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Aligning conservation and public health goals to tackle unsustainable trade of mammals

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Abstract

Unsustainable wildlife trade is a major driver of biodiversity loss and an important public health threat. Yet, effective wildlife trade regulation is currently at odds with food security and economic incentives provided by this global, multibillion-dollar industry. Given such limitations, public health and conservation resources can be aligned to target species for which trade both increases risk of extinction and threatens public health. Here, we developed a simple conservation and health trade risk (CHT) index (range: 2–50) using a case study of traded mammals based on species' extinction and zoonotic risks, weighed by the extent of their trade. We applied this index to 1161 International Union for the Conservation of Nature-listed terrestrial mammals involved in the wildlife trade to identify 284 high-priority species that scored high in the CHT index (CHT ≥ 18). Species ranking high for conservation, public health, and trade risks include those belonging to the orders Primates, Cetartiodactyla (even-toed ungulates), Rodentia (rodents), Chiroptera (bats), and Carnivora (carnivores). Of the high-priority species, 33% ($n = 95$) are country-endemics and may be good candidates for trade regulations and enforcement at national scales. Our study provides a preliminary step in prioritizing species, taxonomic groups, and countries for focused wildlife trade regulation to meet both conservation and public health goals.

KEYWORDS

COVID-19, emerging zoonoses, human health, planetary health, wildlife trade regulation

1 | INTRODUCTION

The unsustainable consumption and trade of wildlife poses a significant threat to biodiversity and to human health. Overall, the wildlife trade affects nearly one-quarter of the vertebrate species on Earth, and in many cases is associated with increased risk of zoonotic pathogen spillover into human populations (Karesh et al. 2005; Scheffers et al. 2019; Wolfe et al. 2005). The coronavirus disease (COVID-19) pandemic, which evidence suggests originated from a wild animal host, demonstrated the immediacy and potentially extreme impacts of both the legal and illegal wildlife trade (Borzée et al. 2020; Shereen et al. 2020).

Despite these risks, both the legal and illegal wild animal trade remain lucrative industries with significant economic drivers (de Wit et al. 2022). The illegal wild animal trade is valued at up to US$2.1 billion per year, while the much larger legal wild animal trade has an estimated annual value of more than US$8.5 billion per year in 2012 (van Uhm 2016; World Bank 2019). Beyond overall value, each sector has important economic considerations: while the illegal trade is generally associated with economic loss associated with criminal activity, the legal trade generates revenue that could fund the sustainable trade of wildlife and can potentially mitigate its impact on threatened species and public health (Nellemann et al. 2014; van Uhm 2016; World Bank 2019). However, the international and regional agencies responsible for enforcing wildlife trade laws and regulations are significantly underfunded (Dobson et al. 2020), and as such even legal trade may be unmonitored and/or unsustainable (Fukushima et al. 2021; Marshall et al. 2020). For all these reasons, both reducing illegal wildlife trade and regulating legal trade are at odds with the economic interests of millions of people worldwide involved in these industries (Nasi et al. 2011; Sas-Rolfes et al. 2019).

Still, calls for restrictions and outright bans on all wildlife trade have been renewed in several countries in response to the COVID-19 pandemic (Borzée et al. 2020; Yang et al. 2020). However, blanket bans on the wildlife trade are likely to trigger negative downstream impacts for human health, conservation, and livelihoods, particularly given the economic drivers described above (Booth et al. 2020; Rivalan et al. 2007; Roe & Lee 2021). Instead, many have called for crackdowns on illegal trade coupled with tighter regulations on legal trade of species for which the trade is an immediate extinction threat (Scheffers et al. 2019) and for species likely to transmit zoonotic disease (Roe & Lee 2021; Shivaprakash et al. 2021). Currently, the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is the main instrument for regulating international legal trade of wildlife, despite notable shortcomings in applicability and efficacy (Wiersema 2018). Beyond and in supplement, successful wildlife trade regulation requires additional international cooperation to regulate trade through important trade routes, reliable enforcement at regional and local scales, and, crucially, alternative sources of income and food accessible to those who currently depend on unsustainable or illegal trade (Biggs et al. 2017; Cooney et al. 2017; Macdonald et al. 2013; Robinson et al. 2018). This framing has been the focus of the recent movement toward a planetary health or "One Health" approach, which considers the interconnectedness of human health and environmental sustainability in developing interventions to address unsustainable wildlife trade (Eskew & Carlson 2020; Scanlon 2021). While such considerable international and domestic policy instruments and livelihood programs are designed and necessary funding is acquired, short-term, taxon-specific efforts can focus on targeting species for which trade-associated risks warrant immediate action.

To address these short-term needs, some research has identified physiological traits and eco-evolutionary predictors of zoonotic reservoir status and heightened risk of transmission (Han et al. 2016; Olival et al. 2017), which can help prioritize species for wildlife market and trade regulation (Wikramanayake et al. 2021). Similarly, prioritization efforts in the conservation sector led by the International Union for the Conservation of Nature's (IUCN) Red List, focus on ranking species based on extinction threat. Given the potential overlap of species that are important for conservation and public health, combining these efforts could make efficient use of limited resources in both sectors.

Here, we use an existing conservation prioritization index and datasets from published literature to present a dual conservation and public health index determined by species' (1) conservation vulnerability and (2) potential to transmit zoonotic pathogens, using a case study of traded mammal species. We weighed this index by the extent of trade a species is the target of and identified key geographic regions that are important for endemic priority species. We consider this a simple tool that represents a first approach to combine existing threat metrics to leverage conservation and public health goals for mammals, and identify substantial data and research gaps that, if addressed, would improve its rigor and applicability. This tool provides a means to guide funding, research, advocacy, and policy toward species and regions with the greatest potential for both mammal conservation and public health gains.

