countries belonging to different continents (Africa, Asia, North America, South America, Europe, Australia, and Oceania). Journal articles that met the requirements of this review were tabulated by the continent and country in which the study was conducted (Supplementary information Tables S2.1 and S2.2). We carried out additional searches to uncover all other potentially relevant literature that might not be found on database searches. We went through all reference sections of relevant peer-review published articles to look for other potentially relevant articles. All the potentially relevant articles were then searched manually using the Google Scholar search engine. We gathered all these data and used descriptive statistics to show the trends.

2.4 Results

2.4.1 Publications

We found a total of 39 publications from 1994 – 2021 that met the requirements of this review (Supplementary information Table S2.1). Our results showed that published studies on the reptile pet trade have increased since 1994 (Fig. 2.1). Globally, before 2000, we found three studies that focused on the reptile pet trade. We noticed a dramatic increase in the number of studies focusing on the reptile pet trade in the subsequent decades (2000 – 2009 = 6; 2010 – 2019 = 22). In the present decade, we found eight studies so far that focused on the reptile pet trade.

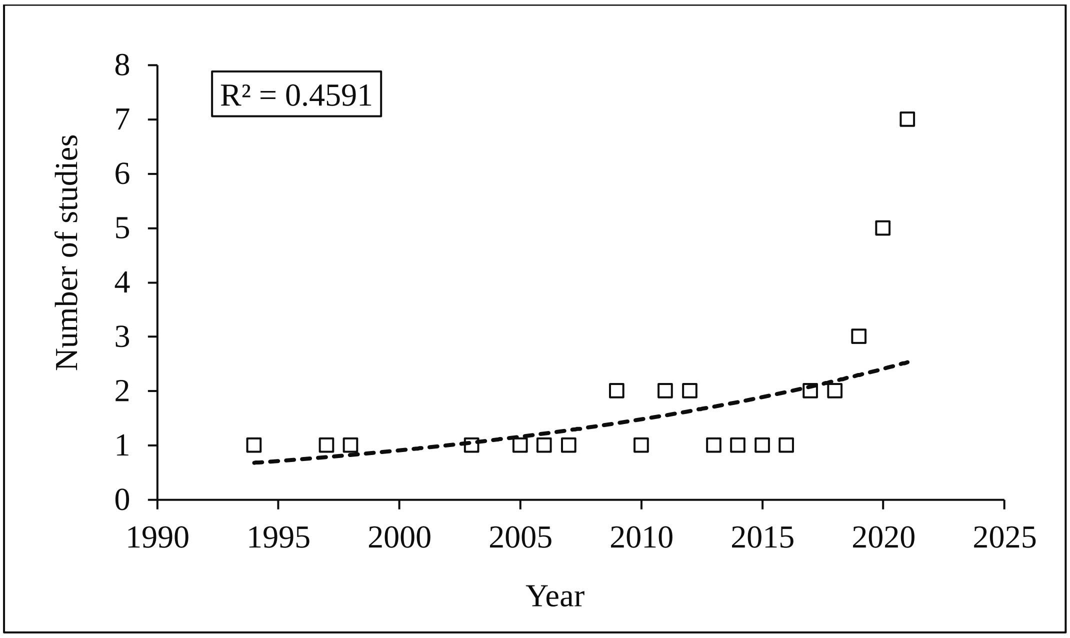

Figure 2.1. Percentage of all studies focusing on the reptile pet trade from 1994 to 2021. Data were presented as the proportion of the total number of studies that met the requirements of this review. An exponential function trendline indicates increasing publication capacity ($y = 5E\text{-}43e^{0,0487x}$).

2.4.2 Geographic focus

We found that studies focusing on the reptile pet trade were disproportionally conducted globally. A large proportion of studies were conducted in Asia (10/39, 25.6%), Europe (7/39, 18.0%), and North America (7/39, 18.0%), followed by Africa (5/39, 12.8%), Australia (4/39, 10.3), and South America (4/39, 10.3%). Oceania had fewer studies conducted compared with other continents (2/39, 5.1%) (Fig. 2.2). When comparing countries in terms of producing the greatest research output from each continent, we found that Togo produced the greatest research output (three publications (60.0%)) in Africa. Other countries were the USA (North America) four studies (50.0%), Indonesia (Asia) five studies (50.0%), Australia (Australia) three studies (75.0%), Germany (Europe) three studies (75.0%), and Brazil (South America) three studies (100%) (Fig. 2.3).

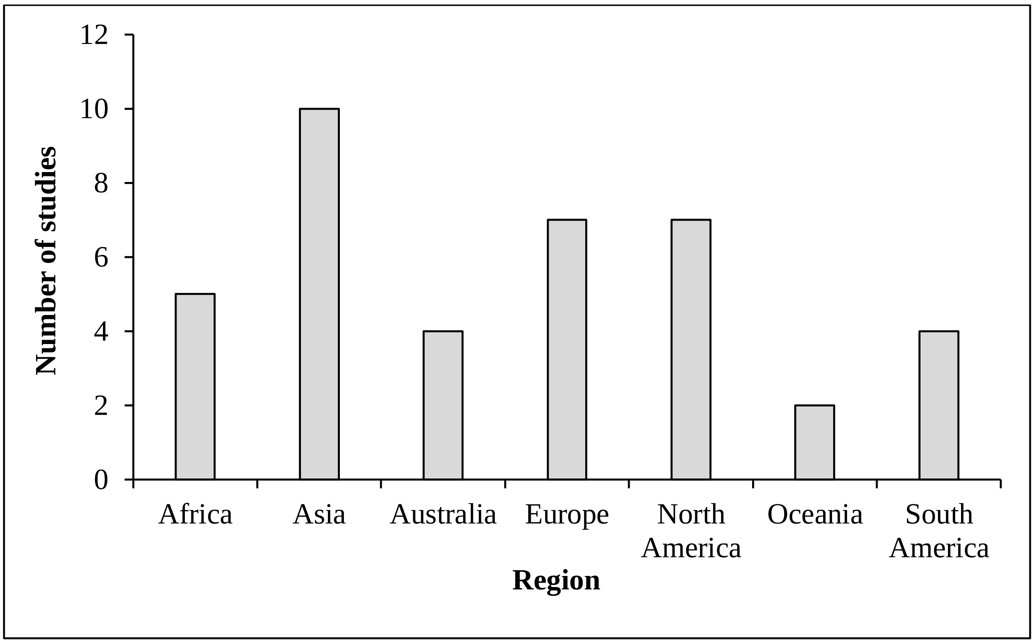

Figure 2.2. The number of reptile pet trade studies published in international peer-reviewed journals from 1994 – 2021 for the respective continents.

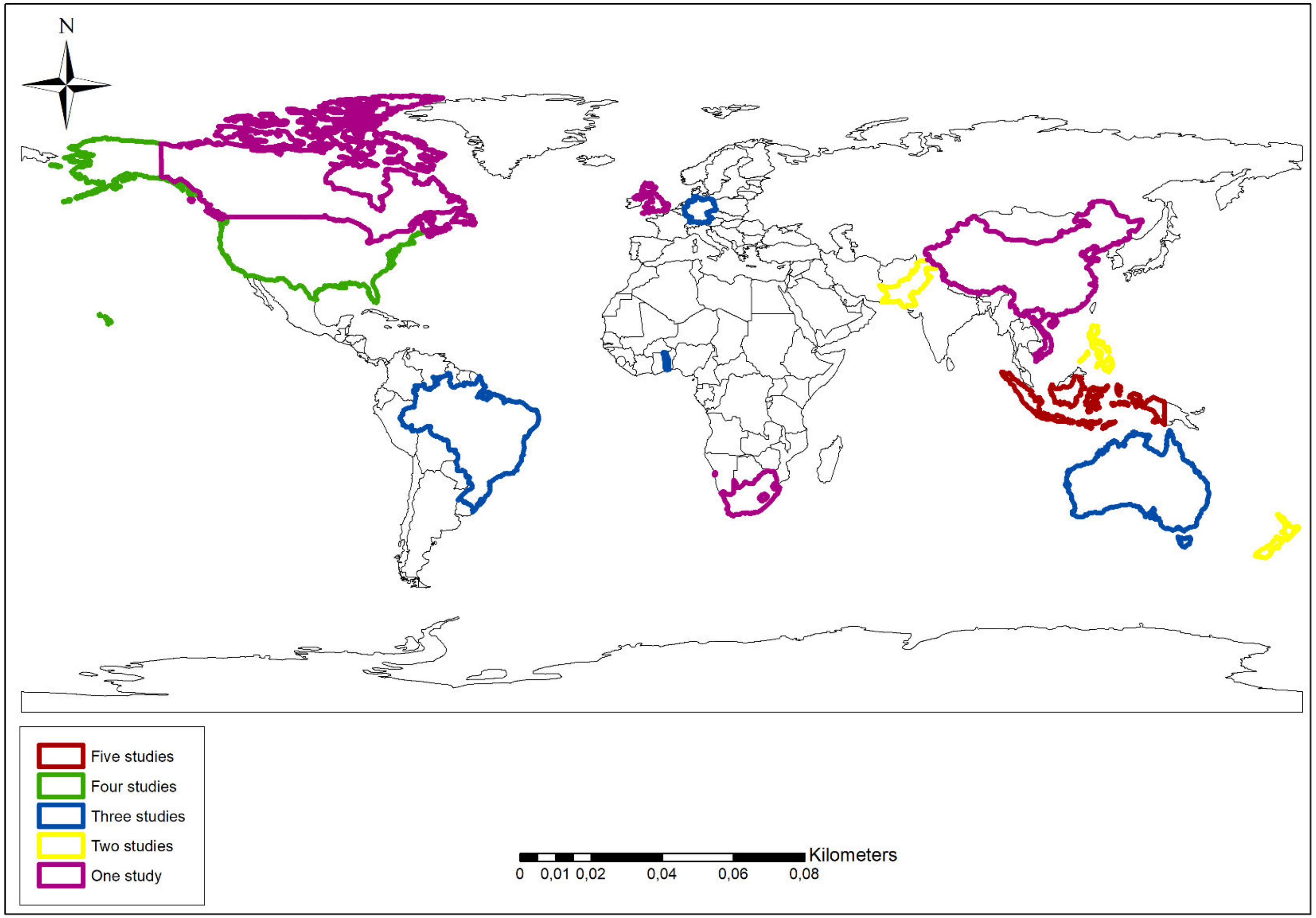

Figure 2.3. The number of reptile pet trade studies published in international peer-reviewed journals from 1994 – 2021 for each country.

2.4.3 Taxonomic focus

We recorded a total of 1147 reptile species belonging to 60 families sold as pets around the world (Supplementary Table S2.1). Of these species, at least 79 are invasive, 29 are critically endangered, while 46 are endangered species (Supplementary Table S2.1). Overall, there were many non-invasive and non-CITES species, 1069 and 601, respectively (Supplementary Table S2.1). The family most frequently studied was Colubridae (16.0%), followed by Viperidae (22.0%) (Fig. 2.4). The least studied families were the Atractaspididae, Felidae, Gavialidae, Gymnophthalmidae, Hoplocercidae, Liolaemidae, Platysternidae, Podocnemididae, Shinisauridae, Xenopeltidae, and Xenosauridae with each recording 0.09% (Fig. 2.4). The most diverse family was the Colubridae (number of species = 178), followed by Gekkonidae (n = 110) and Viperidae (n = 110) (Supplementary Table S2.1). The above-mentioned least studied families were also the least diverse. This was because each family was represented by only one species. Invasive species were frequently studied, with the red-eared slider *Trachemys scripta elegans* being the most studied species (number of studies = 23), followed by the ball python *Python regius* (n = 17), and corn snake *Pantherophis guttatus* (n = 16) (Supplementary Table S2.1). This was followed by threatened species, with African spurred tortoise *Geochelone sulcata* being the most studied species (number of studies = 9) (Supplementary Table S2.1).

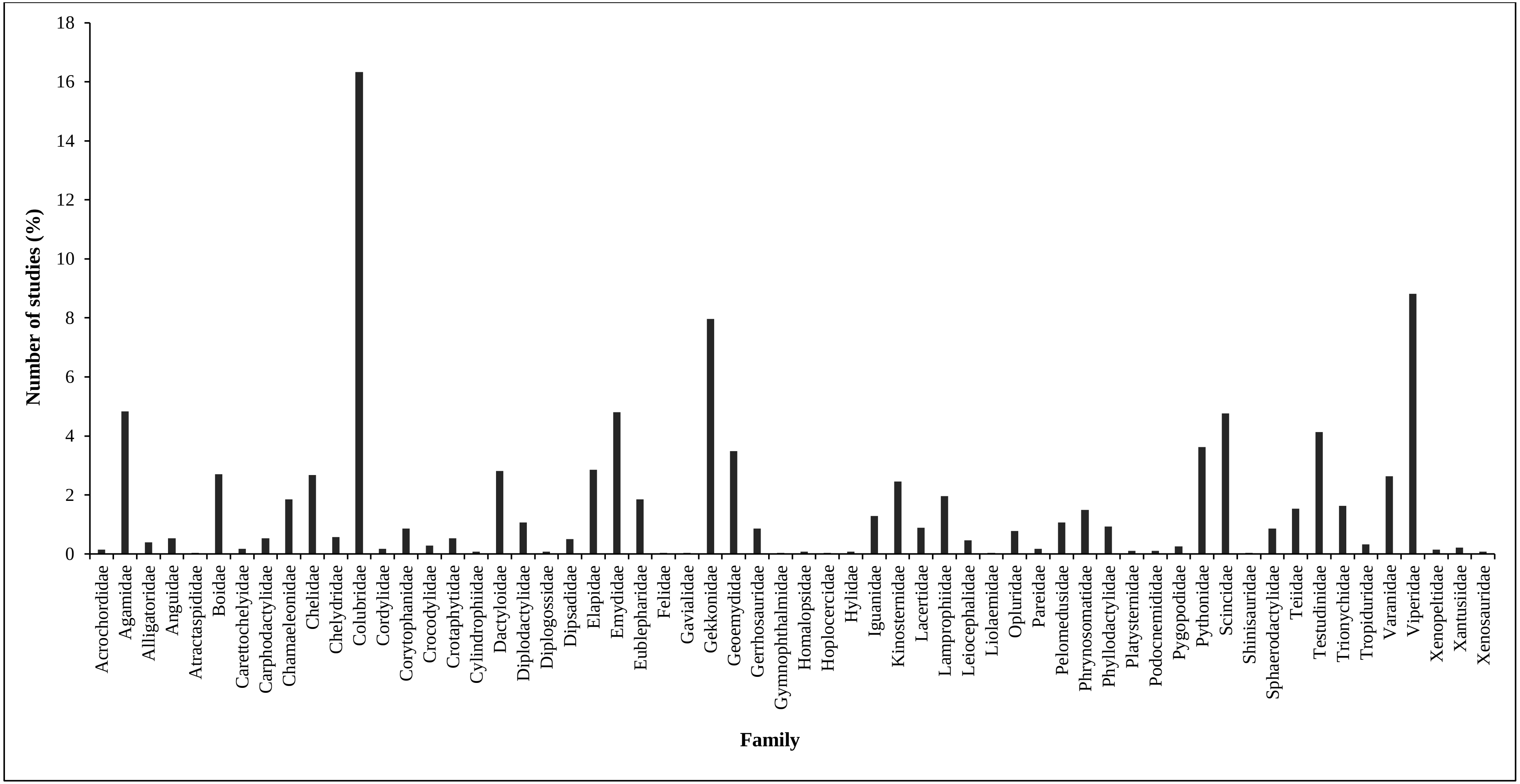

Figure 2.4. The percentage of studies on reptile families present in the global trade industry that have been published in internationally peer-reviewed journals from 1994 to 2021.

2.5 Discussion

2.5.1 Publications

We predicted a dramatic increase in the number of studies focusing on the reptile pet trade in the present decade as the reptile pet trade is increasingly becoming a popular hobby around the world. Our study showed that the number of studies focusing on the reptile pet trade reflects a rapid growth and urgency in researching the global reptile pet trade. Studies focusing on the reptile pet trade in the last decade have doubled the number of those that were published from 2000 – 2010. This is mainly because the wildlife pet trade, particularly the reptile pet trade, has increased globally in recent decades (Lockwood et al., 2019; McMillan et al., 2020; Harrington et al., 2021; Kusrini et al., 2021). Moreover, it has gained much attention recently because of the high significant impacts that it presents on native and non-native biodiversity, economy, and human health (Reed, 2005; Gippet & Bertelsmeier, 2021). This ever-increasing reptile pet trade-based research reflects a necessity and expanding knowledge gap in the global reptile pet trade industry. There is also an urgency in understanding the dynamics of the pet trade, especially in the light of the impacts that it has on the native and non-native biodiversity.

