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Wild animal and zoonotic disease risk management and regulation in China: Examining gaps and One Health opportunities in scope, mandates, and monitoring systems

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ABSTRACT

Emerging diseases of zoonotic origin such as COVID-19 are a continuing public health threat in China that lead to a significant socioeconomic burden. This study reviewed the current laws and regulations, government reports and policy documents, and existing literature on zoonotic disease preparedness and prevention across the forestry, agriculture, and public health authorities in China, to articulate the current landscape of potential risks, existing mandates, and gaps. A total of 55 known zoonotic diseases (59 pathogens) are routinely monitored under a multi-sectoral system among humans and domestic and wild animals in China. These diseases have been detected in wild mammals, birds, reptiles, amphibians, and fish or other aquatic animals, the majority of which are transmitted between humans and animals via direct or indirect contact and vectors. However, this current monitoring system covers a limited scope of disease threats and animal host species, warranting expanded review for sources of disease and pathogen with zoonotic potential. In addition, the governance of wild animal protection and utilization and limited knowledge about wild animal trade value chains present challenges for zoonotic disease risk assessment and monitoring, and affect the completeness of mandates and enforcement. A coordinated and collaborative mechanism among different departments is required for the effective monitoring and management of disease emergence and transmission risks in the animal value chains. Moreover, pathogen surveillance among wild animal hosts and human populations outside of the routine monitoring system will fill the data gaps and improve our understanding of future emerging zoonotic threats to achieve disease prevention. The findings and recommendations will advance One Health collaboration across government and non-government stakeholders to optimize monitoring and surveillance, risk management, and emergency responses to known and novel zoonotic threats, and support COVID-19 recovery efforts.

1. Introduction

1.1. Impacts of emerging and re-emerging zoonotic diseases

Zoonotic diseases have been featured throughout human history, accounting for more than 60% of the known human infectious diseases, and are associated with environmental conditions and human activities interacting with animals. A review reported that approximately 70% of the emerging zoonotic disease events detected during 1940–2006 were originated from wild animals [1]. In China, a number of infectious diseases known or strongly suspected to have zoonotic origins have emerged or re-emerged over the past two decades, leading to local outbreaks and pandemics [2]. These include Severe Acute Respiratory Syndrome (SARS), Highly Pathogenic Avian Influenza (HPAI) H5N1, H7N9 Influenza, and Coronavirus disease 2019 (COVID-19) as a significant threat to the health security in China and elsewhere in the world [3–8].

The impacts of emerging zoonotic diseases extend far beyond disease burden, with demonstrated socioeconomic consequences for multiple sectors at the country, regional, and global levels when the diseases

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spread through international travel [9,10]. As a result of the country-wide lockdown for COVID-19, China's gross domestic product (GDP) in the first quarter of 2020 decreased by 6.8% as compared with the first quarter of 2019, being the first reported economic constriction in China since 1976 [11]. The predicted impact of COVID-19 on the global travel and tourism sector is approximately 100.8 million job losses and a loss of $2.7 trillion contributing to global GDP in 2020 [12]. Many other indirect impacts from COVID-19 on the environment, such as illegal poaching or deforestation, and on human populations including education and psychological effects, have been reported, although they are seldom evaluated in economic terms [13,14].

1.2. Utilization of wild animals as a key risk pathway

As the impacts are multi-sectoral, the proactive management of disease threats will require new approaches for governments, communities, and the private sector to identify and address the key risk pathways. Among many of the human activities driving emerging zoonotic infections, utilization of wild animals for commercial trade, farming, and captivity in China represents the most direct interface and a systematic pattern of interactions between human and wild animal, posing a significant risk of zoonotic spillover from wild animal to domestic animal and human [15–17]. While the connections between wild animals in markets and the initial outbreaks of SARS and COVID-19 are still under active scientific research, the animal origin of SARS-CoV-1 and SARS-CoV-2 and the presence of live animals in the local markets that were linked to early human cases further emphasize the need to assess the disease risk in wild animal utilization practices [18–20]. Therefore, understanding existing policies, mandates, and systems around these at-risk activities in China is essential to characterize the risk pathway, assess zoonotic risk, identify key stakeholders, and develop mitigation strategies.

To strengthen prevention and preparedness measures, many countries are currently examining enhancements to their regulations, institutional mandates, and operations [21]. Given China's importance as a consumer and producer of wild animal products and the fact that it possesses a rapid development trajectory with increasing investment in agriculture and forestry, and being a world leader in emerging zoonotic disease research, we review current systems in place for zoonotic disease monitoring in humans and animals in China; analyze the species coverage against known zoonotic disease sources; present areas of focus for further attention. The prevention and preparedness measures for zoonotic diseases vary in different situations, this article primarily focuses on the systems in place to regulate at-risk human–animal interactions in wild animal trade and captive-breeding relevant to forestry, agriculture, and public health sectors.

2. Review methods and data

This study reviewed the current laws and regulations, government reports and policy documents, and existing literature on zoonotic disease preparedness and prevention across the forestry, agriculture, and public health authorities in China to identify areas of coverage and gaps. Specifically, we reviewed: i) Relevant policies implemented at the national level in response to COVID-19 in China; ii) China's wild animal management and governance structure; and iii) China's zoonotic disease management system. Information was sourced from government reports and websites and peer-reviewed literature, using a One Health lens to provide an overview of the current systems related to the assessment, monitoring, and management of zoonotic diseases and disease emergence risks (Supplementary Material I).

3. Results

3.1. Collaboration across sectors for management of COVID-19

The initial response to, and control of, COVID-19 in China illustrated a collaborative effort of multiple authorities (Fig. 1). In addition to the work of public health and human medicine, six departments, agriculture, forestry, market regulation, public security, customs, and transport, were involved in the regulation of the value chain and activities for wild animal trade [22–28]. A decision was made by the Standing Committee of the National People's Congress in February 2020 to prohibit wild animal consumption [29], followed by the amendment of the National Catalogue of Livestock and Poultry Genetic Resources by the agriculture department to define the legality of which animals can be consumed [30]. Moreover, the Animal Epidemic Prevention Law has been amended and released on January 23, 2021 [31], and the national list of endangered and protected species has been revised in February 2021 with additional 517 species added to the list [32]. These actions simultaneously highlighted existing gaps and fragmentation in the governance of zoonotic disease risk at the human-animal interfaces, which requires considerable coordination and communication to ensure cohesive and effective management among different sectors.

