ANNUAL REVIEWS

Annual Review of Environment and Resources

The Harvest of Tropical Wildlife for Bushmeat and Traditional Medicine

Tien Ming Lee,[1] Amanda Sigouin,[2] Miguel Pinedo-Vasquez,[3,4] and Robert Nasi[5]

[1]State Key Lab of Biological Control, School of Life Sciences and School of Ecology, Sun Yat-sen University, Guangzhou 510275, China; email: tienminglee@gmail.com

[2]Center for Biodiversity and Conservation, American Museum of Natural History, New York, NY 10024, USA

[3]Earth Institute and International Research Institute for Climate and Society, Columbia University, New York, NY 10027, USA

[4]Earth Innovation Institute, San Francisco, California 94111, USA

[5]Center for International Forestry Research, Bogor 16115, Indonesia

Annu. Rev. Environ. Resour. 2020. 45:145–70

First published as a Review in Advance on July 6, 2020

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-102016-060827

Keywords

nutritional security, wildlife trade, sustainability, urbanization, rural livelihood, cultural value, zoonotic diseases, extinction, poverty

Abstract

Bushmeat is not only an important source of fat, micronutrients, and macronutrients, but it also has medicinal uses. Extensive human–wildlife interactions may lead to pathogen exchange and trigger zoonotic infectious disease outbreaks such as severe acute respiratory syndrome, Ebola, and coronavirus disease 2019. In the tropics, bushmeat has become one of the most threatened resources due to widespread habitat loss and overexploitation, largely driven by increased global demand, weak governance, and lack of enforcement. Unsustainable harvesting, consumption, and production practices are common, although drivers are complex and intertwined and vary regionally, pointing to a looming rural nutrition security and wildlife conservation issue. Growing demand in fast urbanizing markets coupled with easy access fuels the illegal trade of bushmeat, medicinal products, and wildlife-based luxury goods. Although bushmeat contributes significantly to rural people's income and poverty alleviation, overharvesting impacts those who are most dependent on the forest. To balance the rural and cultural

importance of bushmeat with conservation and public health priorities, strategies to safeguard tropical biodiversity, sustainable harvest of wildlife with reduced health risk for nutrition and medicine are urgently needed.

Contents

1. TWO WILDLIFE PRODUCT USES AND THE GLOBAL CRISES

Bushmeat: meat taken from any animal native to forests

Livelihood: a means of supporting one's existence, particularly financially

Wildlife continues to be an important source of protein, nutrition, and traditional medicine across the tropics (1–6). However, wildlife has become one of the most threatened resources due to widespread habitat loss, overexploitation, and other factors (1, 2, 7). Unsustainable harvesting practices are common, although drivers are complex and intertwined, pointing to a looming rural nutrition security and wildlife conservation issue (8). Sustaining bushmeat consumption becomes critical for biodiversity conservation and poverty alleviation, particularly in tropical developing countries. Because wildlife conservation issues are closely tied to traditional livelihood sustainability, it becomes necessary to assess bushmeat sustainability and its feedback on traditional livelihood over time.

The effects of market forces and trade, which have a narrow goal of rural livelihood sustainability, on sustainable consumption are also not widely understood (9). Due to the growing threat

of emerging infectious disease outbreaks with increasing wildlife contacts that may directly or indirectly impact livelihood sustainability, there is an urgent need to consider it (5). As such, ensuring the sustainable harvesting of bushmeat and medicinal products is imperative for halting further loss of biodiversity, improving rural livelihoods and enhancing rural people's health and nutritional and food security, and lowering public health risks.

1.1. Wildlife in Multiple Value Chains

In this section, we illustrate the importance of tropical wildlife as a source of protein, nutrition, and livelihood, as well as traditional medicine. We also highlight that due to widespread unsustainable exploitation, the dwindling of this valuable resource is intimately connected to present bushmeat, biodiversity, nutritional security, and public health crises worldwide.

1.1.1. Protein, nutrition, and livelihood. Humans throughout the world have long depended on wild meat as a source of food and medicine (1–3). Wildlife is important in both the developed and developing world for its consumptive and nonconsumptive uses, present and potential nutritional value, medicinal uses, luxury uses, ecological role, and sociocultural significance for human societies (4, 5). Bushmeat is not only an important source of fats, micronutrients, and macronutrients, but it also has medicinal uses, particularly in the tropics (5). For example, in the diets of urban and peri-urban inhabitants within the Tres Fronteras Amazonian region, households consuming bushmeat take in higher levels of micronutrients such as iron, zinc, and vitamin C than households that do not, and hence are at a lower risk of anemia in the near term and other chronic health problems in the long term (10).

The harvest of animals also provides benefits to local people and their livelihoods worth millions of dollars annually and represents approximately 6 million tons of animals extracted yearly (11). Millions of the poorest people in the tropical world are almost entirely dependent on forests for their household income, making forest resources some of the most important sources of income security. For many, the income from forest products, including game or bushmeat, can be substantial. In Asia, for instance, forest product income represents a significant revenue source for rural people, with an average contribution to household income of approximately 20% in the populations sampled (12). The contribution of bushmeat to cash and noncash income of local communities within managed Sangha Tri-National and Dja-Odzala-Minkebe Tri-National forest landscapes in Central Africa illustrates how crucial it is for livelihoods (13). As such, wildlife is a critical source of food and income for rural people in the tropics.

1.1.2. Traditional medicine. Traditional medicine derived from wildlife products is deep-rooted in many cultures across the tropics, which have been harvesting many species for thousands of years. Wild animals are particularly crucial to the culture of rural people, who use animals in religious festivals and traditional medicines (6). The use of animals (e.g., birds, primates, and reptiles) is common as a major source of local medicine for people's well-being in tropical rural and urban areas. For instance, researchers study the medicinal purposes, body parts used, and cost of medicinal animal species traded and used in traditional medicine in Brazil, Vietnam, and Nigeria (6, 14, 15).

Certain countries such as Mauritius possess valuable knowledge on a plethora of animal-based therapies used in the treatment and/or management of human diseases (e.g., 31 animal species belonging to 12 taxonomic groups were used in traditional medicine) (16). Also, at least 130 species are known to be sold for medicinal purposes and used to treat more than 100 illnesses and/or symptoms in Brazil, including species that are endangered (17). In Amazonia, many ethnic and traditional communities are primarily dependent on the traditional medicinal system for their

primary health care, particularly for natives living adjacent to protected and extractive areas [e.g., Northern Brazil (18)]. Therefore, rural people in the tropics also depend on wildlife for medicine.

Zoonotic: any disease of animals communicable to humans

1.2. The Crises: Bushmeat, Biodiversity, Nutritional Security, and Public Health

However, as currently practiced, bushmeat harvesting and consumption have become mainly unsustainable across the tropics, and numerous crises are developing simultaneously. Rural people rely heavily on wild meat, but in many areas, this vital source of food and income is being depleted (1, 7). Due to the widespread unsustainable exploitation of wildlife, the challenges of conservation and the unsustainable use of wildlife-based resources have led to the global bushmeat crisis (2). Comparing two main tropical moist-forest regions, the Amazon and Congo basins, it was estimated that more than 5 million tons of wild mammal meat feed millions of local people in Neotropical and Afrotropical forests annually. The current state of bushmeat extraction in African rainforests, however, is unsustainable and will only get worse (19). On the basis of model projections, even if bushmeat harvests could be sustainable in the Congo Basin, many of its countries would still be greatly affected by the resulting lower wild protein supply. To exacerbate issues, nonbushmeat protein options cannot meet the projected shortfall and are insufficient to feed most of these populations. Therefore, it is likely that many forest mammals could become extinct soon and that protein malnutrition will increase if nutritional security in the region is not urgently addressed (20).

The bushmeat crisis is also a food security issue across the tropics, given that protein and nutrition from bushmeat and rural livelihoods are intrinsically linked. The current bushmeat crisis is tightly coupled with the tropical biodiversity crisis and requires immediate action (**Figure 1**). Unless there is a drastic change to make wildlife exploitation, including for luxury (nonessential) products, more sustainable, the tropics will most certainly lose most of its iconic species, and many others, in the coming decades (8). Because of our close interactions with wildlife, the emergence and spread of zoonotic infectious diseases and epidemics may escalate into public health crises [including Ebola and severe acute respiratory syndrome (SARS)] (5). Addressing the multiple crises will likely involve a multidisciplinary strategy, including political, socioeconomic, and scientific input, to which all major stakeholders (government, nongovernment, national, and international organizations) must contribute (2, 21).

This review on the harvesting of wildlife products for food and medicine in tropical Africa, the Americas, and Asia addresses the following questions: What are the key complex drivers of wildlife harvesting for bushmeat and traditional medicine? What are the impacts of harvesting on biodiversity, environment, and humans? What are the feasible recommendations to promote sustainable harvesting? Finally, what are the emerging issues for sustainable consumption, production, and trade of bushmeat and wildlife medicinal products across the tropics?

2. COMPLEX DRIVERS OF WILDLIFE HARVESTING FOR BUSHMEAT AND TRADITIONAL MEDICINE

The crises are driven in part by a burgeoning global demand and shrinking forests as well as weak enforcement and regulation of protected areas and protected species, respectively (1, 2, 7, 8, 22, 23). Drivers of the recent increase of harvesting and hunting for bushmeat and medicinal products include deforestation; improved access (including road infrastructure) to forests and markets; improved hunting technology; and growing demand in the expanding national, regional, and global markets (8, 23). In this section, we focus on unraveling the following notable complex interrelated drivers of wildlife harvesting for food and medicine as evidenced across the tropics: wildlife trade, urbanization, livelihood opportunities, and culture and tradition.