2 | METHODS

We selected terrestrial mammals listed as "traded," in their IUCN Red List assessment, including those designated as "Terrestrial|Freshwater (=Inland waters)," "Terrestrial|Freshwater (=Inland waters)|Marine," and "Terrestrial|Marine," and identified 1201 mammal species listed as Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), and Least Concern (LC) (IUCN 2022). We constrained this study to terrestrial mammals because they are known as important reservoirs of zoonotic diseases and are relatively data-rich in comparison to other species (Cleaveland et al. 2001; Han et al. 2016; Olival et al. 2017; Woolhouse & Gowtage-Sequeria 2005); however, see (Kilpatrick et al. 2006).

2.1 | Index development

We developed the conservation and health trade risk (CHT) index based on three subcategories: (1) conservation vulnerability, (2) risk of zoonotic pathogen transmission (i.e., zoonotic risk), and (3) trade extent (international, national, subsistence, or a combination of these; Table 1).

The conservation vulnerability subcategory relied on the IUCN Red List designations, for which each designation was assigned a score: Least Concern and Data Deficient = 1, Near Threatened and Conservation Dependent = 2, Vulnerable = 3, Endangered = 4, and Critically Endangered = 5 (IUCN 2022).

For the second subcategory, we combined two variables associated with species' likelihood of being reservoirs of zoonotic pathogens. First, we used each species' phylogenetic proximity to humans, provided by Olival et al. (2017) in which values range from 0 to 1 and those species approaching zero represent species that are more related to humans, and thus have a higher likelihood of sharing pathogens with humans. Species-level phylogenetic proximity to humans was available for 206 species in our database. We found species-level phylogenetic proximity to humans to be highly and significantly correlated to family-level and order-level phylogenetic proximity to humans (species-to-family: $r = .97$, $p < .0001$; species-to-order: $r = .84$, $p < .0001$). Therefore, for the remaining species, we assigned the mean phylogenetic proximity to humans based on the taxonomic family ($n = 741$ species from 50 families), or the mean phylogenetic proximity to humans based on the taxonomic order ($n = 214$ species from 13 orders) when family information was not available. We excluded 40 species from the analysis due to lack of phylogenetic data. We subtracted

TABLE 1 The conservation and public health trade risk (CHT) index is composed of scores for three subcategories: The conservation vulnerability scores (International Union for the Conservation of Nature [IUCN] red list designations), the zoonotic risk scores (a measure of likelihood of zoonotic reservoir status), and the trade extent score (a categorical measure of the extent of trade)

CHT score	Conservation vulnerability	Zoonotic risk	Trade extent
5	Extremely high risk of extinction (e.g., CR and EN)	Belonging to an order that hosts a large proportion of zoonotic pathogens (e.g., Rodentia, Chiroptera, Primates) and is phylogenetically very close to humans (e.g., *Macaca* spp.)	Local subsistence, national and international trade
4	Very high risk of extinction (e.g., EN and VU)	Belonging to an order that hosts a large proportion of zoonotic pathogens (e.g., Chiroptera, Primates) and is phylogenetically close to humans (e.g., *Cercopithecus* spp.)	National and international trade, or only international trade
3	Moderate to high risk of extinction (e.g., VU and CD)	Belonging to an order that hosts zoonotic pathogens (e.g., Chiroptera, Primates, Cetartiodactyla) and is phylogenetically moderately close to humans (e.g., *Pteropus* spp.)	National trade and local subsistence
2	Moderate risk of extinction (e.g., CD and NT)	Belonging to an order that hosts a small proportion of zoonotic pathogens (e.g., Cetartiodactyla, Carnivora) and is phylogenetically not very close to humans (e.g., *Sus* spp.)	Only national trade
1	Low risk of extinction (e.g., NT and LC)	Belonging to an order that hosts a very small proportion of zoonotic pathogens (e.g., Cetartiodactyla, Carnivora) and is phylogenetically not close to humans (e.g., *Procyon* spp.)	Only local subsistence

Note: The CHT index is the sum of the conservation vulnerability and zoonotic risk scores multiplied by the trade extent score. A species with a relatively low conservation vulnerability score (e.g., it is not threatened), a low zoonotic risk score (e.g., hosts few zoonotic pathogens and is not phylogenetically close to humans) that is traded locally only, would score 2 ([1 + 1] * 1). A species with a high IUCN score (e.g., it is globally threatened), a high zoonotic risk score (e.g., hosts a large proportion of zoonotic pathogens and is phylogenetically close to humans) and is subject to local, national and international trade, would score 50 ([5 + 5] * 5). IUCN categories: CD, Conservation Dependent; CR, Critically Endangered; EN, Endangered; LC, Least Concern; NT, Near Threatened; VU, Vulnerable.

the phylogenetic proximity value from 1; thus, those species with phylogenetic proximity values closer to 1 have a higher likelihood of sharing pathogens with humans. Additionally, we assigned each species a value equivalent to the percentage of zoonotic viruses reported among species belonging to a given taxonomic order, reported by Johnson et al. (2020): Rodentia = 0.61, Chiroptera = 0.3, Primates = 0.23, Cetartiodactyla = 0.21, and Carnivora = 0.18, and 0.001 to the remaining 10 orders, assuming all other orders have a nonzero probability of hosting zoonotic pathogens. Finally, zoonotic risk was calculated by multiplying the values for species' phylogenetic proximity and taxonomic order. These values were then split into quintiles and assigned a score from 1 to 5, where species scoring closer to 5 are those that are phylogenetically similar to humans and host a high proportion of zoonotic pathogens (Table 1).

For the third subcategory which relates to trade extent, we reviewed the "use and trade" category description as detailed by the IUCN Red List assessment. Because we aimed to rank species by the extent of trade they were exposed to, we considered internationally traded species as more at risk of trade than nationally traded species, and nationally traded species more at risk than locally traded ones (Table 1). We reviewed the use and trade designation for the type of trade indicated and assigned scores from 1 to 5, where species which are subject to only local subsistence trade were assigned a value of 1, species subject to only national trade a value of 2, species subject to both national trade and subsistence trade a value of 3, species subject to national and international trade or international trade a value of 4, and species subject to all three types of trade a value of 5. We consider the trade extent score as a proxy for relatively greater potential for each of the other two subcategories (conservation vulnerability and zoonotic risk), under the assumption that species whose trade is more geographically widespread are subject to higher demand in greater quantities, pass through more populated areas, increasing the contact rate to humans and therefore the number of opportunities for pathogen spillover (Dezső & Barabási 2002; Kreuder Johnson et al. 2015; Miller et al., 2019; Morton et al., 2021). We used Pearson's correlation tests to test whether any of the three subcategories were correlated.