3.2. Wild animal management and governance structure

3.2.1. Governance of wild animal protection

The Wild Animal Protection Law (WAPL) was enacted in 1988 as the major state law to protect wild animals in China. A list of endangered and protected species was formulated in accordance with the provisions [33]. The WAPL is enforced by both the forestry and fisheries departments, which oversee the terrestrial and aquatic wild animals, respectively, according to the administrative regulations on the protection of terrestrial and aquatic wild animals. Similarly, the capture and breeding of wild terrestrial and aquatic animals are under separate management by the forestry and fisheries departments, respectively, with developed lists of captive-bred endangered and protected terrestrial and aquatic wild animals [34–36] and established technical standards and normative documents for farming activities. Moreover, a list of state-protected terrestrial wild animals with important ecological, scientific, and social values (3-Value) [37] has been formulated by the forestry department, which places under protection species that are not already covered by the list of endangered and protected species. Joint efforts are exerted by other government authorities of environment and ecology, development and reform, customs, and additional laws to protect endangered wild animals from being hunted (stated in the Criminal Law) and manage the access of wild animals or animal products to the market (provided by the Administrative License Law) (Supplementary Materials II). (Fig. 2).

3.2.2. Management of wild animal utilization

With decades of practice, the wild animal industry in China has developed to meet the local and global demand for animal products (e.g. fur), medicines, pets, food, and research. Approximately 2371 animal species or subspecies are documented as medicinal animals in the Annals of Chinese Medicinal Animals [38]; 18 animal species are listed as Class I or Class II wild medicinal species under state protection [39]; and 103 animal species are included in the Pharmacopoeia of the People's Republic of China (2010 version) [40,41]. Wild animal farming, product processing, trade, and tourism have significantly contributed to the national economy, particularly for the economic development of rural areas, generating more than $75 billion in economic output and providing employment for 14 million people in 2016 [42]. It is challenging to estimate the volume of captive and traded wild animals in China, owing to a lack of centralized tracking. Existing data from the literature show that there were at least 517 mammal, reptile, amphibian, and bird species from 114 families belonging to 33 orders being traded

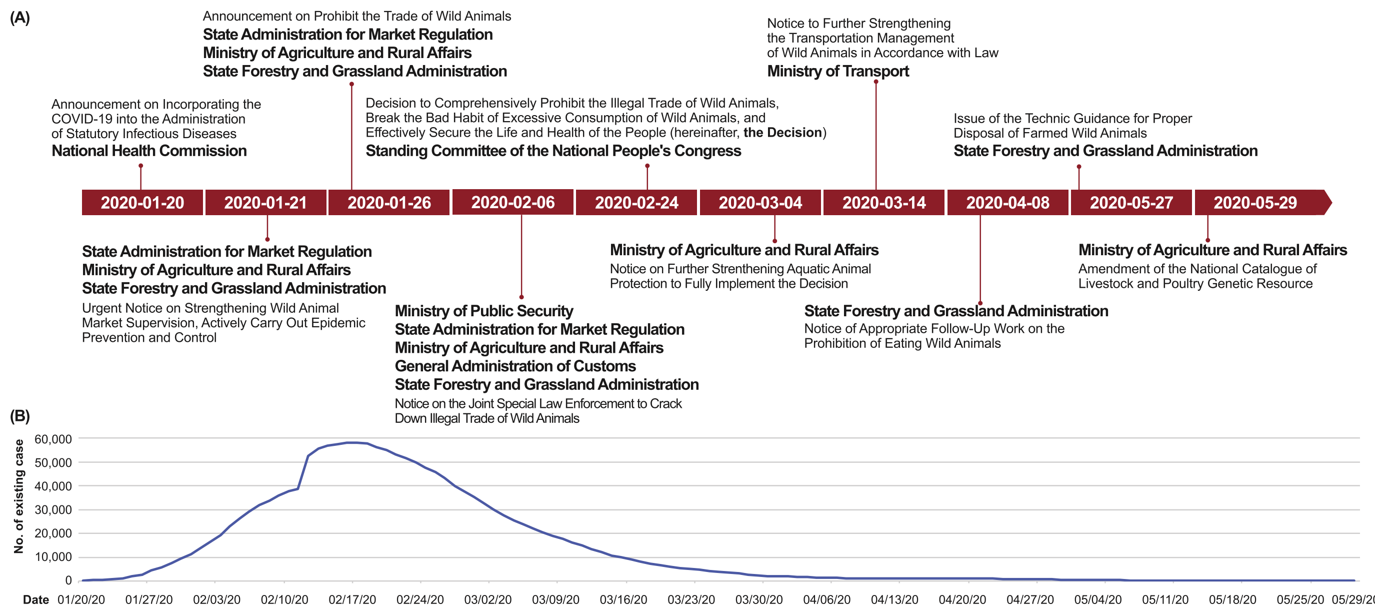

Fig. 1. (A) Relevant policies implemented by multiple government authorities in response to COVID-19 following the initial outbreaks in China, January 20 to May 29, 2020. (B) shows the number of existing COVID-19 cases in China during the same period.

or kept in captivity for commercial purposes during 1996–2017 (Supplementary Materials III). These numbers reveal only the tip of the iceberg of wild animal utilization in China without including aquatic animals and other animals for which data are insufficient.

