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Original Research Article

Dealing in deadly pathogens: Taking stock of the legal trade in live wildlife and potential risks to human health

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ABSTRACT

Zoonotic diseases cause millions of deaths every year. Diseases such as Ebola, severe acute respiratory syndrome (SARS), and avian influenza cause economic losses at the global level and jeopardize diplomatic relations between countries. As wildlife are the source of at least 70% of all emerging diseases and given the on-going concerns associated with wildlife trade as a disease transmission mechanism, we provide a 'global snapshot' of the legal trade in live wild animals and take stock of the potential health risks that it poses to global human health. Our analysis showed that 11,569,796 individual live wild animals, representing 1316 different species were exported from 189 different countries between 2012 and 2016. China was the largest exporter of live mammals (with 98,979 animals representing 58.7% of global trade). Nicaragua was the largest exporter of live amphibians (with 122,592 animals representing 53.8% of global trade). South Africa was the largest exporter of live birds (with 889,607 animals representing 39.2% of global trade). Peru was the largest exporter of live reptiles (with 1,675,490 animals representing 18.8% of global trade). Our analysis showed that mostly the USA and other high-income countries, the largest importers, drive the live animal trade. High-income countries and not the countries where wildlife diseases and pathogens are more likely to occur reported almost all of the disease reports to the World Organisation for Animal Health. Based on our findings, we discuss how maximising trade bans; working on human behaviour change and improving regulatory efforts to improve surveillance will decrease the risk of future pandemics, epidemics and outbreaks.

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1. Introduction

Zoonotic diseases are infectious diseases, caused by a variety of pathogenic agents (including bacteria, parasites, fungi, viruses and prions) that are naturally transmitted from vertebrate mammals to humans and vice versa (Wang and Cramer, 2014). Zoonotic diseases have serious large-scale impacts on human health; they cause about a billion cases of human illness and millions of deaths every year (Karesh et al., 2012), which, in addition to the suffering experienced, in turn affects the national health budgets of governments worldwide. Outbreaks of well-known human diseases of zoonotic origin in recent decades such as Ebola, severe acute respiratory syndrome (SARS) and avian influenza have caused economic losses at the

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global level. For example, the SARS outbreak in 2003 alone cost China's economy \$25.3 billion (Hai et al., 2004) and reduced the gross domestic product (GDP) across East Asia by 2% (King et al., 2006). Similarly, the World Bank estimated that an influenza epidemic could cost \$900 billion globally in one year (King et al., 2006). At a global level, according to one estimate, the economic damage caused by emerging zoonoses is around hundreds of billion US dollars in the past 20 years (Karesh et al., 2012). In addition to the negative impacts of zoonotic diseases on global human health and economy, zoonotic diseases also adversely affect animal health, jeopardize the diplomatic relations between countries and can undermine conservation efforts to protect the world's biodiversity (Karesh et al., 2005; Parliamentary Office of Science and Technology, 2008; Johnson et al., 2015; Greatorex et al., 2016; Olival et al., 2017; see Macdonald and Laurenson, 2006 for key topics in infectious diseases and conservation). According to the "One World - One Health" concept created in 2004, the human health and animal health are interdependent and bound to the health of the ecosystems in which they exist (Destoumieux-Garzón et al., 2018).

Zoonotic infections have always featured among the wide range of human diseases and most (e.g. anthrax, tuberculosis, plague, yellow fever and influenza) have come from domestic animals, poultry and livestock (Wang and Cramer, 2014). However, with changes in the environment, habitat and human behaviour, increasingly these infections are emerging from wildlife species to the extent that wildlife are thought to be the source of at least 70% of all emerging diseases (Kuiken et al., 2005; Wang and Cramer, 2014). For example, the expansion of road networks and the development of agricultural land have facilitated the spread of Nipah virus, West Nile virus, influenza A H5N1, monkeypox, SARS, HIV and other novel pathogens throughout the world (Daszak, 2012; Kilpatrick and Randolph, 2012; Jones et al., 2013; Johnson et al., 2015).

The global trade in wildlife -whether it is legal or illegal-has also been specifically cited as a transmission mechanism of growing concern in recent decades, given that infectious agents are spread when humans capture wild animals from their natural habitats, transport and trade them dead or alive to different parts of a country or the world by land, sea and air (Morens et al., 2004; Karesh et al., 2005; OIE and IUCN, 2014). The first reported occurrence of monkeypox outside Africa in 2003 due to pet prairie dogs (they were infected by African rodents imported to the US) (Bernard and Anderson, 2006) and multistate outbreak of *Salmonella* Agbeni Infections (outbreak was Linked to Pet Turtles) in 2017 are just two examples (Centers for Disease Control and Prevention, 2018). Furthermore, from the point of view of those seeking to curtail wildlife trade, the risk of infectious diseases was the primary factor dissuading those interested in buying a wild animal pet from doing so (Moorhouse et al., 2017). However, quantifying the global wildlife trade is extremely difficult since it ranges in scale from local barter to major international routes, and much is conducted illegally or through informal networks (Karesh et al., 2005). In fact, the complexity of monitoring of wildlife trade has been compared to that of arms trade (Smith et al., 2017).

The World Health Organisation (WHO) and most infectious disease experts agree that the origins of future human pandemics are likely to be zoonotic, with wildlife emerging as the primary source (Wang and Cramer, 2014). Trade in live animals whether it is legal or illegal trade pose risks to global human health since pathogens -via their host organisms-do not care whether they are traded legally or illegally. The illegal trade in live animals represent a serious threat global health due to its clandestine and unregulated nature. Given the on-going concerns associated with the global trade in wildlife as a disease transmission mechanism, and since legal trade records are available, in this study we aim to provide the first 'global snapshot' of the global legal trade in live wild animals and to take stock of the potential health risks that it poses to global human health. In order to do so, we first characterised four of the major taxonomic vertebrate classes (amphibians, birds, reptiles and mammals) and countries for the period between 2011 and 2016 as reported by United Nations Environment Programme (UNEP)- World Conservation Monitoring Centre Monitoring Centre (WCMC) Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Second, we identified the infectious diseases originating from wildlife as reported by the world's governments to the World Organisation for Animal Health (OIE) and the scientific literature for the period 2008-2016 and classified them according to their relevance to particular wild animal taxa. Finally, based on our findings, we provide recommendations for safer trade and a healthier planet.

2. Materials and methods

The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is an international agreement that operates as a licensing system for imports and exports of listed species that must be authorized by Parties (UNEP-WCMC, 2013). The CITES Trade Database currently holds more than 13 million records, involving 34,000 scientifically recognised taxa as listed in the CITES appendices (UNEP-WCMC, 2013), which are managed by the by UNEP and WCMC (UNEP-WCMC, 2013). CITES trade data have proved useful in previous studies to help characterize the levels of international legal trade and also to help assess trade issues (such as animal welfare (D'Cruze and Macdonald, 2016)) and conservation (Bush et al., 2014; D'Cruze and Macdonald, 2017), therefore, we used the data available from the CITES Trade Database website (<https://trade.cites.org>) to make queries for the period 2012-2016 inclusive.

We specifically requested data only using the "live" trade term and the CITES purpose code "P" which refers to "personal" use and CITES purpose code "T" which refers to "commercial use" as outlined in Notification 2002/022 (UNEP-WCMC, 2013). All source codes outlined in Notification 2002/022 that are available to CITES Parties were used in the analysis including specimens sourced from captivity (codes C, D and F), confiscated specimens (code I), pre-convention specimens (code O), ranches specimens (code R), specimens of unknown source (code U), and specimens sourced from the wild (code W) (UNEP-WCMC, 2013). All Appendix classifications used by CITES were also included in the analysis: Appendix I (trade permitted only under exceptional circumstances), Appendix II (non-detriment finding and export permit are required for trade), Appendix III (one Party has asked other CITES Parties for assistance in controlling trade), or non-CITES (CITES, 2017).

We focussed our analyses on the following four taxonomic classes of vertebrate provided in the database: Mammalia (mammals), Amphibia (amphibians), Aves (birds) and Reptilia (reptiles). As specified in Resolution Conf. 12.3 (Rev. CoP16), the one-letter code reported as source of a transaction in CITES trade database indicates the original source of the species being traded. We used the following source codes to identify the individuals that were captive bred:

C: Animals bred in captivity in accordance with Resolution Conf. 10.16 (Rev.), as well as parts and derivatives thereof, exported under the provisions of Article VII, paragraph 5, of the Convention.

D Appendix-I animals bred in captivity for commercial purposes in operations included in the Secretariat's Register, in accordance with Resolution Conf. 12.10 (Rev. CoP15), and Appendix-I plants artificially propagated for commercial purposes, as well as parts and derivatives thereof, exported under the provisions of Article VII, paragraph 4, of the Convention.