2.5.2 Geographic focus

Although the reptile pet trade-based research has been expanding exponentially over the years, we also noted that the extent of influence is geographically biased. Approximately 61.5% of all reptile pet trade studies have been conducted on three continents, Asia, Europe and North America, combined, out of seven continents. A further 38.5% was contributed by the remaining four continents (Africa, South America, Australia, and Oceania). This demonstrated a significant existing geographical bias in the global reptile pet trade-based research. Moreover, our results indicated that the northern-southern hemisphere research gap still exists, with approximately 93.0% of all reptile pet trade-based studies originating from the northern hemisphere. A study by Magle et al. (2012) focused on seven broad fauna taxa (e.g. mammal, bird, fish, herp, and others) established comparable trends.

There are many possible explanations for these geographical biases in reptile pet trade-based research. The most obvious ones are the lack of resources, scientific capabilities, research output, and quality of research (Skopec et al., 2020). Citation counts are directly proportional to the gross domestic product (GDP) (Bornmann et al., 2014), with high-income countries such as the USA, Germany, and Australia linked with many citations and publications. It is, therefore, possible that the research output produced by low-and-medium-income countries is being prematurely discounted and unreasonably because of a bias against the country from which the research is produced. Several authors have argued that a large portion of the world is unfairly overlooked in terms of scientific contributions (Keiser et al., 2004; Bornmann et al., 2011; Pan et al., 2012; Bornmann et al., 2014). Such biases may occur at any stage in the review and publication process and may be the leading cause of the existing sparsity in reptile pet trade-based research, especially in developing countries (Haffar et al., 2019). Although we have an insight into some potential causes of geographical bias in pet trade-based research, we still find it difficult to fully understand the dynamics of the global reptile pet trade-based research because of the existing research sparsity.

2.5.3 Taxonomic focus

We recorded 1140 reptile species belonging to 60 families from our global literature searches of reptile pet trade-based research. Of most concern, approximately 6.9% of these are invasive. Our analyses reveal a developing and fast-growing invasion pathway for invasive reptile species. Given that many pet owners are known to release some of their pets into the wild deliberately (Stringham & Lockwood, 2018; Lockwood et al., 2019; Maceda-Veiga et al., 2019; Gippet & Bertelsmeier, 2021), we expect the global reptile trade to contribute enormously to the spread of invasive species into new environments. This is because the trade of wildlife often involves the translocation of species into new environments either as exports or imports (van Wilgen et al., 2012; Marshall et al., 2020; Harrington et al., 2021). The global reptile pet trade may also provide dispersal opportunities for species that are not yet invasive but have a great potential of becoming invasive in the future. We recorded only 280 species (i.e. 24.6% of all recorded species) listed under the Convention of International Trade in Endangered Species of Wild Fauna and Flora (CITES), suggesting that the remaining species are not protected by any international trade regulations. Therefore, some non-CITES species may become threatened or even extinct to overexploitation and poaching as they are not protected. We further found that at least 6.5% of the recorded species are threatened, with African spurred tortoise being the most frequently studied species. We suspect that this species is frequently studied because it is threatened and regarded as one of the largest tortoise species in the world (Hibbitts & Hibbits, 2021) and thus draws much attention from many scholars. Given that the trade in endangered species is prohibited by the Convention of International Trade in Endangered Species of Wild Fauna and Flora (CITES), the presence of these species, including invasive and non-CITES listed species in the global pet trade, outlines the gaps that are in the global legal system.

Our results revealed that the reptilian family most frequently studied in the global pet trade-based literature was Colubridae. This family was represented in almost all peer-reviewed publications that were used for analyses in the present study. The predominance of the Colubridae in the global literature could be explained because it is the largest snake family with representatives found on almost every continent except Antarctica (Bauer, 1998; Pinthong et al., 2013). Moreover, many pet trade studies have observed a clear preference of pet owners for more patterned and colourful species (van Wilgen et al., 2008; Altherr & Lameter, 2020). This could also explain the predominance of this family in reptile pet trade studies since the majority of Colubrid species are patterned, harmless and not venomous (or have a venom that is not harmful to humans) (Marques, 2000).

Of the 1140 recorded species, the most frequently studied species was the red-eared slider. This species appeared in approximately 64.0% of all studies used in the analyses of this study. This could be explained because the red-eared slider is among the most highly profiled and disastrous invasive species globally (Herrel & van der Meijden, 2014). Several authors have argued that many researchers tend to be biased and focus solely on species that are popular in human societies and with high profiles (i.e. invasive species with highly damaging impacts) (Pyšek et al., 2008; López-Torres et al. 2012; Kraus, 2015; Hagen & Kumschick, 2018; Kesner & Kumschick, 2018). For example, our results showed that invasive species such as red-eared slider, ball python, and corn snake were the most frequently studied species. We understand that some species may not be found in other regions, which might also influence the focus of scientific research. Therefore, to fully understand the extent of the global reptile trade industry, we recommend that global scientific research represent all reptile species involved in the pet trade.

2.6 Conclusions and recommendations

Our results have demonstrated that studies focusing on the reptile pet trade in the last decade have doubled the number published before 2010. This has been the case because of the ever-increasing world's pet trade industry and its impacts on native and non-native biodiversity, economy, and human health (Reed, 2005; Gippet & Bertelsmeier, 2021). However, even with increasing reptile pet trade-based literature, we could not fully understand the dynamics of the global reptile pet trade because of the sparsity of this research. Therefore, we recommend that more studies be conducted to investigate the dynamics of the reptile pet trade, especially in developing and understudied regions. This would help understand the dynamics of the reptile trade in those countries and the dynamics of the global reptile trade. We also recorded a high number of invasive, threatened, and non-CITES species, reflecting the gaps in the global legal system. Given that some of these species may establish in new environments and pose serious threats to native biodiversity, and some may become extinct, we recommend that the trade of these species should be strictly monitored. We also propose that future studies should consider adding other additional variables in their analyses such as Climate Matching and relative propagule pressure to provide more novel comparative measures of establishment risk - which is itself a component of impact.

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2.9 Supplementary information

Supplementary Table S2.1. Publications reporting reptile species advertised for sale in physical and online advertising websites in the world from 1994-2021.

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Supplementary Table S2. Reptile species advertised for sale in physical and online advertising websites in the world from 1994-2021.

https://docs.google.com/spreadsheets/d/1QO4NQqoH1WgzGVuqc_onvIRhWZn39-dkCetGZa9zByI/edit?usp=sharing

CHAPTER 3

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

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3.1 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 current distributions 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 was 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

3.2 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 & Nijman, 2018; Lockwood et al., 2019). These two forms of trade are regarded as significant threats to global biodiversity and species conservation (Nijman & Shepherd, 2007; Challender et al., 2015; Siriwat & 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 & Chen, 2010; Baker et al., 2013; Bush et al., 2014; McFadden et al., 2017; Siriwat & 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 & Nijman, 2018). Pet owners, stores or breeding facilities have contributed significantly to introducing non-native species through either intentional release or accidental escapes (Mazzotti & 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 & 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., 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 & Chng, 2017; Bergin et al., 2018; Siriwat & Nijman, 2018). Consequently, many non-native species, e.g. small mammals (Shivambu et al., 2021a, Shivambu et al., 2021b), tarantulas (Hauke & Herzig, 2017; Shivambu et al., 2021b; Shivambu et al., 2021c), 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 & Chng, 2017). Social media has been used as a tool for sourcing and advertising live non-native animals (Derraik & 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 & Galatowitsch, 2004; IFAW, 2008; Siriwat & 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). 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 & 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 & 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.

3.3 Methods

3.3.1 Pet trade survey

3.3.1.1 *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.

3.3.1.2 *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. 3.1).

3.3.1.3 Physical pet stores

We obtained a list of physical pet shops (n = 114) from Shivambu et al. (2021a, 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. 3.2). 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. 3.2). 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. 3.1. 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).

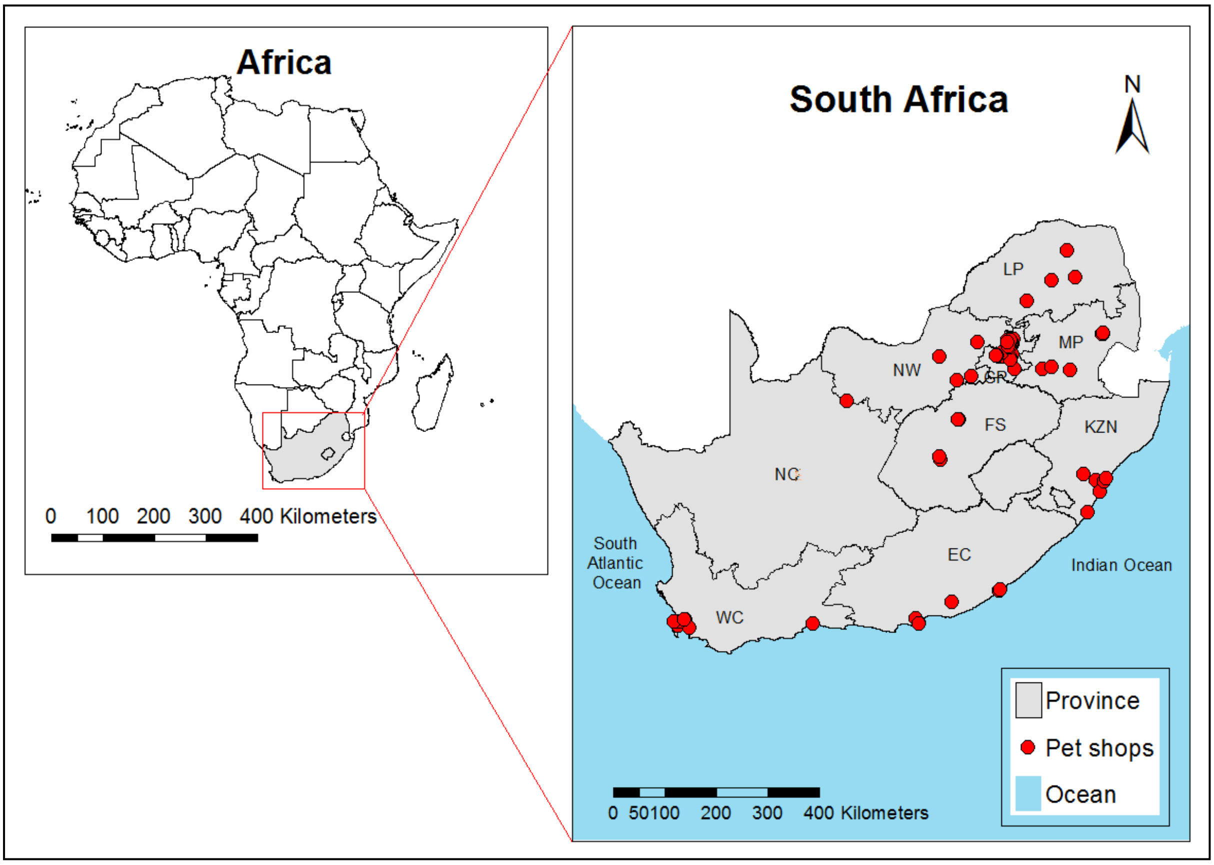

Fig. 3.2. The distribution of physical pet stores surveyed in March and November 2020 in South Africa. (Note: The abbreviations in the map represent names of provinces where LP: Limpopo, GP: Gauteng, MP: Mpumalanga, NW: North West, FS: Free State, KZN: KwaZulu-Natal, EC: Eastern Cape, NC: Northern Cape, and WC: Western Cape).

3.3.2 Species distribution modelling

3.3.2.1 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.

3.3.2.2 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 $\rho = |0.7|$ was used as a benchmark to select the variables that were not highly collinear (i.e. all variables with $\rho < 0.7$) (Dormann et al., 2013).

3.3.2.3 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.

3.3.2.4 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 minutes 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.

3.3.3 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).

3.4 Results

3.4.1 Volume of trade

We recorded a total of 1,912 individuals representing 66 reptiles from 69 physical pet stores (Supplementary Material Table S3.1). We further recorded 859 individuals representing 50 reptiles from online advertising websites selling reptiles (Supplementary Material Table S3.1). 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 S3.1). 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 S3.1). Moreover, 76 (86.4%) of the recorded species are non-natives to South Africa (Supplementary Material Table S3.1).

For our online sampling, 12 new species were recorded during the follow-up searches (Supplementary Material Table S3.1). 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. 3.3). 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 S3.1). 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 S3.1). The remaining 65.9% (58/88) are commonly kept and bred by private keepers around the world (Supplementary Material Table S3.1). 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 S3.1).

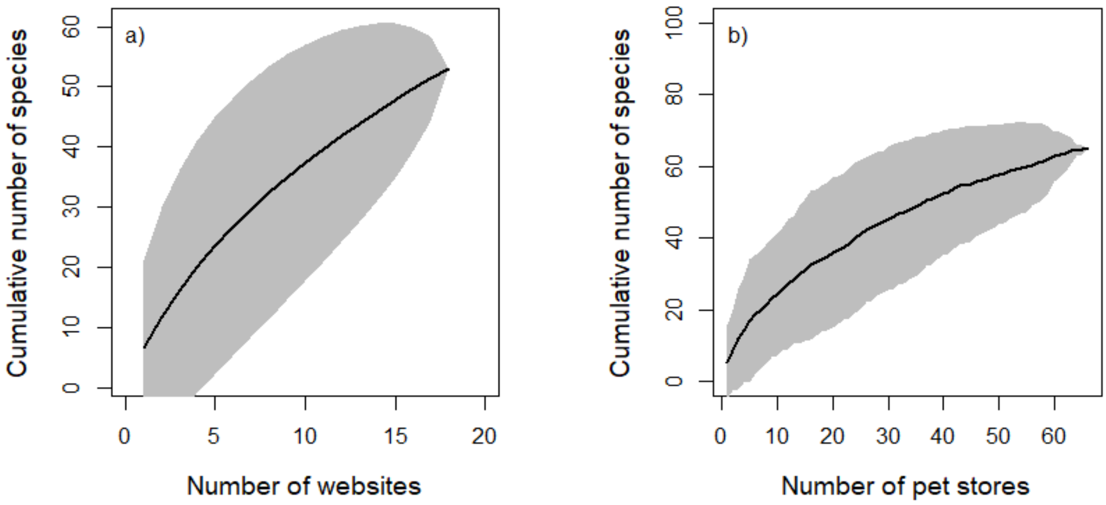

Fig. 3.3. Species accumulation curves estimating the number of reptiles present in the South African pet trade obtained from a) online searches and b) physical pet stores visits in the present study. (Note: A black line represents the mean accumulation curve, and the grey shaded area shows the standard 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; $P = 1.288e\text{-}12$). The provinces of Gauteng, Eastern Cape and KwaZulu-Natal recorded more individuals than the other provinces, with each recording more than 250 individuals (Fig. 3.4a). 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. 3.4b). 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 χ^2 = 28.54; df = 8; P = 1.019e-13) with Gauteng and KwaZulu-Natal recording more than 250 individuals of reptile species each (Fig. 3.4a). Other provinces recorded less than 70 individuals (Fig. 3.4a). We also found a significant difference in species richness in the online trade across all nine South African provinces (Kruskal-Wallis χ^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. 3.4b). Online advertising websites did not record any reptile species for sale in Limpopo and Northern Cape provinces (Fig. 3.4b).

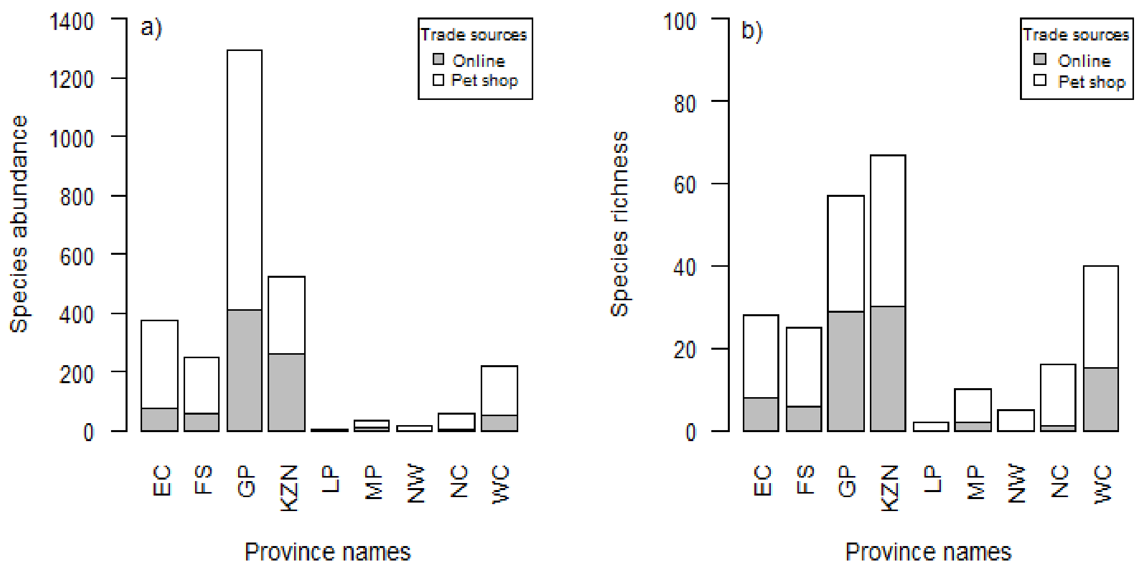

Fig. 3.4. Reptile species a) abundance and b) richness obtained from the two sources of trade (websites and pet stores) across nine South African provinces in the present study. (Note: see Fig. 3.2 for the abbreviations of provinces).