We calculated the overall CHT index by first summing the conservation vulnerability and zoonotic risk scores and then multiplying that sum by the trade extent score. Species for which the CHT was equal to or greater than the 75th percentile of all species' scores were classified as high-priority species. We chose the 75th percentile threshold to restrict this classification to species that rank at least moderately high for at least one of the conservation or zoonotic potential subcategories (≥3) and at least moderately high in the trade extent subcategory (≥3).

2.2 | Geographic distribution of high-priority traded species

We mapped the spatial distribution for the high-priority traded species to identify countries and regions where the

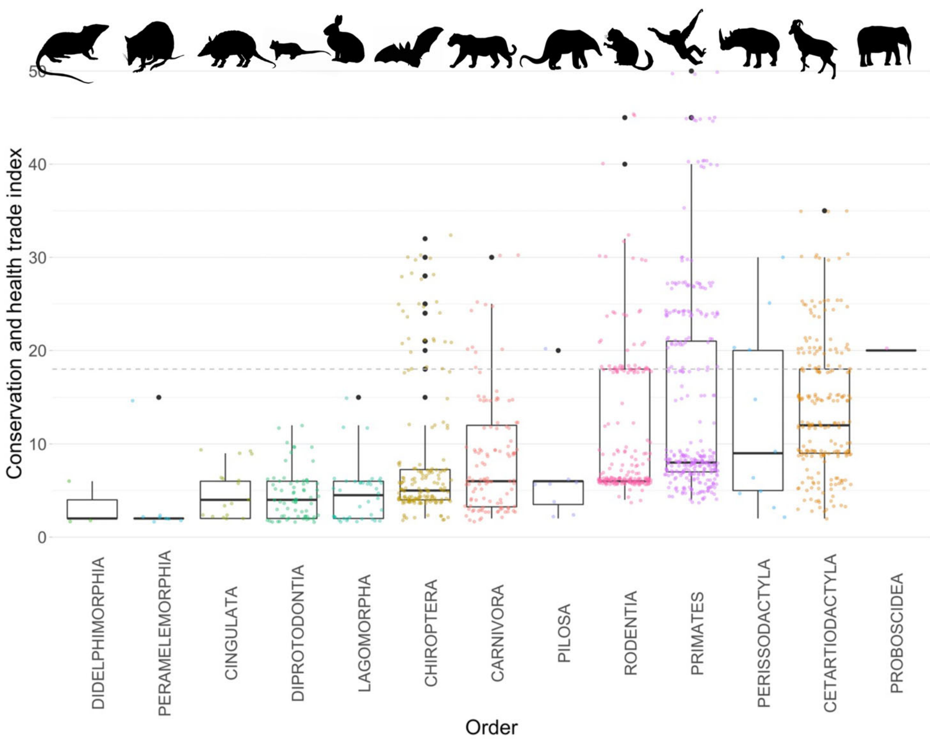

FIGURE 1 Combined conservation, public health, and trade risk (CHT) scores of species included in this study grouped by taxonomic order. The median of each taxonomic order's score is represented by the dark line, the colored and jittered dots represent the data, with black dots representing outliers. All icons are creative commons obtained from Phylopic.org; Didelphimorphia by Sarah Werning; Lagomorpha and Carnivora by Gabriela Palomo-Munoz; Pilosa by Roberto Díaz Sibaja; primate by Kai R. Caspar; Perissodactyla by Zimices; icons for Peramelemorphia, Cingulata, Diprotodontia, Chiroptera, Proboscidea, Rodentia, Perissodactyla, and Cetartiodactyla are all in the public domain

distributions of these species overlap. We used ArcGIS 10.3 to map species' distributions on a global grid of 10,000 km^2. Spatial information was obtained from IUCN Red List database (IUCN 2022).

3 | RESULTS

Of the 1201 traded species initially included in our analysis, complete information for the CHT index existed for 1161 species belonging to 13 taxonomic orders (Figure 1 and Supporting Data S1). Correlation tests did not identify strong correlations between any of the index subcategories ($-.1 < r < .1$). The CHT index ranged from 2 to 50 (median = 8, interquartile range = 10; Figure 1). A total of 284 species had CHT values at or above the 75th percentile (CHT ≥ 18) and were thus classified as high-priority, with high values closely reflecting species with high risk of extinction and high zoonotic risk (Figure 2 and Tables 2 and 3).

High-priority species belonged to eight taxonomic orders: Primates (n = 107), Cetartiodactyla (even-toed ungulates, n = 70), Rodentia (rodents, n = 59), Chiroptera (bats, n = 30), Carnivora (carnivores, n = 12), Perissodactyla (odd-toed ungulates, n = 4), Pilosa (anteaters, n = 1), and Proboscidea (elephants, n = 1; Figure 3 and Supporting Data S2).

3.1 | Geographic distribution of high-priority traded species

The native ranges of the 284 high-priority traded species were distributed throughout 202 countries, with the highest concentration of species found in China (n = 55), Indonesia (n = 52), India (n = 51), Vietnam (n = 47), and Thailand (n = 41; Figure 4). Of the 284 high-priority traded species, 33% (n = 95) of the species are country endemics, 12% (n = 33) are found in only two countries, 15% (n = 43) are found across three countries, and the remaining 40% (n = 113) are distributed in four or more countries.