F Animals born in captivity (F1 or subsequent generations) that do not fulfill the definition of 'bred in captivity' in Resolution Conf. 10.16 (Rev.), as well as parts and derivatives thereof.

Similarly, we used the following source codes to identify the individuals that were sourced from the wild.

R Ranched specimens: specimens of animals reared in a controlled environment, taken as eggs or juveniles from the wild, where they would otherwise have had a very low probability of surviving to adulthood.

W Specimens taken from the wild.

In order to take a stock of the potential global health risks posed by the international legal trade in live wild vertebrates, we made queries in Web of Science database to find relevant articles published since 1945. To do that, we first made queries using the keywords “epidemics”, “pandemics” and “outbreaks” and then within the resulting pool of articles, we identified those that specifically used the terms “exotic pet”, “pet trade” or “wildlife trade”. Thereafter, we also made two separate queries in Web of Science database using the keywords “exotic pets” – a common phrase used in the literature to refer to a particular type of live trade, and “wildlife trade” and then within the respective resulting pool of articles, we identified those that specifically used the terms “pandemic”, “epidemic”, “outbreak”, “zoonotic”, “zoonosis” and “zoonoses”.

The information on the diseases originating from wild species is limited. As information provided by the World Organisation for Animal Health (OIE) World Animal Health Information System (WAHIS)-Wild interface has proven useful in other studies focused on zoonotic diseases of wild animals (e.g. see Devitt, 2017), we consulted the OIE WAHIS-Wild for further information on infectious diseases that are associated with wild animal species. The OIE is the intergovernmental organisation responsible for improving animal (i.e. domesticated livestock) health worldwide (OIE, 2018a). However, the WAHIS-Wild interface provides an inventory of non-OIE listed diseases that have been selected by the OIE's Working Group on wildlife for monitoring purposes given their importance to wild animals and for early warning purposes, in order to protect human and livestock health (OIE, 2017).

We specifically requested data from the OIE WAHIS-Wild interface webpage (http://www.oie.int/wahis_2/public/wahidwild.php/Family/Family). We selected all families using the “Select all families” option for the period 2008–2017 inclusive, which gives the data for all countries. We then organised the output table in Microsoft Excel (Version 14.7.7). Given that the WAHIS-Wild interface does not provide taxonomic information above family level, we assigned class status to each species (i.e. Mammals (Mammalia); Amphibians (Amphibia); Birds (Aves) and Reptiles (Reptilia)) using the International Union for the Conservation of Nature as a source of reference (IUCN, 2018). We used RawGraphs (Mauri et al., 2017) for visualizing the CITES data. At the time of this study, WAHIS-Wild interface included a total of 50 infectious diseases and 4 non-infection diseases under the heading “Non OIE-listed diseases affecting wild animals” (OIE, 2018b). OIE explains the non OIE-listed diseases as “Although these diseases have not met the OIE's criteria to be listed, the OIE's experts of the Working Group on wildlife diseases have selected them to be monitored, both because of their importance for wild animals and also for early warning purposes, in order to protect human and livestock health.” (OIE, 2017).

3. Results

3.1. Most traded taxa

The CITES Trade Database provided information on trade that occurred between 2012 and 2016. Within this five-year period, a total of 11,569,796 live wild animals were exported and 8,018,365 live animals were imported between the countries for commercial and personal use (Fig. 1). Reptiles were the most traded taxonomic group both in terms of the number of animals recorded as exports and imports (Fig. 1). At the global level, with regards to exports between countries, on average every 100 live animal shipments contained 76.99 reptiles, 19.59 birds, 1.97 amphibians and 1.45 mammals. With regards to imports between countries, on average every 100 live animal shipments contained 83.54 reptiles, 12.54 birds, 2.65 amphibians and 1.27 mammals. In terms of species diversity, the trade included 569 species of bird, 465 species of reptile, 210 species of mammal and 72 species of amphibian. The full list of species is given in [Supplementary Material A](#) file.

Among mammals, Primates (94.8% of the legal global trade with 159,549 individuals) was the most traded order (with the family Cercopithecidae, genus *Macaca* forming most of the global trade) followed by the Carnivora (Carnivores) and Artiodactyla (even toed ungulates) (Figs. 2 and 3). Among amphibians, Anura (frogs) (99.6% of the global total with 226,800 individuals) was the most traded order (with the family Hylidae (tree frogs), genus *Agalychnis* forming most of the global trade (Figs. 2 and 4). Among birds, Psittaciformes (parrots) (93.2% of the global trade with 2,112,946 individuals) was the most traded order forming most of the global trade with the family Psittacidae (true parrots), genera *Agapornis*, *Psittacus*, and

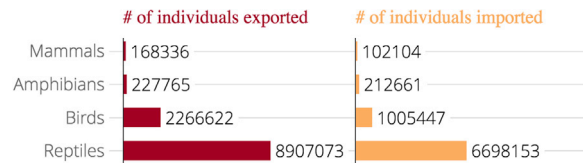


Fig. 1. Breakdown of legal live animal trade carried out for commercial and personal use based on CITES data 2012–2016. The numbers of reported quantities of exported animals by exporter countries and reported quantities of imported animals by importing countries do not match because not all Parties submit complete reports or submits reports at all to the CITES Secretariat (UNEP-WCMC, 2013).

Myiopsitta being the most traded taxa (Figs. 2 and 5). Among reptiles the Testudines (freshwater turtles, sea turtles and tortoises) (62.2% of the global trade with 5,366,041 individuals) was the most traded order forming most of the global trade, with the family Podocnemididae being the most traded taxa (Figs. 2 and 6). The family Iguanidae, genus *Iguana* (iguanas) was the most traded taxa from the order Sauria (lizards) and the genus *Python* was the most traded taxa from the order Serpentes (snakes) (Fig. 6). The world's most traded (i.e. exported and imported) mammal, amphibian, bird and reptile orders are given in Supplementary Material B. For mammals, amphibians and birds, most of the live traded individuals (as exports) were captive bred according to the CITES records (Figs. 7–9). However for reptiles, CITES records showed that most of the live traded individuals were captured from the wild rather than captive bred (Fig. 10).

3.2. Top trading countries

China was the largest exporter for mammals; it sent 98,879 different animals from 7 different species to 10 different countries between 2012 and 2016. The USA was the biggest importer for mammals; it received 63,672 different animals from 73 different species from 36 different countries between 2012 and 2016 (Fig. 3). The USA was also the largest importer for



Fig. 2. Photographs of species representing the top traded families in mammals, amphibians, birds and reptiles (Photographs: top left - *Macaca cyclopis* by Kaur Jmeb [CC BY-SA 2.0 license], top right - *Agalychnis callidryas* by Pavel Kirillov [CC BY-SA 2.0 license], bottom left - *Agapornis personatus* by Epoulin10 [CC BY 3.0] license and bottom right - *Podocnemis unifilis* by <http://opencage.info> [CC BY-SA 2.5 license] via Wikimedia Commons). Macaque species are mostly used for medical research (Southwick and Siddiqi, 1994; Carlsson et al., 2004; Lankau et al., 2014).