Table 3.1. 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
*Boa constrictor**	Red-tailed boa	73	456.17	6	3	568.33	2
Boaedon capensis[1]	Cape house snake	26	256.63	4	12	200.00	2
Correlophus ciliatus	Crested gecko	52	456.25	5	53	260.54	4
Eublepharis macularius	Common leopard gecko	257	536.69	7	57	235.93	4
Gongylophis colubrinus	Kenyan sand boa	48	289.96	6	5	320.00	3
*Pantherophis guttatus**	Corn snake	319	651.47	8	234	421.15	5
Pogona vitticeps	Central bearded dragon	349	277.87	7	70	240.00	5
*Python bivittatus**	Burmese python	53	688.89	7	15	674.50	1
Python regius	Ball python	401	363.18	7	200	451.95	6
Stigmochelys pardalis[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.

3.4.2 Most popular species

The availability of reptile species recorded differed between the two sources (Supplementary Material Table S3.1). 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. 3.5).

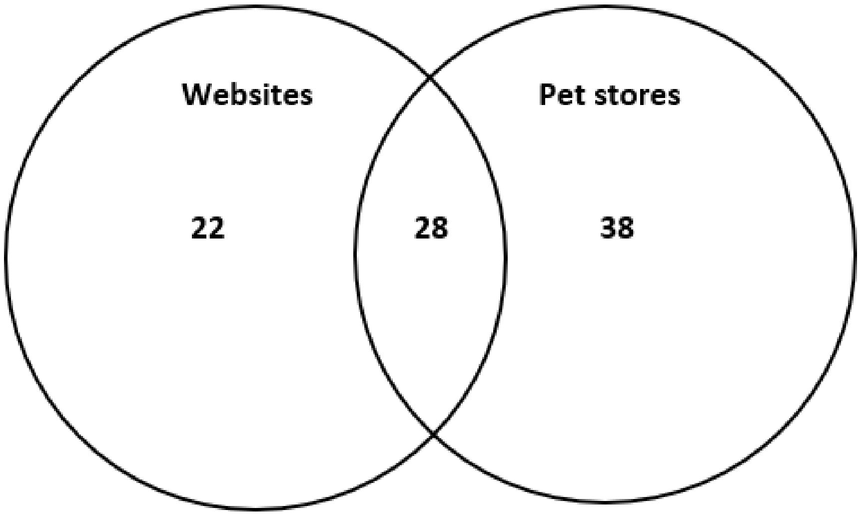

Fig. 3.5. Venn diagram demonstrating the total number of reptiles obtained from two sources (websites and physical pet stores) and those shared among sources in the present study.

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 3.1). Two of these were native species that are not supposed to be traded (Table 3.1). 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 S3.1). We further found that CITES-listed species (Appendix II) determined the selling price of reptile species in physical pet stores (Supplementary Material Table S3.2). For online trade, the model showed that invasion status determined reptile species' selling price (Supplementary Material Table S3.2).

3.4.3 Distribution modelling

3.4.3.1 Present distribution

The mean independent AUC threshold values indicated that the models performed well (AUC > 0.87) in predicting areas that are climatically suitable for all 12 non-native reptile species traded in South Africa (Table 3.2). 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. 3.6a). 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 3.2). 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 3.2; Fig. 3.6b). The corn snake's predicted climatic suitability was relatively large, covering almost all South African provinces besides the Western Cape Province (Fig. 3.6c). The climatic suitability for this species was best described by the mean temperature of the warmest quarter (Bio 10) and isothermality (Bio 3) (Table 3.2). 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. 3.6d, 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 3.2). Whereas for the Colombian boa, the climatic suitability was best described by isothermality (Bio 3) and precipitation of warmest quarter (Bio 18) (Table 3.2). The predicted climatic suitability for Burmese python, beauty rat snake *Orthriophis taeniurus,* ball python *Python regius* and veiled chameleon *Chamaeleo calyptratus* were relatively low (Fig. 3.6f & Fig. 3.7a, b, d).

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. 3.7c). 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 3.2). The predicted climatic suitability areas for the red-eared slider and western diamondback rattlesnake were relatively large, covering all South African provinces (Fig. 3.7e, 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 3.2).

Table 3.2. 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
Anolis sagrei	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
Boa constrictor	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
Boa constrictor imperator	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
Chamaeleo calyptratus	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
Eunectes notaeus	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
Iguana iguana	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
Orthriophis taeniurus	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
Pantherophis guttatus	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
Python bivittatus	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
Python regius	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
Crotalus atrox	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
Trachemys scripta elegans	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

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) (×100), 4: BIO4 = temperature seasonality (standard deviation ×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.

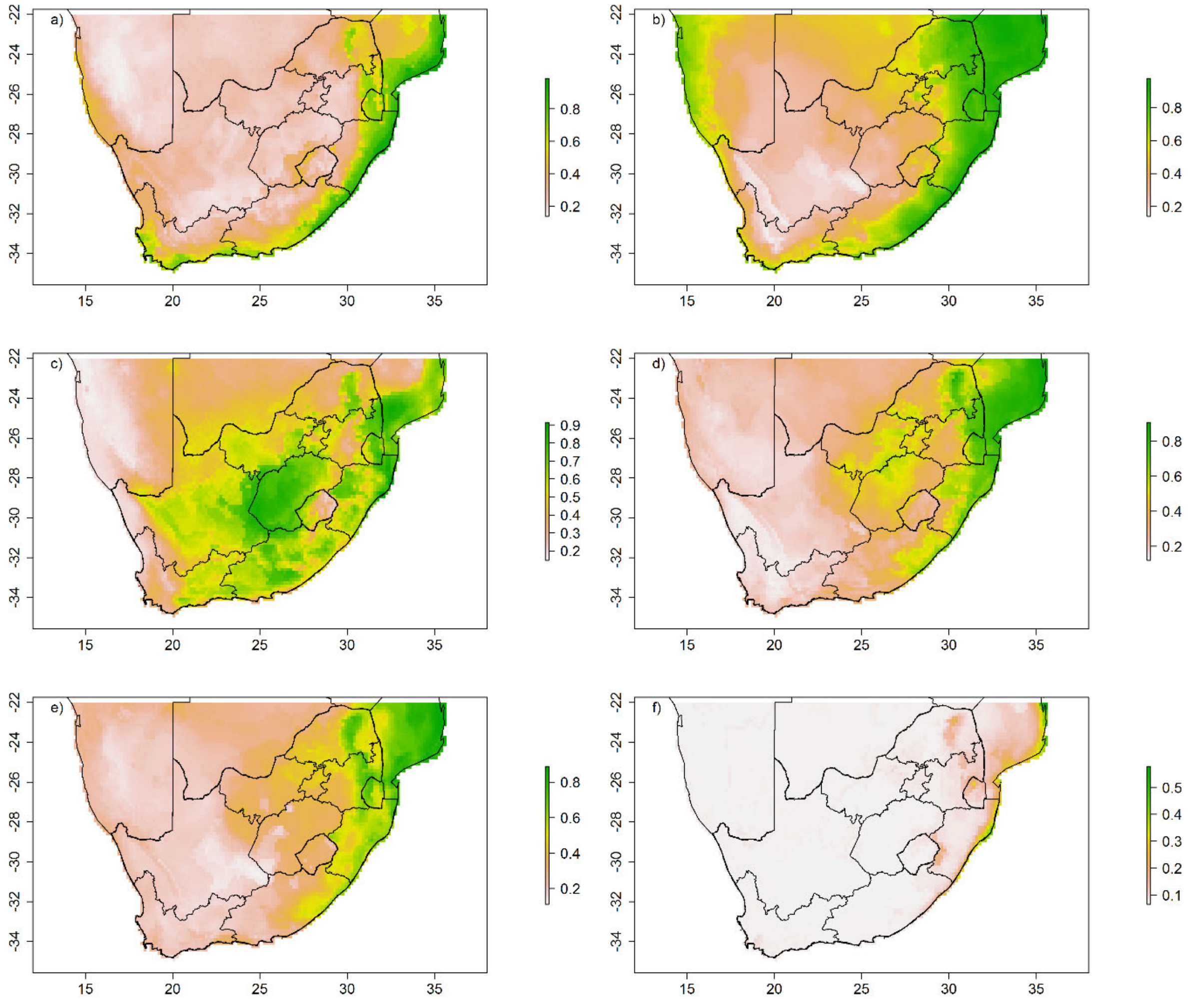

Fig. 3.6. The species distribution modelling showing predicted climatically suitable areas for a) *Anolis sagrei*, b) *Iguana iguanas*, c) *Pantherophis guttatus*, d) *Boa constrictor*, e) *Boa constrictor imperator*, and f) *Python bivittatus* in South Africa. (Note: The climatic suitability is shown by a colour ramp threshold on the right of each map; the strong green colour denotes more suitable areas).

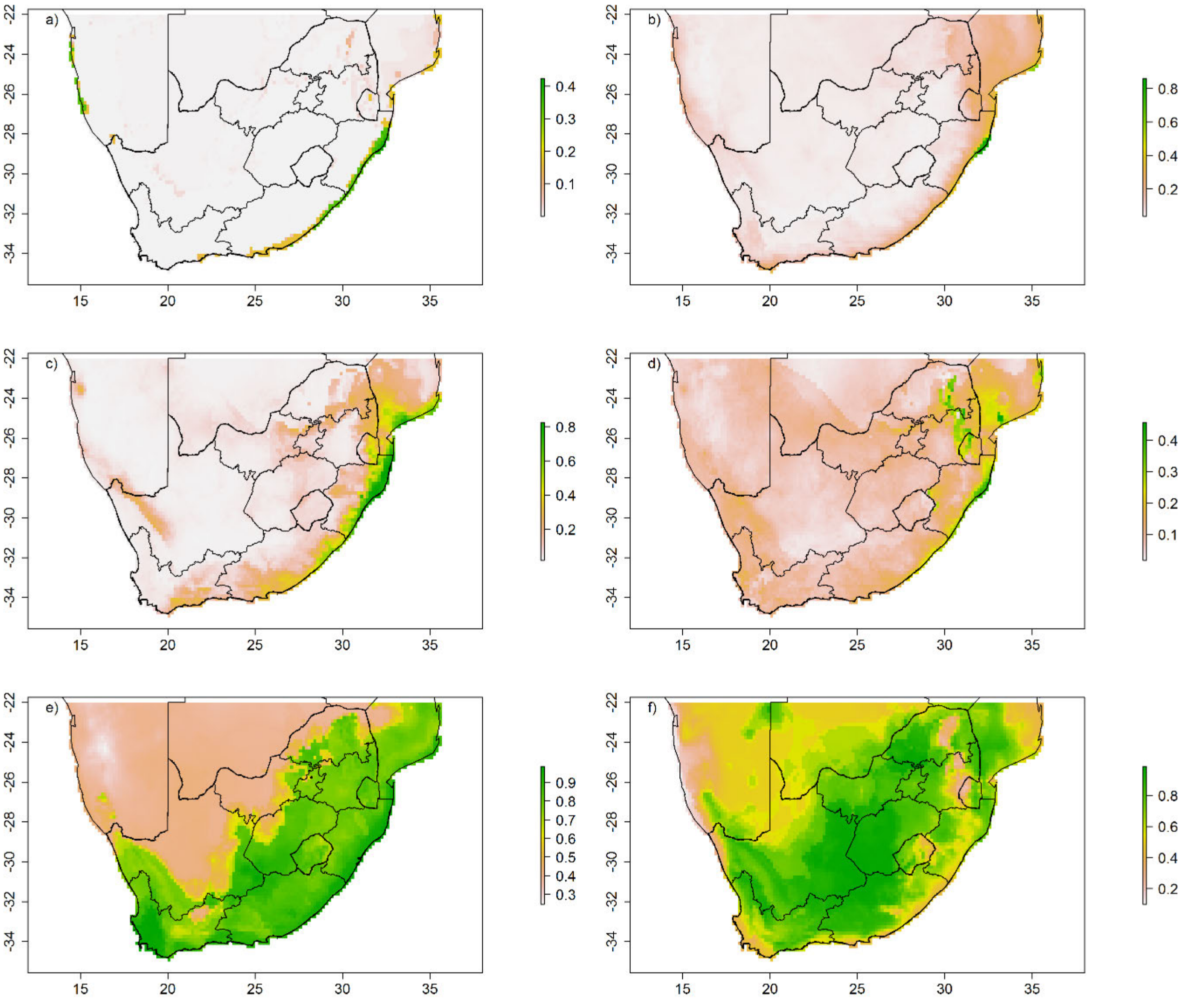

Fig. 3.7. The species distribution modelling showing predicted climatically suitable areas for a) *Orthriophis taeniurus*, b) *Python regius*, c) *Eunectes notaeus*, d) *Chamaeleo calyptratus*, e) *Trachemys scripta elegans*, f) *Crotalus atrox* in South Africa. (Note: The climatic suitability is shown by a colour ramp threshold on the right of each map; the strong green colour denotes more suitable areas).

3.4.3.2 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. S3.1 & S3.2). Our analysis 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. S3.3 & S3.4).

3.5 Discussion

3.5.1 Volume 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 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 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; Shepard et al., 2007; Smith et al., 2017). It is known that some cultural factors often influence how people interact with reptiles (Alves & 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.

3.5.2 Most popular species

Considering the number of pet reptiles recorded in this study, our results reveal that snakes are the most preferred group of reptiles 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 (Su et al., 2015; Vall-llosera & Cassey, 2017, Siriwat et al., 2019, Shivambu et al., 2021a). We also noted that the most traded pet reptiles were sold at relatively lower prices than other more 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 & 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.

3.5.3 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 current 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 & 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.

3.5.4 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.

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3.8 Supplementary materials

Supplementary Table S3.1. Reptile species advertised for sale in physical pet stores and online advertising websites in South Africa in the present study.

