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Policy analysis

Forty-four years of global trade in CITES-listed snakes: Trends and implications for conservation and public health

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ABSTRACT

Trade in venomous and non-venomous snakes can negatively impact wild snake populations and may drive snakebite risk for people. However, we often lack sufficient trade data to identify where the potential risks for snake population decline and snakebite are highest. Currently, the legal, international trade of 164 snake species is regulated by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). We analyzed CITES-listed snake trade from 1975 to 2018 using the recently released shipment-level CITES Trade Database to identify spatiotemporal trends of snake trade and generate insights regarding snake conservation and potential public health risks from snakebite. Commercially purposed pythons dominated the global snake trade, comprising 38.8% of all traded snakes. Live snakes were mainly exported by Ghana, Indonesia, Togo, and Benin, and imported by China and the USA. Venomous snake trade comprised 10.8% of all traded snakes, and over 75% of wild-sourced venomous snakes came from Indonesia. Although traded snakes in recent years are increasingly comprised of captive-bred animals, the majority of snakes are still wild-sourced (> 60% between 2015 and 2017), including IUCN-listed species, with potentially detrimental impacts on conservation status. Further, the CITES Trade Database reveals geographic regions where venomous snakes are sourced from the wild, posing potential risks to snake catchers, traders, and pet owners. The database also documents the movement of non-native snake species through trade, with implications for conservation of native species. This study represents the first global analysis focused specifically on CITES-listed snake trade using the CITES Trade Database.

1. Introduction

Snakes are exploited globally as sources of food and traditional medicine (Alves et al., 2009; Klemens and Thorbjarnarson, 1995; Somaweera and Somaweera, 2010), skin products (Kasterine et al., 2012; Luiselli et al., 2012), and by the pet industry (Auliya et al., 2016; Jensen et al., 2019), with potential detrimental effects on wild populations. Indeed, snakes are thought to be in global decline (Reading et al., 2010), but data deficiencies hinder our ability to accurately assess snake conservation status and the role of human exploitation in driving population trends (Natusch et al., 2016; Schlaepfer et al., 2005). Importantly, snake trade may also lead to the introduction of invasive alien species, pathogens, and disease vectors that can threaten wildlife, domestic animals, and public health (Karesh et al., 2005; Lockwood et al., 2019; Smith et al., 2017). Previous studies have characterized the global trade of live reptiles without detailed analysis of snakes (Herrel and van der Meijden, 2014; Robinson et al., 2015), while others have explored snake trade in specific countries (e.g., China, the USA) (Dodd, 1986; Jiang et al., 2013; Schlaepfer et al., 2005; Zhou and Jiang, 2004) or trade in particular snake families (e.g., Pythonidae) (Luiselli et al., 2012). However, we have limited insight into the global snake trade over a long time period, particularly for endangered snake species and medically important venomous snakes, which can cause snakebite among catchers, traders, and pet owners.

The legal, international trade of snakes is partly regulated by the Convention on International Trade in Endangered Species of Wild

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Fauna and Flora (CITES), which monitors the trade of certain animal and plant species (https://www.cites.org/eng/disc/what.php). CITES-listed snakes (currently 164 species including 2 subspecies with distinct listings) (Species+, https://www.speciesplus.net/, 2019) include both non-venomous and venomous species. Trade in > 3500 other snake species is not regulated by CITES (Cao et al., 2014; Eskew et al., 2019).

CITES came into force in 1975, yet CITES data were previously only available to the public in aggregated form, which led to a variety of misunderstandings regarding proper data use and interpretation (Berec et al., 2018; Pavitt et al., 2019; Robinson and Sinovas, 2018). The recent release of the CITES Trade Database on a per-shipment basis offers an opportunity to analyze the unaggregated global trade of CITES-listed snakes and their products over more than four decades (UNEP-WCMC, 2019). Therefore, in this study, we used a 44-year (1975–2018) CITES trade dataset to identify spatial and temporal trends in the total volume of CITES-listed snake trade, and we contextualize these insights with an emphasis on conservation and public health. To our knowledge, this is the first analysis that uses the CITES Trade Database to specifically assess global snake trade, including stratification by venomous and non-venomous snakes.

2. Methods

2.1. CITES Trade Database

CITES maintains a database that includes trade records reported by exporters and/or importers from all the signatory countries (183 parties), and these records may comprise either direct shipments or re-exports (https://www.cites.org/eng/disc/what.php). The database is maintained by the United Nations Environment Program and World Conservation Monitoring Centre (UNEP-WCMC) and recently was released on a per-shipment basis (UNEP-WCMC, 2019). This non-aggregated dataset contains over 20 million records collected over 44 years, and we recently developed an R package, *citesdb*, to facilitate its use by importing the data into a local, on-disk embedded database (Ross et al., 2019). Information on current and historical CITES-listed species can be retrieved from Species+ (UNEP, 2019), a platform that hosts data on CITES-related taxonomy, legislation status, and species distribution. The *rcites* package allows efficient access to Species+ data from the R programming environment (Geschke et al., 2018).

2.2. Data preparation and analysis

R version 3.5.2 (R Core Team, 2019), in combination with the *citesdb* and *rcites* packages, was used for the analyses of all CITES-recorded wildlife shipments that contained snakes from 1975 to 2018 (described as "Serpentes" in the field "Order"). Shipments for the year 2018 were included in the analyses, despite being incomplete. Since the number of CITES-listed species and signatory parties changes over time, we included both historical and current CITES-listed snake species. Because the number of CITES-listed species and signatory parties in a given year directly influences trade reporting effort, raw observed trade quantities may be biased and could mask important underlying trade trends. To help account for reporting bias of temporal data, we present both raw trade measures and trade measures adjusted for reporting effort (i.e., the number of CITES parties and CITES-listed snake species in a given year). More specifically, for each year from 1975 to 2018, the number of CITES parties and CITES-listed snake species were multiplied together to generate a yearly-level reporting effort metric, and raw trade measures were divided by this correction factor. The database also contains species listed on European trade regulation annexes, which are not necessarily included in the CITES appendices. To exclude European-regulated wildlife trade, we only selected species that were historically or currently listed in the CITES appendices.