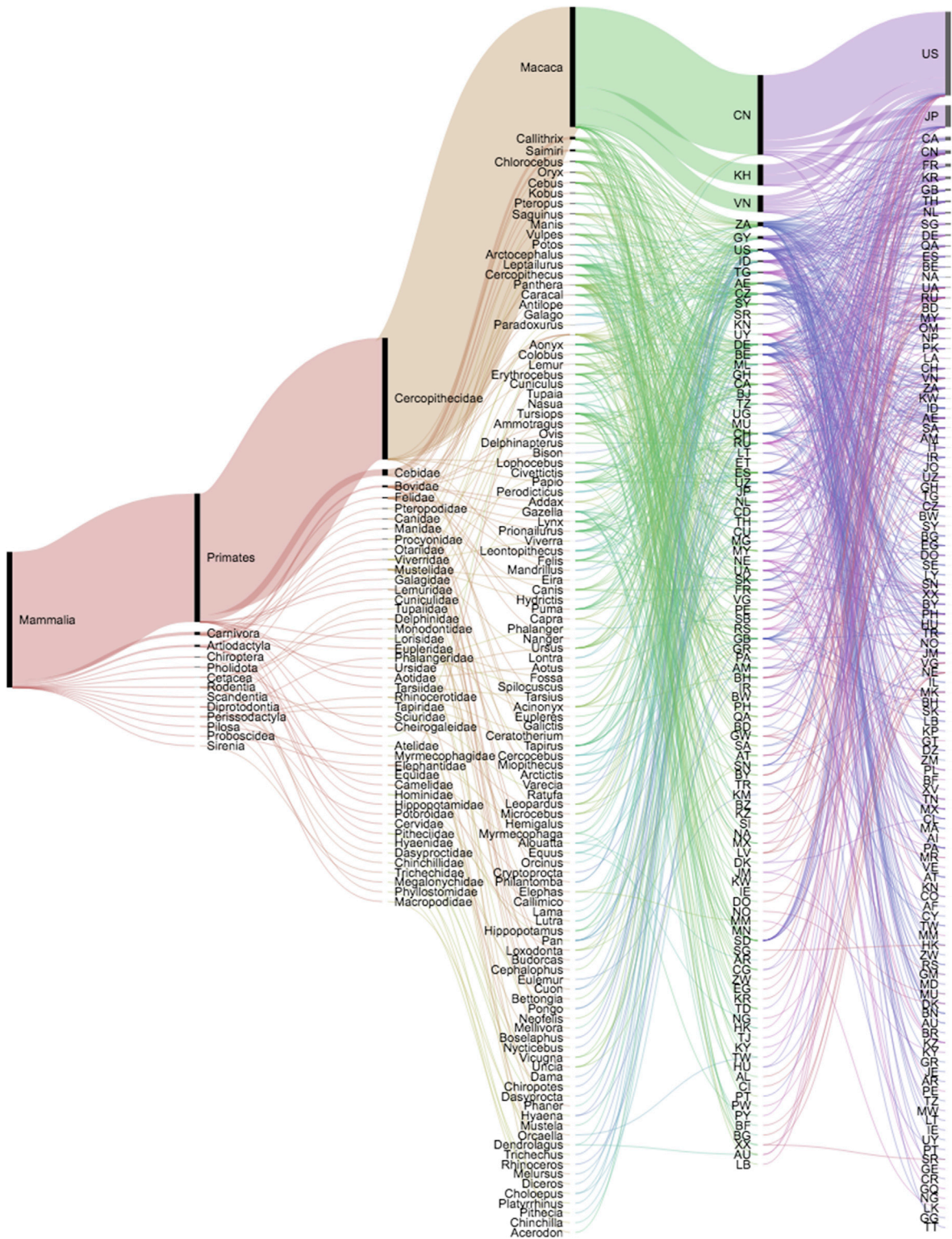


Fig. 3. Magnitude of flow of the global live mammal trade (showing a total of 2147 trade records mapped according to class, order, family, genus, exporter and importer country codes in the CITES database) that occurred between 2012 and 2016. The thicknesses of coloured bands in the figure reflect the number of animals traded and the magnitude of trade between the countries.

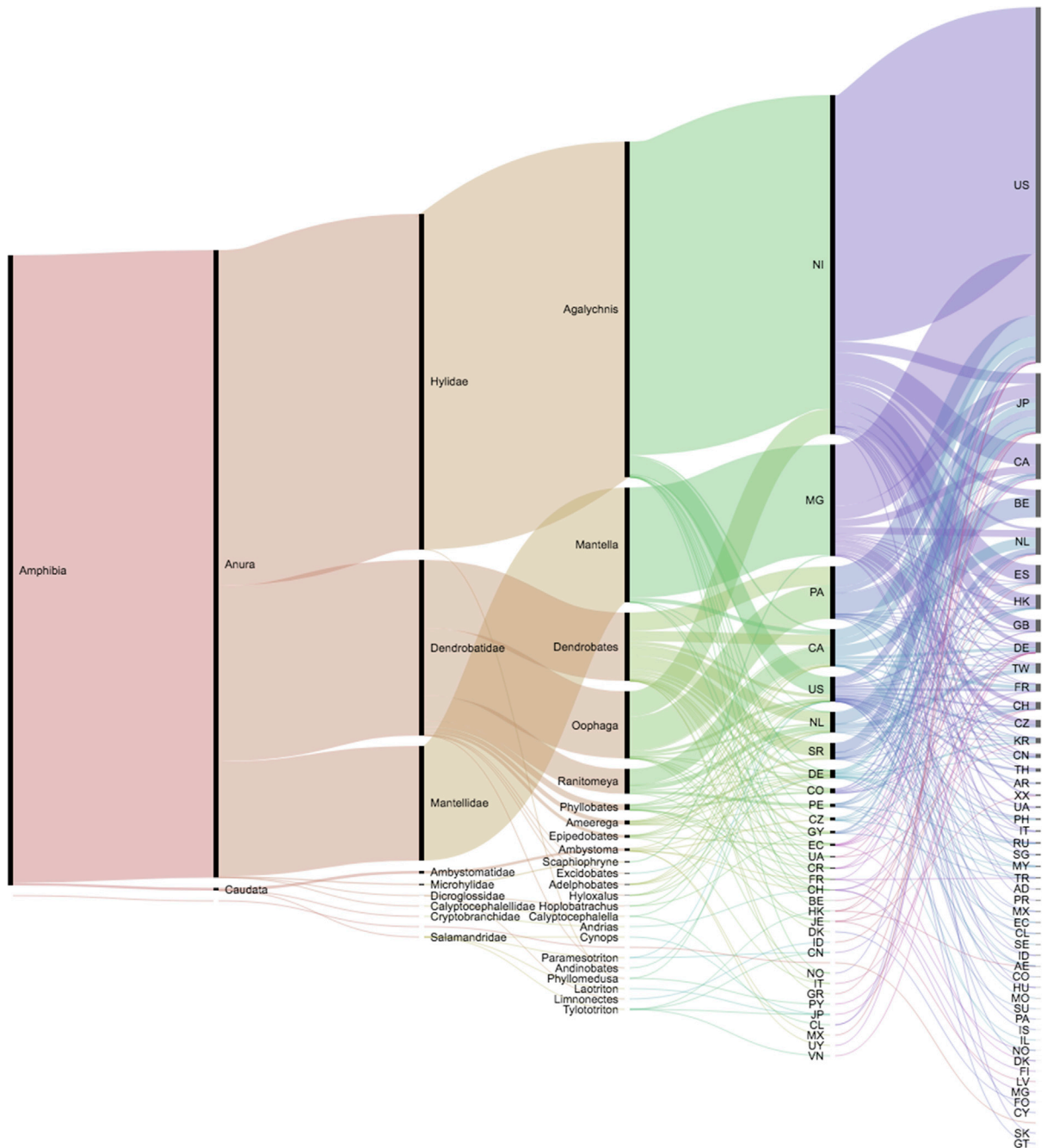


Fig. 4. Magnitude of flow of the global live amphibian trade (showing a total of 1818 trade records mapped according to class, order, family, genus, exporter and importer country codes in the CITES database) that occurred between 2012 and 2016. The thicknesses of coloured bands in the figure reflect the number of animals traded and the magnitude of trade between the countries.

amphibians (Fig. 4) (a total of 104,675 different animals from 55 species from 17 countries) and Nicaragua was the largest amphibian exporter with 122,592 different animals from 2 species to 20 different countries (Fig. 4). South Africa was the largest exporter for birds (889,607 different animals from 217 species to 87 countries) and Mexico was the largest importer (328,304 different animals from 75 species from 14 countries) (Fig. 5). Peru (1,675,490 different animals from 8 species to 21 countries) and Hong Kong (2,390,318 different animals from 192 different species from 57 countries) were the largest reptile exporter and importer countries respectively (Fig. 6). The top ten countries that are involved in live animal trade are listed together with the quantities of individuals they traded in [Supplementary Material C](#).