Scientific names	Common names	Origin (wild/captive bred)	Taxa	Family	Pet shops			Online			Conservation status	
					No. of individuals	No. of pet shops	Mean price (ZAR)	No. of individuals	No. of websites	Mean price (ZAR)	IUCN	CITES
Acrantophis dumerili	Dumeril's boa	Captive bred	Snake	Boidae	9	6	1828.57	4	3	1050	LC	Appendix I
Acrantophis madagascariensis ˆ	Madagascar ground boa	Captive bred	Snake	Boidae	2	1	695	0	0	0	LC	Appendix I
Agkistrodon contortrix ˆ	Copperhead	Wild	Snake	Viperidae	1	1	500	0	0	0	LC	Non-CITES
Alligator mississippiensis ˆ	American alligator	Wild	Alligator	Alligatoridae	3	1	450	0	0	0	LC	Appendix II
Anolis sagrei**	Brown anole	Captive bred	Lizard	Dactyloidae	4	2	300	0	0	0	NE	Non-CITES
Antaresia maculosa ˝	Spotted python	Captive bred	Snake	Pythonidae	6	4	1118.8	1	1	850	LC	Appendix II
Aspidelaps lubricus*	Cape coral snake	Wild	Snake	Elapidae	2	1	1000	11	2	133.33	NE	Non-CITES
Aspidelaps scutatus*	Shield-nose snake	Wild	Snake	Elapidae	0	0	0	3	1	450	NE	Non-CITES
Aspidites ramsayi	Woma python	Captive bred	Snake	Pythonidae	2	1	1600	0	0	0	LC	Appendix II
Bitis arietans*	Puff adder	Captive bred	Snake	Viperidae	6	2	266.67	0	0	0	NE	Non-CITES
Boa constrictor**	Red-tailed boa	Captive bred	Snake	Boidae	73	20	456.17	3	3	568.33	NE	Appendix II
Boa constrictor imperator**	Common boa	Captive bred	Snake	Boidae	2	1	750	0	0	0	LC	Appendix II
Boaedon capensis*	Cape house snake	Captive bred	Snake	Lamprophiidae	26	7	256.63	12	2	200	NE	Non-CITES
Boaedon lineatus ˝	Striped house snake	Captive bred	Snake	Lamprophiidae	0	0	0	2	2	375	NE	Non-CITES
Bothriechis schlegelii	Eyelash viper	Captive bred	Snake	Viperidae	3	1	450	0	0	0	LC	Non-CITES
Centrochelys sulcata** ˝	African spurred Turtle	Wild	Turtle	Testudinidae	0	0	0	3	1	4400	VU	Appendix II
Chamaeleo calyptratus**	Veiled chameleon	Captive bred	Lizard	Chamaeleonidae	23	6	222.14	3	3	433.33	LC	Appendix II

*Chersina angulata**	Angulate Turtle	Wild	Turtle	Testudinidae	0	0	0	2	1	600	LC	Appendix II
Chilabothrus angulifer	Cuban boa	Captive bred	Snake	Boidae	2	2	800	0	0	0	NT	Appendix II
Chondropython viridis	Green tree python	Captive bred	Snake	Pythonidae	0	0	0	2	1	975	LC	Appendix II
Correlophus ciliatus	Crested gecko	Captive bred	Lizard	Diplodactylidae	52	11	456.25	53	7	260.54	VU	Non-CITES
*Crotalus adamanteus***	Eastern diamondback rattlesnake	Captive bred	Snake	Viperidae	3	2	2400	0	0	0	LC	Non-CITES
*Crotalus atrox***	Western diamondback rattlesnake	Wild	Snake	Viperidae	1	1	400	0	0	0	LC	Non-CITES
*Crotalus durissus***	South American rattlesnake	Wild	Snake	Viperidae	4	1	4800	0	0	0	LC	Appendix III
*Crotalus scutulatus*** ˝	Mojave green	Wild	Snake	Viperidae	0	0	0	1	1	500	LC	Non-CITES
*Crotalus viridis***	Prairie rattlesnake	Wild	Snake	Viperidae	1	1	350	0	0	0	LC	Non-CITES
*Dasypeltis inornata**	Southern brown egg eater	Wild	Snake	Colubridae	0	0	0	1	1	100	LC	Non-CITES
Deinagkistrodon acutus acutus	Sharpnosed viper	Wild	Snake	Viperidae	3	1	6000	0	0	0	NE	Non-CITES
*Dendroaspis angusticeps** ˆ	Eastern green mamba	Captive bred	Snake	Elapidae	9	2	420	0	0	0	NE	Non-CITES
Elaphe obsoleta lindheimeri	Texas rat snake	Captive bred	Snake	Colubridae	5	1	600	0	0	0	NE	Non-CITES
Elaphe schrenckii	Russian ratsnake	Captive bred	Snake	Colubridae	1	1	1400	0	0	0	NE	Non-CITES
Epicrates cenchria	Rainbow boa	Captive bred	Snake	Boidae	3	2	833.33	2	1	1000	NE	Appendix II
Eublepharis macularius ˝	Common leopard gecko	Captive bred	Lizard	Eublepharidae	257	27	536.69	57	2	235.93	LC	Non-CITES
Eunectes deschauenseei	dark-spotted anaconda	Captive bred	Snake	Boidae	8	4	250	0	0	0	DD	Appendix II
*Eunectes notaeus*** ˆ	Yellow anaconda	Captive bred	Snake	Boidae	3	2	375	0	0	0	NE	Appendix II
Geochelone elegans ˝	Indian star Turtle	Wild	Turtle	Testudinidae	0	0	0	2	1	800	VU	Appendix I
Gongylophis colubrinus	Kenyan sand boa	Captive bred	Snake	Boidae	48	20	289.96	5	3	320	NE	Appendix II
Gongylophis conicus	Russell's boa	Wild	Snake	Boidae	2	1	1500	0	0	0	NE	Appendix II
Gonyosoma boulengeri	Rhinoceros ratsnake	Wild	Snake	Colubridae	5	2	4266.67	0	0	0	LC	Non-CITES

Gonyosoma oxycephalum	Arboreal ratsnake	Captive bred	Snake	Colubridae	2	1	600	0	0	0	LC	Non-CITES
Hemitheconyx caudicinctus	African fat-tailed gecko	Captive bred	Lizard	Eublepharidae	24	3	833.33	19	1	850	LC	Non-CITES
Heterodon nasicus	Western hognose snake	Wild	Snake	Colubridae	7	4	876	3	1	725	LC	Non-CITES
Hydrodynastes gigas ˝	false water cobra	Captive bred	Snake	Colubridae	3	1	500	0	0	0	NE	Appendix II
Hydrophis platurus	Yellow-bellied sea snake	Wild	Snake	Elapidae	0	0	0	1	1	900	LC	Non-CITES
*Iguana iguana***	Green iguana	Captive bred	Lizard	Iguanidae	24	11	839.29	3	2	825	LC	Appendix II
Lampropeltis calligaster	Yellow-bellied kingsnake	Wild	Snake	Colubridae	0	0	0	1	1	550	LC	Non-CITES
Lampropeltis getula	Common kingsnake	Captive bred	Snake	Colubridae	0	0	0	5	1	830	LC	Non-CITES
Lampropeltis getula california	California kingsnake	Captive bred	Snake	Colubridae	59	17	679.13	11	6	894.44	NE	Non-CITES
Lampropeltis getula floridana	Florida kingsnake	Captive bred	Snake	Colubridae	15	6	1723.17	0	0	0	LC	Non-CITES
Lampropeltis getula nigrita	Mexican black kingsnake	Captive bred	Snake	Colubridae	6	3	2775	4	2	2500	DD	Non-CITES
Lampropeltis mexicana greeri	Greer's Kingsnake	Captive bred	Snake	Colubridae	1	1	1400	0	0	0	LC	Non-CITES
Lampropeltis splendida ˝	Desert kingsnake	Wild	Snake	Colubridae	0	0	0	1	1	650	LC	Non-CITES
Lampropeltis triangulum	Milk snake	Captive bred	Snake	Colubridae	19	13	933	3	2	620	LC	Non-CITES
Lampropeltis triangulum campbelli	Pueblan mi k snake	Wild	Snake	Colubridae	1	1	1100	2	1	600	NE	Non-CITES
Lampropeltis triangulum hondurensis	Honduran milk snake	Captive bred	Snake	Colubridae	2	2	1600	1	1	550	NE	Non-CITES
Lampropeltis triangulum sinaloae	Sinaloan milk snake	Captive bred	Snake	Colubridae	1	1	1095	1	1	900	NE	Non-CITES
Lamprophis abyssinicus	Abyssinian house snake	Captive bred	Snake	Lamprophiidae	0	0	0	2	1	400	NE	Non-CITES
*Lamprophis aurora***	Aurora house snake	Captive bred	Snake	Colubridae	2	1	1780	1	1	450	LC	Non-CITES
Liasis mackloti savuensis	Savu python	Captive bred	Snake	Pythonidae	1	1	780	0	0	0	NE	Non-CITES
*Lycodonomorphus inornatus**	Olive house snake	Captive bred	Snake	Lamprophiidae	0	0	0	1	1	650	LC	Non-CITES
Malaclemys terrapin	Diamondback terrapin	Captive bred	Turtle	Emydidae	0	0	0	4	2	750	VU	Appendix II
Malayopython reticulatus	Reticulated python	Captive bred	Snake	Pythonidae	6	3	1275	0	0	0	LC	Appendix II

Micrurus fulvius	Eastern coral snake	Wild	Snake	Elapidae	1	1	550	0	0	0	LC	Non-CITES
Morelia spilota	Carpet python	Captive bred	Snake	Pythonidae	5	3	1199.75	0	0	0	LC	Appendix II
Naja siamensis	Indochinese spitting cobra	Wild	Snake	Elapidae	2	1	1500	0	0	0	VU	Appendix II
Oplurus cuvieri	collared iguanid lizard	Wild	Lizard	Opluridae	1	1	950	0	0	0	LC	Non-CITES
*Orthriophis taeniurus***	Beauty rat snake	Captive bred	Snake	Colubridae	11	5	1148	5	3	1025	NE	Non-CITES
*Pachydactylus austeni**	Austen's thick-toed gecko	Wild	Lizard	Gekkonidae	0	0	0	1	1	2500	LC	Non-CITES
Pantherophis alleghaniensis	Eastern rat snake	Wild	Snake	Colubridae	1	1	350	0	0	0	LC	Non-CITES
*Pantherophis guttatus***	Corn snake	Captive bred	Snake	Colubridae	319	53	651.47	234	9	421.15	LC	Non-CITES
Pantherophis obsoletus	Black rat snake	Captive bred	Snake	Colubridae	5	2	400	4	2	442	LC	Non-CITES
Pantherophis spiloides	Gray ratsnake	Wild	Snake	Colubridae	3	2	350	0	0	0	LC	Non-CITES
Paroedura pictus ˝	Ocelot gecko	Captive bred	Lizard	Gekkonidae	4	2	497.5	1	1	800	NE	Non-CITES
Phelsuma madagascariensis madagascariensis ˆ	Madagascar day gecko	Captive bred	Lizard	Gekkonidae	5	1	700	0	0	0	LC	Non-CITES
Physignathus cocincinus ˝	Chinese water dragon	Wild	Snake	Agamidae	0	0	0	1	1	800	VU	Non-CITES
Pogona vitticeps	Central bearded dragon	Captive bred	Lizard	Agamidae	349	34	277.87	70	6	240	LC	Non-CITES
*Python bivittatus***	Burmese python	Captive bred	Snake	Pythonidae	53	16	688.89	15	4	674.5	VU	Appendix II
Python regius	Ball python	Captive bred	Snake	Pythonidae	401	53	363.18	200	9	451.95	LC	Appendix II
Rhacodactylus auriculatus	Gargoyle gecko	Captive bred	Lizard	Diplodactylidae	2	1	1800	0	0	0	LC	Non-CITES
Sistrurus catenatus	Massasauga	Wild	Snake	Viperidae	1	1	450	0	0	0	LC	Non-CITES
*Stigmochelys pardalis**	Leopard tortoise	Captive bred	Tortoise	Testudinidae	0	0	0	76	11	539.21	LC	Appendix II
Testudo hermanni	Hermann's tortoise	Captive bred	Tortoise	Testudinidae	0	0	0	13	1	1466.67	NT	Appendix II
Testudo marginata	Marginated tortoise	Captive bred	Tortoise	Testudinidae	0	0	0	2	1	800	LC	Appendix II
*Trachemys scripta elegans***	Red-eared slider turtle	Captive bred	Turtle	Emydidae	0	0	0	5	3	733.33	LC	Non-CITES
Trimeresurus albolabris ˝	White-lipped pit viper	Wild	Snake	Viperidae	2	1	4250	1	1	400	LC	Non-CITES

*Varanus albigulari**	Rock monitor	Wild	Snake	Varanidae	3	2	1750	0	0	0	NE	Appendix II
Varanus exanthematicus	Savannah monitor	Captive bred	Snake	Varanidae	2	1	300	0	0	0	LC	Appendix II
Xenodon pulcher ˝	Tricolor hognose snake	Captive bred	Snake	Colubridae	0	0	0	1	1	5500	LC	Non-CITES

Notes

NT = Not Threatened

LC = Least Concern

NE = Not Evaluated

VU = Vulnerable

DD = Data Deficient

Non-CITES = Species not listed under CITES

Appendix I = includes species threatened with extinction. Trade in specimens of these species is permitted only in exceptional circumstances.

Appendix II = includes species not necessarily threatened with extinction, but in which trade must be controlled in order to avoid utilization incompatible with their survival.

Appendix III = contains species that are protected in at least one country, which has asked other CITES Parties for assistance in controlling the trade.

* = Species native to South Africa

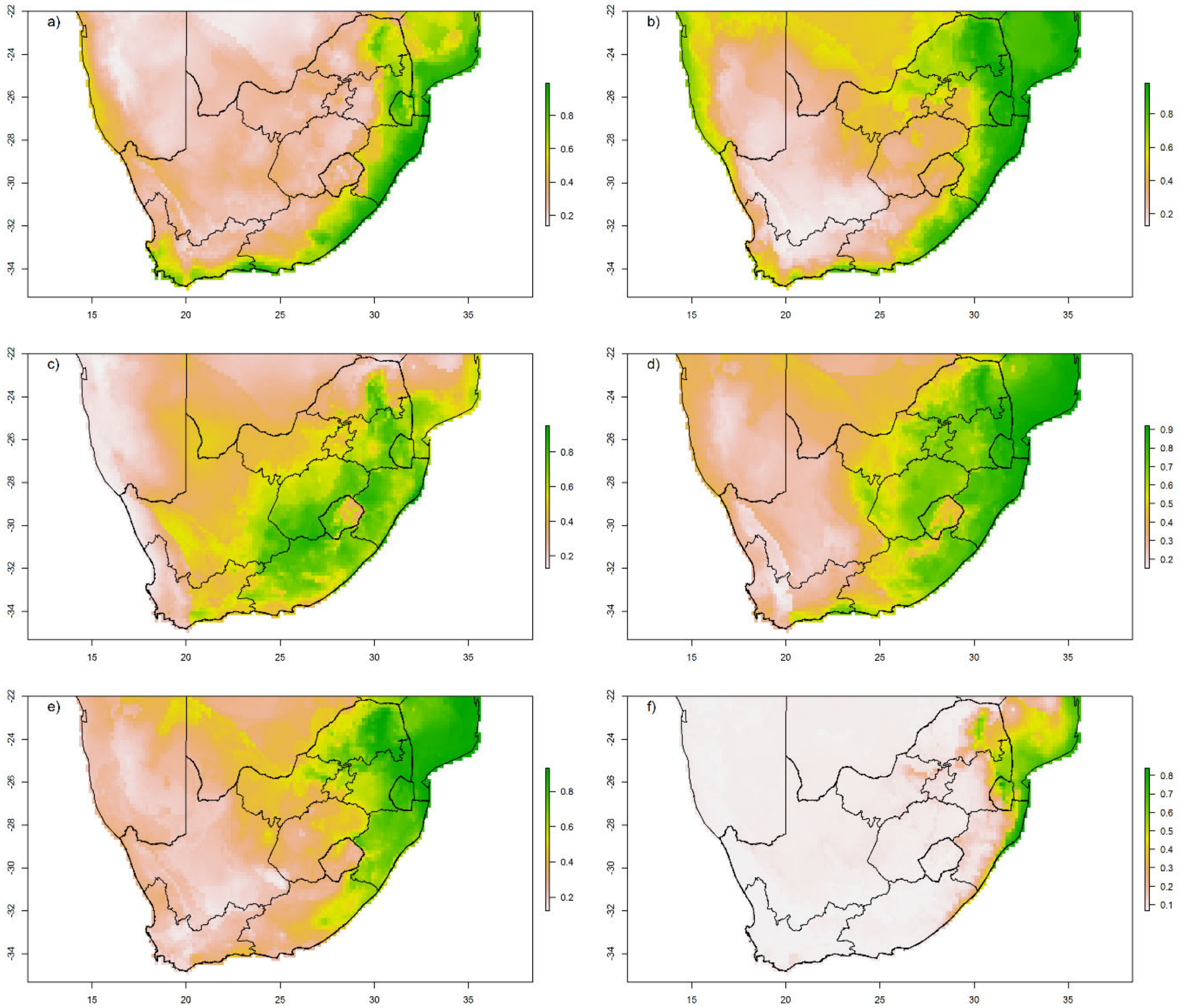
** = Species known to be invasive outside of their range

ˆ = Species recorded during the follow-up visits to pet stores.