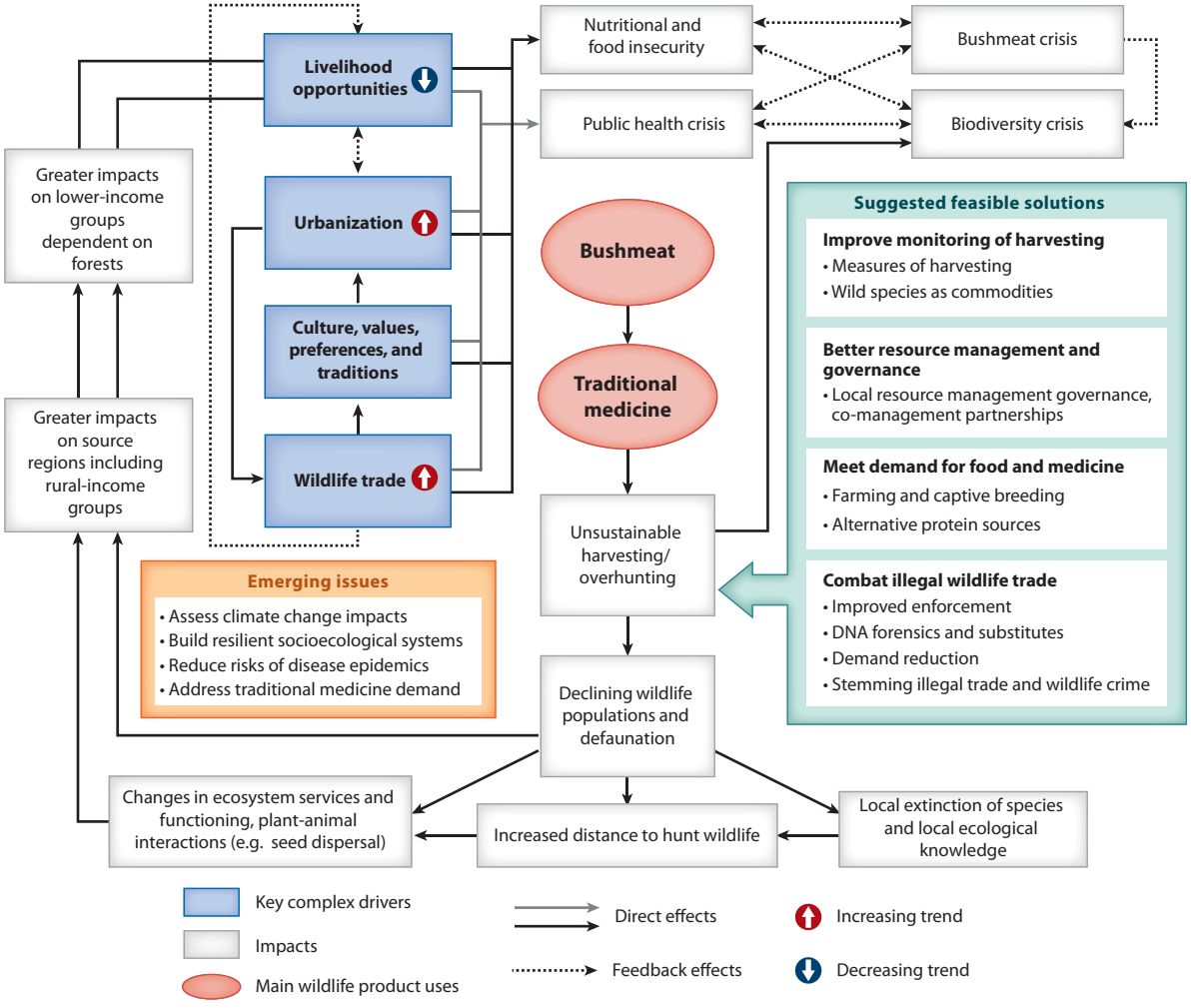

Figure 1

A schematic of the interacting drivers of unsustainable bushmeat consumption in the tropics. The drivers and impacts of unsustainable bushmeat consumption are the ones observed and reported in this review (nonexhaustive list) for the African, Amazonian, and Asian tropics. Figure adapted from Reference 143 (**http://creativecommons.org/licenses/by/4.0/**) (CC BY 4.0).

2.1. Wildlife Trade Drives Overexploitation

The growing animal wildlife (i.e., mammals, birds, reptiles, and amphibians) trade, including illegal trade, is a major threat to tropical biodiversity (9) (**Figure 1**). Commercial poaching, particularly of mammalian species, to supply regional markets and beyond with bushmeat and traditional medicinal products puts immense pressure on wildlife populations in tropical regions (24). As an example, the Javan rhino (*Rhinoceros sondaicus annamiticus*) was declared extinct from Vietnam in 2010, primarily due to extensive poaching motivated by global markets and weak law enforcement (25). In African biomes (e.g., savannas), the impacts of the trade vary from edge effects around protected areas, to disproportionate declines of some species, to severe wildlife declines in areas with inadequate antipoaching activities (26).

Across the tropics, the increasingly commercialized trade to meet the surging demand in rural areas, urban centers, and even international cities transitions from a source of protein to household income, particularly for the low-income urban and rural populations (26, 27). For instance, conservative estimates from carcasses during a 5-month period across nearly 90 urban and rural markets in a 35,000-km^2 area between the Cross River (Nigeria) and the Sanaga River (Cameroon) indicate that almost a million reptiles, birds, and mammals are sold every year by the rural and urban population, which corresponded to approximately 12,000 tons of terrestrial vertebrates (27).

Wildlife trade is in turn driven by a series of factors including human encroachment of wildlife areas, poverty and food insecurity, and inadequate legal frameworks to enable communities to benefit legally from wildlife, which are exacerbated by inadequate wildlife laws and enforcement and in some areas, political instability and conflict (26). Illegal wildlife trade (IWT) is presently a global conservation issue that threatens thousands of species, with many actors involved, including harvesters, intermediaries, and consumers and common IWT network configurations in domestic and international markets (28). For example, wildlife overexploitation is severe in Indonesia, especially on Sulawesi Island, where human resources and funding are inadequate to monitor trade and enforce existing laws. Over a two-year period, thousands of illegally trafficked wild mammals en route to markets were encountered and nearly a hundred thousand wild mammals were observed during market surveys (29).

The Convention on the International Trade of Endangered Species of Wild Fauna and Flora (CITES) is recognized as the most important global initiative to monitor and regulate the international trade of wildlife. Due to the lack of ability to enforce CITES, as shown by the trade of large volumes of illegally sourced animals in many parts of the tropics, IWT has weakened the treaty (30). Illegal global wildlife trade is estimated to be a multi-billion dollar market, making it one of the largest illegitimate businesses globally, and it often involves transnational criminal networks (31). This complexity has obstructed enforcement of laws on IWT, which have been most ineffective in tropical countries. A key driver of the bushmeat crisis is booming local, regional, and international wildlife trade. As such, there is a need to consider a diversity of disciplinary perspectives to better understand the economic, social, and political factors influencing illegal and unsustainable wildlife trade in the tropics (32).

2.2. Urbanization and Trade Flows Lead to Rising Demand

Strong links exist between urbanization and regional and global wildlife trade and markets (**Figure 1**). In particular, urbanization leads to rising demand, and connectivity and marketization facilitate wildlife trade (including illegal trade). In some tropical countries, such as Vietnam, wild meat is widely consumed by successful, high-income, high-status males of all ages and educational levels—and is used as a way of signaling prestige and obtaining social influence (33). In addition, in some countries many from the middle class view bushmeat as a luxury and a status item for private possession or "investing in extinction" (34). Moreover, the rarer something becomes, the more attractive and more valuable it becomes (35). In sum, a growing human population, increased buying power, globalization, and social preferences have all contributed to higher demand for wildlife products (36). Hence, the urban residents' attitudes toward bushmeat consumption, particularly as a luxury product, are critical in understanding the social drivers of the wildlife trade.

Huge improvement to existing infrastructure has greatly facilitated the wildlife trade across the tropics. Improved infrastructure has made forested areas more accessible, creating the opportunity for rural areas to trade wildlife products with distant urban markets (23). Road expansion and associated increases in hunting pressure are rapidly growing threats to Amazonian and African tropical wildlife. In the Yasuni Biosphere Reserve of Ecuador, the presence of roads was associated

with a twofold increase of the extraction area. Rates of bushmeat extraction and trade were higher closer to markets than away from them. Although there are some exceptions in Amazonia, roads within protected areas can undermine their capacity to sustain wildlife populations, as well as potentially threaten the livelihoods of indigenous groups (37). In the rainforests of southern Gabon, even moderate hunting pressure can drastically change the structure of mammal communities in central Africa. Roads had the greatest impacts on large and small ungulates, where road avoidance by the ungulates increases with growing local hunting pressure (38).

In addition, global trade has made it more profitable for many rural, subsistence hunters. In some cases, the increased demand from cities has led to unsustainable harvests as it became more profitable for local people from villages to sell bushmeat to markets than to retain it for their subsistence use. In much of Cameroon, bushmeat is being transported to cities, in particular from the Savannah and central provinces, which are rich in wildlife and contain national parks and safari hunting areas (39). And in Laos, due to market expansion into remote areas, households are navigating the transition from subsistence to market economies (40). The new exposure to external market forces has led to drastic changes in rural communities, with the development of village collectives to manage resources and negotiate with outside traders, for example (41). As such, urbanization has led to rising demand for wildlife beyond tropical rural regions, placing immense pressure on the regions' biodiversity and rural populations' well-being (including health risk to zoonotic diseases).

Overexploitation in China is widespread and is carried out by China's larger, poorer, and more rural population, who operate in the trade of wildlife products (42). The large volume of both legal and illegal trade in wildlife is driving many species to local extinction, with substantial trade occurring in the Guangxi, Yunnan, and Qinghai provinces (43). A growing human population, increased buying power, urbanization, and globalization have led to higher demand for products derived from wildlife including those used in traditional medicines (36). Unlike bushmeat for food, the global surge in demand for traditional medicine, particularly traditional Chinese medicine (TCM), has little known consequences for wildlife species and must be examined more closely.

2.3. Rural Livelihood Opportunities and Wildlife Dependency

Whereas increased urbanization and a growing middle class are driving demand for bushmeat and fueling lucrative IWT, rural people's wildlife dependency is intricately tied to their livelihood opportunities, thus affecting their food and nutritional security (**Figure 1**). The economic importance of bushmeat to rural households was examined from thousands of households in hundreds of communities across more than 20 tropical and subtropical countries in Latin America, Asia, and sub-Saharan Africa. Hunting is more prevalent than generally assumed (39%) but contributes less to rural household income than expected (2%) and mainly through own consumption (87%). Also, bushmeat is the most important to rural households as a source of protein and micronutrients unavailable through their existing domestic animal and staple crop production (44). Only poverty alleviation plans can deter illegal consumption for poor city dwellers without affordable alternatives to eating wildlife (45).

Bushmeat consumption patterns can have profound effects on biodiversity conservation and poverty alleviation in the tropics. Understanding the role of hunting and bushmeat consumption in the daily lives of tropical rural communities will be crucial. In Madagascar, most species are eaten; however, few are preferred over domestic meat. Hunting is regarded as a secondary pursuit, carried out opportunistically during the course of other activities, although its importance spikes in times of food stress (46). Management focused on increasing domestic meat availability and directing hunting effort away from sensitive species may improve the sustainability of hunting, but

interventions to reduce forest dependence may be required to promote conservation and poverty alleviation simultaneously (46).

Conflicts (e.g., civil wars) may also affect hunting patterns, where cases of overhunting or reduced hunting pressures have been documented. In Sierra Leone, West Africa, access to alternative livelihood options and the severity of the war's impact shaped fluctuating patterns in hunting participation across different communities. As such, adaptive management approaches that can adjust management strategies to account for spatial or temporal variations in hunting behavior will be vital (47). In the Colombian Amazon, the increased dependency on industrial chicken in rural communities poses important food security issues because it provides less nutritional balance than wild foods, and access to this protein is dependent on cash availability. Whereas the harvest of wild proteins poses a sustainability issue, industrial foods produce a substantial ecological footprint (48). Therefore, the availability of rural livelihood opportunities can have direct consequences for the sustainability of wildlife harvesting and food and nutritional security.

2.4. Cultural Values, Preferences, and Traditions

Cultural values, preferences, and traditions may play a strong role in driving the consumption of wildlife for food and medicine in the tropics. Primates used in traditional folk medicines and magic-religious rituals and remedies are often linked to folk beliefs (3). The widespread use of primates in traditional medicine points to the need to consider sociocultural factors when establishing management plans concerning the sustainable use of this mammalian group, particularly when approximately half of the primates are threatened with extinction (3). Furthermore, some species are hunted around the world for the perceived potency of certain body parts in traditional medicine and in cultural practices. In Africa, for example, many cultures require animal parts for a wide range of traditional and religious practices, leading to the hunting of a few hundred bird species (49).