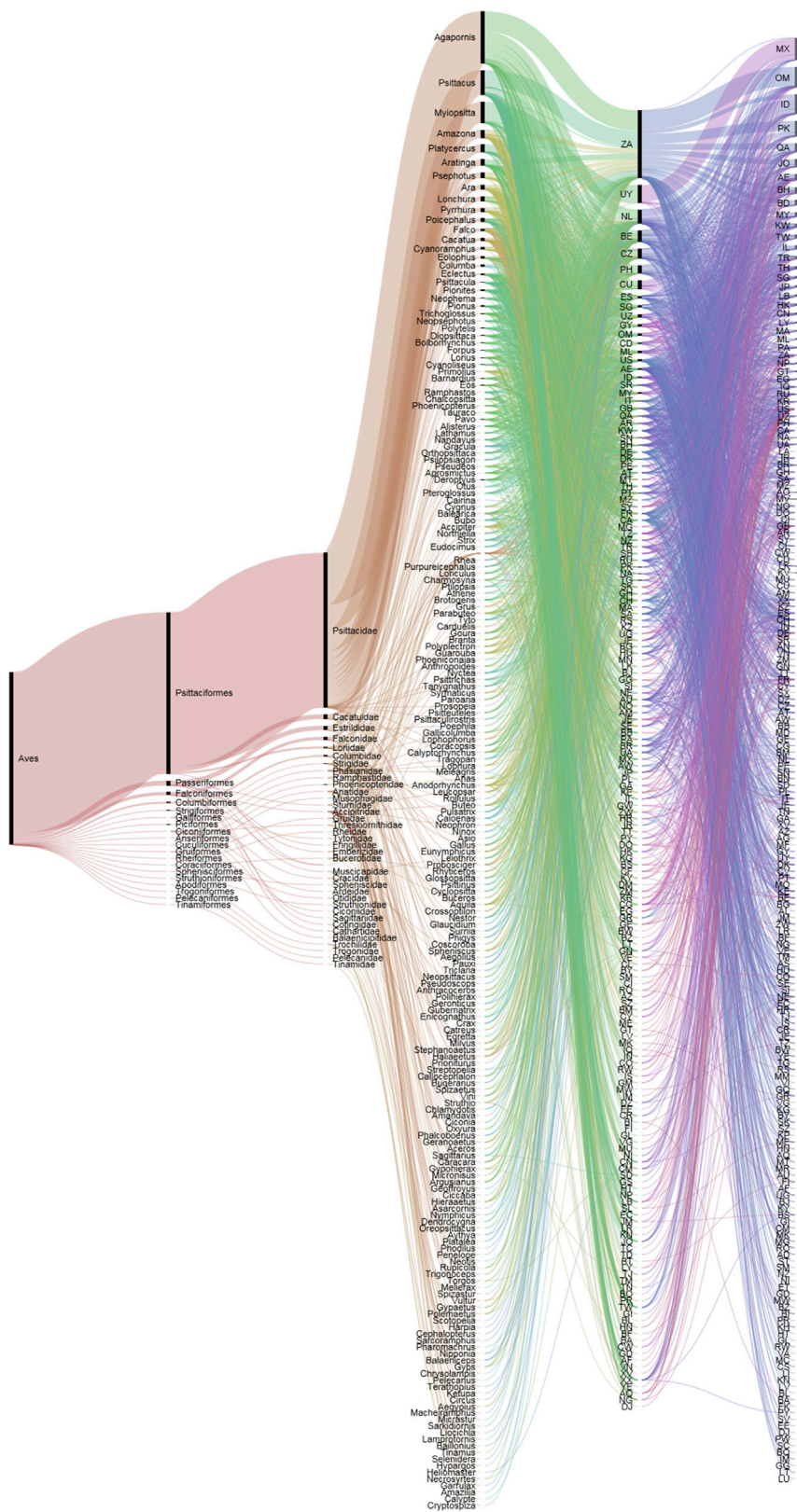


Fig. 5. Magnitude of flow of the global live bird trade (showing a total of 29,351 trade records mapped according to class, order, family, genus, exporter and importer country codes in the CITES database) that occurred between 2012 and 2016. The thicknesses of coloured bands in the figure reflect the number of animals traded and the magnitude of trade between the countries.

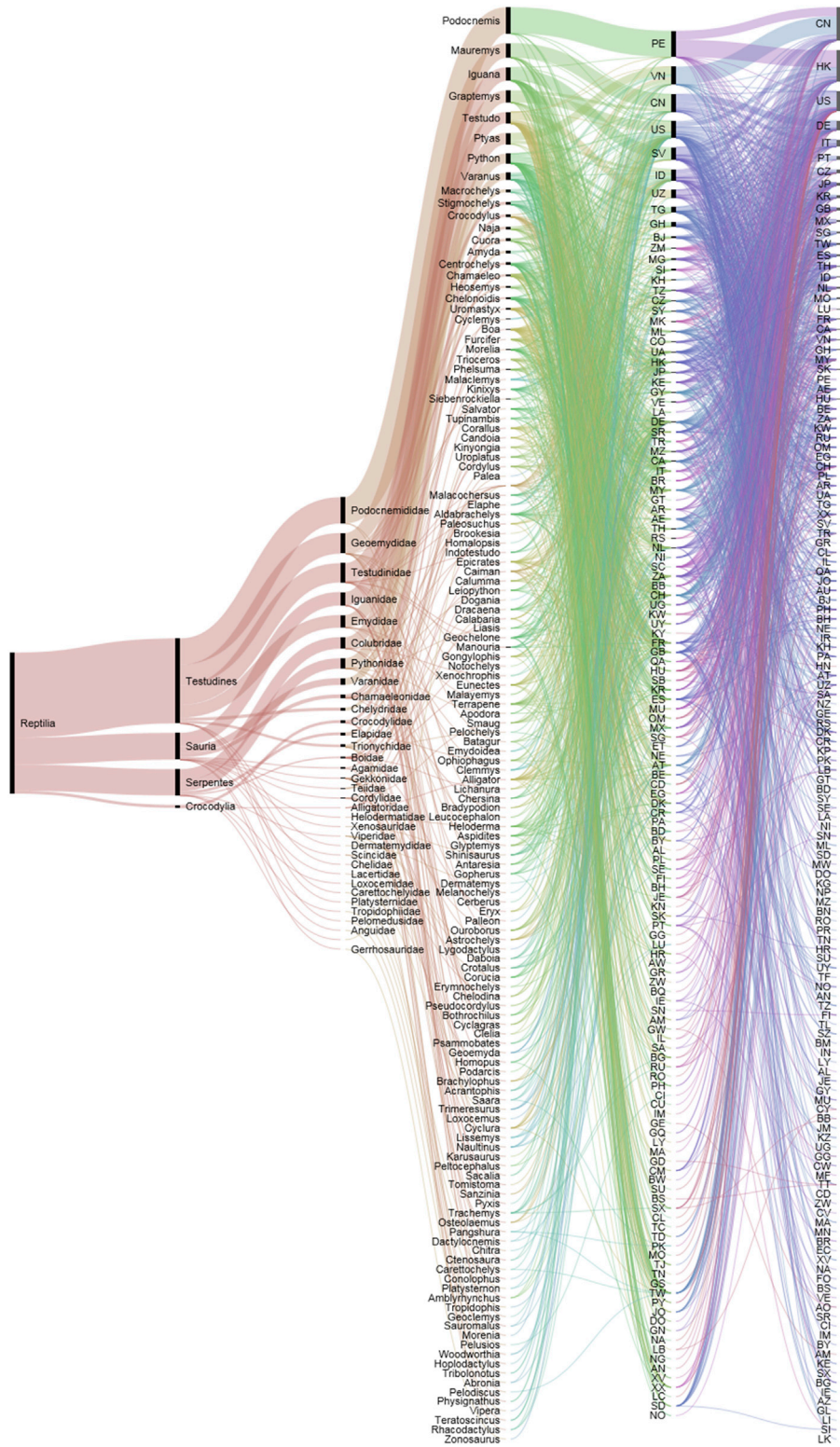


Fig. 6. Magnitude of flow of the global live reptile trade (showing a total of 17,850 records mapped according to class, order, family, genus, exporter and importer country codes in the CITES database) that occurred between 2012 and 2016. The thicknesses of coloured bands in the figure reflect the number of animals traded and the magnitude of trade between the countries.

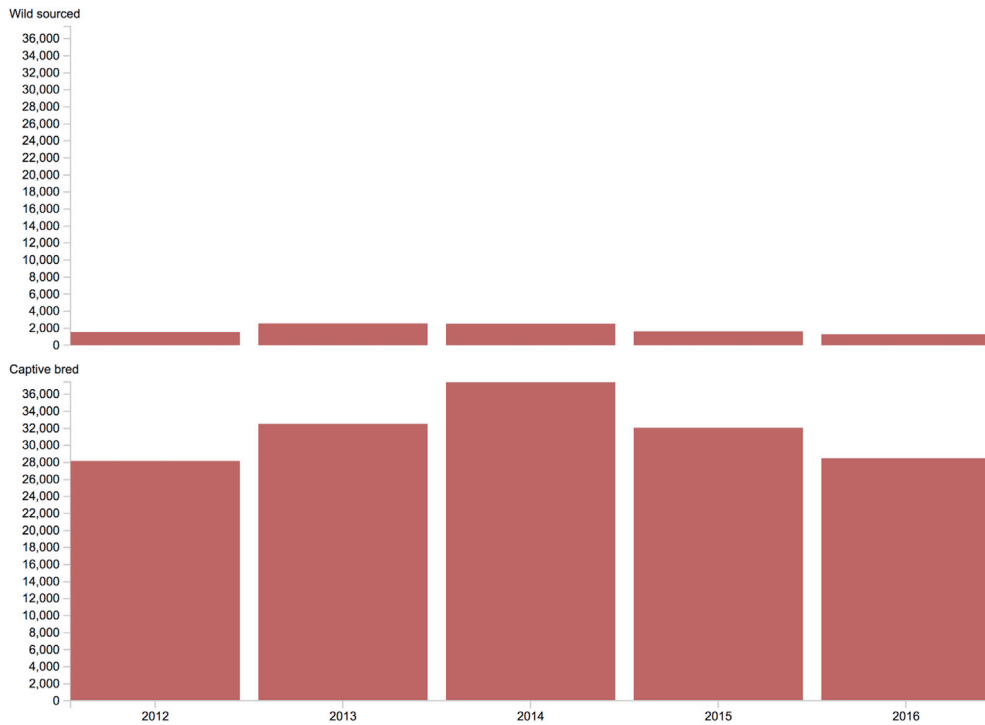


Fig. 7. Number of mammals exported and their origin (caught from the wild vs captive bred) between 2012 and 2016.