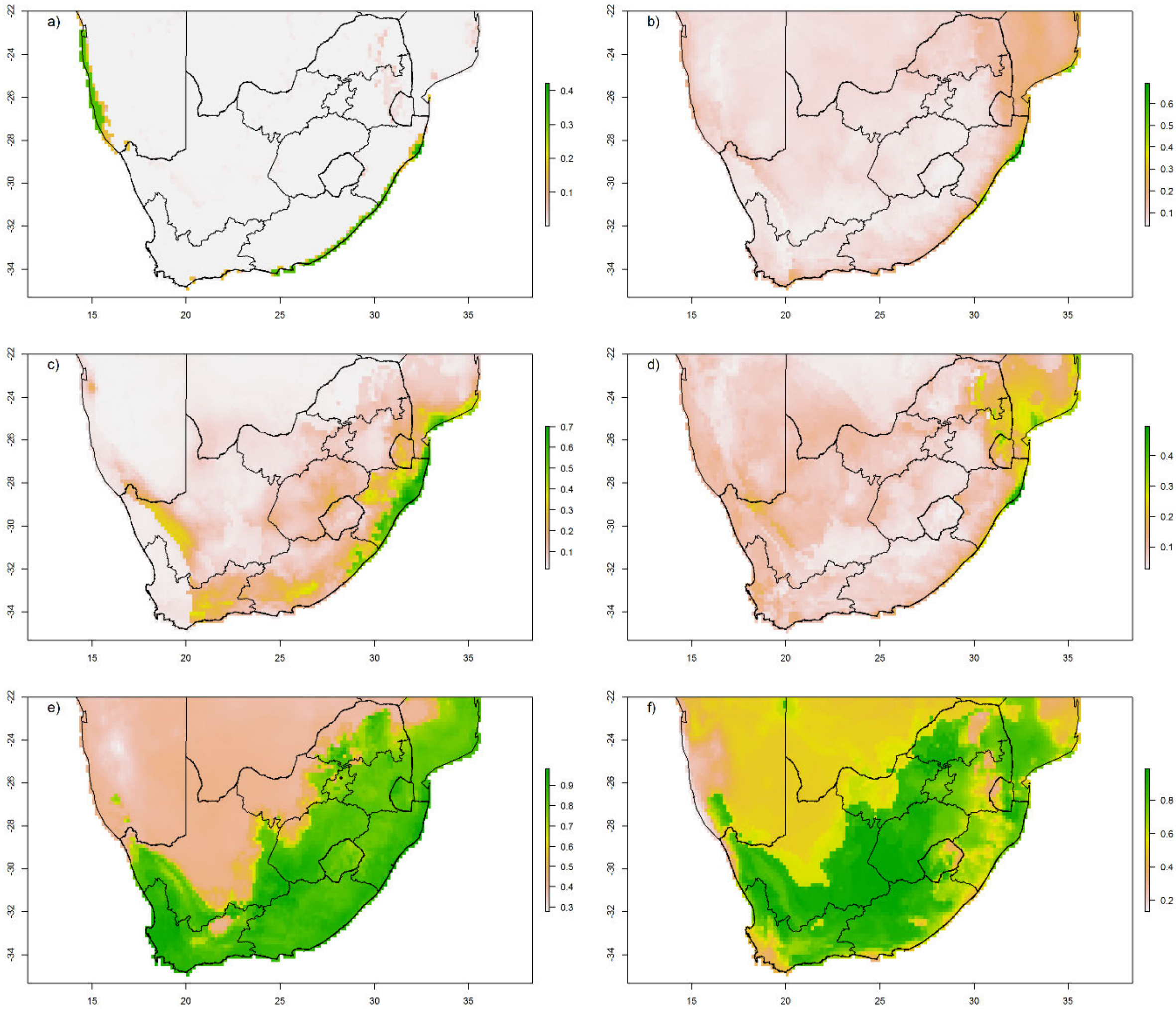
˝ = Species recorded during the follow-up searches to online advertising websites.

Supplementary Table S3.2. The regression models for each predictor variable showing the relationship between the log-transformed price and the number of reptile species traded in South Africa.

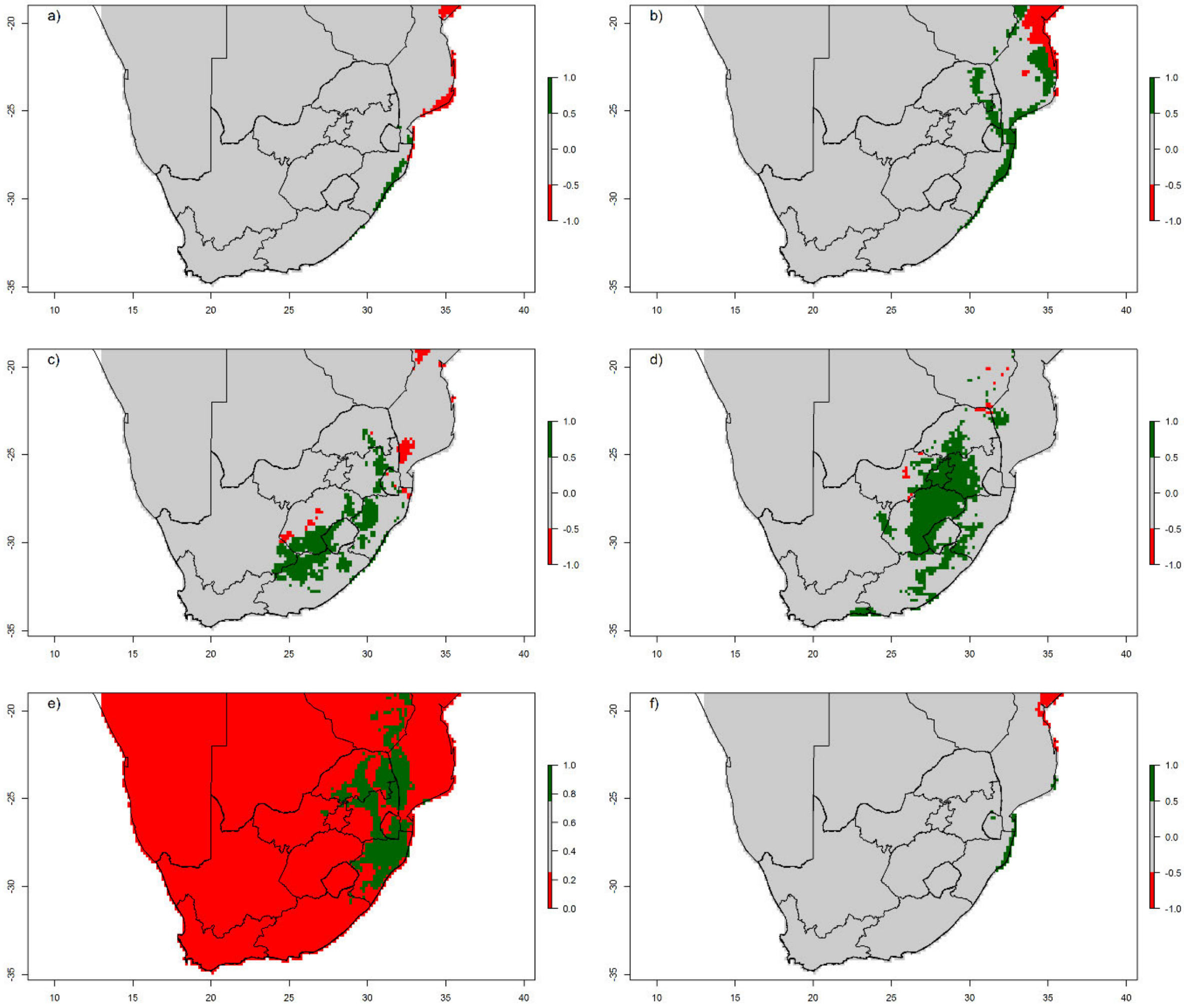
Physical pet stores	**Model**	**Estimates**	**Std. Error**	**t-value**	**P-value**	**AIC**
Invasion status	Price~number + non-invasive	-0.15	0.13	-1.15	0.25	68.2
	Price~number + invasive elsewhere	-0.04	0.22	-0.18	0.86	1072
Conservation status	Price~number + LC	0.66	0.36	1.81	0.07	885.1
	Price~number + NE	0.23	0.37	0.62	0.54	925.7
	Price~number + NT	-0.41	0.76	-0.54	0.59	588.2
	Price~number + VU	0.36	0.41	0.87	0.38	1035
CITES	Price~number + Appendix II	0.84	0.37	2.27	0.02	153.3
	Price~number + Appendix III	0.77	1.17	0.65	0.51	356.3
	Price~number + non-CITES	1.02	0.36	2.78	0.08	658.1
Aggression	Price~number + venomous	-0.59	0.61	-0.97	0.33	77.4
	Price~number + non-venomous	-0.06	0.57	-0.11	0.91	56.3
Online trade	**Model**	**Estimates**	**Std. Error**	**t-value**	**P-value**	**AIC**
Invasion status	Price~number + non-invasive	-0.66	0.31	-2.13	0.04	1054.3
	Price~number + invasive elsewhere	-1.14	0.37	-3.07	0.08	1069
Conservation status	Price~number + LC	0.86	0.63	1.36	0.18	698.3
	Price~number + NE	0.62	0.64	0.97	0.33	146.3
	Price~number + NT	1.56	1.07	1.46	0.15	653.4
	Price~number + VU	0.85	0.66	1.31	0.19	486.3
CITES	Price~number + Appendix II	0.7	0.46	1.52	0.13	136.5
	Price~number + non-CITES	0.25	0.31	0.33	0.07	24.4
Aggression	Price~number + venomous	0.62	0.97	0.64	0.52	36.5
	Price~number + non-venomous	0.32	0.88	0.36	0.72	896.3



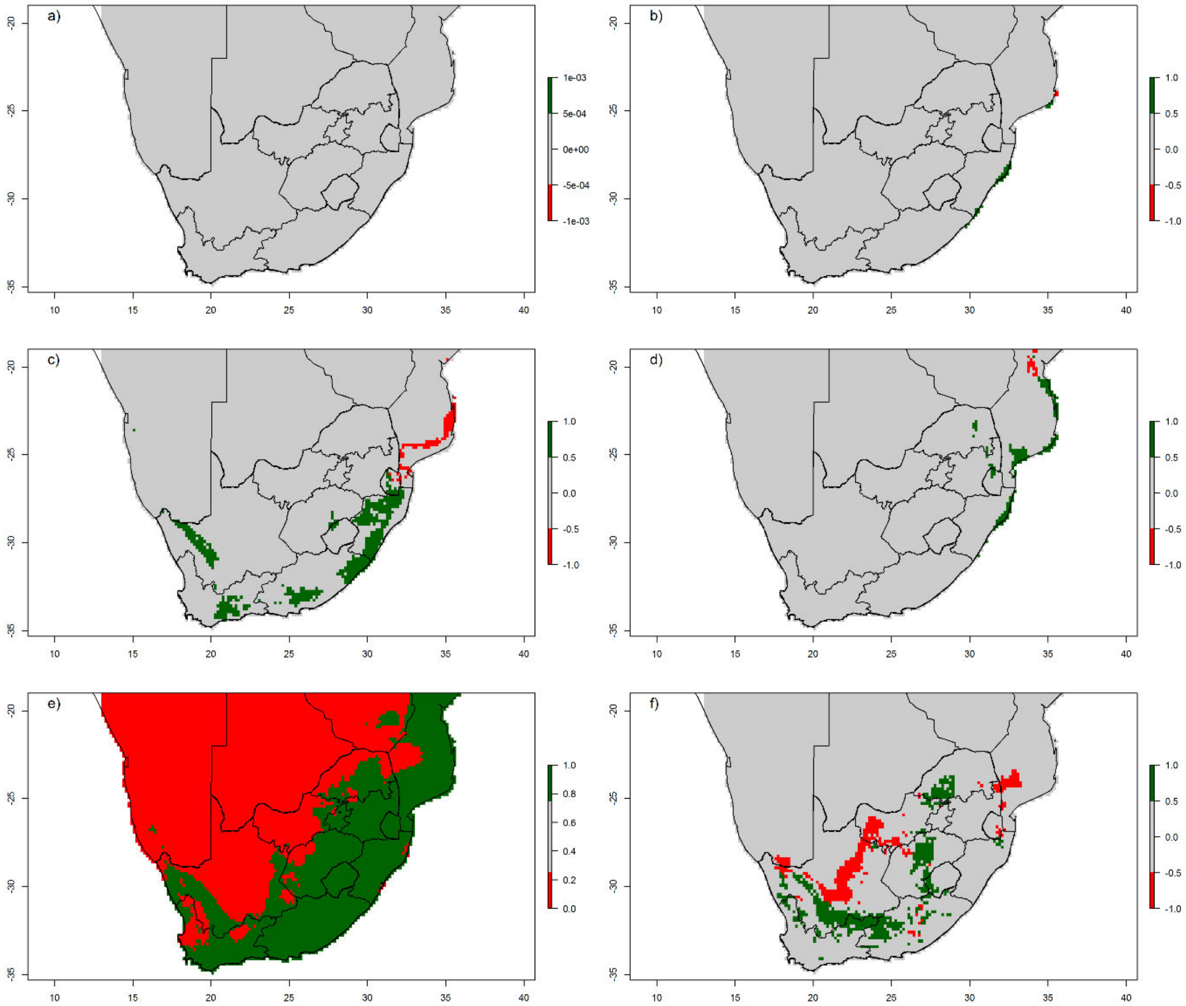
Supplementary Fig. S3.1. The species distribution modelling showing predicted future climatically suitable areas for a) *Anolis sagrei*, b) *Iguana iguanas*, c) *Pantherophis guttatus*, d) *Boa constrictor*, e) *Boa constrictor imperator*, and f) *Python bivittatus* for the year 2070 in South Africa. (Note: The climatically suitability is shown by a colour ramp threshold on the right of each map; the strong green colour denotes more suitable areas).



Supplementary Fig. S3.2. The species distribution modelling showing predicted future climatically suitable areas for a) *Orthriophis taeniurus*, b) *Python regius*, c) *Eunectes notaeus*, d) *Chamaeleo calyptratus*, e) *Trachemys scripta elegans*, f) *Crotalus atrox* for the year 2070 in South Africa. (Note: The climatically suitability is shown by a colour ramp threshold on the right of each map; the strong green colour denotes more suitable areas).



Supplementary Fig. S3.3. The predicted loss and gain future distribution maps 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: red = loss, grey = persistence, and green = gain).



Supplementary Fig. S3.4. The predicted loss and gain future distribution maps for a) *Orthriophis taeniurus*, b) *Python regius*, c) *Eunectes notaeus*, d) *Chamaeleo calyptratus*, e) *Trachemys scripta elegans*, f) *Crotalus atrox* in South Africa. (Note: red = loss, grey = persistence, and green = gain).

CHAPTER 4

Assessing the potential impacts of exotic reptile species advertised for sale in the South African pet trade

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4.1 Abstract

Assessing the impacts of non-native species is a fundamental and necessary process for preventing, monitoring and eradicating introduced species. In South Africa, impact assessment has been adopted for species introduced through various pathways, including the pet trade. We carried out a comprehensive literature search to collate information on the reported impacts associated with 76 non-native reptile pet species in South Africa using the Generic Impact Scoring System (GISS), Environmental Impact Classification for Alien Taxa (EICAT), and Socio-Economic Impact Classification for Alien Taxa (SEICAT). Using GISS, we found that out of 76 species, 13 species were found to have potential environmental impacts (E_GISS), while 11 species had potential socio-economic impacts (SE_GISS). For EICAT and SEICAT, 13 species had potential environmental impacts, and eight had potential socio-economic impacts, respectively. Additionally, the majority of species scored by both E_GISS and EICAT had similar rankings. However, there was a significant difference in the ranking of species by SE_GISS and SEICAT. The lack of literature on the impacts of the scored species could explain the differences observed in the ranking of species by these three schemes. The most popular pet species, red-tailed boa (*Boa constrictor*), green iguana (*Iguana iguana*), Burmese python (*Python bivittatus*), red-eared slider (*Trachemys scripta elegans*), and central bearded dragon (*Pogona vitticeps*) had potential impacts in all three scoring schemes. The later species and corn snake (*Pantherophis guttatus*) scored the highest for all impact schemes. All three scoring schemes are important tools that could be used to adequately inform policy and decision-makers when prioritising species with high or low impacts in South Africa.

Keywords: GISS, Impact assessment, EICAT, SEICAT, Species availability, Pets

4.2 Introduction

Several non-native species have been accidentally translocated into new environments around the world, through stowaways, hitchhikers and as transport contaminants (Hulme 2009; Faulkner et al. 2017). Additionally, some of the species are intentionally introduced as part of the pet trade, ornamentation, recreational purposes, biological agents, research, and food for pets and humans (Cambray 2003; Jojola et al. 2005; Pingel 2011; Fraser et al. 2015; Ng et al. 2016; Mori et al. 2017; Lockwood et al. 2019; Shivambu et al. 2020a). Some species get released deliberately by humans or escape accidentally from captivity into new environments, and such species may establish and become invasive (Ernst et al. 2009; Da Rosa et al. 2018; Shivambu et al. 2020a). For example, the Burmese python (*Python bivittatus*) was introduced in Florida as part of the pet trade and subsequently became invasive (Willson et al. 2011).