4 | DISCUSSION

Here, we present a simple, index-based prioritization framework that researchers, decision-makers, and funders can draw on to minimize the impacts of unsustainable wildlife trade for both human health and biodiversity. We identified

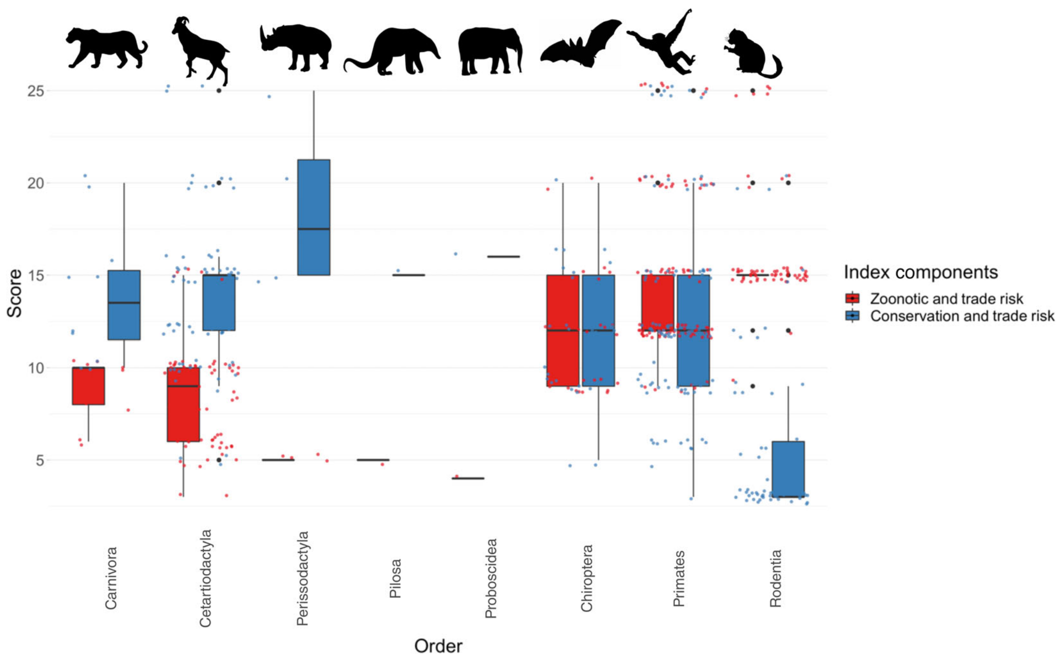

FIGURE 2 Zoonotic risk and conservation vulnerability scores weighed independently by trade extent. The median of each taxonomic order's score is represented by the dark line, the colored and jittered dots represent the data, with black dots representing outliers. Dotted line represents the 75th percentile, which was used to identify high-priority species. All icons are creative commons obtained from Phylopic.org; Carnivora by Gabriela Palomo-Munoz; Pilosa by Roberto Díaz Sibaja; primate by Kai R. Caspar; icons for Chiroptera, Proboscidea, Rodentia, Perissodactyla, and Cetartiodactyla are all in the public domain

TABLE 2 Top 20 high-priority species based on the conservation and public health trade risk (CHT) index score

Species	Order	Zoonotic risk score	Conservation vulnerability Score	Trade extent	CHT score
Macaca nigra	Primates	5	5	5	50
Pongo pygmaeus	Primates	5	5	5	50
Nomascus leucogenys	Primates	5	5	5	50
Pygathrix nemaeus	Primates	4	5	5	45
Rhinopithecus strykeri	Primates	4	5	5	45
Trachypithecus francoisi	Primates	5	4	5	45
Hylobates abbotti	Primates	5	4	5	45
Marmota sibirica	Rodentia	5	4	5	45
Crateromys schadenbergi	Rodentia	5	4	5	45
Cercopithecus roloway	Primates	4	5	5	45
Indri indri	Primates	4	5	5	45
Piliocolobus waldroni	Primates	4	5	5	45
Pygathrix nigripes	Primates	4	5	5	45
Trachypithecus shortridgei	Primates	4	4	5	40
Zyzomys pedunculatus	Rodentia	5	5	4	40
Daubentonia madagascariensis	Primates	4	4	5	40
Nycticebus bengalensis	Primates	4	4	5	40
Macaca arctoides	Primates	5	3	5	40
Ateles fusciceps	Primates	4	4	5	40
Nasalis larvatus	Primates	4	4	5	40

284 mammal species that are high-priority and can be protected through immediate conservation, public health, and trade regulation efforts. We also contextualize patterns in high-priority taxa and regions, discuss the primary drivers of their trade, and provide recommendations for action that the public health and conservation sectors can take to ameliorate the potential conservation and public health impacts of wildlife trade for these high-priority species.

4.1 | Species, regions, and countries of high priority

The 284 species identified here as high-priority for both conservation threat and zoonotic risk were dominated by five orders: nonhuman Primates, Cetartiodactyla (even-toed ungulates), Rodentia (rodents), Chiroptera (bats), and Carnivora (carnivores). From the perspective of zoonotic risk, these findings are in line with previous research on pathogen spillover: in particular, rodents, primates, and some species of bats have been associated with over 75% of zoonotic viruses reported thus far (Johnson et al. 2020), potentially due to some of these species phylogenetic proximity to humans (e.g., primates; Olival et al. 2017) and to their adaptation to human-modified landscapes (e.g., rodents and bats; Gibb et al. 2020). Wild ungulates and carnivores are known pathogen reservoirs, with 32% and 49% of the species in these groups hosting zoonotic pathogens, respectively (Chen et al. 2015; Di Marco et al. 2014; Han et al. 2016; Martin et al. 2011). Further, both these groups have greater spatial extent than bats and primates, increasing potential overlap with human communities (Han et al. 2016). Last, many of the species we identify are sometimes or often consumed as food, which can further increase the risk of zoonotic pathogen transmission, particularly for species that host blood-borne pathogens and for which butchering, handling, and cooking of meat is conducive to greater exposure to these pathogens (Wolfe et al. 2005). From the conservation perspective, major conservation threats (in addition to unsustainable wildlife trade) to members of all these orders—namely, disease, habitat loss, and pollution—are broadly established