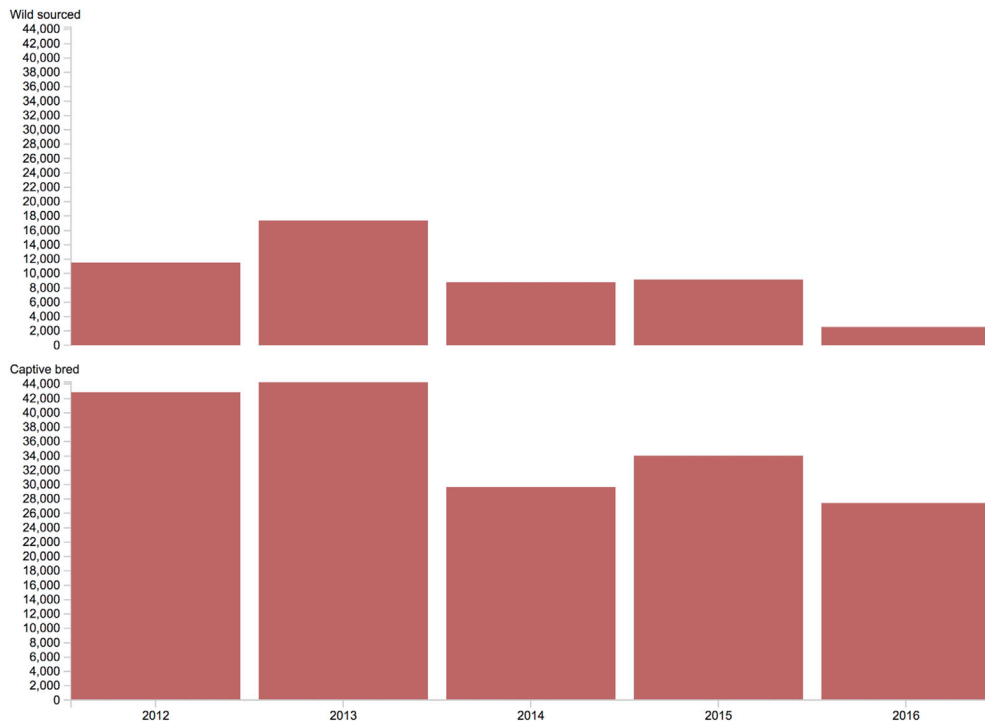


Fig. 8. Number of amphibians exported and their origin (caught from the wild vs captive bred) between 2012 and 2016.

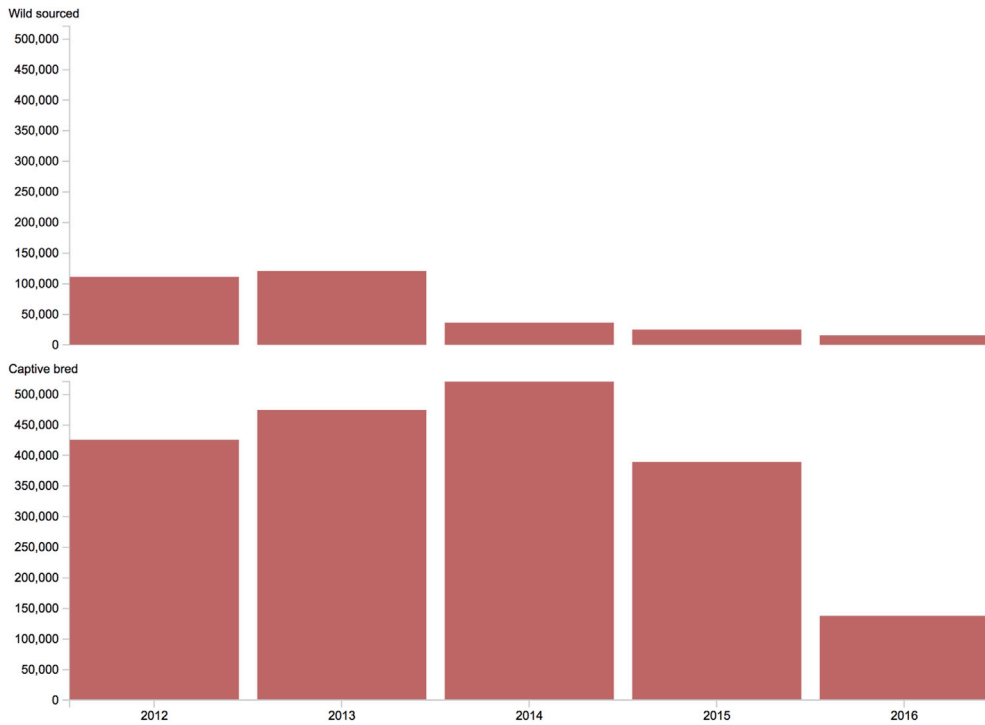


Fig. 9. Number of birds exported and their origin (caught from the wild vs captive bred) between 2012 and 2016.

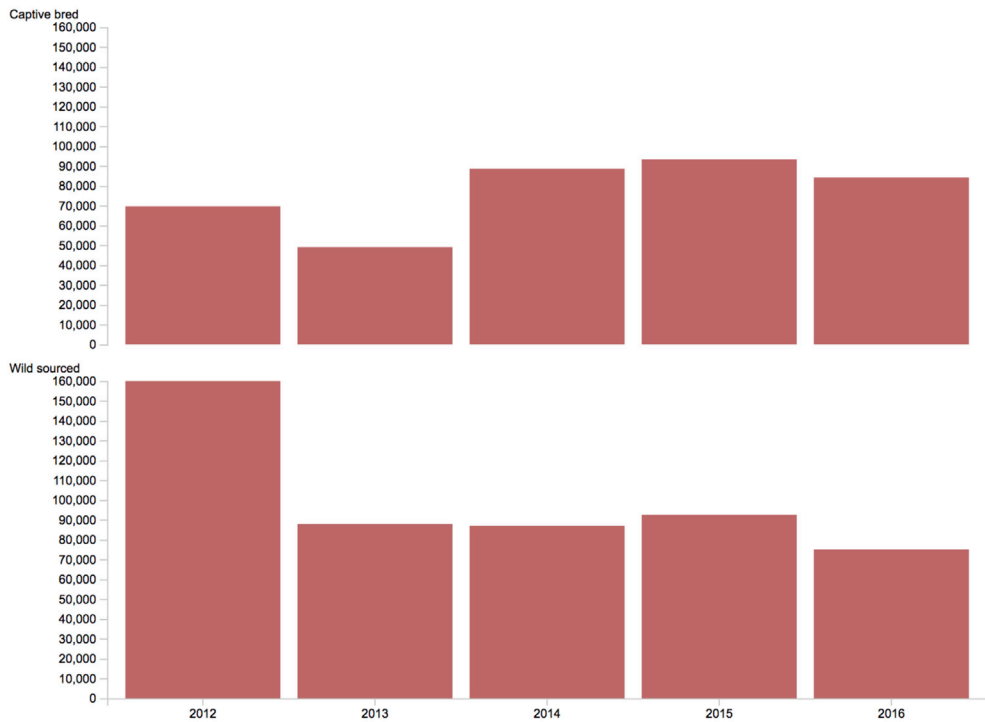


Fig. 10. Number of reptiles exported and their origin (caught from the wild vs captive bred) between 2012 and 2016.

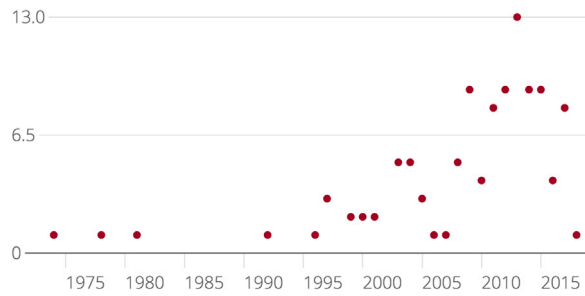


Fig. 11. Distribution of 108 articles that mention the health aspect of exotic pets.