Non-native species have been associated with many negative impacts on native biodiversity, human health, agriculture, and the economy (Dove et al. 2011; Shivambu et al. 2020a). For example, the corn snake (*Pantherophis guttatus*) was declared a major threat to vulnerable amphibians such as Cuban treefrogs (*Osteopilus septentrionalis*) (Meshaka 2011). The trade in amphibians has been associated with the spread and transmission of diseases to other species, e.g. Chytridiomycosis caused by the chytrid fungus (*Batrachochytrium dendrobatidis*) (Herrel and van der Meijden 2014). Furthermore, the green iguana has been reported to cause significant socio-economic impacts by destroying agricultural production and human infrastructure (Thomas et al. 2011; López-Torres et al. 2012; Rivera-Milán and Haakonsson 2020).

Given the complex nature of the impacts associated with non-native taxa, there is a need for standardised measures to quantify environmental and socio-economic impacts associated with them (Measey et al. 2016; Kesner and Kumschick 2018). This need has been recently met by the development of impact scoring schemes such as the Environmental Impact

Classification for Alien Taxa (EICAT), the Generic Impact Scoring System (GISS), and the Socio-Economic Impact Classification of Alien Taxa (SEICAT) (Hawkins et al. 2015; Nentwig et al. 2016; Bacher et al. 2018). These scoring schemes are based on published evidence and are considered reliable, cost-effective, and easy to use (Ward et al. 2006; Ellender et al. 2017; Vanderhoeven et al. 2017; Hagen and Kumschick 2018; Nkuna et al. 2018; Shivambu et al. 2020a). Above all, these scoring schemes provide an important opportunity to estimate and compare environmental and socio-economic impacts across non-native taxa and regions (Kesner and Kumschick 2018; Evans et al. 2020). Many studies have successfully applied these scoring schemes to assess environmental and socio-economic impacts associated with non-native taxa (Nentwig et al. 2010; Laverty et al. 2015; Measey et al. 2016; Bacher et al. 2018; Galanidi et al. 2018; Hagen and Kumschick 2018; Shivambu et al. 2020a; Nelufule et al. 2020; Shivambu et al. 2020b; Sohrabi et al. 2021).

Reptiles are among the most popular groups in the South African pet trade (van Wilgen et al. 2010), yet their impacts are poorly studied. Of most concern, some reptile species present in the South African pet trade have been reported to be invasive and causing relatively great impacts to many ecosystems worldwide, e.g. the Burmese python in Florida (Dove et al. 2011), green iguana (*Iguana iguana*) in Puerto Rico (López-Torres et al. 2012), and the red-eared slider (*Trachemys scripta elegans*) in many parts of the world (Lever 2003). While there are many non-native reptile species sold in South Africa, there is a need to assess and quantify their potential impacts, particularly environmental and socio-economic impacts. This would help in identifying potential harmful non-native reptile species in the South African pet trade and assist in decision-making, especially when prioritising limited resources.

In this study, we aimed to (1) produce a comprehensive list of all threatening non-native reptile species sold as pets in South Africa using EICAT, GISS, and SEICAT, and (2) determine the relationship between the overall impacts scored per species and species availability. Using all three-impact scoring schemes will increase the accuracy and robustness of our results as these schemes focus on different aspects. We predicted to find variation between the impact mechanisms of non-native reptile species sold in South Africa. We further predicted that there would be a relationship between species popularity and impact magnitude.

4.3 Methods

4.3.1 Species selection

Refer to Chapter 3 (2.1).

4.3.2 Literature search

We searched for literature on impacts associated with non-native reptile species sold as pets in South Africa from the biological invasion website journals, Google (https://www.google.com/), Google Scholar (https://scholar.google.com/), Web of Science (https://clarivate.com/), the Global Invasive Species Database (GISD: www.iucngisd.org/gisd), and the Centre for Agriculture and Biosciences International (CABI: www.cabi.org/isc). To search for the impacts, the scientific and common names were used for each species in combination with impact phrases, for example, "Burmese python impacts", "Burmese python impacts on agriculture", "Burmese python compete with native fauna", "Burmese python hybrids", and "*Iguana iguana* diseases on humans". We only used the information (impacts) extracted from literature records exclusively from areas outside South Africa. The recorded information on impacts was then used to assess the magnitude of the impact using different assessment protocols.

4.3.3 Impact scoring

In this study, we used three impact scoring schemes, namely the Environmental Impact Classification for Alien Taxa (EICAT) (Hawkins et al. 2015), Generic Impact Scoring System (GISS) (Nentwig et al. 2016), and Socio-Economic Impact Classification for Alien Taxa (SEICAT) (Bacher et al. 2018). SEICAT and EICAT impact schemes classify non-native species based on the magnitude of their socio-economic and environmental impacts respectively into five impact categories, ranging from Minimal Concern (MC) to Massive (MV) (Table 1). However, for statistical analyses, we transferred all impact scores for EICAT and SEICAT into numerical scores (i.e. MC translated to 1 and MV to 5). EICAT focuses on environmental impacts and is comprised of 12 mechanisms under which non-native species can affect native species. These mechanisms are as follows; (1) competition; (2) predation; (3) hybridisation; (4) transmission of disease to native species; (5) parasitism; (6) poisoning/ toxicity; (7) biofouling; (8) grazing/ herbivory/ browsing; (9) chemical impact on ecosystem, (10) physical impact on ecosystem, (11) structural impact on ecosystem chemical, physical, or structural impact on the ecosystem, and (12) interaction with other non-native species.

SEICAT is similar to EICAT in terms of impact levels but assesses the socio-economic impacts of non-native species (Kesner and Kumschick 2018). The magnitude of impacts is measured based on how people are affected in their activities (e.g. poultry farming) (Bacher et al. 2018). The irreversible loss of an activity from a community caused by non-native species is considered a massive impact (MV). In both EICAT and SEICAT schemes, we assessed species using a confidence score of a high, medium, and low assigned based on the quality of the information obtained from the literature (Hawkins et al. 2015).

The GISS impact scheme consists of 12 mechanisms under which non-native species can affect the native species and communities (Nentwig et al. 2016). There are six mechanisms under environmental impacts (impacts on plants or vegetation, impacts on animals, competition, disease transmission, hybridisation, and impacts on the ecosystem). Socio-economic impacts also comprise of six impact mechanisms (impacts on agricultural production, animal production, forestry production, human infrastructure, human health, and human social impacts) (Nentwig et al. 2016). The impact scores in each category ranged from 0 (no impacts detectable or no data available) to 5 (major impacts) (Nentwig et al. 2010). The maximum overall impact score is 60 (12 impact categories × 5 maximum impact score per category).

Table 4.1 Summary of EICAT and SEICAT impact categories with a brief description of each impact used in the present study (adapted from Blackburn et al. 2014 and Bacher et al. 2018).

	Massive (MV)	**Major (MR)**	**Moderate (MO)**	**Minor (MN)**	**Minimal Concern (MC)**
EICAT	Causes at least local extinction of native species, and irreversible changes in community composition; even if the alien taxon is removed, the system does not recover its original state	Causes at least local extinction of native species and thus changes in community composition, which are reversible if the alien taxon is removed	Causes population declines in native species, but no changes in community composition due to local extinction of one or more native species	Causes reductions in individual fitness, but no declines in native population sizes	No effect in the fitness of individuals of native species
SEICAT	Local disappearance of activity from a local community, irreversible for at least a decade ("regime shift")	Local disappearance of activity from at least part of the area invaded by the alien taxon, likely to be reversible within a decade after removal or control of the alien taxon	Changes in activity size, fewer people participating in an activity, but the activity is still carried out	Difficult for people to participate in their normal activities, but no changes in activity size	Unlikely to have caused deleterious impacts on individual people's wellbeing

4.3.4 Statistical analyses

We conducted all analyses in R statistical software (version 3.4.4, R Core Team 2018). We used paired Wilcoxon's signed-rank test to compare the significant differences between potential environmental and socio-economic impact, where impact scores obtained in EICAT were compared with SEICAT impact scores. For the GISS comparisons, impact scores of E_GISS (Environmental_GISS) were compared with SE_GISS (Socio-economic_GISS) scores. We further used paired Wilcoxon's signed-rank test to test the similarity between summed scores obtained in GISS, EICAT, and SEICAT. To achieve this, summed environmental impact scores obtained per species were used to compare E_GISS with EICAT. Also, socio-economic impact scores were used to compare SE_GISS with SEICAT. The relationship between overall impacts scored per species and the number of publications was assessed using Kendall's tau test.

4.4 Results

4.4.1 Impact schemes and number of literature

A total of 140 publications were used to assess the potential impacts associated with 16 non-native reptile species using the GISS (Table 4.2). For E_GISS, we used a total of 107 publications, while for S_GISS we used 33 publications. Out of 76 reptile species, 13 species were found to have potential environmental impacts, while 11 species were found to have potential socio-economic impacts (Table 4.2). When we examined the relationship between overall impacts scored per species and the number of publications, we found that environmental and socio-economic impacts were positively correlated to the number of publications used for scoring (Kendall's tau: $\tau = 0.882$, $P = 1.1042e\text{-}05$), and (Kendall's tau: $\tau = 0.907$, $P < 0.05$), respectively.

For EICAT, we used a total of 99 publications to score potential impacts associated with the 13 non-native reptile species. When we examined the relationship between the overall potential impacts scored and the number of publications used, we found a negative correlation between the two (Kendall's tau: τ = -0.333, P = 0.75). For SEICAT, we used a total of 19 publications to score potential impacts associated with eight non-native reptile species. We found a negative correlation between the overall potential impacts scored per species and the number of publications used (Kendall's tau: τ = -0.298, P = 0.87).

4.4.2 GISS, EICAT and SEICAT

The sum of potential impact scores obtained from GISS ranged from 0 to 17, with the green iguana and red-eared slider recording the greatest potential impact according to the total impact score (Table 4.2; Supplementary information Table S4.2). Four species, veiled chameleon (*Chamaeleo calyptratus*), Eastern diamondback rattlesnake (*Crotalus adamanteus*), Indian star tortoise (*Geochelone elegans*), and false water cobra (*Hydrophis platurus*) had low or minor potential impacts with an impact score of one (Table 4.2). Under environmental impact (E_GISS), three species (green iguana, red-eared slider, and Burmese python) recorded the highest potential impact with scores of 17, 17 and 16, respectively (Table 4.2). The above-mentioned species recorded the highest potential impact on socio-economic impact (SE_GISS) (Table 4.2). When comparing impact mechanisms, we found that predation, competition and disease transmission scored highest among environmental impacts (E_GISS) (Table 4.2; Supplementary information Table S4.2). In terms of socio-economic impact (SE_GISS) categories, we found that most of the assessed non-native reptile species were highly associated with potential impacts on human health (number of species (n) = 7), animal production (n = 5), agricultural production (n = 3), and human infrastructure (n = 1) (Table 4.2; Supplementary information Table S4.2).

For EICAT, impacts assessed ranged from MC to MR, with two of the assessed species, Western hognose snake (*Heterodon nasicus*) and false water cobra found to have no recorded potential impacts (DD) (Supplementary information Table S4.3). The red-eared slider recorded the greatest potential impact (Major impact: MR), while three species, veiled chameleon, central bearded dragon (*Pogona vitticeps*), and Indian star tortoise, recorded potential impacts of minimal concern (MC) (Table 4.2; Supplementary information Table S4.3). Under EICAT, we found that most of the species were associated with predation (number of species (n) = 8), hybridisation (n = 2), competition (n = 2), and diseases transmission (n = 4) (Table 4.2). Notably, no impacts were assigned for poisoning/ toxicity, biofouling, grazing/ herbivory/ browsing, and chemical impact on ecosystems.

For SEICAT, the impacts ranged from MC to MO; 90% of the species were data deficient, while one species was of minimal concern, and six were of minor concern (Fig. 4.1b; Supplementary information Table S4.4). The Burmese python scored the highest potential impact (Moderate impact: MO), while the red-tailed boa (*Boa constrictor*) scored potential impacts of minimal concern. According to SEICAT, non-native reptile species were mostly associated with effects on health (number of species (n) = 7), material assets (n = 2), and social relations (n = 1) (Table 4.2; Supplementary information Table S4.4).

4.4.3 Comparison between GISS (E_GISS) and EICAT

The green iguana, red-eared slider, and Burmese python recorded high environmental impacts in E_GISS and EICAT. Two species, veiled chameleon and Indian star tortoise, ranked similarly based on the two scoring schemes (Table 4.2). The green iguana and brown anole (*Anolis sagrei*) with minor and moderate potential impacts, respectively, ranked differently in the two scoring schemes (Table 4.2). However, in overall, we found no significant difference between EICAT and E_GISS scores (Wilcoxon's signed-rank test: V = 64.5, P = 0.115).

4.4.4 Comparison between GISS (SE_GISS) and SEICAT

We found a significant difference in socio-economic impact scores obtained in SE_GISS and SEICAT (Wilcoxon's signed-rank test: $V = 35$, $P = 0.012$). The green iguana had maximum recorded potential impacts in SE_GISS but had minor impacts in SEICAT (Table 4.2). The brown anole and eastern rat snake (*Pantherophis alleghaniensis*) had a low potential impact in SE_GISS but were found to have no potential impact (DD) in SEICAT (Table 4.2). However, six species, Madagascar ground boa (*Acrantophis madagascariensis*), copperhead (*Agkistrodon contortrix*), American alligator (*Alligator mississippiensis*), veiled chameleon, Indian star tortoise, and corn snake were found to have no impacts (DD) and ranked similarly according to the two scoring schemes (Table 4.2). Five species, including the red-tailed boa, the green iguana, the central bearded dragon, the Burmese python, and the red-eared slider, had potential impacts on all three scoring schemes (Table 4.2).

4.4.5 Species popularity and impacts

Most of the species with high availability had no impact records (DD) for all the scoring schemes (Fig. 4.1). For EICAT, the most available species (e.g. corn snake and central bearded dragon) had moderate impacts, while the least available species (red-eared-slider) had a major impact (Fig. 4.1a). Under SEICAT, the highest impact category was moderate, with the least popular species, Burmese python, recorded for this impact (Fig. 4.1b). The most available species scoring the highest under SEICAT was the central bearded dragon (Fig. 4.1). For E_GISS, corn snake was the most available species scoring the highest for impacts on animals, disease transmission, hybridisation, and on the ecosystem (Fig. 4.1c). Additionally, the Burmese python and green iguana were the most available species scoring the highest for competition and plant and vegetation, respectively (Fig. 4.1c). Species were found to have impacts under four impact categories for S_GISS, with most of the species recorded for impacts on human health (Fig. 4.1d). The central bearded dragon was the most available species scoring high under S_GISS. (Fig. 4.1d).

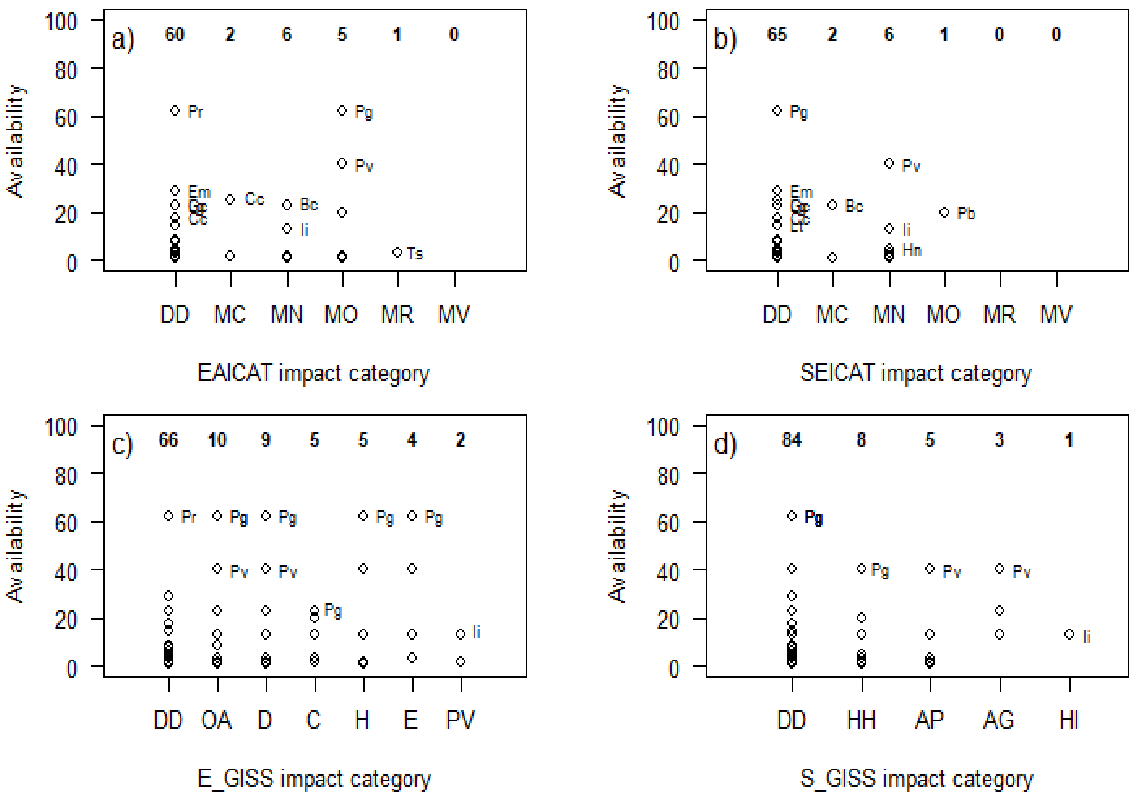

Fig. 4.1 The relationship between impact mechanisms and/or constituents and species availability based on a) EICAT, b) SEICAT, c) E_GISS, and d) S_GISS scores in the present study. The numbers at the top of the figures represent the number of species with recorded impact per category. The impact categories indicated on the figure are DD = Data Deficient, MC = Minimal Concern, MN = Minor, MO = Moderate, MR = Major, MV = Massive, PV = Plant and vegetation, E = Ecosystem, D = Disease transmission, OA = On animal, H = Hybridisation, C = Competition, AG = Agricultural production, HH = Human health, FP = Forestry production, HS = Human social life, HI = Human infrastructure, and AP = Animal production. The abbreviations for species with high impacts are as follows Pr = *Python regius*, Pg = *Pantherophis guttatus*, Ii = *Iguana iguana*, Pv = *Pogona vetticeps*, Bc = *Boa constrictor*, Pb = *Python bivittatus*, Ts = *Trachemys scripta*, and Cc = *Chamaeleo calyptratus*.