Zoo therapies form an integral part of some cultures, and information about animals is passed from generation to generation through oral folklore with many animal species playing an important role in healing practices. In the semiarid region of Northeastern Brazil, animals are used in the form of amulets and charms in magic-religious rituals and ceremonies (50), whereas fetish beliefs are important to the culture of African people (51). The medicinal value of animal species depends on the local ethnopharmacological knowledge that exists within local communities, so the conservation and sustainable use of these species will aid in the preservation of local medicinal knowledge and culture for future generations (52).

The popularity of wildlife consumption may also point to the influence of animals as social objects. In the present context of rapid social and environmental change across Laos, consuming wildlife is widely seen as a form of national identity that combines an idealized tradition with a status-conscious modernity (53). In Vietnam, wild porcupines cost half the price of farmed ones, which leads to more demand for wild animals; thus, prevailing relative pricing is a significant driver of the trade (54). In the semiarid regions of northeastern Brazil, the preference for bushmeat over livestock is traditional and is not tied to the requirement for protein supplementation from the wild but rather about the taste (55).

In Amazonia, respondents from households where hunting and bushmeat consumption occurs more frequently attributed higher material value to forests. But households living in more deforested landscapes and those that visited forests less often attributed lower nonmaterial value to forests. Conversely, a vicious cycle may develop: Low forest cover and the loss of connection with forests may erode forest values and facilitate further deforestation and associated decline in wildlife (56). As seen across the tropics, cultural values and factors, preference, and traditions can impose a strong influence on the consumption of wildlife for food and medicine.

3. IMPACTS OF WILDLIFE HARVESTING

The documented impacts of wildlife harvesting for food, livelihood, and traditional medicine are organized into two broad sections. As concerns of biodiversity and the environment, we discussed the impact of hunting, the signs and consequences of overharvesting, and the unsustainable harvest of traditional medicinal products. With regard to humans and livelihoods, we addressed the differential impacts on socioeconomic groups and nutrition and livelihood insecurity, and the emergence of zoonotic infectious diseases and their impacts on public health.

Defaunation: global, local, or functional extinction of animal populations or species from ecological communities

3.1. On Biodiversity and the Environment

The following sections illustrate the various impacts of hunting, the indicators and cascading effects of overharvesting such as defaunation and the disruption of ecosystem functioning and services. Also, we present some details uncovered on the unsustainable harvest of traditional medicinal products.

3.1.1. Impact of hunting. An increase in hunting pressure to supply growing regional and global markets is the gravest threat to the survival of most endangered vertebrates. In some regions and countries, some highly in-demand species have gone extinct, even within the protected-area networks (22, 57). Evidence from multiple sites in Asia indicated that the populations of game species have been declining since approximately 1980, and many species are now extirpated from substantial portions of their former ranges (8, 23). While hunters typically take common species for subsistence, they take rarer species opportunistically and sell surplus meat and commercially valuable products, often targeting high-value species (8). In certain parts of Amazonia, the local depletion of species, reduction in total biomass, and abundance in different size classes can be at least partially explained by subsistence hunting of wildlife in the region (58). In Africa, wildlife is severely hunted, and bushmeat hunting and trade are major forms of direct human pressure in the backdrop of mineral- and oil-driven and extractive economies (59).

However, although the hunting pressure is immense, the hunting impact on wildlife may vary regionally, due to mediating social factors. For instance, in eastern Madagascar, bushmeat species are not particularly preferred and are often considered inferior to fish and domestic animals. Furthermore, taboos have afforded protection to some species, particularly the endangered Indri, although this taboo is rapidly disappearing (60). In another area in Madagascar, knowledge of laws, level of education, involvement in ecotourism, traditional cultural values, taste preferences, opportunity, and human–wildlife conflict are barriers to lemur hunting (61). To discourage illegal hunting and improve the survival of endangered wildlife populations, it is important to consider improving rural human health and welfare.

3.1.2. Signs and consequences of overharvesting. More than 300 terrestrial mammal species are threatened with extinction because of an increase in bushmeat hunting to supply an increase demand in cities (22). In Gabon, vertebrate composition and diversity decrease along a defaunation gradient radiating from rural villages, with lower abundances of large mammals such as monkeys and ungulates observed near local communities (62). In a nearly decade-long study monitoring the sales of an endangered, endemic, protected species of wild pig (i.e., babirusa) in Sulawesi, Indonesia, dealers were observed traveling significantly farther to buy wild pigs, paying more for them, and buying fewer pigs over time, suggesting a sign of resource depletion (63).

Defaunation as a consequence of overhunting can have negative outcomes and cascading effects on biodiversity and ecosystem services and functioning (e.g., carbon storage). Declining populations of game species can affect plant distribution and structure ecosystems, through seed dispersal

and predation, grazing, browsing, rooting, and other mechanisms, as well as plant–animal interactions (11). For instance, overhunting has caused persistent changes in tree population spatial structure and dynamics, leading to a consistent decline in local tree diversity over time in Lambir Hills, Sarawak (64). In the Brazilian Amazon, large-bodied Atelinae primates and tapirs provide nonredundant seed-dispersal services for many large-seeded Neotropical tree species that on average have higher wood density than smaller-seeded and wind-dispersed trees. As such, defaunation of harvest-sensitive species such as tapirs will lead to losses in aboveground biomass and carbon storage of as high as 26.5–37.8% (65).

Fetish market: a market in West Africa that sells talismans and remedies including those from products of dead animals

Over a duration of four decades, herbivores have been observed to be the most common trophic animal guild hunted and traded in West and central Africa, suggesting an imminent reduction of large-bodied herbivores with cascading effect on superpredators (66). The scale of hunting across the island of Borneo represented a serious threat to the long-term survival of flying fox populations and their role as key pollinators and dispersers, and could have serious public health implications (e.g., emerging infectious diseases; discussed below) due to increasing human–wildlife contacts (67). Consequently, the local extinction of species may also have an impact on local culture, through the loss of local ecological knowledge among the younger generation, as was reported in southwest China (68). Throughout the tropics, we uncovered signs and impacts of overharvesting on biodiversity and environment, with cascading effects on humans.

3.1.3. Unsustainable harvest of traditional medicinal products. Similar to wildmeat, traditional medicine products are often unsustainably harvested across the tropics, particularly Asia, driven by increasing human populations and consumer demand, and greater affluence, coupled with shrinking forest habitat. Unfortunately, some of these targeted species are globally endangered. Threatened species such as the rhinos, elephants, and tigers (including harvest for medicinal purposes) will require novel conservation initiatives, policies, and frameworks that can safeguard the long-term future of these iconic species (69). Increasing access to markets and hunting large fauna for medicinal purposes, even for short durations, have a dramatic impact on population numbers. Anecdotal evidence from interviews with local hunters and park staff suggests that hunting for bezoar stones (visceral excretions found in langurs and used in traditional medicine) was the key reason behind the significant decline in Hose's langur in East Kalimantan, Indonesia, in only a seven-year period (70).

Vultures, hornbills, and other large birds, such as bustards, are most threatened by selective harvesting for the traditional medicine trade and bushmeat among markets across Africa (e.g., Benin, Burkina Faso, and South Africa) and therefore should be prioritized for conservation action (47). Many animals, including reptiles, are traded in fetish markets and used for traditional medicine and for their perceived magical properties. In the largest fetish market of West Africa (Lome, Togo), a total of more than 1,500 reptile individuals, belonging to 37 different species (chameleons, snakes, and the puff adder were frequently traded), were recorded in just a month (49).

TCM has been practiced for thousands of years in China, and it is now increasingly practiced outside Asia (71). Historically, TCM recipes recommend including various animal tissues such as pangolin scales; tiger bones; antelope, buffalo, or rhino horns; deer antlers; and bear or snake bile that are mixed with medicinal herbs. However, ecological, ethico-legal, and health and safety concerns such as hunting, breeding, and trade with endangered species (originating from the tropics), risks of transmission of zoonoses, product quality, and substitutes from endangered species persist (72). In many instances, the use of endangered, trade-restricted species parts as TCM ingredients directly challenges CITES legislation. In Taiwan for instance, the observed levels of usage and trade of turtle shells for traditional medicine appear to be unsustainable and likely have a great impact on the chelonian fauna from source areas in tropical Asia (73).

Pangolins across the tropics are commonly used as food and their scales as a medicinal ingredient in TCM in Asia. These animals are a prized resource, for which solid demand has led to their rapid decline and listing on the CITES appendix (74).

Pathogens: any disease-producing agent such as a virus, bacterium, or other microorganism

3.2. On Humans and Livelihoods

Below, we highlight how wildlife harvesting impacts different human population groups and affects nutrition and livelihood security across the tropics. Increasing human contacts with wildlife during harvesting also facilitate the emergence of zoonotic infectious diseases and public health crises.

3.2.1. Differential impacts and nutrition and livelihood insecurity. Overharvesting of wild meat can threaten nutritional and income security of millions of people in the tropics. Economic analysis suggests that local communities in southern Cambodia, whose traditional livelihoods depend on the sustainable use of Ream National Park, will likely lose the most from the exploitation of timber and marine resources, whereas commercial loggers and fishing fleets will likely gain the most (75). In Ghana, where protein-energy malnutrition is a serious issue, bushmeat is a critical protein source that could also act as a safety net for reducing household expenditure in times of financial hardship (76).

The differential use and dependency of forest resources across different income groups are apparent. Despite wildlife depletion, bushmeat continues to make a substantial contribution to protein consumption, especially during poor agricultural harvest seasons. Income shortages among farmers would likely prevent the purchase of bushmeat or its substitutes, suggesting that wildlife depletion may result in malnutrition, particularly for vulnerable households (77). New migrants who use traditional means of survival require more assistance to supplement livelihoods and to reduce their dependence on forest resources, compared to native residents who do not. The lack of land tenure and the uneven distribution of resources affects the landless segments in society disproportionately (78).

Sustainable consumption may shape the way people value forests, which in turn may affect the level of harvest of bushmeat and forest conservation. And because marginal, degraded, and multiuse landscapes are increasingly widespread across the tropics, it is important that the most vulnerable demographic groups (high forest dependency) have a good understanding of the benefits associated with a heterogeneous landscape (79). Because of the linkages between natural resource management, poverty, and malnutrition, nutritional and income security may be enhanced for the poor in rural areas by managing the landscapes and ecosystems. Due to the multifaceted nature of this crisis, it is crucial to work at the interface of rural livelihood improvement and conservation of natural forests to determine how the goals of poverty alleviation and forest conservation can be optimally aligned (80).

3.2.2. Emergence of zoonotic infectious diseases and public health. The global wildlife trade enables the disease transmission mechanisms that lead to human disease outbreaks as well as threaten livestock, international economies, rural livelihoods, native wildlife populations, and the health of ecosystems (81). Understanding pathogen exchange among human, wildlife, and livestock populations, and the varying ecological and cultural contexts in which it happens, becomes a major challenge to maintaining biodiversity, human well-being, and public health (82). Several pathogens in bushmeat are found to be zoonotic and potentially transmissible to humans through consumption or through exposure to body fluids and feces. The high concentration of IWT seizures in tropical areas make the tropics a hotspot for future emerging infectious diseases, creating a potentially serious public health risk (83).