TABLE 3 High-priority species grouped by family and order ($n = 284$)

Order	Family	No. of species	CHT index range
Carnivora	Ailuridae	1	30
	Mustelidae	3	20–30
	Otariidae	2	20–25
	Ursidae	2	20–25
	Felidae	3	24–18
	Phocidae	1	18
Cetartiodactyla	Bovidae	44	18–35
	Moschidae	6	24–30
	Hippopotamidae	2	18–25
	Cervidae	8	18–25
	Tayassuidae	2	18–25
	Giraffidae	2	18–25
	Suidae	4	18–24
	Camelidae	1	21
	Tragulidae	1	18
Chiroptera	Pteropodidae	29	18–32
	Rhinolophidae	1	21
Perissodactyla	Rhinocerotidae	1	30
	Tapiridae	2	20–25
	Equidae	1	20
Pilosa	Myrmecophagidae	1	20
Primates	Cercopithecidae	69	18–50
	Hominidae	1	50
	Hylobatidae	14	24–50
	Indriidae	1	45
	Daubentoniidae	1	40
	Lorisidae	4	18–40
	Atelidae	6	18–40
	Pitheciidae	2	21–27
	Lemuridae	5	18–24
	Lepilemuridae	1	24
	Cheirogaleidae	1	24
	Tarsiidae	1	18
	Callitrichidae	1	18
Proboscidea	Elephantidae	1	20
Rodentia	Sciuridae	27	18–45
	Muridae	11	18–45
	Nesomyidae	4	18–32
	Capromyidae	1	30
	Caviidae	3	18–30
	Spalacidae	1	30
	Castoridae	1	30
	Erethizontidae	1	24
	Hystricidae	3	18–24
	Dasyproctidae	2	20–21
	Cuniculidae	1	18
	Dipodidae	1	18
	Echimyidae	1	18
	Gliridae	1	18
	Anomaluridae	1	18

(Continues)

TABLE 3 (Continued)

Abbreviation: CHT, conservation and public health trade risk.

and these taxa have been the primary focus of multiple conservation organizations around the world (Estrada et al. 2017; Frick et al. 2020).

However, our findings build on these existing risk prioritization schemes to point taxonomic groups that are important for conservation and public health but are currently overlooked by either or both of these fields. In some cases, as for the high-scoring Bornean orangutan (*Pongo pygmaeus*, CHT = 50), giraffe (*Giraffa camelopardalis*, CHT = 25), tiger (*Panthera tigris*, CHT = 24), and Asian elephant (*Elephas maximus*, CHT = 20), global attention already exists concerning their conservation—though perhaps less attention is given to their zoonotic risk. In other cases, our index points to less "charismatic" species which may receive less attention and investment from the conservation and public health communities (Davies et al. 2018; Fisher 2011; Sitas et al. 2009). For example, rodents make up 20% of the high-priority species we identify. In particular, many of the highest-scoring rodents were relatively large-bodied species, like the Tarbagan marmot (*Marmota sibirica*), the giant bushy-tailed cloud rat (*Crateromys schadenbergi*), and the Ruatan Island agouti (*Dasyprocta ruatanica*). These results suggest that rodents, particularly large-bodied ones which may be more attractive to traders (Scheffers et al. 2019), are just as important as other "charismatic" orders like primates and ungulates in terms of achieving conservation and public health goals and should not be overlooked. Finally, the identification of these 284 high-priority species should also bring attention to the taxonomic families they belong to and other related groups, as the international wildlife trade is likely to impact multiple species of the same family sequentially, following the extirpation of individual species (Scheffers et al. 2019).

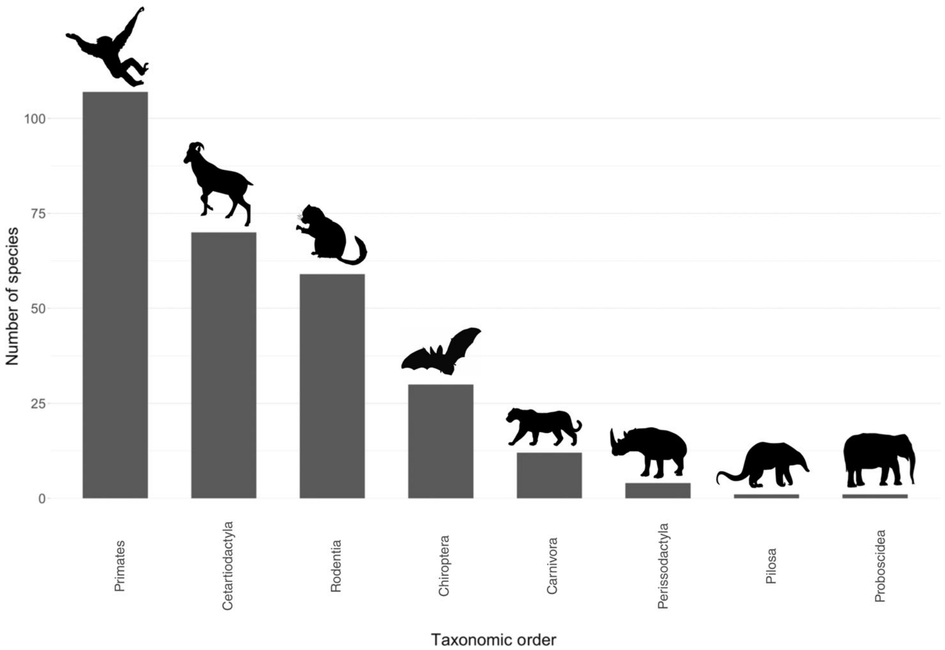

FIGURE 3 Number of high-priority species based on the conservation and public health trade risk index, grouped by taxonomic order. All icons are creative commons obtained from Phylopic.org; Carnivora by Gabriela Palomo-Munoz; Pilosa by Roberto Díaz Sibaja; primate by Kai R. Caspar; icons for Chiroptera, Proboscidea, Rodentia, Perissodactyla, and Cetartiodactyla are all in the public domain