3.3. Taking a stock of global health risks of exotic pet trade

According to Web of Science database, there were a total of 348,872 articles published since 1945 that mention the terms “outbreak” (199,560 articles) or “epidemic” (164,504 articles) or “pandemic” (34,537 articles) when duplicates were removed. Out of these more than quarter million articles, there were only 28 articles (0.008%) that mentioned the terms “exotic pet” or “pet trade” or “wildlife trade” when duplicates were removed. Also according to Web of Science database, there were a total of 898 articles published between 1945 until April 2018 that mention the term “exotic pet” or “exotic pets”. Out of these 898 articles, a total of 108 articles mentioned one or more of the terms “zoonotic”, “zoonosis”, “zoonoses”, “epidemic”, “pandemic” or “outbreak” (Fig. 11) (Supplementary Material D). Majority (73%, n = 79) of the articles were published since 2008 indicating that health risks associated with exotic pets have been a significant topic for researchers only in the last decade. However, the focus of those articles has been mostly (38%, n = 41) high-income countries (according to Worldbank, 2018) and only 9.3% (n = 10) of the articles were about lower income countries (six (5.5%) of the articles had global focus and 51 (47.2%) of the articles didn't mention their country of focus) (Supplementary Material D).

3.4. OIE WAHIS-Wild database

Analysis of the disease reports included in the OIE WAHIS-Wild database showed that there were 3131 disease reports belonging to 82 different diseases/infections from 54 countries for the 2008–2016 period (Table 1). Out of 3131 records, there were seven reports on fish (six reports by the Netherlands and one report by Canada) and one report on insects (report by Switzerland). Almost half of the disease reports were on birds (51.7%, n = 1616) and the other half on mammals (47.1%, n = 1472). There were only a few reports on the diseases of reptiles (0.8%, n = 34) and amphibians (0.03%, n = 1). The number of diseases reported by the world's governments to OIE has decreased since 2008 (Fig. 12).

3.5. OIE WAHIS-Wild records: diseases/infections according to species

Reports on birds and mammals made up almost all of the disease/infection records (Fig. 13). Diseases for mammals, birds and reptiles were reported throughout the years with the exception of amphibians (Fig. 14). The ten most frequently reported diseases/infections in the OIE WAHIS-Wild interface (that account for majority of the records (73.4%, n = 2293)) are given in Table 1. The full list of diseases/pathogens (in terms of either bacteria or viruses) relating to mammals, amphibians, birds and reptiles are given in Supplementary Material E. For mammals, the ten most frequently reported diseases/infections are given in Table 2 and the remaining 56 diseases/infections reported are given in Supplementary Material E. For birds, the ten most frequently reported diseases/infections are given in Table 3 and the remaining 22 diseases/infections are given in

Table 1

The ten most frequently reported diseases/infections for mammals, amphibians, birds and reptiles as they are reported in OIE WAHIS-Wild Interface (asterisk sign indicates zoonotic diseases).

Rank	Disease/Infection
1	Infection with low pathogenic avian influenza viruses/Low pathogenic avian influenza*
2	Infection with <i>Salmonella enterica</i> /Salmonellosis (<i>S. enterica</i>)*
3	Infection with <i>Pasteurella</i> spp./Pasteurellosis*
4	Infection with <i>Trichomonas</i> spp. in birds and reptiles/Trichomonas sp.*
5	Infection with <i>Sarcoptes scabiei</i> /Sarcoptic mange*
6	Botulism*
7	Infection with <i>Toxoplasma gondii</i> /Toxoplasmosis*
8	Infection with <i>Yersinia pseudotuberculosis</i> /Pseudotuberculosis*
9	Infection with Pox viruses*
10	Infection with morbillivirus (canids and felids)*

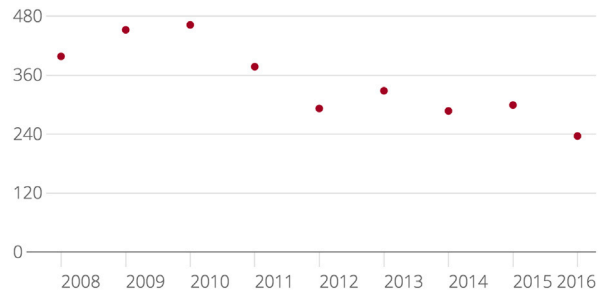


Fig. 12. Distribution of disease reports in OIE WAHIS-Wild database as they are reported by world's governments between 2008 and 2016.



Fig. 13. Number of disease/infection reports according to animal classes for the period 2008–2016.

[Supplementary File E](#). For amphibians the single record made during the nine-year period for which records were available was an infection with ranaviruses. The diseases of reptiles are given in [Supplementary File E](#).

3.6. OIE WAHIS-Wild records: diseases according to countries

In the last nine years, Italy (followed by Canada, Netherlands, Finland and United Kingdom) provided the most disease reports in the OIE WAHIS database (see [Supplementary Material F](#) for the full list of countries and number of records

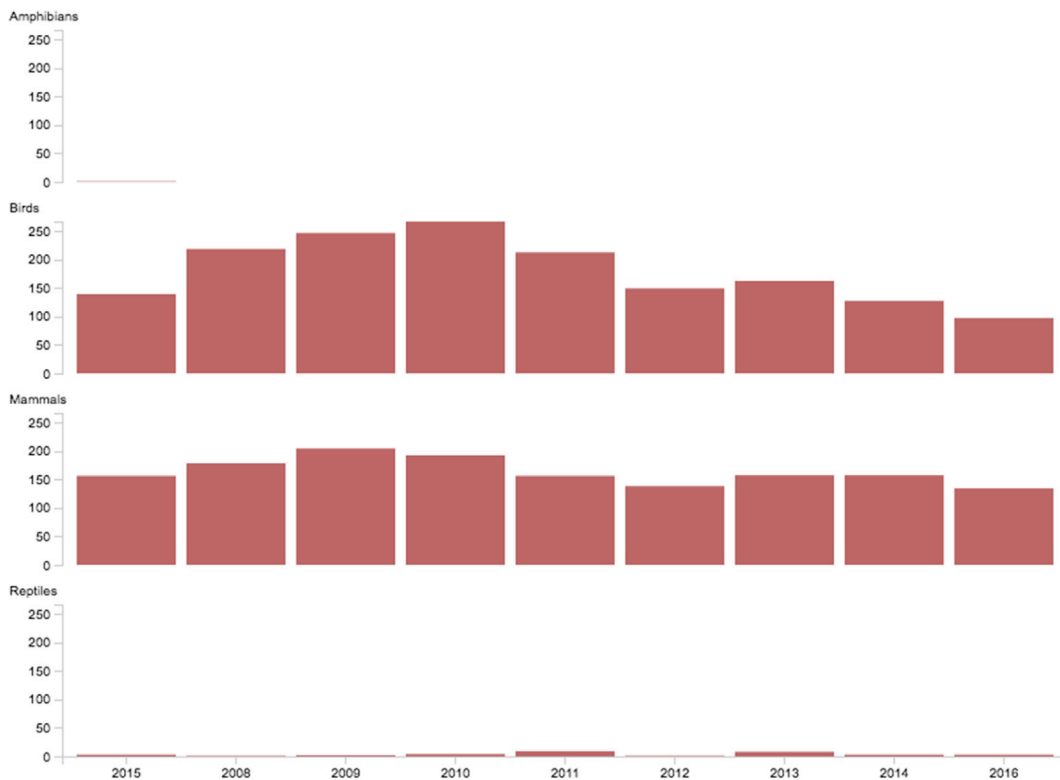


Fig. 14. Distribution of disease reports per animal classes in OIE WAHIS database for the period of 2008–2016.

Table 2

The ten most frequently reported diseases/infections for mammals as they are reported in OIE WAHIS-Wild Interface (asterisk sign indicates zoonotic diseases).

Rank	Disease/Infection
1	Infection with <i>Sarcoptes scabiei</i> /Sarcoptic mange*
2	Infection with <i>Pasteurella</i> spp./Pasteurellosis*
3	Infection with <i>Toxoplasma gondii</i> /Toxoplasmosis*
4	Infection with <i>Salmonella enterica</i> /Salmonellosis (<i>S. enterica</i>)*
5	Infection with <i>Yersinia pseudotuberculosis</i> /Pseudotuberculosis*
6	Infection with morbillivirus (canids and felids)*
7	Infection with <i>Leptospira interrogans</i> ssp.*
8	Listeriosis/Infection with <i>Listeria monocytogenes</i> *
9	Canine distemper
10	Infection with parvoviruses

Table 3

The ten most frequently reported diseases/infections for birds as they are reported in OIE WAHIS-Wild Interface (asterisk sign indicates the Zoonotic diseases).