Commodity: an article of trade or commerce

The illegal trafficking of large volumes of animals and bushmeat has led to the introduction and spread of pathogens (83). Indeed, through a surveillance program, samples collected at several international airports in the United States, one of the largest wildlife-importing countries, uncovered parts originating from nonhuman primate and rodent species from tropics carrying retroviruses and/or herpesviruses (84). Large-scale importation of bushmeat from West and Central Africa into Europe has also been reported. In 2010, all bushmeat samples seized at Charles de Gaulle Airport in Paris, France, had viable counts of aerobic bacteria considered unsafe for human consumption, as well as zoonotic bacterial pathogens (85).

Wildlife trade poses a threat to human health, as highlighted by the 2003 SARS coronavirus outbreak, where a Chinese subtropical wildlife market was found to have facilitated pathogen transmission (86). When illegal wildlife and bushmeat are sold in legal markets, where they are poorly enforced, quarantined, and supervised, the convergence of wild and domestic animals allows the exchange of pathogens among diverse species and the spillover from wild hosts to humans (83). In seven markets in Laos, nearly 2,000 alive or freshly dead mammals were observed for sale over 3 years, including mammals from a dozen taxonomic families previously known to host 36 zoonotic pathogens. With high wildlife volumes, high-risk taxa for zoonoses, and poor biosafety, these markets greatly increase the potential for pathogen presence and transmission (87).

One of the two great pandemics, HIV/AIDS, appears to have originated from bushmeat hunting in Africa before emerging globally (88). One of the lessons from the 2003 SARS coronavirus outbreak is that the origins of emergent zoonotic diseases may lie in the biodiversity crisis, with massive species loss resulting from overexploitation of wild animal populations and the destruction of natural habitats by increasing human populations (86). As more species are hunted for food and medicine consumption and trade, the probability of global epidemics increases. It is projected that with local biodiversity loss and increasing rates of wildlife trafficking, and trade and transportation of wild animals to urban cities—where there is a greater potential for human-to-human transmission—the probability of disease outbreaks grows exponentially (89).

Indeed, the ongoing novel zoonotic coronavirus COVID-19 pandemic has hinted at the role of wildlife trade in facilitating the transmission of zoonotic infectious diseases from wild hosts to humans (90). The genetic epidemiology revealed that the earlier cases were retrospectively traced to an urban wildlife market in Wuhan, China (90). In just a matter of weeks, the infection was rapidly spread by national and international travel over the Lunar New Year holidays, killing thousands and infecting hundreds of thousands, and devastating economies worldwide, thereby becoming a global public health and socioeconomic concern (90).

4. SUGGESTED RECOMMENDATIONS AND RESEARCH NEEDS TO PROMOTE SUSTAINABLE HARVESTING

This section presents potentially feasible suggestions and relevant research needs to promote sustainable harvesting of wildlife for bushmeat and traditional medicine. The recommendations and further research needs can be categorized into four main areas: (*a*) improve monitoring of wildlife harvesting, (*b*) provide better resource management and governance, (*c*) meet demand for food and medicine, and (*d*) combat IWT.

4.1. Improve Monitoring of Wildlife Harvesting

In this section, we focus on some key measures of harvesting as documented in the literature. In addition, we discuss the need to understand the bushmeat commodity chain.

4.1.1. Measures of harvesting. For more sustainable harvesting of bushmeat, it is important to understand the rates of harvest through monitoring systems. We present some promising harvesting measures that could aid in monitoring the precious resources. While the supply of, and access to, wild food may be diminishing for dependent societies as natural habitats suffer from numerous pressures (e.g., increased development, more conservation exclusions, and agricultural expansion), it is difficult but critical to measure the extent of the decline (91). By quantifying hunting effort, for example, harvest rates and wild meat consumption and sales (in markets), it is possible to evaluate if the hunting of certain native and threatened species might be sustainable (92). In Equatorial Guinea, locally based catch and effort of hunting trips have been shown to accurately reflect those recorded with the more professional standard measures; this approach can be particularly useful when there is an absence of national and local capacity for monitoring and management (93).

In Papua New Guinea, major sources of marsupial mammal game and their annual harvest have been indirectly used to estimate extraction and maximum sustainable production, which is regarded as an estimate of the sustainability of hunting (94). Hunters frequently exhibit preferences for large body size and trophy value, and thus it may be possible to understand local population dynamics and sustainability through hunter interviews (95). Other desirable indicators of sustainability include the price of bushmeat and level of penalties for illegal trade, both of which are known to affect hunter behavior in terms of amount of bushmeat sold in the Ecuadorian Amazon (96). Long-term, spatially explicit studies are important for the assessment of the sustainability of the wildlife trade, as they provide the potential for disentangling the influences of market dynamics from population declines, and contribute to understanding changes in prices and quantities on sale in end markets (63). Throughout the tropics, there is an urgent call for a better assessment of a sustainable level of exploitation; initiatives to make regulatory mechanisms more effective (e.g., monitoring selected wildlife trade hubs); and better licensing, registration, and science-based monitoring of harvested populations (36).

4.1.2. Wild species as commodities. Understanding the commodity chain of wild animals (hunting, transportation, trade, consumption) can help target conservation and sustainability initiatives. Wild meat commodity chain research has focused on the formal trade and less so on the informal enterprises, although informal enterprises contribute to a large portion of the wild meat trade. To monitor the trade, there is a need to identify hunting strategies used to capture different wildlife; analyze patterns of movement of wild meat from the source location to the end consumer; examine prices, volumes, and venues of sale; and estimate the volume of wild meat consumption (97). In addition, the socioeconomic importance of the bushmeat sector should be estimated by assessing the financial and economic benefits of the bushmeat commodity chain (hunters to end consumers). Only by improving our ability to measure and monitor harvesting indicators and the trade chain can the wildlife harvesting be sustainable.

4.2. Provide Better Resource Management and Governance

In this section, we present details on the importance of building local management and governance and co-management partnership in providing better resource management and governance of wildlife.

4.2.1. Build local management and governance and co-management partnerships. Protected areas may present an opportunity to reconcile biodiversity conservation and human development, particularly in the tropics where there is a high level of dependency on the reserves; to support local livelihoods, protected areas should be managed by local people and their institutions

(98). The long-term viability of protected area networks is crucial for both biodiversity conservation and for achieving poverty alleviation and development objectives (e.g., Laos) (99). By exploring patterns in pricing and condition of bushmeat carcasses, wildlife harvests in and around protected areas in Nigeria and Cameroon may be managed to minimize depletion of wildlife populations, such as marine no-take zones, and be sustainable sources for controlled harvests (100). To balance conservation with the need for economic development and wild meat intake in Central Africa, landscapes should be spatially managed to include protected areas, community hunting zones, as well as production forests (101).

The market institutions have largely been unsuccessful when it comes to conserving natural resources globally. The Western notion of resource conservation through complete exclusion is rejected repeatedly in the tropics. Sustainable wildlife management plans are needed or protected areas could become "island parks" if buffer zones become empty of fauna and flora, as is being documented in some Neotropical forests (e.g., Manu National Park in Peru) (102). In contrast, local community and participatory management of resources may be more effective. Affording greater power to local people in the management of tropical forests in East Kalimantan, with clearly defined cobenefits and trade-offs, has led to both environmental and human development benefits (103).

Nevertheless, considerations such as local conservation agenda, household income, and employment must be key components of co-management partnerships. In the Udzungwa Mountains, Tanzania, challenging governance outcomes may emerge due to poor design and implementation undermining hunters' willingness to conform with management rules (104). In Amazonia, effective conservation requires conservation professionals to work closely with indigenous groups to manage resource use. For sustainable hunting to work, self-monitoring and biodemographic modeling of indigenous hunters, for example, can be used effectively in a co-management approach (105).

Although local people overharvest, they can aid in formulating solutions through improved partnerships that incorporate local ecological knowledge into problem diagnosis. Local people and reserve managers need to communicate more, initiate joint monitoring and patrolling, and establish wildlife recovery zones, as demonstrated in Thailand (24). There is evidence that enhancing community-based conservation to engage local people can reduce the trade in endangered species of animals (106). Also important is the need to foster a relationship of trust between conservationists and local people, which is essential in establishing effective collaborative wildlife management, as shown in southeastern Cameroon (107).

4.3. Meet Demand for Food and Medicine

We explore two ways, i.e., farming and captive breeding and producing alternative protein sources, to meet the increasing demand of wildlife for food and medicine.

4.3.1. Farming and captive breeding. Another suggestion to make wildlife consumption more sustainable across the tropics is to find ways to meet increasing bushmeat and wildlife for medicine demand via popular methods such as farming and captive breeding. It is possible to improve existing farming techniques to lower dependency on bushmeat and to explore the potential farming of certain wildlife species that are being harvested unsustainably. Although captive breeding operations may reduce the supplies of wild-caught animals in theory, CITES-registered and nonregistered programs must be closely monitored and evaluated for legitimacy (108). This is because there is a known risk that breeding farms may be used to launder illegally caught wildlife (e.g., green python), as observed in Indonesia (109). Conversely, farming to meet demand may be controversial. Concerns about the viability of such farming, its cost effectiveness, and its impact

on wildlife populations will need to be thoroughly looked into. Consequently, farming may not be an effective tool in reducing demand for illegal wildlife products and may in fact stimulate greater demand for wild-caught products, as was seen in countries such as Vietnam (110).

4.3.2. Alternative protein sources. Another option to ensure protein and nutritional security is to look into other nonconventional animal species for food derived from either wild harvesting or farming. The need to develop cheap protein alternatives to bushmeat and fish in Ghana is vital, as it was observed that years of poor fish supply coincided with increased hunting in nature reserves and sharp declines in biomass of wildlife species (111). A lack of alternative protein sources pushed even the wealthiest among surveyed households to consume bushmeat. As such, providing affordable, alternative protein sources to all households would likely reduce unsustainable levels of bushmeat consumption, for example in rural Gabon (112).

However, alternative food programs that fail to consider indigenous and cultural contexts risk inefficiency, restricted improvement of health outcomes, and the potential to worsen inequities in the health of indigenous populations, as observed in Peru (113). When considering the comparative food security and nutritional values, rodents may present great potential for becoming large commercial food commodities (114). Hunting within oil palm plantations, which cover large areas in Asian tropics, may not only reduce crop damage from wild boar but may also yield large amounts of wild meat with relatively little bycatch of threatened animals, as reported in Jambi, Sumatra (115). Regulations may need to be adapted to enable bushmeat harvesting where it is appropriate, such as harvesting pigs in oil palm estates, but without jeopardizing the protection of threatened species or protected habitats (115).

4.4. Combat Illegal Wildlife Trade

In this section, we discuss four specific approaches to combat IWT. We need to improve enforcement, conduct DNA forensic testing and search for species substitutions, reduce demand for endangered and protected species, and stem illegal trade and wildlife crimes.