Trade data are presented as the quantity of Whole Organism Equivalents (WOEs) (adapted from Harfoot et al., 2018). WOEs represent snakes traded under the terms "live", "bodies", "skins", "gall bladder", "skulls", "heads", "tails", "trophies", and "skeletons". Each of these trade terms is assumed to equate to one whole organism, and all products (e.g., heads and gall bladders) are expected to be sourced from different animals, as in Harfoot et al. (2018). Although the assumption that all body parts are sourced from different animals might lead to an overestimate of trade, we expect this bias to be minimal. Quantities of these terms were summed when there was no ambiguous unit indicated. Snakes shipped under the term "live" were also separately isolated from WOEs to study potential introduction of health risks. Some terms cannot be converted to WOEs (e.g., derivatives, shoes, leather items, etc.) and were therefore excluded from our analysis (n = 32,149; 23.9% of exporter-reported shipments).

CITES Trade Database shipments may be reported by either importer or exporter parties. When possible, quantities are presented for both reporting types. In cases where we report a single quantity (e.g., percentages quoted in text), exporter-reported trade was used because importer-reported trade is expected to be underreported as CITES parties are not required to issue import permits for Appendix II listed species (76.1% of all WOE exports) (Robinson and Sinovas, 2018). To prevent double counting of trade quantities, re-exports were excluded from all datasets for analysis except for the dataset that represents flows of snake WOE quantities. In the absence of standardized guidelines, different methods have been used to identify re-exports. For example, Robinson and Sinovas (2018) stated that the presence of a value for the origin country data field indicates that a shipment is a re-export. However, the per-shipment database also allows the identification of re-exports by the origin permit ID, as stated in the CITES Trade Database supplementary information (available when downloading the shipment-level database). Therefore, we aimed to isolate direct trade by filtering for data rows that had no origin country and no origin shipment ID (Robinson and Sinovas, 2018; UNEP-WCMC, 2019).

Comparisons between wild-sourced and captive-bred snake trade were made based on a re-categorization of the source variable, adapted from Harfoot et al. (2018). Specifically, the sources "wild specimens" (W category in the CITES Trade Database), "unknown source" (U), "specimens taken from the marine environment" (X), and "ranched specimens" (R) were categorized as wild-sourced shipments, whereas "captive bred" (C and D), "artificially propagated" (A), and "animals born in captivity" (F) shipments were classified as captive-bred animals (Appendix 1).

Our taxonomy follows the 12 August 2019 release of The Reptile Database (Uetz et al., 2019). We noted species that were medically important venomous snakes as defined by the World Health Organization (WHO, 2010), with taxonomic updates after Uetz et al. (2019) (Appendix 2). Species were linked to their respective conservation status based on the IUCN Red List of Threatened Species (IUCN, 2019).

Spatial comparisons were made by matching the ISO 3166 country codes to their full CITES party names and broader geographic regions (Africa, Asia, Europe, North America, Oceania, and South America). Initially, all trade between unique shipment directions was summed by WOE quantity. These flows were then visualized with chord diagrams from the R *circlize* package (Gu et al., 2014). For a more straightforward presentation of chord diagrams that minimizes background noise caused by small shipment flows, several cut-off thresholds were applied to the data. As indicated in figure captions, WOE quantities in trade of all snake products had a cut-off value of < 500,000, live snake quantities were cut-off at values < 50,000, and for chord diagrams representing trade flows in different time series, the top 5% of all shipment flows are presented.

3. Results

3.1. Global trade volume: whole organism equivalents

A total of 40,858,302 snake WOEs (hereafter, "snakes") were

Table 1
Number of exported snake WOEs disaggregated by CITES term and snake family.

Term	Boidae	Bolyeriidae	Colubridae	Elapidae	Loxocemidae	Pythonidae	Tropidophiidae	Viperidae	Total
Bodies	525	4	26,905	19,781	2	216	15	922	48,370
Heads	0	0	0	0	0	200	0	0	200
Live	878,199	22	930,073	515,511	356	3,957,866	215	2471	6,284,713
Skeletons	2	0	0	0	0	9	0	0	11
Skins	192,488	2	14,060,914	3,599,645	0	16,414,670	0	256,777	34,524,496
Skulls	1	0	0	0	0	225	0	0	226
Tails	0	0	0	0	0	100	0	0	100
Trophies	0	1	0	8	0	177	0	0	186
Total	1,071,215	29	15,017,892	4,134,945	358	20,373,463	230	260,170	40,858,302

exported globally between 1975 and 2018, of which 76.1% consisted of Appendix II CITES-listed species. Snakes were mainly traded for commercial purposes (64.0% of all snake trade, representing 26,134,412 snakes) (Appendix 3). The most common export terms were "skins" (n = 34,524,496) and "live" (n = 6,284,713) (Table 1).

Pythons dominated the trade, comprising 49.9% (n = 20,373,463) of all traded snakes. In particular, commercially purposed pythons were a large proportion of the trade, representing 38.8% of all traded snakes (n = 15,860,472). Most pythons were traded as skins (n = 16,414,670, 40.2% of all traded snakes) or live (n = 3,957,866, 9.7% of all traded snakes). Of all python trade, the majority were *Python reticulatus* (reticulated python; 28.7% of total snake exports), *Python regius* (ball python; 7.6% of total snake exports), and *Python bivittatus* (Burmese python; 6.2% of total snake exports) (Appendix 4). *Python reticulatus* is now more commonly known as *Malayopython reticulatus*, and *P. bivittatus* was formerly a subspecies of *P. molurus* (Indian python) and has often been reported as such.

Snakes from the family Colubridae comprised 36.8% of the snake trade (n = 15,017,892; Appendix 5) and were mostly shipped as skins (n = 14,060,914, 34.4% of all traded snakes), with distinct trade peaks in 1986 and 1990 (Fig. 1A). Even when correcting for reporting effort, trade peaks in these years remain clearly visible (Fig. 1C). In contrast, importer-reported trade data showed less distinct trade peaks. The most traded colubrid species was *Ptyas mucosa* (oriental ratsnake) (n = 11,341,419; 27.8% of total snake exports).

Venomous snake trade made up 10.8% of all exporter-reported snake trade, with *Naja sputatrix* (Indonesian cobra; n = 2,200,915 snakes exported), *N. naja* (Indian cobra; in CITES data sometimes including *N. kaouthia* as a subspecies; n = 1,865,752 snakes exported), and *Daboia russelii* (Russell's viper; n = 258,429) being the most traded venomous species (Appendix 4). Exporter-reported venomous snakes were mainly traded with the terms "skins" (n = 3,856,422) and "live" (n = 517,982). Venomous snakes (Elapidae and Viperidae) were largely traded for commercial purposes (n = 3,090,626 and n = 60,272) (Appendix 3). They were mainly shipped from Indonesia to Singapore (n = 1,127,643), with Elapidae comprising the majority of this trade (n = 1,067,643). Viperidae were mainly exported from Thailand and imported by Italy (n = 151,867) (Appendix 6 and 7).