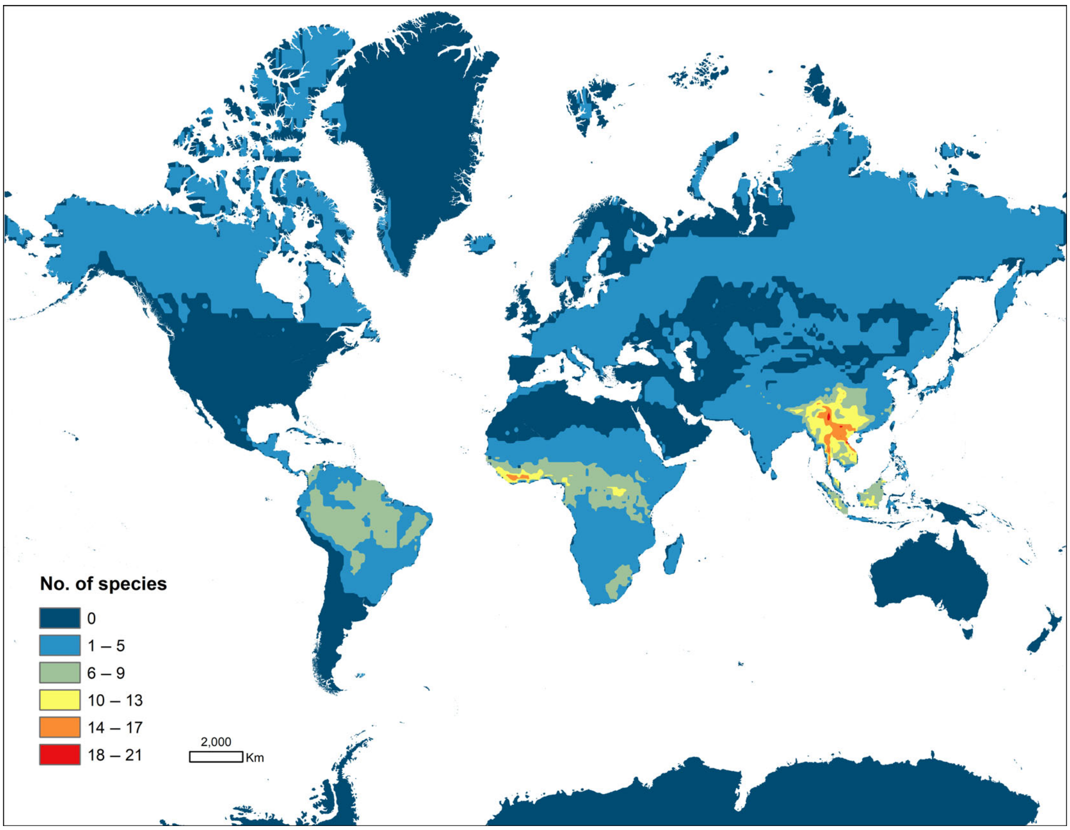

FIGURE 4 Global distribution of the 284 high-priority traded mammal species. Colors represent the number of species per 10,000 km^2 grid cell

To help concentrate effort in geographies with potentially high reward, we identify geographic hotspots for high-priority species. Our analysis shows that the native ranges of the 284 high-priority traded species are mainly distributed within tropical and subtropical regions and that nearly a third (33%) of these species are endemic to a single country, highlighting a potential opportunity for substantial conservation and public health gains from country-specific interventions for these species (Supporting Data S3). Of particular relevance are China and Indonesia, which contain 55 and 52 of the endemic high-priority traded species we identify here, respectively. It is notable that most countries with 10 or more high-priority species are low-income and middle-income countries located in Asia, South America, and Africa, some of which may lack resources and capacity for effective enforcement of wildlife trade regulations (Polner & Moell 2016; Fukushima et al. 2021). In such cases, efforts to reduce wildlife trade could involve developing alternative livelihoods and incentives for wildlife stewardship (Biggs et al. 2017). In addition to developing socioeconomic substitutions for trade of these species, conservation interventions including the establishment of new protected areas and the enforcement of existing spatial conservation strategies in these areas can reduce human–wildlife interactions, bringing the added benefit of reduced pathogen spillover to humans (Sokolow et al. 2019).

4.2 | Trade for high-priority species

We considered in our analysis whether trade was driven by local subsistence, national, or international markets (or a combination of these), according to IUCN Red List designations (Table 1). This distinction rests on the assumption that international trade is more likely than national or local trade to drive higher demand for wildlife (e.g., greater conservation impact) and greater potential for pathogen spillover (e.g., greater number of people involved in trade and therefore opportunities to transmit pathogen). At least in very broad terms, there is some research to support the fact that internationally traded species are subject to greater conservation threats: they are often traded in large quantities, are subject to higher demand (Miller et al. 2019), and are experiencing more severe declines than locally traded species (Morton et al. 2021). There is also evidence that larger globalized trade routes are more likely to facilitate pathogen transmission as they access more densely populated transportation hubs (Dezső & Barabási 2002). However, this assumption has not been empirically tested, and further research should seek to understand the differential role of trade extent and scale on both conservation vulnerability and zoonotic risk to inform future prioritization efforts.