4.4.1. Improved enforcement. Although the evidence is scant, if enforcement efforts can improve, illegal trade may be halted, preventing the unsustainable harvest of wildlife across the tropics. Novel methods, such as social network analysis, for analyzing trade patterns using seizure data reported in the media revealing key nodes of the illegal wildlife market. Mining for trends and patterns in seizure data may offer guidance for future law enforcement and policy interventions for combatting wildlife trade internationally (74). Ensuring better bilateral border control (e.g., China–Myanmar and China–Vietnam) and enforcement of existing regulations prohibiting trade of endangered and overexploited animals will help to ease the harvesting pressure on wildlife (30). Other challenges to overcome in terms of improved enforcements are the deficiencies in wildlife trade management (particularly the short supply and low motivation of government personnel) and ineffective targeting of public awareness initiatives (116). Furthermore, minimum technical and financial resources must be increased, and wildlife trade-specific training must be provided to wildlife officials as well as those responsible for market management, transportation, public security, and border control (116).

4.4.2. DNA forensics and substitutes. A strategy for the balance between conservation of threatened animals and the development of traditional medicine should include both trade monitoring (including law enforcement) and the search for authentic substitutes. Recent advances in DNA metabarcoding and forensics involve next-generation sequencing of DNA barcodes for the

simultaneous detection of multiple species in complex samples as well as in processed materials such as TCM containing highly degraded DNA. These powerful techniques can be used for monitoring the trade of animal species (including identifying the geographic origins of confiscated specimens), potentially helping to limit unsustainable use and illegal trade of endangered species and illegal adulterants (117). For instance, new methods could detect if the horns of Mongolian gazelle (*Procapra gutturosa*) and red deer (*Cervus elaphus*) were exploited as a substitute for some functions of endangered saiga antelope (*Saiga tatarica*) and sika deer (*Cervus nippon*) in traditional medicine, respectively (118).

4.4.3. Demand reduction. As a recommendation, demand reduction efforts are a challenging undertaking, particularly given the cultural customs and social status associated with many traditional medicine products. For example, it is difficult to act on personal rather than collective interests, and the symbolic role of wild meat in a status-conscious society (e.g., Vietnam) makes reducing demand even more complex (33). Other possible suggestions include cracking down on the online IWT, increasing public awareness through campaigns, and advocating sustainable wildlife consumption. This is required particularly when the biological reproduction of some valuable species (e.g., rhino and pangolin) in medicinal markets cannot meet global demands, implying that we need to understand the demographics of wildlife consumers and to find ways to change their behavior (119). Opinions about wildlife conservation carried out in Hunan Province, China, before and after the SARS epidemic, revealed that postepidemic consumption may be reduced due to a threatening disease outbreak related to wildlife consumption, thereby lowering potential public health risk (120). Governments should strengthen the capacity of the agencies responsible for fighting the trade and increase their budgets. There is also a need to use education to encourage target populations to stop consuming illegal wildlife products (121).

4.4.4. Stemming illegal trade and wildlife crime. International trade in wildlife is a major threat to biodiversity conservation. Although CITES has a noble goal in maintaining sustainability in IWT, the effectiveness of this mechanism is undermined by the disregard of the economic reality of wildlife trade. CITES largely fails to accurately monitor supply and to consider the complex nature of demand and changing market dynamics. Therefore, there is a need to improve monitoring of supply (both illegal and legal trade) and of demand and prices for wildlife (through national wildlife consumption surveys) (122). To tackle IWT for instance, it is key to (*a*) suppress the illegal wildlife markets and forbid the sale of wildlife in restaurants (consisting of species listed in national protection lists), (*b*) increase international cooperation in the control of the trade, (*c*) heighten enforcement of CITES for both countries, (*d*) control the invasion of exotic species and disease epidemics in the trade, and (*e*) encourage wildlife conservation education (123).

An alternative approach in reducing the IWT is a combination of making it more difficult to poach (i.e., situational crime prevention) and incentivizing local people to stop poaching (124). Illegal trade is due in part to an inadequate understanding of the species being traded and is facilitated by poor monitoring and enforcement at trade hubs. As an initial step to fight illegal trade and to better understand the effects of harvest on wild populations, we should increase monitoring and enforcement, improving the knowledge base of species traded and educating consumers about how their demand affects these species (125).

5. EMERGING ISSUES FOR SUSTAINABLE WILDLIFE CONSUMPTION AND PRODUCTION

Sustainable consumption and production is one of the sustainable development goals (SDG12). In the context of bushmeat, SDG12 deserves special attention. Four key emerging issues are

prioritized and highlighted in this section. The intricately linked issues include the need to assess the impact of climate change on the sustainable harvest of wildlife for food and medicine, build resilience of the forest social-ecological system, reduce the risk of zoonotic infectious disease epidemics, and address the rising traditional medicine demand.

Social-ecological system: a biogeophysical unit and its associated social actors and institutions that is complex and adaptive

5.1. Assessing Climate Change Impacts

The potential impacts of climate change and how it could impact sustainable bushmeat harvesting and production as a source of food and medicine is a critical issue. In Brazil, infectious disease outbreaks and climate change events (e.g., El Niño, heatwaves, floods, higher levels of rainfall) or environmental changes (e.g., deforestation, urbanization, bushmeat consumption) are tightly intertwined (126). To avoid or control outbreaks, integrated surveillance and response systems for emerging zoonotic diseases will need to be reinforced and maintained at national and international levels (127). Due to strong global and local influence on emergence of infectious diseases, a more holistic approach is necessary to mitigate or control them in tropical developing nations and beyond (126, 128). The current bushmeat crisis should be more widely considered by climate change experts because by removing the animal dispersers of carbon-rich tree seeds, hunting may be reducing the global carbon sink provided by tropical forests. This degradation of carbon storage can be driven by overhunting, particularly of large-bodied vertebrates. As such, mitigation strategies should aim to conserve tropical animals to keep the carbon on the ground into the future (129).

5.2. Building Resilience in Social-Ecological Systems

Complex challenges linked to changing socioeconomic, environmental (e.g., climate change), political, and cultural conditions continue to disrupt the delivery of ecosystem services (including bushmeat) to resource-dependent communities. In rural semiarid Ghana, sharing intensifies during the long dry season. But it is unclear how this sharing affects rural households' livelihoods and ecosystem sustainability under changing conditions (130). To reduce the impact of animal product consumption by humans and to meet nutritional needs of local people, bushmeat could be replaced with poultry, integrated aquaculture, and other more efficient protein sources and reintegrating livestock production away from single-product, intensive, fossil-fuel-based systems into diverse, coupled systems designed more closely around the structure and functions of ecosystems that conserve both energy and nutrients (131).

For the Tsimane' Amerindians in Bolivia, the unsustainable hunting of wildlife for food may be reduced by making fish more affordable and by regulating the price of meat from domesticated animals relative to that of wildlife, as the free market price of bushmeat may be inflated by high demand from the urban rich and middle class in other parts of Amazonia. However, increasing the production of livestock without causing environmental degradation will require long-term public investment in agricultural research and extension, and care must be taken with the substitution of fish for game meat as further overexploitation of fish stocks may result in the absence of sustainable management regimes (132).

Bushmeat hunting systems in the tropics are seen as social-ecological systems. There is a need to understand the complex and dynamic relationships between the hunting ground, its resources, the stakeholders, and the different exogenous drivers of change that affect the components of the system across scales. Accordingly, the resilience theory in the context of bushmeat hunting bypasses the need to assess stocks by incorporating the uncertainty and stochasticity inherent to complex systems in participatory and adaptive management processes. This approach thus provides an opportunity for the sustainable use of bushmeat and allows the identification of strategies to strengthen resilience when the system nears a given threshold (133).

5.3. Reducing the Risk of Zoonotic Infectious Disease Epidemics

The leading causes of the reemergence of controlled zoonoses are human behavior and modifications to natural habitats (expansion of human populations and their encroachment on wildlife habitat), climate change, changes in agricultural practices, and globalization of trade. Instead of eradicating pathogens or the wild species hosts, a practical approach would include decreasing the contact rate among species, including humans, at wildlife markets (81). The public in rural areas and urban centers should be educated about the health risks associated with wildlife, bushmeat, and exotic pet trades, and proper surveillance systems for zoonotic diseases should be implemented from sources to markets (134). The development of innovative handling, conservation, and cooking practices, adapted to each sociocultural context, could aid in potentially reducing the negative impacts of bushmeat consumption on human well-being (5).

During the recent Ebola outbreak in West Africa, it is likely that human dietary behavior and local attitudes toward bushmeat consumption transformed in response to the crisis, and that the rate of change depended on prevailing socioeconomic conditions, including wealth and education (135). This provides an opportunity to understand how disasters affect social-ecological systems and improve our management of future crises (135). Bats are widely known to be a natural reservoir for many disease pathogens and can spread several diseases. Despite major campaigns during the Ebola outbreak, dimensions of risky behavior including disbelief and disregard for some preventive measures and indifference to post-bat exposure prophylaxis were recorded among a section of the community (136). Public health education for the communities living near pathogen hosts and reservoirs must also be a priority.

To address the real and perceived threat from emerging infectious diseases, a One Health research framework may offer a research and policy-generation strategy to help overcome challenges posed by emerging zoonoses (128). In essence, the One Health program is a collaborative, multisectoral, and transdisciplinary approach—working at the local, regional, national, and global levels—with the aim of attaining optimal health outcomes, and accounting for the interconnectedness between people, wildlife, and their overlapping environment (128). Such a holistic effort might be useful in mitigating and lowering the risk of future zoonotic disease outbreaks in and out of the tropics. A more interdisciplinary approach that combines the research expertise of ecologists, conservation scientists, veterinarians, epidemiologists, virologists, as well as human health professionals fits well in a sustainability research framework (86).

5.4. Addressing Rising Traditional Medicine Demand

With growing demand in Asia and beyond, there is an urgency to understand the attitudes, motivations, and consumer behavior toward substitutes of wildlife products for traditional medicine. These substitutes could have potential benefits, by not only taking pressure off wild populations, but also by removing the health risks that are associated with consuming products from wild animals, particularly by consumers who are not local and are not dependent on them (137). More research needs to be done to understand if traditional medicine from farmed animals could potentially take pressure off wild populations or instead act as a front for wild harvesting of individuals (i.e., wildlife laundering) (109).

In a stated preference test, a study demonstrated that when Chinese consumers, on being told to imagine that they are sick, tend to be willing to pay far more for the wild-based product over synthesized medicine (138). Public attitude toward the farming of threatened animals may also guide conservation. A recent attitudinal survey shows that regarding bear bile extraction from live bears, younger and more educated people tend to oppose such methods on the grounds of animal welfare (139). As such, conservation measures that seek to promote a transition to farmed animal,

plant, and synthetic ingredients and provide clear directions for future social marketing, education, and engagement efforts should be pursued (140). Although it is vital to search for sustainable and effective substitutes for tiger bone and rhino horn, for example, these products will not be as highly demanded if people ultimately do not want to use them and begin to question the validity of their effects (141).