Rank	Disease/Infection
1	Infection with low pathogenic avian influenza viruses/Low pathogenic avian influenza*
2	Infection with <i>Trichomonas</i> spp. in birds and reptiles/ <i>Trichomonas</i> sp.*
3	Infection with <i>Salmonella enterica</i> (all serovars)/Salmonellosis (<i>S. enterica</i>)*
4	Botulism*
5	Infection with <i>Pasteurella</i> spp./Pasteurellosis*
6	Infection with Pox viruses*
7	Avian pox
8	Infection with circoviruses/Circoviruses
9	Infection with <i>Yersinia pseudotuberculosis</i> *
10	Infection with <i>Plasmodium</i> spp.

reported). For mammals and reptiles, Italy with 439 and 15 reports respectively reported the most disease cases. For amphibians the only disease record reported in the nine years period was from the United Kingdom. For birds, the Netherlands reported the most disease occurrences with 307 reports (see [Supplementary Material G](#) for number of records submitted by countries as per mammals, amphibians, birds and reptiles).

3.7. OIE WAHIS-Wild records and CITES records

The disease reports in the OIE WAHIS-Wild database for the 2008–2017 period belong to a total 517 species and 108 of those species (57 bird species; 38 mammal species; 13 reptiles species) are subject to legal trade. The remaining 409 species doesn't have any trade record in the CITES database. We provided the list of all the 3131 disease reports according to individual species and indicated whether each species is subject to trade or not in [Supplementary File H](#).

4. Discussion

The international legal trade in live animals for commercial and personal use is a big and burgeoning business ([Baker et al., 2013](#); [Bush et al., 2014](#); [Harrington, 2015](#)). Our analysis of records within the CITES Trade Database shows that 11,569,796 individual live wild animals, representing 1316 different species were exported from 189 different countries between 2012 and 2016. This type of commercial trade activity is already recognised as a dangerous transmission pathway for zoonotic diseases ([Karesh et al., 2012](#)), and the OIE WAHIS-Wild interface contained a total of 82 zoonotic diseases/pathogens of mammals, amphibians, birds and reptiles causing 3131 disease cases in 54 countries during 2008–2016.

There are many complex multifaceted socio-economic, biological and ecological factors that influence a country's risk of transmitting zoonotic diseases of wild animal origin and its ability to respond to them ([Devitt, 2017](#)). The volumes of live wild animals traded between countries is only one of those important factors; yet a proper understanding of this particular trade dynamic is important and can help to direct limited resources (such as funds and expertise) currently available to prevent zoonotic disease outbreaks ([Karesh et al., 2005](#); [Pavlin et al., 2009](#); [Smith et al., 2009](#)). In this regard, our review of the CITES Trade Database identified a number of countries that warrant particular attention: China (the largest exporter of live mammals with 98,979 animals representing 58.7% of all such trade), Nicaragua (the largest exporter of live amphibians with 122,592 animals representing 53.8% of all such trade), South Africa (the largest exporter of live birds with 889,607 animals representing 39.2% of all such trade) and Peru (the largest exporter of live reptiles with 1,675,490 animals representing 18.8% of all such trade).

Our review showed that legal live animal trade is being mostly driven by high income countries included in the [WorldBank \(2018\)](#) and by western, educated, industrialised, rich and democratic countries that are referred as WEIRD countries in the

literature (for example [Henrich et al., 2010](#)) ([Supplementary Material C](#)). The USA was the biggest importer of live mammals legally (63,672 animals representing 62.4% of all such mammal trade between 2012 and 2016) and live amphibians (135,327 animals; 63.6% of such trade between 2012 and 2016). In fact, the USA is the global leader in illegal and legal wildlife consumption and between 2000 and 2009, more than 1.48 billion live animals were legally imported to USA where 92% of imports were for commercial purposes, largely the pet trade ([Smith et al., 2009, 2017](#)). Although the USA was second to Hong Kong with regards to legal live reptile imports, it still involved 1,275,892 individual animals and represented 14.3% of all such live trade between 2012 and 2016. The fact that Mexico, a non-WEIRD country, imported the most live birds legally (328,304 animals representing 32.7% of such live trade) is likely due to the fact that both the USA (following the Wild Bird Conservation Act) and the EU (in response to avian influenza) have opted to ban international imports in wild caught live birds since 1992 and 2007 respectively ([Cardador et al., 2017](#)).

Our review of the CITES Trade Database also provides insight into shifting patterns regarding how live wild animals involved in trade are being sourced. We found that the number of individual wild animals that were sourced from wild situations fell by 949,521 individual animals in 2016 representing 55.2% reduction in this type of trade globally compared to 2012. We also found that the number of individual animals that were sourced from captive situations decreased by 157,542 individual animals in 2016 representing a 13.2% decrease in this type of trade globally compared to 2012. The benefits and impacts of captive breeding for supplying commercial trade in wildlife on human health are both poorly understood and subject to debate (for example see [Ballou, 1993](#); [Kock et al., 2010](#); [Gerhold and Hickling, 2016](#)). On one hand, captive breeding at registered facilities provides relevant health authorities with an opportunity to better monitor the disease risks that this type of trade poses to the public both now and in the future. However, if managed poorly, captive breeding can also involve large numbers of animals in poor welfare conditions which are a likely source of zoonotic diseases (for example see [Ballou, 1993](#); [Kock et al., 2010](#); [Gerhold and Hickling, 2016](#)).

Our review of the OIE WAHIS-Wild interface demonstrated that from a taxonomic perspective birds were of most common human health concern as they featured in 1616 (51.6%) of zoonotic disease reports submitted during the period 2008–2016. Low pathogenic avian influenza was the most frequently reported disease among reports solely focussed on birds (235; 14.5%) and all reports (235; 7.5%) made during the study period. However, mammals were of almost equal concern as they featured in 1472 (47%) of disease reports submitted during this time. Infection with *Pasteurella* spp. was the most frequently reported disease among reports solely focussed on mammals (123; 8.4%).

The literature search revealed the global health risks posed by the international legal live trade in wild animal species both as pandemics, epidemics and outbreaks have received little research attention so far as our search methods identified only 28 relevant articles published since 1945. Previous research has shown that substantial risk of zoonotic diseases originate in areas where research effort is low, with the majority of surveillance effort focused on countries from which emerging infections were least likely to occur ([Jones et al., 2008](#)). Similarly, as our review of the OIE WAHIS-Wild interface showed, the disease reports of wildlife species available from the OIE reflect a similar pattern. We found that almost all of the disease reports were submitted by WEIRD countries –arguably due to higher reporting rates in such countries– and not from poorer parts of the world where arguably diseases and pathogens are more likely to occur (see [Jones et al., 2008](#) for in depth analysis).

4.1. Recommendations

4.1.1. Maximising trade bans

Rather than attempting to eradicate pathogens or the wild animals that harbour them, it has been suggested that efforts to decrease contact between wild animals and people could prove to be the most practical and cost effective approach in reducing the global human health threat posed by zoonotic diseases ([Karesh et al., 2005](#)). Consequently, from a policy perspective, trade bans have been proposed as a tool to help achieve these threat reduction goals. Arguably, the most prominent application of a trade ban was made by the EU on wild bird imports to prevent the spread of avian influenza ([McGrath, 2017](#)). However, a recent analysis of CITES Trade Database records has confirmed that, despite a sharp global decline in bird trade, new trade routes emerged that pose an on-going, and potentially increased, threat to human health ([Reino et al., 2017](#)). Therefore, although national and regional bans can curtail invasion risk globally, to be fully effective and prevent rerouting of trade flows, arguably bans should be global ([Reino et al., 2017](#)). However enforcing such bans will probably be a challenging endeavour.

Similarly, and again using the on-going EU ban on wild bird imports as a case in point, it is important to note that this particular trade ban did not extend to birds of captive bred origin. Wildlife farming is a growing industry ([Tensen, 2016](#)). The merits of such commercial captive breeding as a wildlife conservation tool are subject to debate (see [Tensen, 2016](#) for a comprehensive list of relevant articles). However, findings focused on the human health threat that such operations potentially pose have not featured prominently in these discussions to date. This is of particular concern given that evidence strongly suggests that in several cases many species reported to CITES as captive-bred are in reality taken from the wild (e.g. [Nijman and Shepherd, 2015](#); [Poole and Shepherd, 2017](#)) and that poorly managed commercial captive breeding facilities –where standardized risk management plans are needed– could provide the ideal environments to harbour the emergence of zoonotic diseases. Therefore, although national and regional bans can curtail invasion risk globally, to be fully effective and

prevent rerouting of trade flows, arguably bans should also incorporate individuals sourced from commercial captive breeding facilities that aren't inspected to be qualified for exemption by the local authorities.