Table 4.2 Summary of E_GISS, SE_GISS, EICAT, and SEICAT assessments for all non-native reptile species sold as pets in the South African pet trade in the present study.

Species name	E_GISS			SE_GISS			EICAT			SEICAT		
	Maximum score	Mechanism(s)	No. publications	Maximum score	Mechanism(s)	No. publications	Maximum impact	Mechanism(s)	No. publications	Maximum impact	Constituent(s) of human well-being	No. publications
Acrantophis madagascariensis	3	On animals	4	DD		0	MN	Predation	4	DD		0
Agkistrodon contortrix	2	Hybridisation	2	DD		0	MN	Hybridisation	2	DD		0
Alligator mississippiensis	3	On animals; disease transmission	4	DD		0	MN	Predation	3	DD		0
Anolis sagrei	14	On plants or vegetation; on animals; competition; disease transmission; hybridisation	23	1	Animal production	1	MO	Predation	12	DD		0
Boa constrictor	7	On animals; competition; disease transmission	9	1	Agricultural production	1	MN	Transmission of diseases to native species; Predation	7	MC	Material assets	1
Chamaeleo calyptratus	1	On animals	1	DD		0	MC	Predation	1	DD		0
Crotalus adamanteus	DD		0	1	Human health	1	DD		0	MN	Health	1

Species name	E_GISS			SE_GISS			EICAT			SEICAT		
	Maximum score	Mechanism(s)	No. publications	Maximum score	Mechanism(s)	No. publications	Maximum impact	Mechanism(s)	No. publications	Maximum impact	Constituent(s) of human well-being	No. publications
Geochelone elegans	1	Disease transmission	1	DD		0	MC	Transmission of diseases to native species	1	DD		0
Heterodon nasicus	DD		0	2	Human health	4	DD		0	MN	Health	2
Hydrophis platurus	DD		0	1	Human health	1	DD		0	MN	Health	1
Iguana iguana	17	On plants or vegetation; on animals; competition; disease transmission; hybridisation	11	13	Agricultural production; animal production; human infrastructure; human health	10	MN	Hybridisation	2	MN	Material assets; social relations; health	4
Pantherophis alleghaniensis	4	On animals	7	2	Animal production	3	MO	Predation	7	DD		0
Pantherophis guttatus	9	On animals; disease transmission; hybridisation; ecosystem	9	DD		0	MO	Predation	4	DD		0

Species name	E_GISS			SE_GISS			EICAT			SEICAT		
	Maximum score	Mechanism(s)	No. publications	Maximum score	Mechanism(s)	No. publications	Maximum impact	Mechanism(s)	No. publications	Maximum impact	Constituent(s) of human well-being	No. publications
Pogona vitticeps	2	Disease transmission	2	1	Human health	1	MC	Transmission of diseases to native species	2	MN	Health	1
Python bivittatus	16	On animals; competition; disease transmission; hybridisation; ecosystem	13	7	Agricultural production; animal production; human health	6	MO	Competition; Predation	9	MO	Health	3
Trachemys scripta elegans	17	On animals; competition; disease transmission; ecosystem	15	5	Animal production; human health	3	MR	Transmission of diseases to native species; Competition	13	MN	Health	5

4.5 Discussion

4.5.1 Impact schemes and number of publications

Our study assessed the potential impacts of non-native reptile species sold in South Africa using three scoring schemes. Most of the species were not assessed impacts because of the lack of information on them. For example, 79% of the species scored for GISS, 83% for EICAT, and 90% for SEICAT could not be assessed because of data deficiency. It has been noticed that researchers tend to focus exclusively on species with high profiles (i.e. highly damaging impacts) when assessing the impacts of non-native species (Pyšek et al. 2008; Hagen and Kumschick 2018; Kesner and Kumschick 2018). For example, invasive species such as the red-tailed boa, the Burmese python and the red-eared slider were found to have potential impacts in both environmental and socio-economic realms. These results also showed an existing literature gap in environmental and socio-economic impacts for most species sold in the pet trade.

4.5.2 GISS, EICAT and SEICAT

The sum of impact scores captures the impacts of species and the magnitude of potential threats, providing useful information for decision-makers, particularly when prioritising limited resources (Sohrabi et al. 2021). We predicted to find a variation in the magnitude of the environmental and socio-economic potential impacts for non-native reptile species sold as pets in South Africa. Our results indicated that most of the assessed species were associated with high environmental impacts compared with socio-economic impacts. A possible explanation could be that the socio-economic impacts of non-native reptile species are less studied or not known compared with environmental impacts (Evans et al. 2020). It is also possible that some of the studied species do not exert socio-economic impacts at all, and hence no impacts were detected, for example, the brown anole, corn snake, and eastern rat snake. Many of the assessed species may have minor socio-economic impacts and/or do not affect human beings, thus getting little attention from researchers or the public (Hagen and Kumschick 2018). In addition, the socio-economic impacts of some non-native reptiles might not be noticeable because they occur in regions where impacts are not easily recorded or with fewer resources to study (Evans et al. 2020). However, the difference in magnitude between environmental and socio-economic impacts does not suggest that non-native reptile species do not have socio-economic impacts, e.g. the Burmese python had moderate socio-economic impacts. Therefore, this suggests a need for more research, especially on the socio-economic impacts, to better understand the impacts associated with this taxon and better inform policymakers about their potential impacts.

When comparing impact mechanisms under E_GISS, we found that non-native reptile species had more impacts through predation on other animals, competition and disease transmission, with Burmese python scoring high impact through these categories. This could be explained by that most of the reptile species are carnivores (Guarino 2001). For example, the Burmese python predates on small mammals and birds (Dove et al. 2012; McCleery et al. 2015), competes with threatened native species, such as the indigo snake (*Drymarchon couperi*) (Harvey et al. 2008), and was reported to have introduced lung pentastome parasites, *Raillietiella orientalis* to Florida (Miller et al. 2018). Of most concern, the green iguana was the only species that scored high through effects on plants or vegetation and ecosystem in the present study. This is because it feeds on plants in gardens, affecting seed germination and dispersal in Puerto Rico (Benítez-Malvido et al. 2003; Burgos-Rodríguez et al. 2016). Additionally, this species has also been reported to consume the fruits of invasive plants and defecate them (Meshaka et al. 2007; Sementelli et al. 2008). This may subsequently facilitate the establishment and spread of invasive plants in the introduced ranges.

Under SE_GISS, we found that impact categories that contributed enormously to the final impact score were impacts on human health, animal production and agricultural production.

The green iguana scored high in these categories more than any other species assessed in this study. This species has been reported to be damaging and destroying crops (Thomas et al. 2011; López-Torres et al. 2012), feeding on bird eggs and chicks (Schwartz and Henderson 1991; Rivero 1998; Falcón et al. 2013), and causing erosion that further undermine foundations, canal banks, seawalls, and other infrastructure (Kern 2004; Krysko et al. 2007; Rivera-Milán and Haakonsson 2020).

The red-eared slider scored major impacts under EICAT through competition and disease transmission. This species is extremely competitive as it aggressively competes with native species such as the European pond turtle (*Emys orbicularis*), Spanish terrapin (*Mauremys leprosa*), and the red-bellied turtle (*Pseudemys rubriventris*) (Cadi and Joly 2003; Somma et al. 2009a; Polo-Caiva et al. 2010; Pearson et al. 2015). The dominance of this mechanism (competition) might be attributed to the fact that it is among the most studied categories in ecology (Sohrabi et al. 2021). The red-eared slider also carries nematodes and facilitate the spread of parasites and diseases to native taxa (Hays et al. 1999; Feldman 2005; O'Keefe 2005; Scalera 2006; Hidalgo-Vila et al. 2009). This species poses an invasion risk to South Africa, given increasing reports of wild populations reported in water bodies (Nxele per. comm.; Northglrn News 2018).

When comparing constituents of human well-being under SEICAT, we found that they differed significantly from each other, with Burmese python scoring high on health impacts. This is because the Burmese python was reported to have killed a person in Irwin Pennsylvania (Murphy 2020). In addition, a teenage boy was also reported to have been attacked by a captive Burmese python in Colorado (Reed and Snow 2014). However, although SEICAT has been successfully applied in many studies (e.g. Kumschick et al. 2015; Hagen and Kumschick 2018), the lack of impact data remains the biggest challenge. Therefore, there is an urgent need for future research to focus more on socio-economic impacts so as to improve impact data and provide information on non-native reptile species that threaten human health.

4.5.3 Comparing GISS (E_GISS) and EICAT

We found that environmental impact scores obtained in E_GISS and EICAT were not significantly different from each other, suggesting that the results obtained from the two scoring schemes complement each other. Both E_GISS and EICAT emphasized the effect of competition and disease transmission, suggesting that they are suitable tools for interaction studies and epidemiology. The overall classifications for E_GISS and EICAT were similar, e.g. EICAT impact categories (MC to MV) corresponded to E_GISS classifications (1 to 5) (Sohrabi et al. 2021). The observed differences in ranking of species may be attributed to the lack of literature to quantify significant environmental impacts caused by the assessed non-native species on native taxa. The results presented in this study suggests that both GISS and EICAT should be applied so as to ensure high precision and accuracy of the results. This would subsequently assist in decision making and policy development for high impacting species.

4.5.4 Comparing GISS (SE_GISS) and SEICAT

When comparing socio-economic impact scores obtained in GISS and SEICAT, we found that they differed significantly from each other. Additionally, we observed a significant difference in the ranking of species between the two scoring schemes. A possible explanation for these results could be that GISS and SEICAT are based on different endpoints when comparing socio-economic impacts (Nentwig et al. 2016; Bacher et al. 2017). For example, SE_GISS addresses the economic impacts of species while SEICAT addresses changes in human well-being and activities caused by non-native taxa (Hagen and Kumschick 2018). The impacts caused by green iguana on agricultural production could be seen as relatively high in the SE_GISS scoring scheme (score (n) = 3), but according to SEICAT, damages caused by this species are relatively low (score (n) = MN (2)). This, therefore, emphasises the need to apply both scoring schemes to better understand and get a complete picture of socio-economic impacts caused by non-native taxa.

4.5.5 Species popularity and impacts

Overall, we found that most of the species with high availability had no impact records for all the scoring schemes. Notably, only five species, the red-tailed boa, green iguana, central bearded dragon, Burmese python, and red-eared slider, had impacts in all three schemes. Species with high impacts in EICAT and SEICAT had a low availability index (e.g. red-eared slider and Burmese python, respectively), while species with high availability (e.g. corn snake and central bearded dragon) had minor or moderate impacts. Three species, the corn snake, red-eared slider, and Burmese python, were the most available species with significant impact under E_GISS, with the central bearded dragon scoring high in S_GISS. Many ecological studies have reported that popular pet species are often available in high numbers, and this subsequently increases their likelihood of being released or escape into the wild as pet owners or traders might not have sufficient space to accommodate high these species (Su et al. 2015; Vall-llosera and Cassey 2017; Stringham and Lockwood 2018; Lockwood et al. 2019; Siriwat et al. 2019). In addition, some of the recorded species with high popularity, such as the Burmese python, often grow into larger body sizes which increases their likelihood of being introduced (van Wilgen et al. 2010). Therefore, popular species should be assessed for their impacts, and their trade should be strictly monitored. This, however, does not suggest that the least available species should be neglected as some of the least available species in this study had major impacts on the native taxa, e.g. the red-eared slider. This indicates the importance of scoring for all traded species despite their popularity.

4.6 Conclusion and recommendations

Given that some of the non-native reptile species traded in South Africa had significant potential environmental and socio-economic impacts, we recommend that their trade should be strictly monitored and prioritised for policy development. For example, the red-eared slider, Burmese python, green iguana, brown anole, corn snake, and central bearded dragon need to be prioritised due to the high impacts that they pose on native taxa. The proportion of species scored in this study had higher environmental impacts; therefore, we recommend that future research should focus on studying socio-economic impacts, especially impacts on human infrastructure, human health, and human social impacts. The results presented in this study suggest that GISS, EICAT, and SEICAT are important tools that could be used to inform policy and decision-makers when prioritising species with high or low impacts.

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4.9 Supplementary information

Supplementary information Table S4.1 Reptile species advertised for sale in physical pet shops and online advertising websites in South Africa.

Species names	**Common name**	**Number of pet shops**	**Number of online websites**	**Total**
Acrantophis dumerili (Jan, 1860)	Dumeril's boa	6	3	9
Acrantophis madagascariensis (Duméril & Bibron, 1844)	Madagascar ground boa	1	0	1
Agkistrodon contortrix (Linnaeus, 1766)	Copperhead	1	0	1
Alligator mississippiensis (Daudin, 1802)	American alligator	1	0	1
Anolis sagrei (Duméril & Bibron, 1837)	Brown anole	2	0	2
Antaresia maculosa (Peters, 1873)	Spotted python	4	1	5
Aspidelaps lubricus (Laurenti, 1768)	Cape coral snake	1	2	3
Aspidelaps scutatus (Smith, 1849)	Shield-nose snake	0	1	1
Aspidites ramsayi (Macleay, 1882)	Woma python	1	0	1
Bitis arietans (Merrem, 1820)	Puff adder	2	0	2
Boa constrictor (Linnaeus, 1758)	Red-tailed boa	20	3	23
Boa constrictor imperator (Daudin, 1803)	Common boa	1	0	1

Species names	Common name	Number of pet shops	Number of online websites	Total
Boaedon capensis (Duméril & Bibron, 1854)	Cape house snake	7	2	9
Boaedon lineatus (Bibron & Duméril, 1854)	Striped house snake	0	2	2
Bothriechis schlegelii (Berthold, 1846)	Eyelash viper	1	0	1
Centrochelys sulcate (Miller, 1779)	Dumeril's boa	0	1	1
Chamaeleo calyptratus (Duméril & Duméril, 1851)	Madagascar ground boa	6	3	9
Chersina angulate (Schweigger, 1812)	Copperhead	0	1	1
Chilabothrus angulifer (Cocteau & Bibron, 1840)	American alligator	2	0	2
Chondropython viridis (Boulenger, 1893)	Brown anole	0	1	1
Correlophus ciliatus (Guichenot, 1866)	Spotted python	11	7	18
Crotalus adamanteus (Palisot De Beauvois, 1799)	Cape coral snake	2	0	2
Crotalus atrox (Baird & Girard, 1853)	Shield-nose snake	1	0	1
Crotalus durissus (Linnaeus, 1758)	Woma python	1	0	1
Crotalus scutulatus (Kennicott, 1861)	Puff adder	0	1	1
Crotalus viridis (Rafinesque, 1818)	Red-tailed boa	1	0	1
Dasypeltis inornata (Smith, 1849)	Common boa	0	1	1
Deinagkistrodon acutus acutus (Günther, 1888)	Cape house snake	1	0	1