3.2. Global trade volume: live animals

Live snake quantities represented 15.4% of all traded snakes, with a total of ~6.3 million live CITES-listed snakes traded between 1975 and 2018. Between 2002 and 2017, live traded snakes declined by 58.4%, from 274,758 snakes in 2002 to 114,199 in 2017. This decline was caused by a reduction of 86.3% in traded pythons during this period. The largest numbers of live snakes, as reported by exporters, were exported from Ghana (n = 1,180,361), followed by Indonesia (n = 942,246), Togo (n = 931,895), and Benin (n = 885,587) (Fig. 2A). The largest live snake importers were the USA (n = 3,035,701), Hong Kong (n = 934,044), China (n = 363,529), and Germany (n = 316,736) (Fig. 2B). The vast majority of live shipped

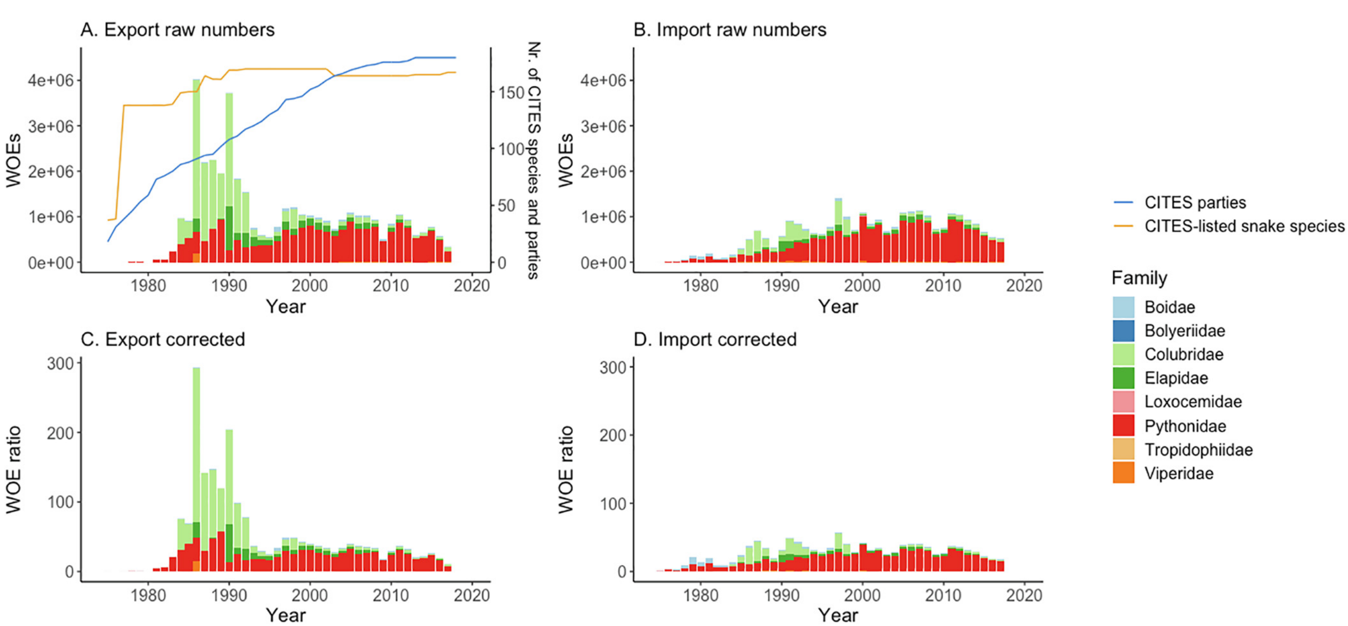

Fig. 1. Temporal trends in quantities of shipped whole organism equivalents (WOEs), by snake family, reported as either exported or imported shipments. Raw numbers represent the exact WOE quantity over time (A and B), with an indication of the number of CITES-listed snake species and CITES parties over time (A). Corrected WOE ratios are adjusted for CITES reporting effort (i.e., number of CITES parties and CITES-listed snake species) over time (C and D).