Sometimes, perceptions of a product can shift over time from functional (e.g., curative) to symbolic. Many Vietnamese males reported health benefits, such as body detoxification and hangover treatment, as the most common reasons for rhino horn usage. Some even believe the horn can treat cancer, although this has never been recorded in 2,000 years of TCM history (141). Rhino horn is used to display economic wealth, acquire social status, and initiate business and political relationships. As such, it becomes crucial to understand the shift in the use of wildlife products to develop strategies to reduce or prevent further loss of such wildlife (142).

SUMMARY POINTS

1. Bushmeat has long provided a source of protein, nutrition, and traditional medicine for local people throughout the global tropics. However, the levels of exploitation for this important resource are increasingly under pressure due to forest loss and overharvesting, among other factors.
2. The bushmeat crisis is also a nutritional security issue across the tropics as protein and nutrition from bushmeat and rural livelihoods are intrinsically linked. The key complex and interrelated drivers of wildlife harvest for food and traditional medicine include wildlife trade; urbanization; livelihood opportunities; and cultural values, preferences, and traditions.
3. Strong links exist between urbanization and regional and global wildlife trade and markets. Urbanization leads to rising demand and connectivity, and marketization facilitates wildlife trade (including illegal trade) outside of rural areas and into cities beyond the tropics.
4. This review highlights the impacts of wildlife harvesting on biodiversity, environment, and humans. Hunting has decimated wildlife populations in the past decades, particularly for high-value species.
5. We illustrate signs of overharvesting and highlight that defaunation as a consequence of overhunting has negative outcomes and cascading effects on biodiversity and ecosystem services and functioning (e.g., carbon storage), as well as on plant–animal interactions.
6. The harvest of traditional medicinal products is becoming unsustainable, and the growing demand for traditional Chinese medicine has impacted high-value species in Asia and beyond.
7. The bushmeat trade and markets are economically important and can alleviate poverty in the rural tropics. Differential impacts from overharvesting are observed across different socioeconomic groups, with the highly forest-dependent people being the most vulnerable.
8. The extensive human–wildlife interactions facilitate the exchange of pathogens, can trigger the emergence of zoonotic infectious diseases (e.g., Ebola, SARS), and have led to public health crises in recent years.

FUTURE ISSUES

1. The global community needs to consider the sustainable consumption and production of bushmeat across the tropics, as it is part of one of the sustainable development goals (SDG12).
2. Several feasible recommendations and future research proposed for sustainable harvesting have been identified in the areas of improving harvest indicators for monitoring purposes, developing better resource management and governance, finding alternative ways to meet the demand for food and medicine, and combating illegal wildlife trade.
3. Emerging issues are intricately linked and they include the need to assess climate change impacts on bushmeat and nutritional and food security, to build resilience in forest social-ecological systems, to reduce the risk of zoonotic infectious disease epidemics, and to address the rising demand for traditional medicine.
4. To balance the rural and cultural dependencies on bushmeat in the tropics with conservation and public health priorities, we urgently need strategies to safeguard tropical biodiversity, sustainable harvest of wildlife with reduced risk for food and medicine.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

This review was made possible by financial support from the United States Agency for International Development and the United Kingdom's Department for International Development as part of the International Forestry Knowledge programme. The work is also supported by research grants from the National Natural Science Foundation of China (grants 41180944 and 41180953), the Guangdong Provincial Research Fund (grant 42150016), and the European Commission (grant ENV/2018/403-527) to T.M.L.

LITERATURE CITED

1. Milner-Gulland EJ, Bennett EL. 2003. Wild meat: the bigger picture. *Trends Ecol. Evol.* 18(7):351–57
2. Nasi R, Brown D, Wilkie D, Bennett E, Tutin C, et al. 2008. Conservation and use of wildlife-based resources: the bushmeat crisis. *Secretariat of the Convention on Biological Diversity, Montreal and Center for International Forestry Research (CIFOR), Bogor. Technical Series* 33. **https://www.cbd.int/doc/publications/cbd-ts-33-en.pdf**
3. Alves RRN, Rosa IL, Albuquerque UP, Cunningham AB. 2013. Medicine from the wild: an overview of the use and trade of animal products in traditional medicines. In *Animals in Traditional Folk Medicine*, ed. RRN Alves, IL Rosa, pp. 25–42. Heidelberg, Ger.: Springer
4. Chardonnet P, des Clers B, Fischer J, Gerhold R, Jori F, Lamarque F. 2002. The value of wildlife. *Rev. Sci. Tech.-Off. Int. Épizoot.* 21(1):15–52
5. van Vliet N, Moreno J, Gomez J, Zhou W, Fa JE, et al. 2017. Bushmeat and human health: assessing the Evidence in tropical and sub-tropical forests. *Ethnobiol. Conserv.* 6:1–45
6. Adeola MO. 1992. Importance of wild animals and their parts in the culture, religious festivals, and traditional medicine, of Nigeria. *Environ. Conserv.* 19:125–34

7. Bennett EL, Rao M. 2002. Wild meat consumption in Asian tropical forest countries: Is this a glimpse of the future for Africa? In *Links Between Biodiversity, Conservation, Livelihoods and Food Security: The Sustainable Use of Wild Species for Meat*, ed. S Mainka, M Trivedi, pp. 39–44. Gland, Switz.: Int. Union Conserv. Nat.
8. Harrison RD, Sreekar R, Brodie JF, Brook S, Luskin M, et al. 2016. Impacts of hunting on tropical forests in Southeast Asia. *Conserv. Biol.* 30(5):972–81
9. Carpenter AI, Andreone F, Moore RD, Griffiths RA. 2014. A review of the international trade in amphibians: the types, levels and dynamics of trade in CITES-listed species. *Oryx* 48(4):565–74
10. Sarti FM, Adams C, Morsello C, van Vliet N, Schor T, et al. 2015. Beyond protein intake: bushmeat as source of micronutrients in the Amazon. *Ecol. Soc.* 20(4):22
11. Nasi R, Taber A, Van Vliet N. 2011. Empty forests, empty stomachs? Bushmeat and livelihoods in the Congo and Amazon Basins. *Int. For. Rev.* 13:355–68
12. Vedeld P. 2004. *Counting on the environment: forest incomes and the rural poor*. Work. Pap. 30026, Environ. Dep., World Bank, Wash., DC
13. Endamana D, Angu KA, Akwah GN, Shepherd G, Ntumwel BC. 2016. Contribution of non-timber forest products to cash and non-cash income of remote forest communities in Central Africa. *Int. For. Rev.* 18(3):280–95
14. Van NDN, Tap N. 2008. An overview of the use of plants and animals in traditional medicine systems in Viet Nam. *TRAFFIC Southeast Asia, Greater Mekong Programme, Ha Noi, Viet Nam*. **https://www.traffic.org/site/assets/files/5366/traditional-medicine-systems-in-viet-nam.pdf**
15. Alves RR, Lima HN, Tavares MC, Souto WM, Barboza RR, Vasconcellos A. 2008. Animal-based remedies as complementary medicines in Santa Cruz do Capibaribe, Brazil. *BMC Complement. Altern. Med.* 8:44
16. Mootoosamy A, Mahomoodally MF. 2014. Ethnomedicinal application of native remedies used against diabetes and related complications in Mauritius. *J. Ethnopharmacol.* 151(1):413–44
17. Ferreira FS, Fernandes-Ferreira H, Leo Neto NA, Brito SV, Alves RRN. 2013. The trade of medicinal animals in Brazil: current status and perspectives. *Biodivers. Conserv.* 22(4):839–70
18. Barros FB, Varela SA, Pereira HM, Vicente L. 2012. Medicinal use of fauna by a traditional community in the Brazilian Amazonia. *J. Ethnobiol. Ethnomed.* 8:37
19. Fa J, Peres C, Meeuwig J. 2002. Bushmeat exploitation in tropical forests: an intercontinental comparison. *Conserv. Biol.* 16(1):232–37
20. Fa J, Currie D, Meeuwig J. 2003. Bushmeat and food security in the Congo Basin: linkages between wildlife and people's future. *Environ. Conserv.* 30(1):71–78
21. Sodhi N, Koh L, Brook B, Ng P. 2004. Southeast Asian biodiversity: an impending disaster. *Trends Ecol. Evol.* 19(12):654–60
22. Ripple WJ, Abernethy K, Betts MG, Chapron G, Dirzo R, et al. 2016. Bushmeat hunting and extinction risk to the world's mammals. *R. Soc. Open. Sci.* 3(10):160498
23. Corlett RT. 2007. The impact of hunting on the mammalian fauna of tropical Asian forests. *Biotropica* 39(3):292–303
24. Steinmetz R, Chutipong W, Seuaturien N. 2006. Collaborating to conserve large mammals in Southeast Asia. *Conserv. Biol.* 20(5):1391–401
25. Brook SM, Dudley N, Mahood SP, Polet G, Williams AC, et al. 2014. Lessons learned from the loss of a flagship: the extinction of the Javan rhinoceros *Rhinoceros sondaicus annamiticus* from Vietnam. *Biol. Conserv.* 174:21–29
26. Lindsey PA, Balme G, Becker M, Begg C, Bento C, et al. 2013. The bushmeat trade in African savannas: impacts, drivers, and possible solutions. *Biol. Conserv.* 160:80–96
27. Fa JE, Seymour S, Dupain J, Amin R, Albrechtsen L, Macdonald D. 2006. Getting to grips with the magnitude of exploitation: bushmeat in the Cross-Sanaga Rivers region, Nigeria and Cameroon. *Biol. Conserv.* 129(4):497–510
28. Phelps J, Biggs D, Webb EL. 2016. Tools and terms for understanding illegal wildlife trade. *Front. Ecol. Environ.* 14:479–89
29. Lee RJ, Gorog AJ, Dwiyahreni A, Siwu S, Riley J, et al. 2005. Wildlife trade and implications for law enforcement in Indonesia: a case study from North Sulawesi. *Biol. Conserv.* 123(4):477–88