Managing the utilization of wild animals in relation to the practices of hunting, farming, processing, transport, and sale in local markets is the responsibility of multiple departments (Fig. 3). Even though there are a series of checks and barriers, most wild animals can enter the value chain with appropriate permits regardless of their protection status [43]. Wild animals or their products can reach consumers directly from the wild or farms, or most commonly through a wholesale or retail point. Quarantine is required for transporting and trading wild animals at markets, but the procedures are insufficiently enforced, compounded by the involvement of multiple stakeholders including middlemen, processors, and abattoirs in the value chain [44]. Additionally, international value chains have been established to meet global demand. For example, China produced roughly 50% of the world's fur pelts in 2014 [45], farms in China are the leading suppliers of non-human primates

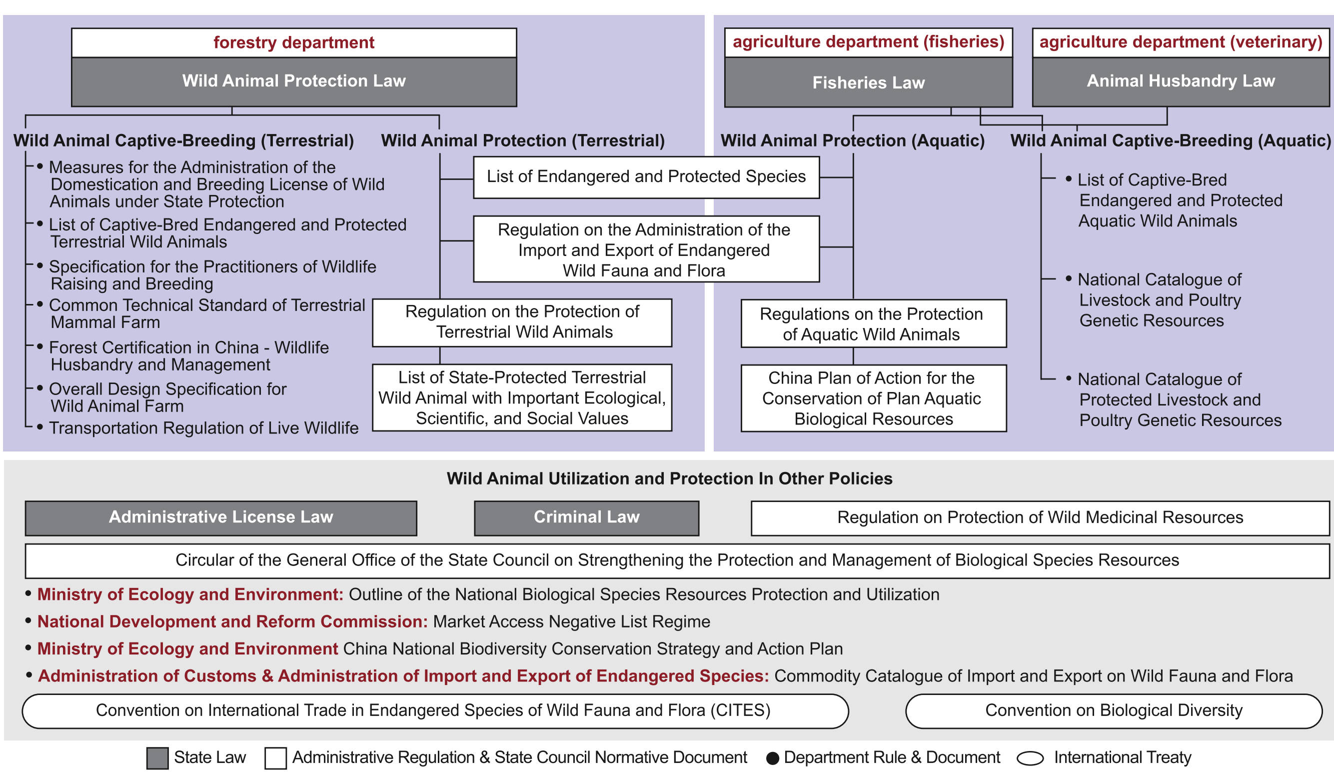

Fig. 2. Wild animal protection and management by forestry and agriculture departments, and other government stakeholders in wild animal utilization and protection via a variety of policies in China.

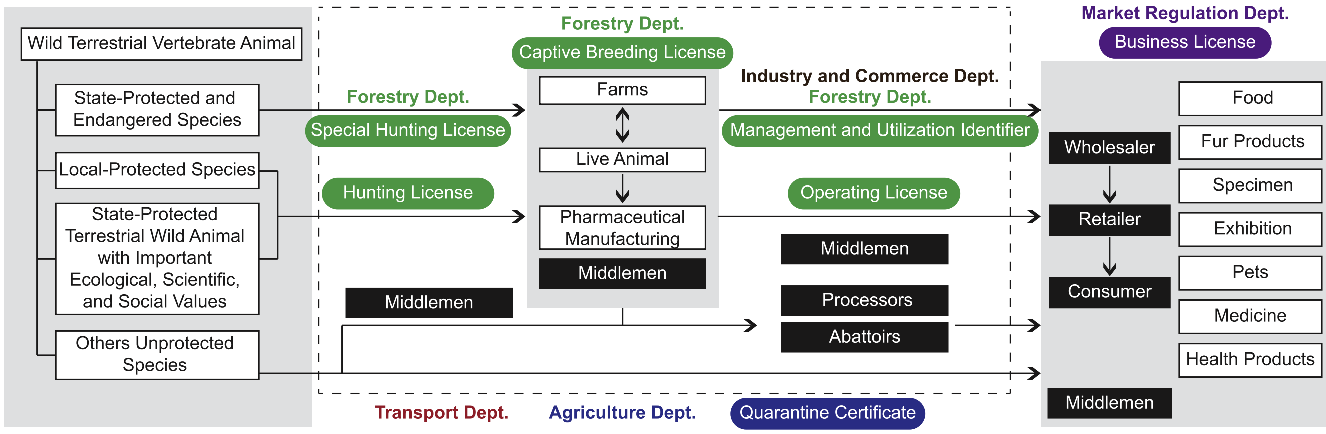

Fig. 3. Governance structure for the utilization of wild terrestrial vertebrate animals in China, adapted from [44].

(NHP) used in scientific research [46,47], which not only accelerates the industry development but also add challenges in management.

3.2.3. *Limited and uneven coverage of wild animals for protection*

The protection of wild animals is considered to be an approach to help reduce at-risk human-animal interactions to prevent potential zoonotic pathogen spillover. However, the coverage of species in the current wild animal protection system is limited and uneven. A review of 2888 vertebrate animals present in China showed that 1077 species are outside the scope of state protection [48]. The protection status of many species needs to be updated in accordance with changes in their populations. Many newly discovered species, as well as some endangered or critically endangered species recognized by the International Union for Conservation of Nature (IUCN), have not been considered or evaluated for the current protection list [49]. Species and taxonomic groups relevant for disease emergence, for example, all 135 known bat species and many rodent species in China, are not protected from hunting or trade [50].