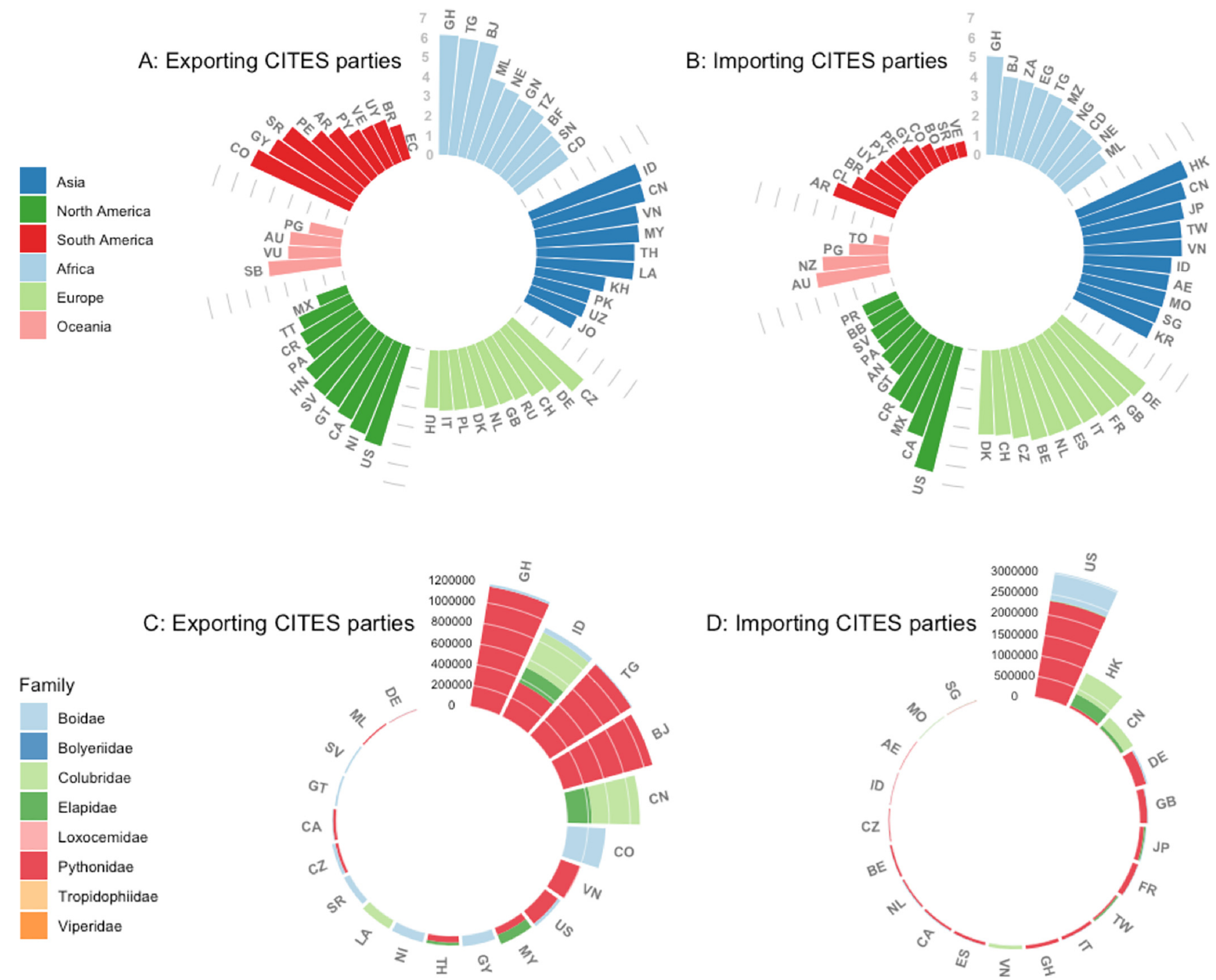

Fig. 2. Number of live snakes exported (A) and imported (B), disaggregated by CITES parties and geographic regions (units are log-transformed [base 10] numbers of live shipped snakes). Number of live snakes exported (C) and imported (D), disaggregated by CITES parties and snake families (units are in live shipped snake quantity). CITES parties were labelled by ISO2 code, and full names can be retrieved from Appendix 8.

snakes were traded for commercial purposes (95.8%). Half of all live traded snakes comprised *Python regius* (ball python; n = 3,110,127). There were strong regional differences in the taxonomic composition of live exported snakes (Fig. 2C, D). Ghana, Togo, and Benin were the largest exporters in live Pythonidae, whereas Colombia, Guyana, Nicaragua, and Suriname were mostly responsible for trade exports in Boidae. Live snakes traded from Southeast Asia comprised a heterogeneous combination of Boidae (mostly *Candoia* and *Eryx*), Colubridae, Elapidae, and Pythonidae. The USA was the primary northern hemisphere country exporting live snakes, the majority of which were pythons.

3.3. Snake sources

Although snake WOEs were increasingly sourced from captive animals beginning around the year 2000, with yearly proportional wild-sourced decreases from 2000 to 2009, overall, the majority of traded snakes remain wild-sourced (Fig. 3). Results stratified by snake family highlight taxonomic differences in this trend (Appendix 9). For example, venomous snake families were mainly wild-sourced: of all Viperidae and Elapidae WOEs, 97.8% and 96.4% were wild-sourced, respectively. In contrast, 41.3% of Boidae and 76.0% of Pythonidae were wild-sourced.

The most traded wild-sourced snake species was *P. reticulatus*, representing 40.4% of all wild-sourced snakes (*n* = 6,851,004) (Appendix 10). Interestingly, *P. bivittatus* was also wild-sourced in relatively large quantities (*n* = 20,484) despite being listed as vulnerable on the global IUCN Red List of Species (Appendix 10) (IUCN, June 2019).

Indonesia was the largest exporting country of all wild-sourced snakes (n = 7,436,998), followed by Myanmar (n = 4,979,633), and Ghana (n = 1,034,959) (Appendix 11). Comparisons between wild-sourced WOEs and wild-sourced live snakes reveal different trade patterns. For wild-sourced live snakes, Ghana, Benin, and Togo are the largest exporters, with the majority of snakes belonging to Pythonidae (Appendix 12).

Traded venomous snakes were mainly wild-sourced, but source locations differed for the two families. Of all wild-sourced venomous snakes (n = 2,359,956), Elapidae comprised the vast majority of trade (n = 2,300,426, 97.5%). Of all wild-sourced venomous snakes 77.5% were exported from Indonesia (n = 1,829,403). However, stratification by snake family showed that 98.2% of all wild-sourced Viperidae were

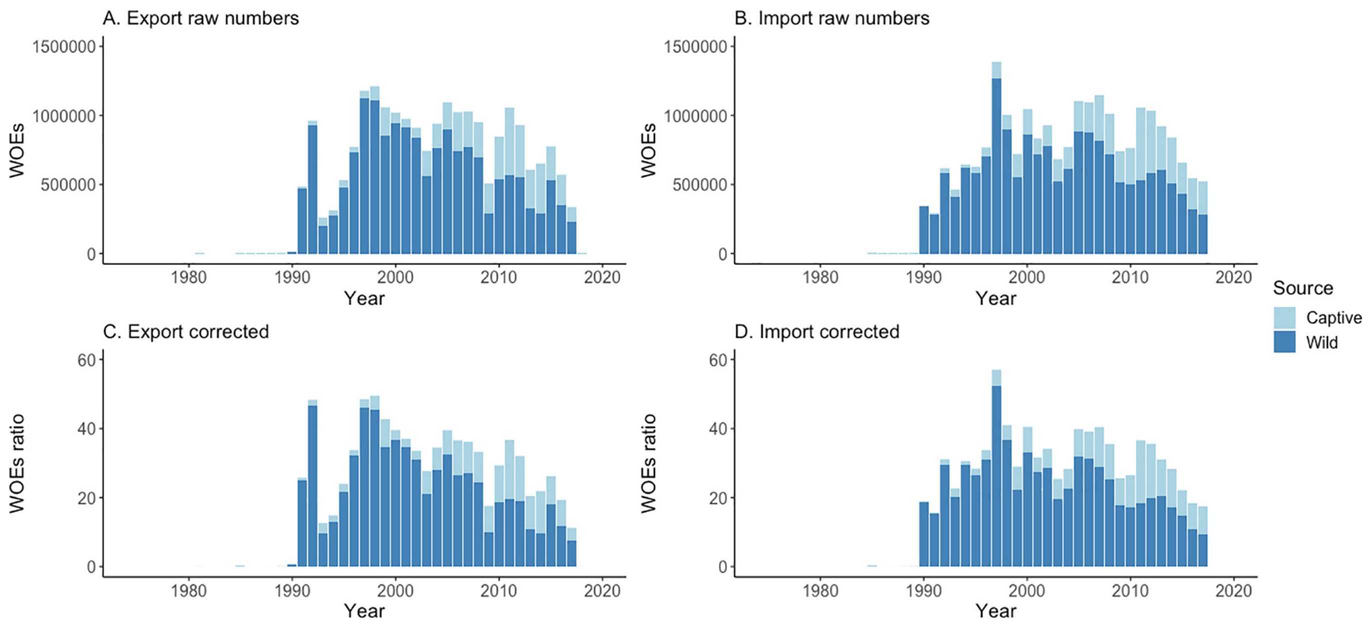

Fig. 3. Number of exported and imported snakes, expressed as whole organism equivalents (WOEs), disaggregated by year and source (captive or wild). Raw trade numbers represent the exact number of traded WOEs over time (A and B), whereas corrected WOEs are adjusted for CITES reporting effort (i.e., number of CITES parties and CITES-listed snake species) over time (C and D). Trade patterns are visually different from Fig. 1, since source data is missing for a large number of records.

exported from Thailand, and 79.5% of all wild-sourced Elapidae were exported from Indonesia.