Further, these distinctions are important for the implications of this study, as trade regulations targeting species that are locally consumed for subsistence, particularly in low-income countries, have fueled debate over potential unintended socioeconomic consequences for other aspects of human well-being (i.e., nutrition and food security) (Booth et al. 2021; Roe & Lee 2021). It has been widely established that much of the international trade for wildlife products is driven by markets for pets, entertainment, luxury items, research, and "exotic" meats (e.g., luxury primate meat trade from Africa to Europe [Chaber et al. 2010; Scheffers et al. 2019]). Until better information is available about the differential impacts of local versus national or international trade on conservation and disease risks, we suggest that trade regulation efforts that focus on high-priority species traded for luxury items can meet conservation and public health goals with less risk to food security. For those species hunted for subsistence which are still high-priority for conservation and public health, we suggest that trade regulation interventions should be context-specific and location-specific and consider the type of demand, lest they negatively impact food security. Broadly, some research has suggested that these efforts can be subsidized or incentivized by wealthy countries, given the fact that the global wildlife trade generally flows from poor countries to rich countries (Liew et al. 2021).

A closer examination at the high-priority species we identify suggests that some species are traded for multiple different and sometimes overlapping reasons, and that the local-national-international delineation may be too simplistic to account for spectrum of drivers associated with the wildlife trade (e.g., Figure 5). For example, the trade in primate species we identify here is highly variable across geographic locations, yet the primary drivers of demand are for the live pet, entertainment, and biomedical research industries (Nijman et al. 2011; Norconk et al. 2020). However, some primates are legally or illegally hunted for their meat (Estrada et al. 2017) or in conflict with agriculture (Azhar et al. 2012). Rodents are generally traded internationally as pets, furs, and for human consumption (Huong et al. 2020; Lankau et al. 2017), whereas bats are generally traded for human consumption (Shivaprakash et al. 2021). Ungulates and carnivores are frequently traded live or for their parts like pelts, horns, bones, and as trophies (Chen et al., 2015; Di Marco et al. 2014; Harrington 2015). Complicating things further, different wildlife parts have different associated zoonotic risks—for example, live animals are often more likely to transmit pathogens than dried hides or bones (Kruse et al. 2004). These multiple and diverse drivers and risks, which are excluded from this analysis, underscore the importance of, and challenges associated with, improving understanding of fine-scale drivers of the illegal wildlife trade. Investigating and characterizing the drivers of trade, particularly in those regions and countries we identify with high concentrations of high-priority species, is an important first step that could help guide funding for trade regulation and enforcement, as well as evaluate the fairness of any proposed regulatory policy.

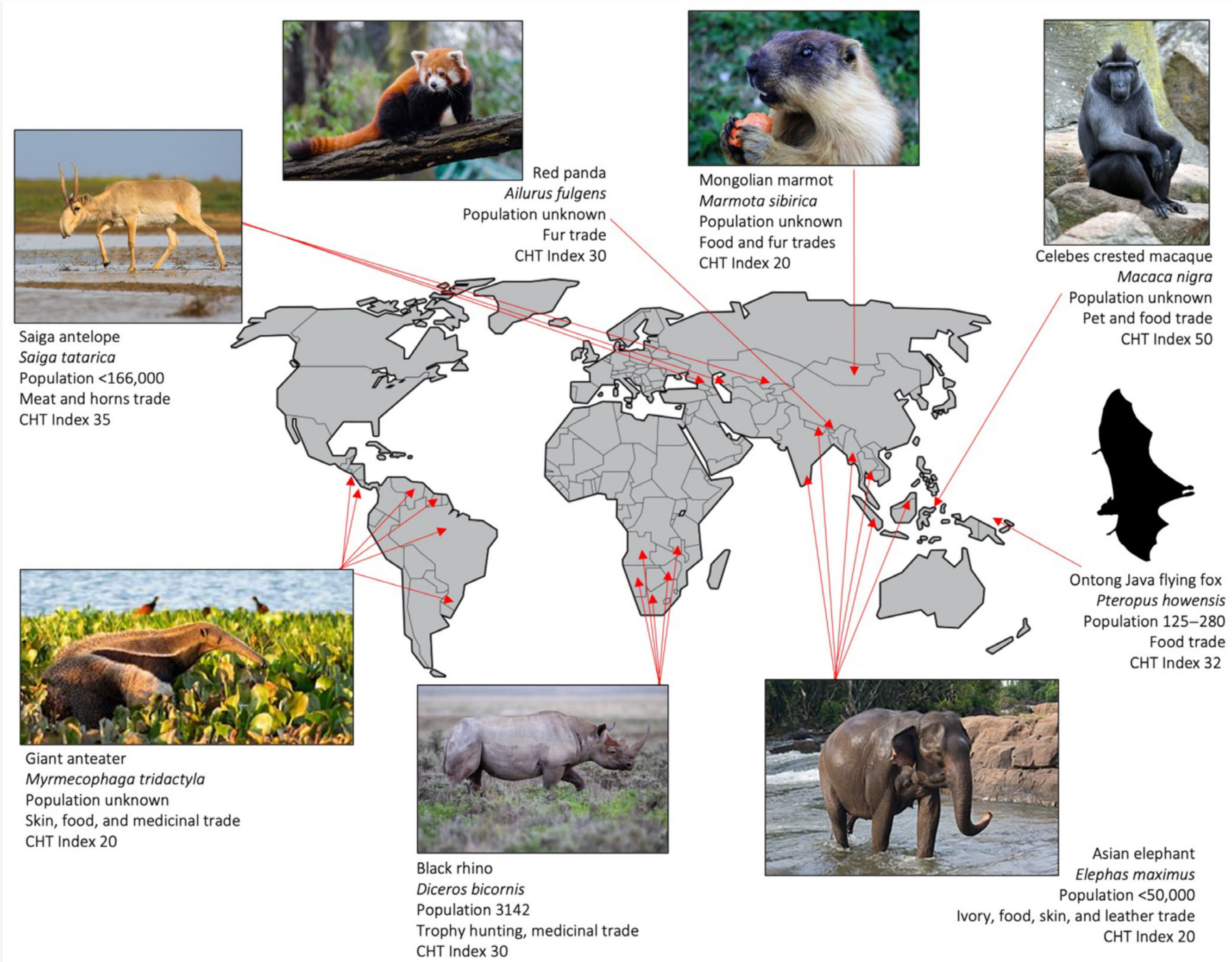

FIGURE 5 Top high-priority traded species from the representative taxonomic orders. Population estimates and threats are as listed by the IUCN red list. Photographs: *Macaca nigra* by Tim Strater, *Myrmecophaga tridactyla* by Fernando Flores [CC BY-SA 2.0 licenses], *Diceros bicornis* by Yathin S Krishnappa, *Marmota sibirica* by Stéphane Magnenat [CC BY-SA 3.0 licenses], *Elephas maximus* by Basile Morin, *Saiga antelope* by Andrey Giljov [CC-BY-SA-4.0 license], *Ailurus fulgens* by Mathias [Appel CC0], *Pteropus howensis* from Phylopic.org. CHT, conservation and public health trade risk; IUCN, International Union for the Conservation of Nature