3.2.4. *Ambiguous wild animal governance hinders disease monitoring*

The current wild animal regulation and management system represent a fundamental challenge to implementing disease risk monitoring and reduction among wild animals. Overlapping or separate management of aquatic and terrestrial wildlife by the forestry and agriculture departments undermines the responsibility and accountability in enforcement, neglecting the management of many reptile and amphibian species [48,51]. The same situation is true for animal species that are not clearly defined as domestic or wild due to the long captive-breeding histories (e.g., deer, mink, and fox), leading to ambiguities in the management between the forestry and agriculture departments [44]. Amendments have been made to the relevant laws in China as the initial step to address these challenges in the management system [30,52,53], but incorporating these changes into the disease monitoring system among wild animals requires more enabling mechanisms and coordination of mandates.

3.2.5. *Understanding the wild animal trade value chains*

Limited understanding of the wild animal trade value chains (Fig. 3) in China is one of the greatest challenges in the risk assessment of zoonotic transmission and disease emergence at the wildlife–livestock–human interface, particularly in the peri-domestic or domestic setting. There are few published studies documenting the value chains of farming and trading wild animals, and as a result, very little is known about how wild animals are produced and traded or their interactions with domestic animals and humans before reaching consumers, or which populations are involved along the value chains and how they operate and interact with wild-sourced stock, which is further compounded by the vague definitions of "wild animal" and "farmed wild animal" in Chinese regulations across different authorities [54]. Given the high volume of wild animal farming and consumption in China, such information will be important for understanding the epidemiological, economic, and social aspects of zoonotic disease transmission risks. A solid understanding of wild animal trade value chains not only allows for the evaluation of potential pathogen transmission pathways and critical control points in risk assessment but also helps to form practical risk mitigation measures that are viewed as economically viable and socially acceptable by stakeholders.

3.3. *Zoonotic disease management system*

3.3.1. *Cross-sectoral management of zoonotic disease in human, domestic and wild animal*

Zoonotic diseases in China have been primarily monitored and regulated by the human health and veterinary departments. A list of notifiable human infectious diseases has been established for monitoring and reporting under the Law of Prevention and Treatment of Infectious Diseases [55]. Similarly, the veterinary department under the Ministry of Agriculture and Rural Affairs has developed a list of animal epidemic diseases for regular monitoring and reporting, and measures for the administration, investigation, evaluation, and contingency plans of animal epidemics [56–64]. Technical guidance or standard documents for specific animal epidemics are also developed and distributed by the veterinary department on a regular basis [65,66]. In 2009, the Health and Agriculture Ministries collaboratively issued a list of zoonotic infectious diseases [67,68]. These schemes together serve as part of the national emergency response system.

A wild animal epidemic and epidemic source monitoring center was founded under the forestry department in 2005. It has developed into a wide network that consists of national (305), provincial (918), and city/county-level monitoring stations, and 2000 institutions for an online reporting system [69]. This system is centered around terrestrial wild animals, while disease monitoring for aquatic animals is implemented by the agriculture department. In 2013, the administrative measures for monitoring and controlling epidemics and epidemic sources for terrestrial wild animals was enacted by the forestry department to outline the procedure and accountability for terrestrial wild animal disease monitoring, reporting, and response. Several rules and normative documents were issued by the forestry department including the lists of wildlife epidemics for monitoring and technique standards for wildlife disease investigation and wild animal captive breeding [70–75]. The China National Biodiversity Conservation Strategy and Action Plan (2011–2030) has set goals to conduct a nationwide assessment of wild animal diseases to build a database for preventing and controlling animal epidemics [76]. (Fig. 4; Supplementary Materials II).

Among these multiple systems, 55 zoonotic diseases (59 disease agents) are under regular monitoring in China by the human health (43), agriculture (29), and forestry (7) departments. More than half of these diseases (35 disease agents) are endemic in human populations in China, seven have caused local outbreaks over the past 20 years, and five have been linked to imported cases (Table 1).

3.3.2. Wild animal hosts and the transmission routes of monitored zoonotic diseases

Analysis of the potential wild animal hosts for the 59 zoonotic disease agents monitored in China shows that wild animals in the class Mammalia are potential hosts for 71% of the agents, followed by the classes Aves (17), Reptilia (5), and Amphibia (2). Many monitored zoonotic agents are associated with wild animals in the orders Carnivora (20), Artiodactyla (18), and Rodentia (15), bats (order Chiroptera) are hosts of 13 monitored zoonotic agents and known as reservoirs for SARS-related coronaviruses. In addition, fish and other aquatic animals are potential hosts for 10 zoonotic agents under monitoring (Table 2).

These monitored disease agents vary in their transmission routes and zoonotic risks from causing endemics to be only linked to single or rare spillover events thus far. Diseases such as anthrax and tularemia can be transmitted from animals to humans through multiple routes, ranging from direct contact with infected animals to food- or waterborne exposures, while rabies and leishmaniasis are known to have a single route of transmission. More than half of the monitored zoonotic diseases (32) are associated with direct or indirect contact with animal hosts, and 17 are transmitted via vectors. Among the five zoonotic diseases that are currently reported as imported cases, four are vector-borne diseases with the potential of local emergence affected by climate conditions and the presence of competent arthropod vector species in China. The role of wild animals may not be significant for some diseases if the transmission cycle between humans and arthropods sustains the pathogen within human populations (e.g., lymphatic filariasis), or the pathogens have been readily spread within the humans without an animal host (e.g., HIV/AIDS, SARS) (Table 2).

3.3.3. Limited scope of zoonotic disease monitoring

Many wild animals as hosts of zoonotic pathogens are being traded and kept in captivity in China, including rats or other small rodent species as primary hosts for several zoonotic infections. The practices of capturing, transporting, handling, or processing wild animals, including holding animals in markets and farms, create routes for zoonotic pathogens transmission and provide chances for pathogen evolution and amplification. Meanwhile, many other zoonotic diseases with increasing human cases in China, and emerging zoonotic diseases of public health concerns occurring in other Asian countries in recent years are not systematically monitored [77–80]. The lack of investigation on the source of reported disease incidence also limits our understanding of the zoonotic transmission routes to identify the animal origins for better risk assessment and monitoring. Therefore, the number of zoonotic diseases with endemic risks in China and the wide range of wild animal host species require an expanded review and scope of the monitoring system regarding the pathogens, wild animal species, and at-risk human populations.