3.4. Geographic patterns of live venomous snake trade

Live venomous snakes comprised 8.2% (*n* = 517,982) of all live traded snakes (n = 6,284,713) and were mainly traded within Southeast Asia. Of all live exported venomous snakes (n = 517,982), 45.0% were shipped from China. The second and third largest exporters were Indonesia and Malaysia, with 30.5% and 18.1% of all global live venomous snake exports, respectively. Indonesia and Malaysia combined were mainly responsible for *N. sputatrix* trade (61.7%), followed by *N. naja kaouthia* (34.9%). Interestingly, China, as well as Thailand, Myanmar, Vietnam and Laos, mainly export *N. naja kaouthia*, representing 92.6% and 98.9% of their trade, respectively (Fig. 4A). Live venomous snakes are largely imported by China (*n* = 87,424) and the affiliated regions Hong Kong (*n* = 309,033), Taiwan (*n* = 38,476), and Macau (*n* = 10,642). These CITES parties combined are responsible for 86.2% of all live venomous snake imports (*n* = 445,575), with *N. naja* and *N. sputatrix* being the main species imported (63.9% and 31.6%, respectively). Small fractions of the total global trade in live venomous snakes are imported to Japan, Korea, the USA, Singapore, and Germany (Fig. 4B).

3.5. Global trade flows: dominant importer and exporter countries

Of all exporter-reported trade flows between 1975 and 2018, re-exports included, Indonesia was the largest snake exporter (n = 19,467,376 snakes) (Fig. 5). The largest trade flow took place from Indonesia to Singapore (n = 12,957,211 snakes) and was largely driven by commercially purposed snakes (n = 3,804,590). Other large trade flows took place from Singapore to Italy (n = 5,379,980 snakes), Myanmar to Singapore (n = 3,277,060 snakes), and Singapore to Great Britain (n = 2,857,207 snakes).

Considering only live snake trade flows, the majority of trade took place from Ghana (n = 1,369,040 snakes), Indonesia (n = 968,809 snakes), and Vietnam (n = 964,961 snakes). Live snakes from Ghana to the USA comprised the largest trade flow (n = 789,490 snakes) and mostly contained snakes from the family Pythonidae (*n* = 777,330 snakes), whereas live snake trade within Asia was mainly comprised of snakes from the family Colubridae.

Comparing live snake trade flows in five-year timeframes showed that the USA has always been one of the largest importers. However, exporters shipping to the USA have changed over time. From 1980 to 1984, Thailand was responsible for the largest trade volumes to the USA. However, this pattern shifted, with Ghana, Togo, Benin, and Colombia becoming the predominant exporters between 1990 and 1994. Indonesia became involved in exports to the USA and China between 1995 and 1999. Since 2000, the trade has been dominated by snake products from Ghana, Benin, and Togo to the USA. In recent years (2010–2018), Vietnam and Indonesia started dominating live snake trade flows to China, while Ghana and Togo remained the primary exporters to the USA (Appendix 13).

4. Discussion

4.1. Global trends in snake trade

Over the past 44 years, the global snake trade has been dominated by commercially purposed pythons, both as skins and live animals. Python trade still dominates contemporary snake trade flows, yet overall trade quantities have declined in recent years. The majority of all exporter-reported snake quantities were Pythonidae (49.8%), specifically *P. reticulatus* (28.7%), *P. regius* (7.6%), and *P. bivittatus* (6.2%). *Python reticulatus* and *P. bivittatus* are some of the world's largest snakes (7–9+ m and 4.5–8 m, respectively) and the most heavily traded. They are exported from Southeast Asia, and products made from their skins are imported on a large scale throughout Eurasia and the Americas (Kasterine et al., 2012; Shine and Harlow, 1999). This trade contributes to the livelihood of the poorest people in Southeast Asia (Nossal et al., 2016a; Nossal et al., 2016b) and may be sustainable (Natusch et al., 2019). The value of the python skin trade is estimated to be around US $1 billion per year (Kasterine et al., 2012). *Python regius* was the second most imported live reptile according to Robinson et al. (2015), with approximately 2.7 million live imported snakes between 1996 and 2012. Both importer-and exporter-reported CITES trade give a similar