4.3 | Limitations and data needs

The CHT index is meant to provide an initial step at identifying species of dual conservation and public health concern; however, the classification we provide here is constrained by data limitations at all levels. In particular, data was limited for 40 species' phylogenetic proximities to humans, leading to the exclusion of several potentially high-priority taxa, and the zoonotic risk data we used is specific to viruses, excluding other pathogens (Johnson et al. 2020). Thus, the 284 high-priority species here are likely to be species with better published biological information relative to those that were excluded. The development and release of more complete datasets for each of these data sources would allow for the inclusion of more species in this analysis. Similarly, reliable fine-scale information on markets and trade routes for high-priority species is not currently available from IUCN Red List designations, limiting the ability of this analysis to identify patterns in trade drivers. One short-term remedy for this data gap is the collection and addition of more specific trade driver information to be included in the IUCN Red List categorizations for high-priority traded species, which would help contextualize these results and inform trade regulations that are tailored to specific markets and drivers. Additionally, the application of this work to include other nonmammal taxa involved in unsustainable wildlife trade, particularly birds and reptiles, would allow for a fuller prioritization framework (Kilpatrick et al. 2006).

Further, species listed as Data Deficient by the IUCN Red List were scored low in the CHT index; however, there is building evidence that many Data Deficient species are highly threatened (Bland et al. 2014; Morais et al. 2013). This is particularly true for bats, which ranked high for our index and have a higher proportion of species listed as Data Deficient than other mammals (Frick et al. 2020). Further research should investigate and prioritize data-poor species using methods that are more robust to missing data (e.g., bootstrapping to simulate missing data points). A risk assessment framework could also be useful to identify understudied but potentially high-scoring species for which precautionary management is needed given poor data availability (Wassénius & Crona 2022). Finally, the classification of species as high-priority is relative to other species' CHT score, thus, the CHT index might change depending on the pool of species evaluated, and high-priority species should be reassessed under scenarios in which species are reclassified by the IUCN-Red list.

In addition to conservation classifications, considering a broader diversity of pathogens is a natural next step for research. While viruses (particularly RNA viruses) represent a large proportion of the recent pandemics and epidemics that have emerged in the past century, the emergence of zoonotic pathogens from other groups like bacteria, protozoa, and fungi has had and could have important public health consequences in the future (Christou 2011; Woolhouse & Gowtage-Sequeria 2005). Thus, as more data for other pathogen groups become available, future efforts to align conservation and public health goals could seek to prioritize other types of pathogens.

Beyond data limitations, we focus this study broadly on species involved in the wildlife trade, rather than on potentially high-risk locations like “wet” markets where live animals are sold and where the COVID-19 virus may have originated (Worobey et al., 2022). While this approach may omit the high-risk setting of wet markets, sufficient evidence suggests that wildlife trade, collection, handling, and transport are associated with risk of disease transmission, both at the point of capture and of destination (Borsky et al. 2020; Rosen & Smith 2010). We suggest this study as a companion to others that have investigated the utility of regulating the trade of wildlife at wet markets to reduce the risk of zoonotic pathogen transmission (Aguirre et al. 2020; Wikramanayake et al. 2021).

Finally, it is important to emphasize that because of these limitations, the index we present here contains substantial uncertainty. While uncertainty is pervasive and unavoidable in many conservation and management prioritization settings, novel quantitative approaches can help minimize uncertainty and should be explored in future efforts (Johnson & Gelder 2019; McCarthy 2014; Wassénius & Crona 2022). Given this uncertainty, we suggest that this type of cross-discipline prioritization approach could be refined and improved upon for other sectors interested in achieving mutual goals within a planetary health framework.

4.4 | Conservation and public health efforts

Incremental progress toward more sustainable and safer wildlife trade is more likely to reduce species' extinction vulnerability and zoonotic potential than bans with inadequate compliance and enforcement (Ribeiro et al. 2020). This study provides a first step toward prioritizing traded species, taxonomic groups, and countries for which the conservation and public health sectors can simultaneously meet urgent goals. Our findings support the targeted focus of conservation and public health efforts for 284 high-priority species, with particular emphasis on geographic regions and countries with high concentration of these species. To minimize the impact of unsustainable wildlife trade on these high-priority species, mitigation efforts can focus on reducing illegal trade and ensuring that legal trade regulations are properly set, monitored, and enforced. For those high-priority species not listed on CITES; listing efforts would help increase trade data so that the full impact of their trade can be assessed.

Our study also supports current efforts to build upon and reform existing wildlife trade laws and create new international agreements (e.g., CITES, the Convention for Biological Diversity). Overall, modifications to existing national and international regulations, increased data collection and transparency, and greater scrutiny and enforcement of trade measures could address the risks posed to and by the species we identify here. These recommendations must be linked to interventions and incentives in the global food and economic systems as well as education campaigns about the impacts of unsustainable wildlife consumption. Given current global attention and interest in reducing the risk of emerging infectious diseases, the identification of high-priority wildlife taxa and locations presents unique opportunities for simultaneously preventing biodiversity loss and future pandemics.

AUTHOR CONTRIBUTIONS

All authors contributed equally to the design, analysis, and writing of this article.

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CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

All data used in this study are available in supplementary files.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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