4. Discussion

The present review indicates that there are existing scope and operations in China for wild animal management and zoonotic disease risk monitoring. However, the coverage of diseases or pathogens with zoonotic risk, as well as the management of potential wild animal hosts to prevent disease emergence, are limited in the current system. Proactive screening of zoonotic diseases or emerging pathogens with zoonotic potential in wild animal populations is often overlooked by the system; instead, it relies heavily on the research community that would require additional mechanisms for integration into government monitoring and policy. The gaps in the completeness of mandates and enforcement about wild animal management in the at-risk scenarios of wild animal utilization remain a concern for emerging zoonotic disease prevention and preparedness. The lack of a cohesive strategy has resulted in data gaps that make it challenging to precisely identify the practices and aspects of disease risks in the wildlife animal trade value chains. A more coordinated governance structure and regulation system are needed for the systematic assessment and management of zoonotic disease emergence risks in China.

4.1. Coordinated and collaborative disease monitoring

In line with China's recent investment in epidemic preparedness [81], which emphasizes a One Health approach to zoonotic and other

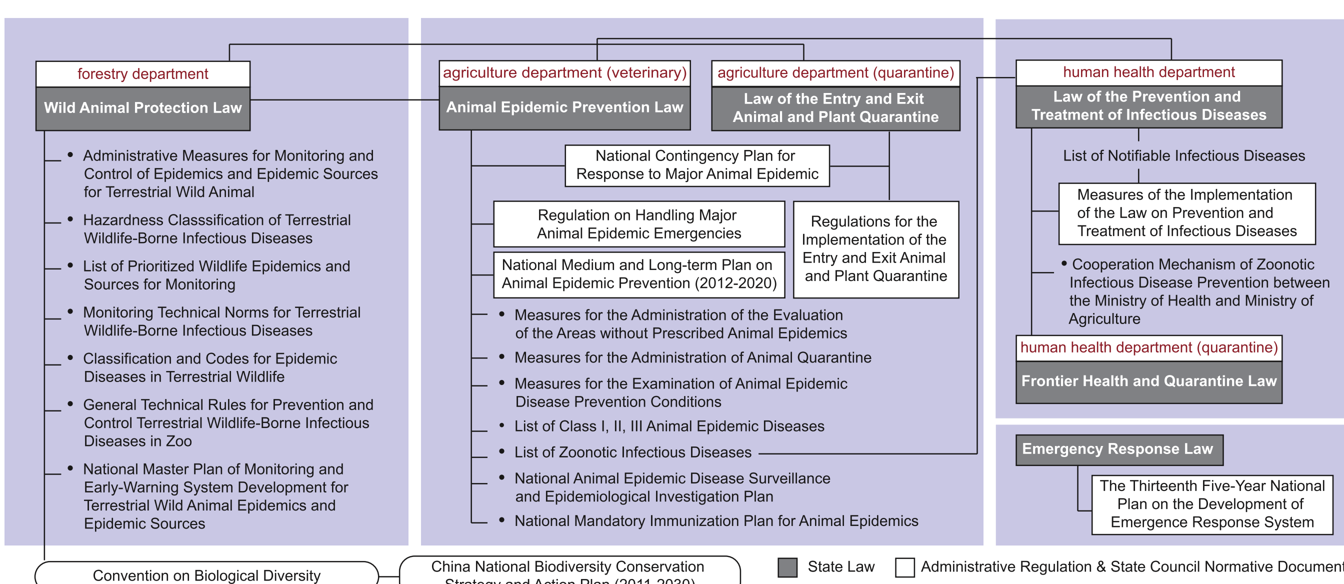

Fig. 4. Zoonotic disease monitoring and management policies in China.

Table 1
Zoonotic disease classification and monitoring under the human health, agriculture, and forestry departments in China [92–136].

Disease or disease agent	Type of pathogen	Epidemiological occurrence of human case in China	Monitoring & reporting regulations					
			Notifiable infectious diseases	Class I, II, III animal epidemic diseases	Zoonotic infectious diseases	Prioritized wildlife epidemics and resources for monitoring	Hazardness classification of terrestrial wildlife-borne infectious diseases	OIE-listed diseases 2020
Cholera	Bacteria	Sporadic	A					
Plague	Bacteria	Endemic/sporadic	A			X	B	
Avian influenza A (H7N9)	Virus	Endemic/*re*-emerging	B	II	X	X	B	X
Highly pathogenic avian influenza (H5N1)	Virus	Outbreak/no case reported since 2017	B	I	X	X	A	X
Acquired immunodeficiency syndrome (AIDS)	Virus	Endemic	B					
Rabies	Virus	Endemic	B	II	X	X	A	X
Brucellosis	Bacteria	Endemic	B	II	X	X	A	X
Bovine tuberculosis	Bacteria	Sporadic	B	II	X	X	A	X
Anthrax	Bacteria	Endemic	B	II	X		A	X
Leptospirosis	Bacteria	Sporadic	B	II	X		B	
Schistosomiasis japonica	Parasite	Endemic	B	II	X		A	
Japanese encephalitis (epidemic encephalitis B)	Virus	Endemic	B	II	X		C	X
Avian tuberculosis	Bacteria	Endemic/sporadic	B	III	X			X
Hemorrhagic fever with renal syndrome (HFRS) (hantavirus)	Virus	Endemic	B				C	
Severe acute respiratory syndrome (SARS)	Virus	Outbreak, 2002–2003	B				C	
Dengue fever	Virus	Endemic	B				C	
Hepatitis E	Virus	Endemic	B					
Coronavirus disease 2019 (COVID-19)	Virus	Outbreak, 2019-present	B					
Zoonotic malaria (Plasmodium knowlesi)	Parasite	Eliminated	B					
Echinococcosis	Parasite	Endemic	C	II	X		B	X
Colibacillosis: *E. coli* (O157:H7) (STEC) (infectious diarrhea)	Bacteria	Endemic	C	III	X		B	
Nontyphoidal Salmonella infections (infectious diarrhea)	Bacteria	Endemic	C	II	X			
Rotavirus disease (infectious diarrhea)	Virus	Endemic	C				B	
Giardiasis (infectious diarrhea)	Parasite	Endemic	C					
Yersiniosis (infectious diarrhea)	Bacteria	Endemic	C				B	
Cryptosporidiosis (infectious diarrhea)	Parasite	Endemic	C				B	
Lymphatic filariasis	Parasite	Eliminated	C	III	X			
Leishmaniasis: cutaneous and visceral (Kala-azar)	Parasite	Endemic	C	III	X		B	X
Epidemic typhus	Bacteria	Endemic	C					
Scrub typhus	Bacteria	Endemic	C					
Leprosy	Bacteria	Endemic/sporadic	C					
Chagas disease	Parasite	No	Others					
Lassa fever	Virus	No	Others				B	
Yellow fever	Virus	Imported cases	Others				C	
Ebola hemorrhagic fever	Virus	No	Others				B	
Zika virus	Virus	Imported cases	Others					
Angiostrongyliasis	Parasite	Endemic/emerging	Others					
Middle East respiratory syndrome (MERS)	Virus	Imported case, 2015	Others					
Rift Valley fever	Virus	Imported case, 2016	Others				B	X
Marburg hemorrhagic fever	Virus	No	Others				B	
Chikungunya	Virus	Imported cases/ outbreaks, 2010, 2017	Others				C	
Amoebiasis	Parasite	Endemic	Others					
Gnathostomiasis	Parasite	Endemic	Others					