4.1.2. Human behaviour change

Trade bans alone are unlikely to be effective in reducing the global human health threat posed by the commercial trade in live wild animals (TRAFFIC, 2008). For example, even when supported by a coalition of governmental institutions and non governmental organisations, such policy decisions have the potential to stimulate illegal wildlife trade activity and can run counter to the values of human equity and sustainable development (Reino et al., 2017) unless they are accompanied by associated human behaviour change initiatives focused on reducing the involvement and dependency of those involved in both purchase and sale. With regards to consumers, as Moorhouse et al. (2017) has shown, providing information on the health threats posed by exotic pets can play a significant role in affecting consumer attitudes. Therefore, human behaviour change initiatives focused on consumers in WEIRD countries could prove particularly pivotal in this regard. However, practitioners should be reminded of the basic assumption of knowledge-deficit theory and that is providing facts to people will translate into a change in behaviour, is rarely met in real-world (see Schultz, 2002; Simis et al., 2016; Can and Macdonald, 2018 for real-world examples). Since the demand for legal wildlife trade is parallel to demand for illegal trade (Wyler and Sheikh, 2008), reducing the demand for legal trade by affecting consumer attitudes in Western societies will also decrease the demand for the illegal trade. Reducing the demand for trade in the resource limited countries (non-WEIRD countries) through behaviour change remains to be a bigger challenge.

4.1.3. Improving regulatory efforts to improve worldwide surveillance

Trade bans are not always the preferred option for Governments and International Governmental organisations due to competing priorities such as income generation for local livelihoods (Rivalan et al., 2007). Although the human health risks associated with live animal trade can never be eliminated, proper pathogen surveillance focused on this type of international commercial activity is critical to protect global human health. At the international level, there is lack of integration in pathogen surveillance; efforts in less developed countries are either non-existent or focused on tiny areas relative to the worldwide distribution of animals (Kuiken et al., 2005).

To improve existing international surveillance efforts, Kuiken et al. (2005) proposed establishing a team of 10 international experts involving members from OIE, FAO, WHO and International Union for the Conservation of Nature (IUCN) and estimated that this would require a funding of \$5 million for the first three years. The 13 highest income countries (Belgium, France, Germany, Italy, Japan, Netherlands, Portugal, Qatar, Singapore, Spain, UK, United Arab Emirates, USA) that create the biggest demand for wildlife trade can lead the establishment of such intergovernmental body to work for better integration of surveillance efforts worldwide. This initiative could help to steer available resources to countries where large volumes of live wild animals are being sourced and sent to help prevent zoonotic virus spill over from wildlife to humans.

Monitoring efforts need to focus on animals (and people who handle those animals) coming from areas where research effort is low, such as tropical Africa, Latin America and Asia (Jones et al., 2008). Specifically, our study suggests that the 20 major countries, according to the size of live animal shipments they export, where early warning signs can be searched -via mandatory testing for pathogens-for are Benin, Cambodia (particularly for mammals), China (particularly for mammals and reptiles), Columbia, Cuba (particularly for birds), El Salvador (particularly for reptiles), Ghana (particularly for birds and reptiles), Indonesia (particularly for reptiles), Madagascar (particularly for amphibians), Nicaragua (particularly for amphibians), Panama (particularly for amphibians), Peru (particularly for reptiles), Philippines (particularly for birds), Singapore, South Africa (particularly for birds), Suriname, Togo, Uruguay (particularly for birds), Uzbekistan (particularly for birds and reptiles) and Vietnam (particularly for mammals and reptiles).

However, even in USA (where between 2000 and 2006, 80% of shipments contained animals from wild populations and a majority of these shipments had no mandatory testing) current regulations are inadequate to assess the risk of imported wildlife as hosts of harmful pathogens (Smith et al., 2009). Therefore relevant national strategies should be prepared and testing should be made mandatory for the countries that we identified.

4.2. Limitations of the study

We acknowledge a significant caveat in our study specifically about the legal trade records and their limitations. Available records on wildlife trade are problematic. Even in USA, trade records kept by the US Fish and Wildlife Service (arguably the world's most powerful and technically capable wildlife service) have limitations, particularly non-CITES-listed species are largely undocumented, meaning that the species that entered the country are not really known (see Smith et al., 2017 for details). When the species are not known, then the pathogens those species potentially carry cannot be inferred. Therefore the risks associated with live animal trade (including exotic pet trade) can neither be fully estimated nor eliminated. There is very sparse data for disease records and most of the countries have reported no diseases. However, absence of disease records isn't evidence of absence. Sparse records for diseases and absence of disease reports in OIE WAHIS-Wild records reflect the lack of effort in reporting the diseases by the countries. Moreover, with regards to particular trade chains, within the CITES trade records, there is not always a perfect match between reported quantities of exported animals by exporter countries and reported quantities of imported animals by importing countries. For example, for carnivores, there were a total of 938 CITES records but in 558 of these records, the importer countries didn't specify the quantity of animals they imported. Similarly, in

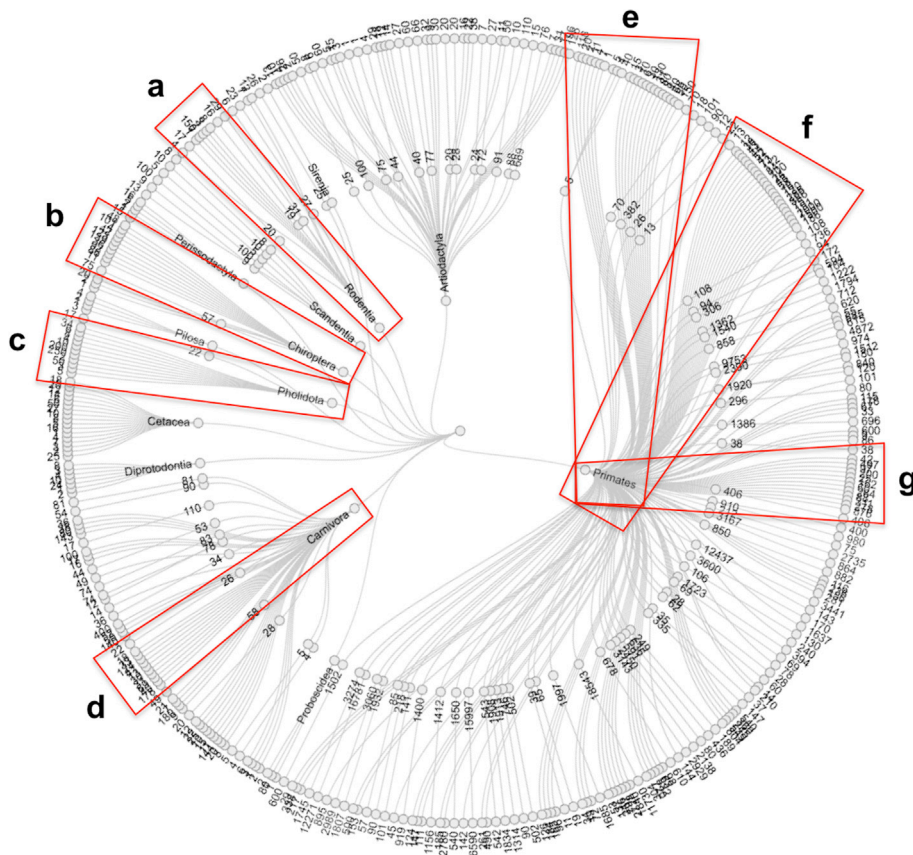


Fig. 15. The distribution of hierarchical clustering of trade records for mammals according to taxonomic Order for the period 2012–2016. On the diagram each CITES record is represented by a line originating from the centre going through two nodes: the inner node represents the quantity of trade reported by the exporting country, the outer node represent the quantity of trade documented as received by the importer country. The sections (a-Rodentia, b-Chiroptera, c-Pholidota, d-Carnivora, e, f and g-Primates) on the graph indicate the mammalian Orders where quantities from the exporter country were null.

220 out of 938 CITES records concerning carnivores, the exporter countries didn't specify the quantities of animals they exported. Similar paradoxes were apparent in mammal trade records (see Fig. 15) as well as for amphibians, birds and reptiles. The reason for such paradoxes might be explained by the fact that not all Parties submit complete reports or submits reports at all to the CITES Secretariat due to various reasons such as lack of personnel or resources (UNEP-WCMC, 2013). Finally, we recognise that another factor that would determine the risk the legal live animal trade pose to global health might not only be related with the number of animals traded (i.e. volume of trade) but it might be also related with how frequent the trade occurs. This remains to be an interesting question that can be investigated by further studies in the field by actually sampling from the shipments.

4.3. Conclusion

There are many reasons, linked to conservation, animal welfare and wider matters of ethics to be concerned about the regulation of wildlife trade, but amongst them the risks posed by pathogens (and of emerging zoonoses) should not be underestimated.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.gecco.2018.e00515>.

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