Species names	Common name	Number of pet shops	Number of online websites	Total
Dendroaspis angusticep (Smith, 1849)	Striped house snake	2	0	2
Elaphe obsoleta lindheimeri (Crother, 2000)	Eyelash viper	1	0	1
Elaphe schrenckii (Strauch, 1873)	Russian ratsnake	1	0	1
Epicrates cenchria (Linnaeus, 1758)	Rainbow boa	2	1	3
Eublepharis macularius (Blyth, 1854)	Common leopard gecko	27	2	29
Eunectes deschauenseei (Dunn & Conant, 1936)	Dark-spotted anaconda	4	0	4
Eunectes notaeus (Cope, 1862)	Yellow anaconda	2	0	2
Geochelone elegans (Schoepff, 1795)	Indian star Turtle	0	1	1
Gongylophis colubrinus (Mcdiarmid *et al.*, 1999)	Kenyan sand boa	20	3	23
Gongylophis conicus (Wagler, 1830)	Russell's boa	1	0	1
Gonyosoma boulengeri (Mocquard, 1897)	Rhinoceros ratsnake	2	0	2
Gonyosoma oxycephalum (Boie, 1827)	Arboreal ratsnake	1	0	1
Hemitheconyx caudicinctus (Duméril, 1851)	African fat-tailed gecko	3	1	4
Heterodon nasicus (Baird & Girard, 1852)	Western hognose snake	4	1	5
Hydrodynastes gigas (Duméril *et al.*, 1854)	False water cobra	1	0	1
Hydrophis platurus (Linnaeus, 1766)	Yellow-bellied sea snake	0	1	1

Species names	Common name	Number of pet shops	Number of online websites	Total
Iguana iguana (Linnaeus, 1758)	Green iguana	11	2	13
Lampropeltis calligaster (Harlan, 1827)	Yellow-bellied kingsnake	0	1	1
Lampropeltis getula (Linnaeus, 1766)	Common kingsnake	0	1	1
Lampropeltis getula californiae (Crother, 2000)	California kingsnake	17	6	23
Lampropeltis getula floridana (Blanchard, 1919)	Florida kingsnake	6	0	6
Lampropeltis getula nigrita (Zweifel & Norris, 1955)	Mexican black kingsnake	3	2	5
Lampropeltis mexicana greeri (Webb, 1961)	Greer's Kingsnake	1	0	1
Lampropeltis splendida (Baird & Girard, 1853)	Desert kingsnake	0	1	1
Lampropeltis triangulum (Lacépède, 1789)	Milk snake	13	2	15
Lampropeltis triangulum campbelli (Quinn, 1983)	Pueblan milk snake	1	1	2
Lampropeltis triangulum hondurensis (Williams, 1978)	Honduran milk snake	2	1	3
Lampropeltis triangulum sinaloae (Williams, 1978)	Sinaloan milk snake	1	1	2
Lamprophis abyssinicus (Mocquard, 1906)	Abyssinian house snake	0	1	1
Lamprophis aurora (Linnaeus, 1758)	Aurora house snake	1	1	2
Liasis mackloti savuensis (Brongersma, 1956)	Savu python	1	0	1
Lycodonomorphus inornatus (Duméril & Bibron, 1854)	Olive house snake	0	1	1

Species names	Common name	Number of pet shops	Number of online websites	Total
Malaclemys terrapin (Schoepff, 1793)	Diamondback terrapin	0	2	2
Malayopython reticulatus (Schneider, 1801)	Reticulated python	3	0	3
Micrurus fulvius (Linnaeus, 1766)	Eastern coral snake	1	0	1
Morelia spilota (Lacépède, 1804)	Carpet python	3	0	3
Naja siamensis (Laurenti, 1768)	Indochinese spitting cobra	1	0	1
Oplurus cuvieri (Gray, 1831)	Collared iguanid lizard	1	0	1
Orthriophis taeniurus (Cope, 1861)	Beauty rat snake	5	3	8
Pachydactylus austeni (Hewitt, 1923)	Austen's thick-toed gecko	0	1	1
Pantherophis alleghaniensis (Holbrook, 1836)	Eastern rat snake	1	0	1
Pantherophis guttatus (Linnaeus, 1766)	Corn snake	53	9	62
Pantherophis obsoletus (Say, 1823)	Black rat snake	2	2	4
Pantherophis spiloides (Duméril *et al.*, 1854)	Gray ratsnake	2	0	2
Paroedura pictus (Glaw & Vences, 1994)	Ocelot gecko	2	1	3
Phelsuma madagascariensis madagascariensis (Gray, 1831)	Madagascar day gecko	1	0	1
Physignathus cocincinus (Cuvier, 1829)	Chinese water dragon	0	1	1
Pogona vitticeps (Ahl, 1926)	Central bearded dragon	34	6	40

Species names	**Common name**	**Number of pet shops**	**Number of online websites**	**Total**
Python bivittatus (Kuhl, 1820)	Burmese python	16	4	20
Python regius (Shaw, 1802)	Ball python	53	9	62
Rhacodactylus auriculatus (Bavay, 1869)	Gargoyle gecko	1	0	1
Sistrurus catenatus (Rafinesque, 1818)	Massasauga	1	0	1
Stigmochelys pardalis (Bell, 1828)	Leopard tortoise	0	11	11
Testudo hermanni (Gmelin, 1789)	Hermann's tortoise	0	1	1
Trachemys scripta elegans (Wied, 1838)	Red-eared slider turtle	0	3	3
Trimeresurus albolabris (Gray, 1842)	White-lipped pit viper	1	1	2
Varanus albigulari (Daudin, 1802)	Rock monitor	2	0	2
Varanus exanthematicus (Bosc, 1792)	Savannah monitor	1	0	1
Xenodon pulcher (Jan, 1863)	Tricolor hognose snake	0	1	1

Supplementary information Table S4.2

https://docs.google.com/spreadsheets/d/1tm-CAw-QfeMJ0eEg2cfAE2Bs_HryjqwpP0V88AdjG50/edit?usp=sharing

Supplementary information Table S4.3

https://docs.google.com/spreadsheets/d/1unGPXE7SupatzMES1FkjZSkUNC2T3RkdUzgwRECm1eI/edit?usp=sharing

Supplementary information Table S4.4

https://docs.google.com/spreadsheets/d/1rsJ9z0FTuMXdAjp3el6Znliw7rw2IEwZEvPeMA8gRwo/edit?usp=sharing

CHAPTER 5

General discussion and conclusions

5.1 Background and discussion

Several non-native species have been freely translocated into new or non-native environments around the world accidentally through stowaways, hitchhikers and as transport contaminants (Hulme, 2009; Faulkner et al., 2017). Additionally, some species have been introduced into new environments deliberately as part of the pet trade, ornamentation, recreational purposes, research and food for pets and humans (Mori et al., 2017; Lockwood et al., 2019; Shivambu et al., 2020). Pet trade has been identified as one of the major pathways through which many non-native pet species are introduced to new environments (Lockwood et al., 2019). Pet species are sold or advertised through various platforms, including online trade (e.g. advertising websites and social media), breeders and physical pet stores (Maligana et al., 2020; Nelufule et al., 2020). The global pet trade involves many taxa, including reptiles, birds, mammals and invertebrates (van Wilgen et al., 2010; Nelufule et al., 2020; Maligana et al., 2020; Shivambu et al., 2020).

Reptiles are among the most traded groups of animals, and as a result, many non-native pet reptile species have been introduced, established feral populations, become invasive and are causing significant impacts in new environments (Thomas et al., 2011; López-Torres et al., 2012; Dove et al., 2012; McCleery et al., 2015). For example, Burmese python *Python bivittatus* was reported to be causing significant impacts by predating on native species, competing and hybridising with native species in invaded areas (Harvey et al., 2008; Dove et al., 2012; McCleery et al., 2015). Moreover, green iguana *Iguana iguana* was reported to be damaging and destroying crops, feeding on bird eggs and chicks and causing erosion that further undermine foundations, canal banks, seawalls, and other infrastructure in non-native environments (Kern, 2004; Krysko et al., 2007; Thomas et al., 2011; López-Torres et al., 2012; Falcón et al., 2013; Rivera-Milán and Haakonsson, 2020).

There are approximately 275 reptiles in the South African pet trade (van Wilgen et al., 2010). Of greatest concern, some of these species are critically endangered, and some are invasive. Trade in critically endangered species may lead to the extinction of some species (Li and Jiang, 2014; Schneider, 2012). Additionally, trade in invasive species may pave the way for new introductions and may pose serious implications to native biodiversity (Marsh et al., 2021). This study aimed to determine; 1) the extent of trade in reptile species globally (Chapter 2); 2) the extent of trade in reptile species in South Africa and their potential distribution (Chapter 2); and 3) environmental and socio-economic impacts associated with non-native pet reptiles (Chapter 4).

5.2 Main findings

5.2.1 Global reptile pet trade

The global trade in reptile pets has increased over the years and is regarded as one of the major threats to many of the world's wildlife ecosystems (Auliya et al., 2016; Hierink et al., 2020; Pragatheesh et al., 2021). This increase was evident in this study after reviewing a total of 39 reptile pet trade-based studies. Reptile pet trade-based studies published in the last decade have doubled the number published from 2000 – 2010 (Chapter 2). This could be explained by the fact that the trade in reptiles has increased globally in recent decades (McMillan et al., 2020; Harrington et al., 2021; Kusrini et al., 2021). Moreover, it has gained much attention recently because of the impacts that it has on the native biodiversity, economy and human health (Reed, 2005; Gippet and Bertelsmeier, 2021). However, the scarcity of this research, especially in developing countries, remains the biggest challenge in understanding the dynamics of the global pet trade, especially in light of its impact on the native and non-native biodiversity.

Majority (61.5%) of reptile pet trade-based studies have been conducted in three continents (Asia, Europe and North America) (Chapter 2). Furthermore, the United States of America (North America) and Indonesia (Asia) produced the greatest research outputs (12.1% each) compared with other countries in the world (Chapter 2). This demonstrated a significant existing geographical bias in the global reptile pet trade-based research. There are many possible explanations for these geographical biases in research focusing on the reptile pet trade, including lack of resources, scientific capabilities, research output, and quality of research. It was found that there are approximately 1140 reptile species belonging to 60 families involved in the global pet trade (Chapter 2). Of these, 6.9% are invasive, with the red-eared slider *Trachemys scripta elegans* being the most frequently studied species (number of studies = 23/39) compared with other reptiles involved in the global pet trade (Chapter 2). This could be explained by the fact that the red-eared slider is among the most highly profiled and disastrous invasive species globally (Herrel and van der Meijden, 2014). Our analyses suggest that the reptile pet trade is becoming an important pathway through which many non-native pet reptiles are introduced. Additionally, 6.5% of the recorded species are threatened, with African spurred tortoise *Centrochelys sulcata* being the most frequently studied species (Chapter 2). Finally, 24.6% of the recorded species are listed under the Convention of International Trade in Endangered Species of Wild Fauna and Flora (CITES), suggesting that the remaining species are not protected by any international trade regulations (Chapter 2).

5.2.2 Reptiles as pets in South Africa

A study done by van Wilgen et al. (2010) recorded 275 reptile species imported to South Africa. This is far more than the number of pet reptiles recorded in the present study as van Wilgen et al. (2010) data comprised of reptile species imported for various purposes, including zoo and pet trade. Our results recorded at least 88 unique reptiles sold as pets in 69 physical pet stores and 18 online websites in South Africa (Chapter 3). We recorded 1,912 individuals representing 66 reptile species from physical pet stores and 859 individuals of 50 reptile species from online trade (Chapter 3). A total of 31 unique reptile species recorded in this study were not in the list of reptiles observed by van Wilgen et al. (2010), suggesting new introductions to the reptile pet trade market. Approximately 86.4% of the recorded pet reptiles were non-native species (Chapter 3). Of greatest concern, 15 of these are invasive to South Africa. This could facilitate new introductions in the country. The most commonly traded pet reptiles included the ball python *Python regius* (n = 601), corn snake *Pantherophis guttatus* (n = 553) and central bearded dragon *Pogona vitticeps* (n = 419) (Chapter 3). This could be explained by that these species are easy to handle, cheaper and not high maintenance. Cheaper pet reptiles were sold at an average of ZAR100.00, and the most expensive species was the sharp-nosed viper *Deinagkistrodon acutus acutus* (ZAR6000.00) (Chapter 3). It was found that the selling price for these species in physical pet stores was determined by the CITES status (particularly Appendix II) (Chapter 3). Furthermore, the price was determined by the invasion status (particularly non-native species) in online trade (Chapter 3). This suggests that species listed under CITES Appendix II were more expensive compared with non-CITES species in physical pet stores. Also, non-native species were more expensive compared with native species. Red-eared slider *Trachemys scripta elegans*, *P. guttatus*, and western diamondback rattlesnake *Crotalus atrox* had the largest predicted climatic suitability for present distributions. The future predictions for the latter two species were predicted to increase while the red-eared slider suitability shifted. These species represent the most serious threat to South African wildlife as they showed a wider potential distribution in the country. In addition to the corn snake's extensive climatic suitability distribution ranges, this species was the second most traded species and recorded in eight provinces of South Africa (Chapter 3). This is highly concerning as species generally traded in high numbers and with larger climatic suitability are most likely to be released or escape from captivity (Ramírez-Ortiz et al., 2020). It was further found that most commonly available species were sold at relatively low prices and had high climatic suitability, representing a high potential invasion risk (Chapter 3).

5.2.3 Potential impacts associated with non-native reptiles sold as pets in South Africa

To assess the potential environmental and socio-economic impacts associated with 76 non-native pet reptiles, we used three scoring schemes, namely the Generic Impact Scoring System (GISS), Environmental Impact Classification for Alien Taxa (EICAT) and Socio-Economic Impact Classification for Alien Taxa (SEICAT) (Chapter 4). Using GISS, 13 pet reptiles were found to have environmental impacts (E_GISS), while 11 had socio-economic impacts (SE_GISS) (Chapter 4). Three species, the green iguana, red-eared slider, and Burmese python were found to have the highest potential impact with scores of 17, 17 and 16, respectively (Chapter 4). For EICAT and SEICAT, 13 species had environmental impacts, and eight had socio-economic impacts (Chapter 4). The red-eared slider recorded major environmental impacts under EICAT through competition and predation (Chapter 4). Burmese python recorded moderate socio-economic impacts under SEICAT through impacts on human health (Chapter 4). Our analyses suggested that the assessed non-native pet reptiles may pose potential serious environmental impacts to our native biodiversity through predation, competition, and disease transmission (Chapter 4). When comparing the scores obtained by E_GISS and EICAT, it was found that species had similar rankings (Chapter 4). However, there was a significant difference in the ranking of species by SE_GISS and SEICAT (Chapter 4). The most popular pet species, the red-tailed boa *Boa constrictor*, green iguana, Burmese python, red-eared slider, and central bearded dragon, impacted all three scoring schemes (Chapter 4). Moreover, the later species and corn snake scored the highest for all impact schemes (Chapter 4).

5.3 Concluding remarks

The present study's results revealed that the extent of trade in pet reptiles both globally and South Africa is increasing at an alarming rate. The reptile pet trade-based research has also increased significantly following an increase in the reptile pet trade industry. However, even with increasing reptile pet trade-based literature, the global reptile pet trade dynamics could not be fully understood because of the sparsity of this research. Therefore, it is recommended that more studies should be conducted especially in understudied regions, to give a complete picture of the global reptile pet trade. Of most concern, the trade in live reptiles in South Africa involves many species, including endangered, native, CITES-listed and invasive species with a high risk of posing serious environmental and socio-economic impacts on the native biodiversity, economy and human health. Therefore, strict legislation and enforcement from an international level to a provincial level are recommended. Moreover, existing pet trade regulations should be revised accordingly by policymakers working with pet owners, breeders, and the pet trade industry to include an outright ban on the trade of endangered, CITES-listed and invasive pet species with high potential impacts and invasion risk. The results suggested that there might probably be many more species that we could have missed during the survey, given the list of reptiles reported by van Wilgen et al. (2010) and the impact of Covid-19. Therefore, it is recommended that the reptile pet trade be monitored to understand the extent of trade in South Africa fully. This could be achieved by microchipping all pet species and keeping an online registry at the Department of Environmental Affairs (DEA). This would help monitor the number of individuals and species bred and sold as pets and their cause of death.

5.4 Recommendations for future studies

This study provides a comprehensive assessment of the trade in pet reptiles in South Africa. Despite the insight provided by this study about the extent of trade in pet reptiles, more work still needs to be done in future studies:

1. This study investigated the extent of trade in reptiles in South African physical pet stores and online trade. However, these are not the only sources through which pet reptiles are traded in the country. Future studies should investigate the dynamics of pet reptile trade in breeding facilities as these are the main suppliers of pets (Shivambu et al., 2021).
2. The present study also investigated the potential impacts associated with non-native traded reptiles. Since this study did not investigate the welfare of species involved in the reptile trade, future studies should investigate the welfare of all pet reptiles impacted by the trade as there are some species that develop diseases because of poor welfare (Benn et al., 2019).

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