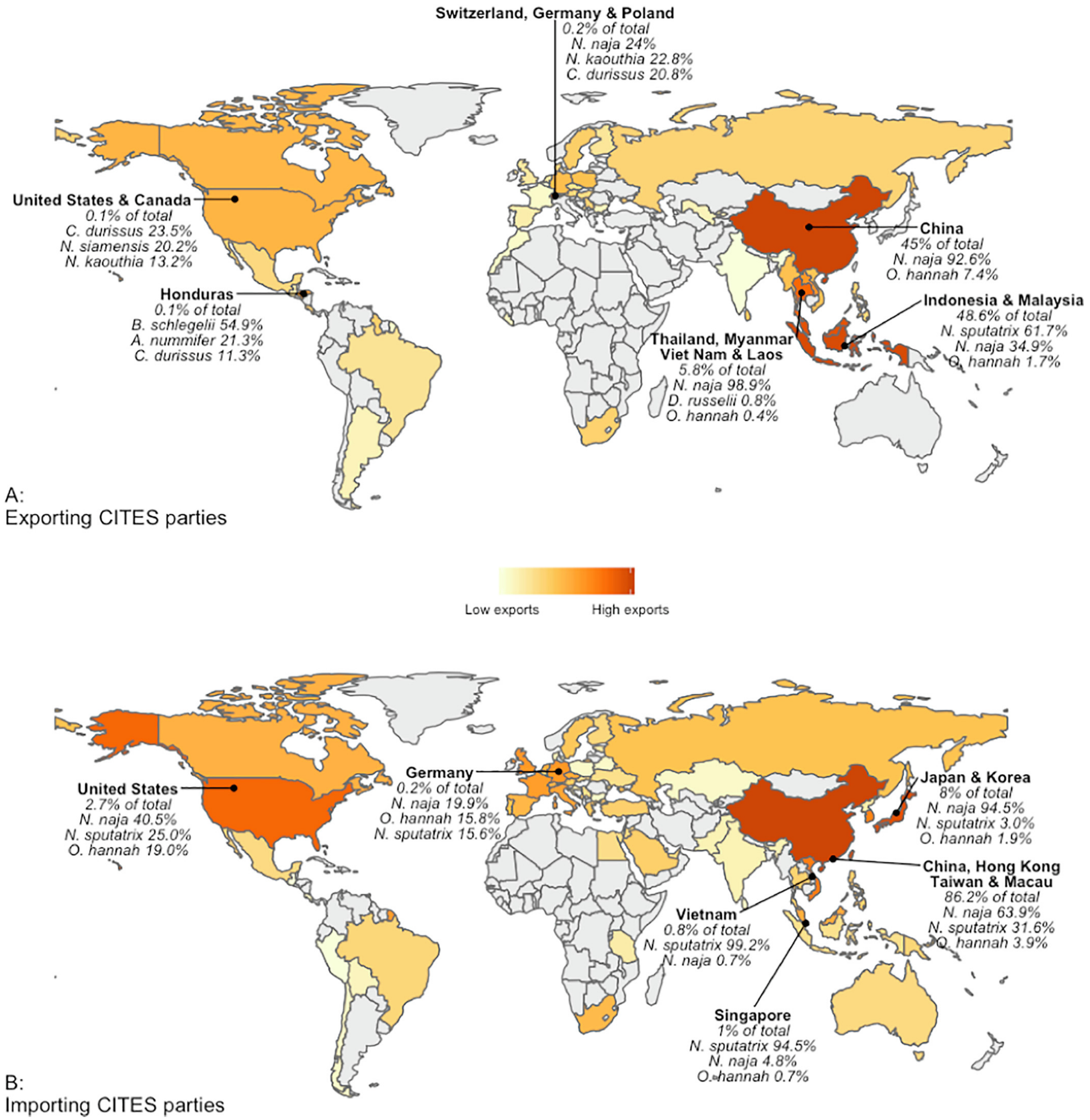

Fig. 4. Geographic visualization of exported (A) and imported (B) live venomous snakes, with indications of the top CITES parties and their associated top species.

picture, with *P. regius* being the second most traded snake (14.2% and 7.6%, respectively) (Appendix 4). There is a strong negative correlation between annual currency exchange rates and *P. regius* trade intensity (Luiselli et al., 2012), and a steadily increasing supply of captive-bred animals has likely reduced wild-sourced exports for the pet trade over the past decade.

Colubridae was the second most traded snake family (36.8%), as defined by exporter-reported trade. In particular, *Ptyas mucosa* (oriental ratsnake) was heavily traded, comprising 27.8% of all export quantities reported by exporters. This species has been commercially harvested for the international skin trade for at least a century (Auliya, 2010). Concern over the effects of trade, especially in Indonesia, led to the CITES listing of *P. mucosa* in the early 1990s, and discrepancies in the trade volume reported by importers compared to that reported by the major exporter, Indonesia, led to a ban from 1993 to 2005, during which time 50,000–100,000 *P. mucosa* per year were nevertheless illegally harvested and exported in Indonesia, trade which continues into the present (Auliya, 2010).

The USA was the leading exporter and importer of non-native live snakes (i.e., pythons, boas) among developed countries, confirming trade in captive-bred snakes. This mostly reflects increasing consumer enthusiasm for uniquely colored python and boa morphs and USA breeders specializing in their trade (Collis and Fenili, 2011).

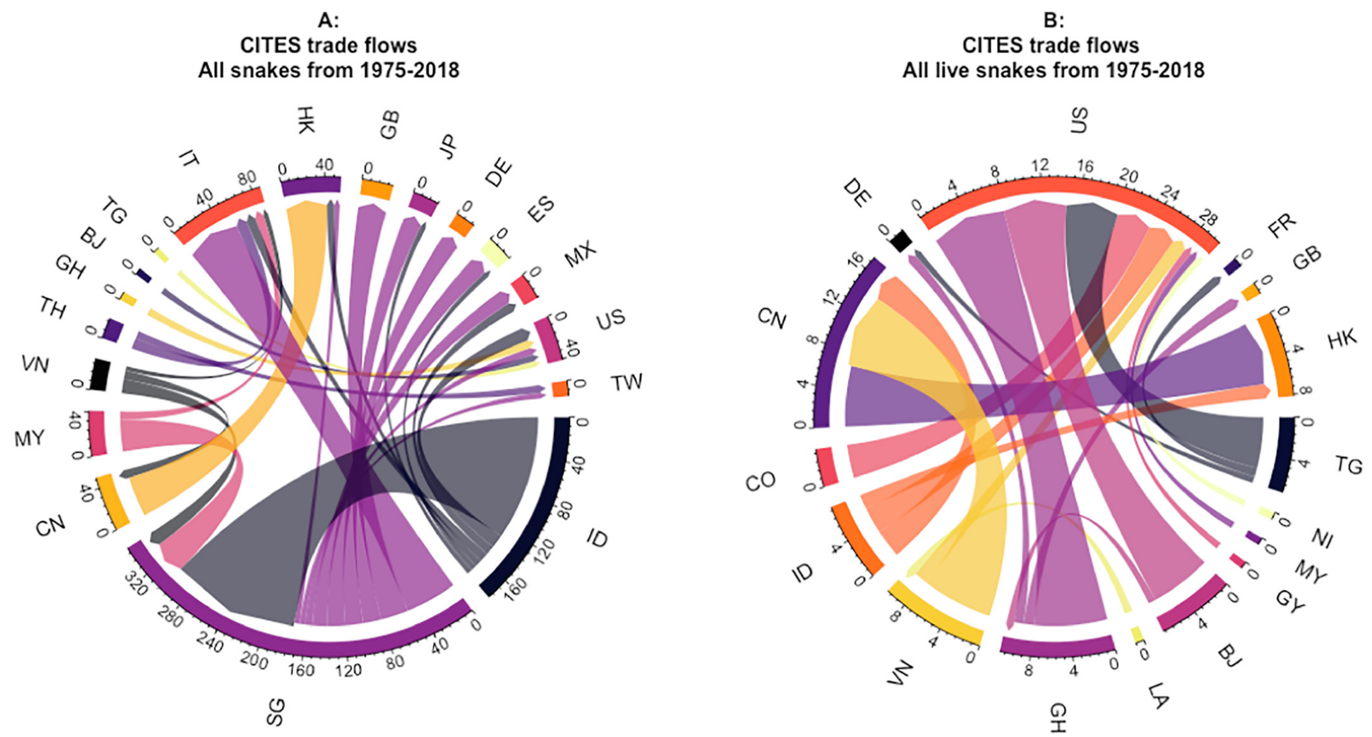

Fig. 5. Chord diagrams showing all snake [$n > 500{,}000$] (A) or only live snake [$n > 50{,}000$] (B) trade flows [in 100,000 s] among CITES parties, with units of whole organism equivalents (WOEs) and arrow heads indicating flow direction. CITES parties are labelled by ISO2 code, and full names can be retrieved from Appendix 8.