(*continued on next page*)

Table 1 (*continued*)

Disease or disease agent	Type of pathogen	Epidemiological occurrence of human case in China	Monitoring & reporting regulations					
			Notifiable infectious diseases	Class I, II, III animal epidemic diseases	Zoonotic infectious diseases	Prioritized wildlife epidemics and resources for monitoring	Hazardness classification of terrestrial wildlife-borne infectious diseases	OIE-listed diseases 2020
West Nile fever	Virus	Endemic/sporadic/ emerging	Others			X	A	X
Norovirus	Virus	Endemic/outbreaks	Others					
Glanders/malleus	Bacteria	No	Others	II	X		B	X
Melioidosis	Bacteria	Endemic	Others	III	X		B	
Streptococcus suis	Bacteria	Sporadic/outbreak, 2005	Others	II	X			
Transmissible spongiform encephalopathies (TSE)	Prion	No		I	X		A	X
Toxoplasmosis	Parasite	Endemic		II	X		B	
Trichinellosis/trichinosis	Parasite	Endemic		II	X		B	X
Cysticercosis	Parasite	Endemic		II	X		B	X
Tularemia (rabbit fever)	Bacteria	Sporadic		II	X		B	X
Liver flukes (foodborne trematodiases)	Parasite	Endemic		III	X			
Q fever	Bacteria	Sporadic		III	X		B	X
Foot-and-mouth disease (FMD)	Virus	Sporadic		I			A	X
Listeriosis	Bacteria	Endemic/outbreaks		III	X		B	
Actinomycosis	Bacteria	Sporadic		III	X		B	
Eperythrozoonosis	Bacteria	Endemic/emerging		III			C	

Note: Epidemiologic Occurrence of Human Case in China: The epidemiological occurrence of human cases for each disease was classified as "Sporadic" when a disease occurs on occasion, singly, or as scattered instances; "Endemic" when a disease constantly present in the human population; "Outbreak" when a disease has led to many cases in a given area in a short time period; "Emerging" or "*Re*-emerging" when a disease that was increasing in incidence or spreading to new geographic areas; "Imported cases"; or combination of them. Pathogen isolated from animal hosts or serological evidence among human populations are not counted as occurrence. Lymphatic Filariasis was eliminated in China in 2007, and Malaria was eliminated in China in 2021.

emerging health threats, a highly coordinated and collaborative mechanism among different departments is required for effective monitoring of, and response to, disease emergence and transmission risks in animal value chains. Design and implementation of this envisioned system offer an opportunity to fill knowledge gaps about risks throughout the value chain for risk reduction, which is expected to improve the utility of the monitoring system in wild animals as a sentinel to identify potential zoonotic disease risks and prevent disease introduction into domestic animals and human populations. One practical application will be the design of a flow of information, as part of the monitoring system, from wild animal monitoring to trigger real-time risk alerts for human health, agriculture, and forestry authorities (and potentially others as needed, such as commerce or customs) to guide implementation of risk reduction strategies. As an existing example, the influenza monitoring and surveillance network established in China across human hospitals, the conservation community, and poultry and livestock industries demonstrated the feasibility of a cross-sectoral system to take joint responsibility for disease monitoring and biosecurity in markets and natural habitats to protect human and wild and domestic animal health [82,83]. Meanwhile, a centralized information system and the clearly defined responsibility and accountability of different authorities will lay the foundation for effective coordination and collaboration to improve wild animal management and disease monitoring in China.

4.2. Integrated surveillance and zoonotic risk analysis

Building on China's existing monitoring system for zoonotic diseases and pathogens, potential enhancements should be considered to shed light on relevant animal populations, dynamics between host species and microbes, and at-risk human activities to guide cost-effective monitoring and surveillance. While some wild animal species of relevance are overseen by the forestry authority, wild animals in peri-domestic or captive breeding settings should be emphasized given the high potential for inter-species contact and the fundamental changes in ecological and evolutionary dynamics in these settings. Beyond disease monitoring, upstream surveillance of potential zoonotic pathogens among wild animal hosts and at-risk human populations is a proactive approach for disease risk assessment and prevention if paired with follow-up risk reduction actions. Surveillance will advance our knowledge of other pathogens present in wild animal populations in China with zoonotic risk but outside the current monitoring and reporting system. Such work has elucidated the reservoir species for several high-consequence pathogens, such as SARS-CoV [84], and may help to elucidate the origins of SARS-CoV-2. It will also provide serological or molecular evidence indicating early spillover events and information on the animal host distribution and zoonotic transmission routes, which are valuable for assessing the potential of disease emergence and guiding targeted risk monitoring and mitigation efforts [85,86].