30. Nijman V, Shepherd CR. 2007. Trade in non-native, CITES-listed, wildlife in Asia, as exemplified by the trade in freshwater turtles and tortoises (Chelonidae) in Thailand. *Contrib. Zool.* 76(3):207–12
31. Jiao Y. 2016. Greater China and transnational environmental crime: understanding criminal networks and enforcement responses. In *Handbook of Transnational Environmental Crime*, ed. L Elliott, W Schaedla, pp. 255–75. Cheltenham, UK: Edward Elgar Publ.
32. TRAFFIC. 2008. What's driving the wildlife trade? A review of expert opinion on economic and social drivers of the wildlife trade and trade control efforts in Cambodia, Indonesia, Lao PDR and Vietnam. In *East Asia and Pacific Region Sustainable Development Discussion Papers*. Wash., DC: E. Asia Pac. Region Sustain. Dev. Dep., World Bank
33. Drury R. 2011. Hungry for success: urban consumer demand for wild animal products in Vietnam. *Conserv. Soc.* 9(3):247–57
34. Zhou Z-M, Johnson RN, Newman C, Buesching CD, Macdonald DW, Zhou Y. 2015. Private possession drives illegal wildlife trade in China. *Front. Ecol. Environ.* 13:353–54
35. Courchamp F, Angulo E, Rivalan P, Hall RJ, Signoret L, et al. 2006. Rarity value and species extinction: the anthropogenic Allee effect. *PLOS Biol.* 4(12):e415
36. Nijman V. 2010. An overview of international wildlife trade from southeast Asia. *Biodivers. Conserv.* 19(4):1101–14
37. Espinosa S, Branch LC, Cueva R. 2014. Road development and the geography of hunting by an Amazonian indigenous group: consequences for wildlife conservation. *PLOS ONE* 9(12):e114916
38. Laurance WF, Croes BM, Tchignoumba L, Lahm SA, Alonso A, et al. 2006. Impacts of roads and hunting on central African rainforest mammals. *Conserv. Biol.* 20(4):1251–61
39. Edderai D, Dame M. 2006. A census of the commercial bushmeat market in Yaounde, Cameroon. *Oryx* 40(4):472–75
40. Bouahom B, Douangsavanh L, Rigg J. 2004. Building sustainable livelihoods in Laos: untangling farm from non-farm, progress from distress. *Geoforum* 35(5):607–19
41. Thongmanivong S, Fujita Y. 2006. Recent land use and livelihood transitions in northern Laos. *Mt. Res. Dev.* 26(3):237–44
42. Li Y, Wilcove DS. 2005. Threats to vertebrate species in China and the United States. *BioScience* 55(2):147–53
43. Zhang L, Hua N, Sun S. 2008. Wildlife trade, consumption and conservation awareness in southwest China. *Biodivers. Conserv.* 17(6):1493–516
44. Nielsen MR, Pouliot M, Meilby H, Smith-Hall C, Angelsen A. 2017. Global patterns and determinants of the economic importance of bushmeat. *Biol. Conserv.* 215:277–87
45. Parry L, Barlow J, Pereira H. 2014. Wildlife harvest and consumption in Amazonia's urbanized wilderness. *Conserv. Lett.* 7(6):565–74
46. Gardner CJ, Davies ZG. 2014. Rural bushmeat consumption within multiple-use protected areas: qualitative evidence from Southwest Madagascar. *Hum. Ecol.* 42(1):21–34
47. Conteh A, Gavin MC. 2017. Influence of war on hunting patterns and pressure in Sierra Leone. *Environ. Conserv.* 44(2):131–38
48. van Vliet N, Quiceno-Mesa MP, Cruz-Antia D, Tellez L, Martins C, et al. 2015. From fish and bushmeat to chicken nuggets: the nutrition transition in a continuum from rural to urban settings in the Colombian Amazon region. *Ethnobiol. Conserv.* 4(6):1–12
49. Atuo FA, O'Connell TJ, Abanyam PU. 2015. An assessment of socio-economic drivers of avian body parts trade in West African rainforests. *Biol. Conserv.* 191:614–22
50. Alves RRN, Neto NAL, Brooks SE, Albuquerque UP. 2009. Commercialization of animal-derived remedies as complementary medicine in the semi-arid region of Northeastern Brazil. *J. Ethnopharmacol.* 124:600–608
51. Segniagbeto GH, Petrozzi F, Aidam A, Luiselli L. 2013. Reptiles traded in the fetish market of Lome, Togo (West Africa). *Herpetol. Conserv. Biol.* 8(2):400–8
52. Alves RRN, Rosa IL. 2010. Trade of animals used in Brazilian traditional medicine: trends and implications for conservation. *Hum. Ecol.* 38:691–704

53. Singh S. 2010. Appetites and aspirations: consuming wildlife in Laos. *Aust. J. Anthropol.* 21(3):315–31
54. Brooks EGE, Roberton SI, Bell DJ. 2010. The conservation impact of commercial wildlife farming of porcupines in Vietnam. *Biol. Conserv.* 143(11):2808–14
55. Barboza RR, Lopes S, Souto W, Fernandes-Ferreira H, Alves R. 2016. The role of game mammals as bushmeat in the Caatinga, northeast Brazil. *Ecol. Soc.* 21(2):2
56. Torres PC, Morsello C, Parry L, Pardini R. 2016. Who cares about forests and why? Individual values attributed to forests in a post-frontier region in Amazonia. *PLOS ONE* 11(12):e0167691
57. Harrison RD. 2011. Emptying the forest: hunting and the extirpation of wildlife from tropical nature reserves. *BIOSCIENCE* 61(11):919–24
58. Peres C. 2000. Effects of subsistence hunting on vertebrate community structure in Amazonian forests. *Conserv. Biol.* 14(1):240–53
59. Malhi Y, Adu-Bredu S, Asare RA, Lewis SL, Mayaux P. 2013. African rainforests: past, present and future. *Philos. Trans. R. Soc. B* 368(1625):20120312
60. Jenkins RKB, Keane A, Rakotoarivelo AR, Rakotomboavonjy V, Randrianandrianina FH, et al. 2011. Analysis of patterns of bushmeat consumption reveals extensive exploitation of protected species in Eastern Madagascar. *PLOS ONE* 6(12):e27570
61. Borgerson C, McKean MA, Sutherland MR, Godfrey LR. 2016. Who hunts lemurs and why they hunt them. *Biol. Conserv.* 197:124–30
62. Koerner SE, Poulsen JR, Blanchard EJ, Okouyi J, Clark CJ. 2017. Vertebrate community composition and diversity declines along a defaunation gradient radiating from rural villages in Gabon. *J. Appl. Ecol.* 54(3):805–14
63. Milner-Gulland EJ, Clayton L. 2002. The trade in babirusas and wild pigs in North Sulawesi, Indonesia. *Ecol. Econ.* 42(1–2):165–83
64. Harrison RD, Tan S, Plotkin JB, Slik F, Detto M, et al. 2013. Consequences of defaunation for a tropical tree community. *Ecol. Lett.* 16(5):687–94
65. Peres CA, Emilio T, Schietti J, Desmouliere SJM, Levi T. 2016. Dispersal limitation induces long-term biomass collapse in overhunted Amazonian forests. *PNAS* 113(4):892–97
66. Petrozzi F, Amori G, Franco D, Gaubert P, Pacini N, et al. 2016. Ecology of the bushmeat trade in west and central Africa. *Trop. Ecol.* 57(3):545–57
67. Harrison ME, Cheyne SM, Darma F, Ribowo DA, Limin SH, Struebig MJ. 2011. Hunting of flying foxes and perception of disease risk in Indonesian Borneo. *Biol. Conserv.* 144(10):2441–49
68. Kai Z, Shu Woan T, Jie L, Goodale E, Kitajima K, et al. 2014. Shifting baselines on a tropical forest frontier: extirpations drive declines in local ecological knowledge. *PLOS ONE* 9(1):e86598
69. Clements R, Rayan DM, Zafir AWA, Venkataraman A, Alfred R, et al. 2010. Trio under threat: Can we secure the future of rhinos, elephants and tigers in Malaysia? *Biodivers. Conserv.* 19(4):1115–36
70. Nijman V. 2005. Decline of the endemic Hose's langur *Presbytis hosei* in Kayan Mentarang National Park, East Borneo. *Oryx* 39(02):223–26
71. Tang J-L, Liu B-Y, Ma K-W. 2008. Traditional Chinese medicine. *Lancet* 372:1938–40
72. Still J. 2003. Use of animal products in traditional Chinese medicine: environmental impact and health hazards. *Complement. Ther. Med.* 11:118–22
73. Chen T-H, Chang H-C, Lue K-Y. 2009. Unregulated trade in turtle shells for Chinese traditional medicine in East and Southeast Asia: the case of Taiwan. *Chelonian Conserv. Biol.* 8(1):11–18
74. Cheng W, Xing S, Bonebrake TC. 2017. Recent pangolin seizures in China reveal priority areas for intervention. *Conserv. Lett.* 10:757–64
75. De Lopez TT. 2003. Economics and stakeholders of Ream National Park, Cambodia. *Ecol. Econ.* 46(2):269–82
76. Schulte-Herbrueggen B, Cowlishaw G, Homewood K, Rowcliffe JM. 2013. The importance of bushmeat in the livelihoods of West African cash-crop farmers living in a faunally-depleted landscape. *PLOS ONE* 8(8):e72807
77. Schulte-Herbruggen B, Cowlishaw G, Homewood K, Rowcliffe JM. 2017. Rural protein insufficiency in a wildlife-depleted West African farm-forest landscape. *PLOS ONE* 12:e0188109

78. Coad L, Campbell A, Miles L, Humphries K. 2008. *The Costs and Benefits of Protected Areas for Local Livelihoods: A Review of the Current Literature*. Cambridge, UK: UNEP World Conserv. Monit. Cent.
79. Abram NK, Meijaard E, Ancrenaz M, Runting RK, Wells JA, et al. 2014. Spatially explicit perceptions of ecosystem services and land cover change in forested regions of Borneo. *Ecosyst. Serv.* 7:116–27
80. Sunderlin WD, Angelsen A, Belcher B, Burgers P, Nasi R, et al. 2005. Livelihoods, forests, and conservation in developing countries: an overview. *World Dev.* 33(9):1383–402
81. Karesh WB, Cook RA, Bennett EL, Newcomb J. 2005. Wildlife trade and global disease emergence. *Emerg Infect. Dis.* 11(7):1000–2
82. Daszak P, Cunningham AA, Hyatt AD. 2000. Emerging infectious diseases of wildlife–threats to biodiversity and human health. *Science* 287(5452):443–49
83. Rosen GE, Smith KF. 2010. Summarizing the evidence on the international trade in illegal wildlife. *Ecohealth* 7(1):24–32
84. Smith KM, Anthony SJ, Switzer WM, Epstein JH, Seimon T, et al. 2012. Zoonotic viruses associated with illegally imported wildlife products. *PLOS ONE* 7(1):71–79
85. Chaber A-L, Cunningham A. 2016. Public health risks from illegally imported African bushmeat and smoked fish. *Ecohealth* 13(1):135–38
86. Bell D, Roberton S, Hunter P. 2004. Animal origins of SARS coronavirus: possible links with the international trade in small carnivores. *Philos. Trans. R. Soc. B* 359(1447):1107–14
87. Greatorex ZF, Olson SH, Singhalath S, Silithammavong S, Khammavong K, et al. 2016. Wildlife trade and human health in Lao PDR: an assessment of the zoonotic disease risk in markets. *PLOS ONE* 11(3):e0150666
88. Butler CD. 2012. Infectious disease emergence and global change: thinking systemically in a shrinking world. *Infect. Dis. Poverty* 1:5
89. Swift L, Hunter PR, Lees AC, Bell DJ. 2007. Wildlife trade and the emergence of infectious diseases. *Ecohealth* 4(1):25–30
90. Heymann DL, Shindo N. 2020. COVID-19: What is next for public health? *Lancet* 395(10224):542–45
91. Bharucha Z, Pretty J. 2010. The roles and values of wild foods in agricultural systems. *Philos. Trans. R. Soc. B* 365(1554):2913–26
92. Pangau-Adam M, Noske R, Muehlenberg M. 2012. Wildmeat or bushmeat? Subsistence hunting and commercial harvesting in Papua (West New Guinea), Indonesia. *Hum. Ecol.* 40(4):611–21
93. Rist J, Milner-Gulland EJ, Cowlishaw G, Rowcliffe M. 2010. Hunter reporting of catch per unit effort as a monitoring tool in a bushmeat-harvesting system. *Conserv. Biol.* 24(2):489–99
94. Cuthbert R. 2010. Sustainability of hunting, population densities, intrinsic rates of increase and conservation of Papua New Guinean mammals: a quantitative review. *Biol. Conserv.* 143(8):1850–59
95. Milner JM, Nilsen EB, Andreassen HP. 2007. Demographic side effects of selective hunting in ungulates and carnivores. *Conserv. Biol.* 21(1):36–47
96. de la Montana E, del Pilar Moreno-Sanchez R, Maldonado JH, Griffith DM. 2015. Predicting hunter behavior of indigenous communities in the Ecuadorian Amazon: insights from a household production model. *Ecol. Soc.* 20(4):30
97. Reuter KE, Randell H, Wills AR, Janvier TE, Belalahy TR, Sewall BJ. 2016. Capture, movement, trade, and consumption of mammals in Madagascar. *PLOS ONE* 11(2):e0150305
98. Scherl LM. 2004. *Can Protected Areas Contribute to Poverty Reduction? Opportunities and Limitations*. Gland, Switz.: Int. Union Conserv. Nat.
99. Chape S. 2001. An overview of integrated approaches to conservation and community development in the Lao People's Democratic Republic. *Parks* 11(2):24–32
100. Macdonald DW, Johnson PJ, Albrechtsen L, Seymour S, Dupain J, et al. 2012. Bushmeat trade in the Cross–Sanaga rivers region: evidence for the importance of protected areas. *Biol. Conserv.* 147(1):107–14
101. Poulsen JR, Clark CJ, Bolker BM. 2011. Decoupling the effects of logging and hunting on an Afrotropical animal community. *Ecol. Appl.* 21(5):1819–36
102. Nunez-Iturri G, Howe HF. 2007. Bushmeat and the fate of trees with seeds dispersed by large primates in a lowland rain forest in western Amazonia. *Biotropica* 39(3):348–54