4.2. Potential conservation impacts of global snake trade

Python reticulatus and *P. bivittatus* have been among the most heavily traded snake species for decades (Appendix 4). This has raised concern about the conservation impacts of their wild harvest. They are currently categorized as "least concern" and "vulnerable" by the IUCN Red List of Species, respectively (IUCN, 2019). We showed that the snake trade has shifted from wild-sourced to increasingly captive-bred snakes over the last few years. Similar trade findings were reported by Harfoot et al. (2018) and Robinson et al. (2015), where the trend towards captive-bred animals was demonstrated for several reptilian taxa. The ban on *P. reticulatus* and *P. bivittatus* wild harvest in several Asian countries (e.g., Thailand, Vietnam, Laos, China) may have contributed to this shift in reporting from wild to captive-sourced animals (Jiang et al., 2013; Natusch and Lyons, 2014). Python farming (*P. bivittatus* and *P. reticulatus*) for the leather industry occurs in Vietnam and, to a lesser extent, in China and Thailand (Natusch and Lyons, 2014). From 2000 to 2011, *P. bivittatus* skins were mainly sourced from captive-bred animals in Thailand and Vietnam (Natusch and Lyons, 2014). Misreporting of wild-caught snakes as being captive-bred may occur as CITES relies on self-reporting by CITES parties. For example, many of the boas imported from South America are declared as "ranched" or "farm bred", although there are no checks on the validity of these declarations, and many such boas may essentially be wild-caught (Fogel, 1997), as is also the case with *Morelia viridis* (green tree python; Lyons and Natusch, 2011). Similarly, poaching of *B. constrictor* is ongoing in the Cayos Cochinos, Honduras (Reed et al., 2007; Wilson and Cruz Díaz, 1993). Finally, significant discrepancies between exports and imports (including from non-CITES parties) and erratic patterns in wild vs. captive-bred sourcing in CITES data from Thailand point to misreporting or possible violations of the rules and intentions of CITES (Groombridge and Luxmoore, 1991; Nijman and Shepherd, 2011).

In addition to the risk of depleting wild populations in exporting countries, the trade of snakes may impact biodiversity and conservation in importing countries. For instance, *P. bivittatus*, which are widely traded as pets, have become established as an exotic invasive species in Florida (Dorcas and Willson, 2011). Population estimates suggest > 100,000 individuals now inhabit the Everglades ecosystem (Willson et al., 2011), threatening local wildlife (Dorcas et al., 2012). Ironically, *P. bivittatus* is listed as "vulnerable" by the IUCN in its native range. *Python reticulatus* is not known to have been successfully introduced outside its native range, despite occasional records from the USA, Germany, and the Canary Islands (Kasterine et al., 2012; Kraus, 2009). However, it is considered to be a potential risk for establishment as an alien species, largely due to the same set of factors that promote escape or release of other large-bodied snake species (Reed and Rodda, 2009). For example, *P. regius* pets regularly escape or are released into the wild in Europe, the continental Americas, and the Caribbean (Kraus, 2009), although no established populations are known. *Boa constrictor* has also been introduced to several Caribbean islands, Cozumel (Mexico), and Florida (USA), but it is not present in the large numbers that Burmese pythons have attained. Importantly, snake trade could also lead to the spread of pathogens and vectors that threaten local wildlife (Karesh et al., 2005). For instance, exotic ticks were introduced into the UK, USA, Taiwan, Poland, and South America on imported snakes (Burridge and Simmons, 2003; González-Acuña et al., 2005; Norval et al., 2009; Nowak, 2010; Pietzsch et al., 2006), and Asian pentastome parasites have spilled over from invasive *P. bivittatus* to native Florida snakes (Farrell et al., 2019; Miller et al., 2018).

4.3. Public health implications of global snake trade

Live venomous snake trade made up 8.2% of all live traded snakes. The majority of venomous snake trade were wild-caught snakes, which may expose collectors, handlers, customs officials, or others involved in their transport to snakebite risk. These snakes are mainly exported by Indonesia, Malaysia, China, Vietnam, or Myanmar. Snake farming in China for food and traditional medicine largely drives international trade in venomous snakes in this region (Aust et al., 2017; Zhou and Jiang, 2004; Zhou and Jiang, 2005). When focusing on wild-sourced venomous snakes, 77.5% were exported from Indonesia, and stratification by snake family showed that 98.2% of all wild sourced Viperidae were exported from Thailand while 79.5% of all wild-sourced Elapidae were exported from Indonesia. Epidemiological studies on snakebite in countries exporting live venomous snakes are scarce (Kasturiratne et al., 2008). Among 292 recorded cobra bites in China, snake-hunting (56.2%) was the most common activity associated with snakebite (Wang et al., 2014). Similarly, snake bites have resulted from the harvest of sea snakes in Thailand (Cao et al., 2014). Underreporting of snakebite is common, especially in rural areas where victims may seek initial treatment with traditional healers (Schioldann et al., 2018). As such, it is difficult to assess the true impact of snakebite on communities engaged in this dangerous activity, although some local tribes are skilled snake catchers (e.g., Irulas of Tamil Nadu, India; Whitaker and Andrews, 1996).

Daboia russelii is one of the most traded venomous snakes and one of the "Big 4" (together with *N. naja*, *Bungarus caeruleus* [common krait], and *Echis carinatus* [saw-scaled viper]). The "Big 4" reflect the four venomous snakes that cause the majority of snakebite-related deaths in India (Simpson and Norris, 2007). The majority of traded *D. russelii* products are venom, produced from captive snakes in the USA and sent to research institutes or hospitals in other developed countries, especially in Europe, for use in research or medicine (Thiagarajan et al., 1986). Snake venom is indeed intensively used in research to develop new drugs to treat a diversity of medical conditions like hypertension and cancer (Mohamed Abd El-Aziz et al., 2019).