Results from both disease monitoring and pathogen surveillance in wild animals and human populations should be considered in the ongoing risk analysis procedures and the refinement of animal protection listings and regulations. In addition to the potential human health impact, socioeconomic impacts associated with the restriction of trade, human and animal movement, and animal-based food production are important determinants of the prioritization of disease monitoring and surveillance efforts to best inform mitigation options [87]. Recognizing the growing infectious disease threat as a result of globalized trade and travel, authorities must also strengthen the quarantine of potential pathogen animal hosts at the borders [88]. Given China's strong history of research on emerging pathogens, as well as decisive whole-of-society action to monitor and reduce HPAI risks, alignment of surveillance activities to guide additional research questions (e.g., specific reservoir species) can help efficiently fill the gaps to improve the understanding and future control and prevention of emerging pandemic threats and zoonotic diseases existing outside of the routine monitoring system.

Table 2
Potential animal hosts and transmission of monitored zoonotic pathogens in China [137–183].

Disease or disease agent	Type of pathogen	(potential) Wild animal host	(potential) Domestic animal host	Major animal-human transmission route	Vector	Human-to-human transmission
Cholera	Bacteria	Shellfish, fish, waterfowl incl. waders, egrets, herons, cormorants, pelicans, gulls	Farmed aquatic animals	Waterborne Foodborne	NA	Yes (fecal-oral)
Plague	Bacteria	Marmots, rodents, wild carnivores, wild cloven-hoofed mammals	Rodents	Direct contact Vector	Fleas	Yes (direct contact)
Avian Influenza A (H7N9)	Virus	Bar-headed geese, swans and other migratory or non-migratory birds of Anatidae	Poultry	Direct contact Indirect contact	NA	Limited
Highly pathogenic avian influenza (H5N1)	Virus	Bar-headed geese, swans and other migratory or non-migratory birds of Anatidae	Poultry	Direct contact Indirect Contact	NA	Limited
Acquired immunodeficiency syndrome (AIDS)	Virus	Great apes, monkeys (Hominidae, Cercopithecidae)		Direct contact	NA	Yes (direct contact)
Rabies	Virus	Bats, Carnivora esp. wolves, jackals, foxes, badgers	Domestic dogs	Direct contact	NA	No
Brucellosis	Bacteria	Bison, deer, wild boar, and other marine mammals	Sheep, goats, cattle, swine, domestic dogs	Direct contact Indirect Contact	NA	Rare
Bovine tuberculosis	Bacteria	Cloven-hooved mammals and non-human primates (wildlife reservoirs in certain countries incl. badgers, deer)	Cattle	Foodborne	NA	Rare
Anthrax	Bacteria	Herbivorous mammals (primary), birds	Cattle, sheep, horse, swine	Direct contact Indirect contact Foodborne	NA	Rare
Leptospirosis	Bacteria	Rodents (pathogen isolated from 67 animal species in China)	Rodents, swine, cattle, dogs	Direct contact Waterborne	NA	No
Schistosomiasis japonica	Parasite	Rodents, carnivores, freshwater snails	Cattle, buffalos	Waterborne	NA	No
Japanese encephalitis (epidemic encephalitis B)	Virus	Waterfowls, bats, great apes, monkeys	Swine	Vector	Mosquitoes (Culex spp.)	No
Avian tuberculosis	Bacteria	Wild birds	Poultry and captive birds, swine, cattle	Indirect contact (occasional)	NA	Unconfirmed
Hemorrhagic fever with renal syndrome (HFRS) (hantavirus)	Virus	Rodents (primary)		Direct contact Indirect contact	NA	No
Severe acute respiratory syndrome (SARS)	Virus	Bats, civets, raccoon dogs		(potential) Direct contact	NA	Yes (direct contact)
Dengue fever	Virus	Non-human primates	Domestic dogs	Vector (rare)	Mosquitoes (Aedes spp.)	Yes (vector presence, possible vertical transmission)
Hepatitis E	Virus	Wild boars (primary), deer, rabbits, mongooses	Swine (primary)	Direct contact Foodborne Waterborne	NA	Yes (fecal-oral)
Coronavirus disease 2019 (COVID-19)	Virus	Bats, pangolins, minks, tigers, lions	Domestic cats, macaques (experimental)	Unknown	NA	Yes (direct contact)
Zoonotic malaria (Plasmodium knowlesi)	Parasite	Non-human primates		Vector	Mosquitoes (Anopheles)	No
Echinococcosis	Parasite	Foxes, wolves and other Canidae, small rodents, other mammals	Domestic dogs	Direct contact Foodborne Waterborne	NA	No
Colibacillosis: *E. coli* (O157:H7) (STEC) (infectious diarrhea)	Bacteria	Rodents, birds, deer (found in a wide range of wild mammals and birds)	Cattle, sheep, goats, chicken, rabbits	Direct contact Foodborne Waterborne	NA	Yes (fecal-oral)
Nontyphoidal salmonella infections (infectious diarrhea)	Bacteria	Wild mammals, birds, reptiles, amphibians	Poultry, swine, cattle, pets incl. cats, dogs, reptiles, amphibians, birds	Foodborne (primary) Direct contact	NA	Yes (fecal-oral)
Rotavirus disease (infectious diarrhea)	Virus	Wild mammals, birds	Young calves and piglets, foals	Direct contact Indirect contact	NA	Yes (fecal-oral)
Giardiasis (infectious diarrhea)	Parasite	Non-human primates, rodents, wild boars	Cattle, goats, cats, dogs, swine, farmed raccoon dogs, deer, horses, donkeys	Direct contact Foodborne Waterborne	NA	Yes (fecal-oral)
Yersiniosis (infectious diarrhea)	Bacteria	Rodents, hares, birds, reptiles, aquatic animals	Swine, dogs, cats, sheep	Foodborne (primary) Direct contact	NA	Rare
Cryptosporidiosis (infectious diarrhea)	Parasite	Wide range of wild mammals	Cattle, sheep, cats, dogs	Direct contact Waterborne Foodborne	NA	Yes (fecal-oral)

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Table 2 (*continued*)