103. Basuki I, Sheil D, Padmanaba M, Liswanti N, Mulcahy G, Wan M. 2011. The evolving role of tropical forests for local livelihoods in Indonesia. *Int. J. Environ. Sustain. Dev.* 10(3):267–87
104. Nielsen MR, Treue T. 2012. Hunting for the benefits of joint forest management in the eastern Afromontane biodiversity hotspot: effects on bushmeat hunters and wildlife in the Udzungwa Mountains. *World Dev.* 40(6):1224–39
105. Shaffer CA, Milstein MS, Yukuma C, Marawanaru E, Suse P. 2017. Sustainability and comanagement of subsistence hunting in an indigenous reserve in Guyana. *Conserv. Biol.* 31(5):1119–31
106. McNeely JA, Kapoor-Vijay P, Lu Z, Olsvig-Whittaker L, Sheikh KM, Smith AT. 2009. Conservation biology in Asia: the major policy challenges. *Conserv. Biol.* 23(4):805–10
107. Yasuoka H, Hirai M, Kamgaing TOW, Dzefack ZCB, Kamdoum EC, Bobo KS. 2015. Changes in the composition of hunting catches in southeastern Cameroon: a promising approach for collaborative wildlife management between ecologists and local hunters. *Ecol. Soc.* 20(4):25
108. Thomson J. 2008. *Captive Breeding of Selected Taxa in Cambodia and Viet Nam: A Reference Manual for Farm Operators and CITES Authorities. TRAFFIC Southeast Asia, Greater Mekong Programme, Ha Noi, Viet Nam.* **https://www.traffic.org/site/assets/files/10083/captive-breeding-cambodia-vietnam.pdf**
109. Lyons JA, Natusch DJ. 2011. Wildlife laundering through breeding farms: illegal harvest, population declines and a means of regulating the trade of green pythons (*Morelia viridis*) from Indonesia. *Biol. Conserv.* 144(12):3073–81
110. Drury R. 2009. Reducing urban demand for wild animals in Vietnam: examining the potential of wildlife farming as a conservation tool. *Conserv. Lett.* 2(6):263–70
111. Brashares J, Arcese P, Sam M, Coppolillo P, Sinclair A, Balmford A. 2004. Bushmeat hunting, wildlife declines, and fish supply in West Africa. *Science* 306(5699):1180–83
112. Foerster S, Wilkie DS, Morelli GA, Demmer J, Starkey M, et al. 2012. Correlates of bushmeat hunting among remote rural households in Gabon, Central Africa. *Conserv. Biol.* 26(2):335–44
113. Zavaleta C, Berrang-Ford L, Llanos-Cuentas A, Cárcamo C, Ford J, et al. 2017. Indigenous Shawi communities and national food security support: right direction, but not enough. *Food Policy* 73:75–87
114. Hoffman LC, Cawthorn DM. 2012. What is the role and contribution of meat from wildlife in providing high quality protein for consumption? *Anim. Front.* 2(4):40–53
115. Luskin MS, Christina ED, Kelley LC, Potts MD. 2014. Modern hunting practices and wild meat trade in the oil palm plantation-dominated landscapes of Sumatra, Indonesia. *Hum. Ecol.* 42(1):35–45
116. Li W, Wang H. 1999. Wildlife trade in Yunnan Province, China, at the border with Vietnam. *Traffic Bull.* 18(1):21–30
117. Luo J, Yan D, Song J, Zhang D, Xing X, et al. 2013. A strategy for trade monitoring and substitution of the organs of threatened animals. *Sci. Rep.* 3:3108
118. Yan D, Luo JY, Han YM, Peng C, Dong XP, et al. 2013. Forensic DNA barcoding and bio-response studies of animal horn products used in traditional medicine. *PLOS ONE* 8(2):e55854
119. TRAFFIC. 2012. Creative experts' meeting on messaging to reduce consumer demand for tigers and other endangered wildlife species in Vietnam and China: Meeting Report. TRAFFIC Int., Cambridge, UK. **https://www.traffic.org/site/assets/files/7030/creative-experts-meeting-hong-kong.pdf**
120. Yang D, Dai X, Deng Y, Lu W, Jiang Z. 2007. Changes in attitudes toward wildlife and wildlife meats in Hunan Province, central China, before and after the severe acute respiratory syndrome outbreak. *Integr. Zool.* 2(1):19–25
121. Van Song N. 2008. Wildlife trading in Vietnam: situation, causes, and solutions. *J. Environ. Dev.* 17(2):145–65
122. Challender DWS, Harrop SR, MacMillan DC. 2015. Understanding markets to conserve trade-threatened species in CITES. *Biol. Conserv.* 187:249–59
123. Li Y, Li D. 1998. The dynamics of trade in live wildlife across the Guangxi border between China and Vietnam during 1993–1996 and its control strategies. *Biodivers. Conserv.* 7(7):895–914
124. Pires SF, Moreto WD. 2011. Preventing wildlife crimes: solutions that can overcome the 'tragedy of the commons.' *Eur. J. Crim. Policy Res.* 17(2):101–23
125. Natusch DJ, Lyons JA. 2012. Exploited for pets: the harvest and trade of amphibians and reptiles from Indonesian New Guinea. *Biodivers. Conserv.* 21(11):2899–911

126. Nava A, Shimabukuro JS, Chmura AA, Bessa Luz SL. 2017. The impact of global environmental changes on infectious disease emergence with a focus on risks for Brazil. *ILAR J.* 58(3):393–400
127. Merianos A. 2007. Surveillance and response to disease emergence. *Curr. Top. Microbiol. Immunol.* 315:477–509
128. Coker R, Rushton J, Mounier-Jack S, Karimuribo E, Lutumba P, et al. 2011. Towards a conceptual framework to support one-health research for policy on emerging zoonoses. *Lancet Infect. Dis.* 11(4):326–31
129. Brodie JF, Gibbs HK. 2009. Bushmeat hunting as climate threat. *Science* 326(5951):364–65
130. Boafo YA, Saito O, Jasaw GS, Otsuki K, Takeuchi K. 2016. Provisioning ecosystem services-sharing as a coping and adaptation strategy among rural communities in Ghana's semi-arid ecosystem. *Ecosyst. Serv.* 19:92–102
131. Machovina B, Feeley KJ, Ripple WJ. 2015. Biodiversity conservation: The key is reducing meat consumption. *Sci. Total Environ.* 536:419–31
132. Apaza L, Wilkie D, Byron E, Huanca T, Leonard W, et al. 2002. Meat prices influence the consumption of wildlife by the Tsimane Amerindians of Bolivia. *Oryx* 36(4):382–88
133. van Vliet N, Fa J, Nasi R. 2015. Managing hunting under uncertainty: from one-off ecological indicators to resilience approaches in assessing the sustainability of bushmeat hunting. *Ecol. Soc.* 20(3):7
134. Chomel BB, Belotto A, Meslin F-X. 2007. Wildlife, exotic pets, and emerging zoonoses. *Emerg. Infect. Dis.* 13(1):6–11
135. Ordaz-Nemeth I, Arandjelovic M, Boesch L, Gatiso T, Grimes T, et al. 2017. The socio-economic drivers of bushmeat consumption during the West African Ebola crisis. *PLOS Negl. Trop. Dis.* 11(3):e0005450
136. Gbogbo F, Kyei MO. 2017. Knowledge, perceptions and attitude of a community living around a colony of straw-coloured fruit bats (*Eidolon helvum*) in Ghana after Ebola virus disease outbreak in West Africa. *Zoonoses Public Health* 64(8):628–35
137. Friant S, Paige SB, Goldberg TL. 2015. Drivers of bushmeat hunting and perceptions of zoonoses in Nigerian hunting communities. *PLOS Negl. Trop. Dis.* 9(5):e0003792
138. Dutton AJ, Hepburn C, Macdonald DW. 2011. A stated preference investigation into the Chinese demand for farmed versus wild bear bile. *PLOS ONE* 6. **https://doi.org/10.1371/journal.pone.0021243**
139. Liu Z, Jiang Z, Yang A, Xu B, Fang H, et al. 2017. Attitudes toward bile extraction from living bears: survey of citizens and students in Beijing. *J. Appl. Anim. Welfare Sci.* 20:205–18
140. Liu Z, Jiang Z, Fang H, Li C, Mi A, et al. 2016. Perception, price and preference: consumption and protection of wild animals used in traditional medicine. *PLOS ONE* 11(3):e0145901
141. Graham-Rowe D. 2011. Biodiversity: endangered and in demand. *Nature* 480(7378):S101–3
142. Truong VD, Dang NVH, Hall CM. 2016. The marketplace management of illegal elixirs: illicit consumption of rhino horn. *Consum. Mark. Cult.* 19:353–69
143. Lee TM, Sigouin A, Pinedo-Vasquez M, Nasi R. 2014. *The harvest of wildlife for bushmeat and traditional medicine in East, South and Southeast Asia: current knowledge base, challenges, opportunities and areas for future research*. Occas. Pap. 115, Cent. Int. For. Res. (CIFOR), Bogor, Indones. **http://dx.doi.org/10.17528/cifor/005135**

Annual Review of Environment and Resources

Volume 45, 2020

Contents

IV. Management and Governance of Resources and Environment

V. Methods and Indicators

Indexes

Errata

An online log of corrections to *Annual Review of Environment and Resources* articles may be found at http://www.annualreviews.org/errata/environ