The USA and European countries also import live venomous snakes, mainly from Singapore and Thailand. Although snakes are popular pets (i.e., there were 1.15 million pet snakes in the USA) (AVMA, 2012), most pet snakes are non-venomous. Yet bites by exotic snakes (some CITES-listed) have been reported outside their native range in North America (Gummin et al., 2017; Lubich and Krenzelok, 2007; Warrick et al., 2014), Europe (Chew et al., 2003; de Haro, 2014; Schaper et al., 2004; Schaper et al., 2009; Stadelmann et al., 2010), and Asia (Wong et al., 2009). The number of such snakebite cases is increasing (Minton, 1996; Warrell, 2009), possibly because of easier access to these snakes via the internet (Jensen et al., 2019; e.g., http: //market.kingsnake.com/index.php?cat=101), but remains relatively rare (de Haro, 2012; Valenta et al., 2014; Warrell, 2009). When they do occur, clinical management of exotic snakebite is challenging due to limited experience of local healthcare providers and availability of antivenoms.

4.4. Data challenges/discrepancies

The CITES Trade Database allows for the analysis of trade trends, patterns, and flows for CITES-listed wildlife. However, the challenges of working with the CITES Trade Database are also well known and widely described (Berec et al., 2018; Foster et al., 2016; Robinson and Sinovas, 2018; Schlaepfer et al., 2005). This literature reflects the importance of proper interpretation of the CITES Trade Database, highlighting the need for more standardized analysis practices (Berec and Šetlíková, 2019; Eskew et al., 2019; Pavitt et al., 2019).

Some of our analyses were presented in terms of number of exporter-reported WOE quantities or live snake quantities rather than importer-reported numbers. This decision was made because CITES parties are not required to report imports of Appendix II CITES-listed species (Robinson and Sinovas, 2018). Because snake trade is dominated by Appendix II species (76.1% of all exports), import volume would likely be an underestimate of actual trade volume. Conversely, some CITES parties are known to report allowed trade quantities as issued on the requested permits, rather than actual shipped quantities, which potentially results in overestimation when presenting export numbers (Robinson and Sinovas, 2018; UNEP-WCMC, 2019). Finally, importers and exporters may report different quantities for the same shipments. For example, we found that in one case, the exporter reported 18 snake leather items, whereas the importer reported 36 snake leather items, a discrepancy that could reflect differences in counting of items that appear as pairs (i.e., shoes).

We excluded re-exports based on the presence of an origin country or origin permit ID. Since there are no comprehensive guidelines to support data preparation for the CITES Trade Database, there was uncertainty regarding the appropriate procedure for exclusion. Robinson and Sinovas (2018) stated that the presence of an origin country indicates a shipment being a re-export. However, the per-shipment database also allows the identification of re-exports by the origin permit ID, as stated in the CITES Trade Database supplementary information. However, excluding shipments solely on origin country or origin permit ID results in different outcomes. Therefore, we decided to exclude re-exports based on both columns, resulting in 134,785 direct exports after filtering.

The exclusion of re-exports implies that many of the identified importers may represent re-export hubs and not final product destinations. Re-exports were excluded to prevent double-counting of traded quantities, as re-exports often represent smaller fractions of an earlier shipment. Ideally, the results of the analyses should reflect all trade between CITES parties, including re-exports, because they enable identification of end-user countries and re-export hubs and could be used to calculate net trade per CITES party. The per-shipment CITES Trade Database that was recently released contains anonymized permit IDs, which should theoretically allow one to connect initial shipments to re-exports. However, permit IDs are not unique across countries and years, making it impossible to link initial shipments to re-exports. The current data are, therefore, insufficient for matching re-exports to original shipments.

In a further complication, both CITES-listed species and CITES parties change over time. Therefore, to account for differing yearly CITES reporting effort, we applied a correction metric to temporal data (Figs. 1, 3). The product of the number of CITES-listed species and CITES parties in each year offers a simple metric for correction and allows for the calculation of a trade ratio (number of yearly traded snakes per CITES parties and CITES-listed species). Both corrected and uncorrected results revealed snake export peaks around 1986 and 1990 (Fig. 1A, C). However, corrected exported WOEs reveal a less distinct trade peak in 1990 than raw export trade quantities. The correction method was also applied to shipment numbers (Appendix 14). Corrected shipment numbers revealed snake shipment export peaks around 1985 and 1991 that were previously less pronounced (Appendix 14C). Further, the overall increase in shipment numbers seems to be less distinct when drawing conclusions based on adjusted trade quantities instead of raw shipment numbers (Appendix 14). To our knowledge, this study presents one of the first attempts at correcting reporting bias in CITES data and illustrates the importance of interpreting CITES data with fluctuations in CITES-listed species and parties in mind.

The presentation of raw trade quantities instead of corrected trade quantities may be exploited by bad actors who attempt to conceal illegal activity by reporting significant discrepancies between exports and imports (including from non-CITES parties; Nijman and Shepherd, 2011). Furthermore, many snake species of conservation concern are not CITES-listed, which makes the trade in nationally-protected non-CITES species hard to detect (Janssen and Leupen, 2019). More generally, the CITES Trade Database represents a small subset of the entire global trade in snakes (< 200 of > 3700 total species are controlled by CITES; Eskew et al., 2019; Uetz et al., 2019). For example, few African snakes are regulated by CITES, and many of the most traded African snake species are not CITES-listed (Jensen et al., 2019; Roll et al., 2017; Appendix 15).

5. Conclusion

The 44-year CITES Trade Database offers a unique opportunity to assess the global trade in CITES-listed snake species and to identify trends in trade volume, purposes, terms, and sources. We showed that pythons and colubrids are the most traded snake species, both as live animals and skins. Despite an increasing shift towards captive breeding of pythons, a large proportion of traded snakes are still harvested from the wild, with potential implications for snake conservation. We also revealed that venomous snakes are globally traded, describing for the first time the trends and geographic patterns of this legal trade in CITES-listed species and discussing the associated public health concerns.

CRediT authorship contribution statement

Fleur Hierink: Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Software, Visualization, Supervision. **Isabelle Bolon:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision. **Andrew M. Durso:** Writing - original draft, Writing - review & editing, Visualization, Validation. **Rafael Ruiz de Castañeda:** Writing - original draft, Writing - review & editing. **Carlos Zambrana-Torrelio:** Writing - original draft, Writing - review & editing, Validation. **Evan A. Eskew:** Validation, Writing - original draft, Writing - review & editing. **Nicolas Ray:** Writing - original draft, Writing - review & editing, Validation, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

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