Disease or disease agent	Type of pathogen	(potential) Wild animal host	(potential) Domestic animal host	Major animal-human transmission route	Vector	Human-to-human transmission
Lymphatic filariasis	Parasite	Felines, non-human primates (no reservoir hosts in China)		Vector (rare)	Mosquitoes (Aedes spp., Culex spp., Anophles spp.)	Yes (vector presence)
Leishmaniasis: cutaneous and visceral (kala-azar)	Parasite	Canines, hares, rodents	Domestic dogs (primary), cats,	Vector	Sandflies (Phlebotomus spp.)	Yes (vector presence)
Epidemic typhus	Bacteria	Flying squirrels (*Glaucomys volans*) (rare)		Vector	Human body lice (*Pediculus humanus* corporis)	Yes (vector presence)
Scrub typhus	Bacteria	Wild rodents (genus Rattus)		Vector	Larval mites (trombiculid)	No
Leprosy	Bacteria	Nine-banded armadillo (*Dasypus novemcinctus*), chimpanzee, non-human primates		Direct contact (rare)	NA	Yes
Chagas disease	Parasite	Wide range of mammal species		Vector	Triatomines (kissing bugs)	Rare
Lassa fever	Virus	Rodents (genus Mastomys)		Direct contact Indirect contact	NA	Yes (direct contact)
Yellow fever	Virus	Non-human primates		Vector	Mosquitoes (Aedes spp., Hemagogus spp.)	Yes (vector presence)
Ebola hemorrhagic fever	Virus	Non-human primates, fruit bats, antelope, porcupines		Direct contact	NA	Yes (direct contact)
Zika virus	Virus	Non-human primates		Vector	Mosquitoes (Aedes spp.)	Yes (direct contact)
Angiostrongyliasis	Parasite	Rodents, freshwater snails	Freshwater shrimp, prawns, crabs, frogs.	Foodborne	NA	No
Middle East respiratory syndrome (MERS)	Virus	Bats	Dromedary camels	Direct contact Indirect Contact	NA	Yes (direct contact)
Rift Valley fever	Virus	Wild ruminants	Cattle, sheep, camels and goats.	Vector Direct contact	Mosquitoes (Aedes spp. & Culex spp.)	No
Marburg hemorrhagic fever	Virus	African fruit bat, non-human primates		Direct contact	NA	Yes (direct contact)
Chikungunya	Virus	Non-human primates, bats, palm squirrel		Vector	Mosquitoes	Yes (vector presence)
Amoebiasis	Parasite	Non-human primates	Swine	Foodborne Waterborne	NA	Yes (direct contact)
Gnathostomiasis	Parasite	Wild canines, felines, fish, eels, other aquatic animals	Domestic dogs, cats, swine (primary)	Foodborne	NA	No
West Nile fever	Virus	Migratory and non-migratory birds of Passeriformes, Corvidae (found in a wide range of vertebrates)	Poultry	Vector (primary) Direct contact	Mosquitoes (Culex spp.)	No
Norovirus	Virus	Wild birds, rodents, bats, marine mammals	Swine, cattle, cats, dogs, sheep	Unknown, potential reverse zoonosis	NA	Yes (direct contact)
Glanders/malleus	Bacteria	Wild equids, camels, wild carnivores, rodents	Domestic horses, mules, donkeys	Direct contact Indirect contact (rare)	NA	Rare
Melioidosis	Bacteria	Non-human primates, rodents, dolphins and other captive marine mammals (found in a wide range of mammals, birds, reptiles)	Swine, goats, cattle, horses, cats, dogs	Indirect contact Waterborne	NA	Rare
Streptococcus suis	Bacteria	Wild boars	Swine	Direct contact	NA	No
Transmissible spongiform encephalopathies (TSE)	Prion	Cervidae, Felidae, mustelidae	Cattle (bovine spongiform encephalopathy)	Foodborne	NA	No
Toxoplasmosis	Parasite	Felidae (primary), bats, birds, farmed sika deer, minks have been found infected in China	Swine, chicken, sheep, cattle, cats, dogs	Direct contact Foodborne	NA	No
Trichinellosis/trichinosis	Parasite	Wild carnivores, rodents Over 15 wild/domestic species can be infected in China	Swine and domestic dogs	Foodborne	NA	No
Cysticercosis	Parasite	Wild boars	Swine	Direct contact Foodborne	NA	Yes (fecal-oral)
Tularemia (rabbit fever)	Bacteria	Hares, rodents, hedgehogs, canids, felids, mustelids, deer, fish, crayfish	Domestic rabbits, dogs, cats	Direct contact Indirect contact Waterborne Vector	Ticks, deer flies	No
Liver flukes (foodborne trematodiases)	Parasite	Fish-eating mammals, aquatic animals incl. fish & crustaceans Freshwater snails	Domestic dogs, cats	Foodborne	NA	No
Q Fever	Bacteria	Rodents, birds, hares, other mammals and arthropods	Cattle, sheep, goats, cats, dogs	Direct contact Indirect contact Tick (rare)	Ticks	Rare
	Virus	African buffalos			NA	No

(*continued on next page*)

Table 2 (*continued*)

Disease or disease agent	Type of pathogen	(potential) Wild animal host	(potential) Domestic animal host	Major animal-human transmission route	Vector	Human-to-human transmission
Foot-and-mouth disease (FMD)			Cattle, swine, sheep, goats and other cloven-hoofed ruminants	Direct contact Indirect contact (rare)		
Listeriosis	Bacteria	Wide range of mammals, birds, and aquatic animals	Poultry, domestic ruminants	Foodborne Direct contact	NA	Rare (vertical transmission)
Actinomycosis	Bacteria	Wild deer species (Odocoileus spp., *Cervus elaphus*), moose, pronghorm, caribou, mountain sheep (Ovis spp.)	Cattle, horses, dogs , horses	Rare	NA	Rare
Eperythrozoonosis	Bacteria	Wild boar	Swine, cattle, rodents, sheep, llamas	Direct contact Vector	Lice, fleas, mosquitoes	Rare (vertical transmission)

Note:

• **Human-to-Human Transmission**: Human-to-human transmission for each disease was categorized as direct contact ("Yes") including close contact with blood, reparatory secretion, urine, feces; direct contact ("Yes") through fecal-oral route or vectors; "Limited" for viral pathogens represents non-sustained transmission of one or more generations without further spread; "Rare" for bacterial pathogens and parasite represents occasional transmission with sporadic cases reported; and 'Unconfirmed" for which the transmission route is under study.

• **Major Animal-Human Transmission Route**: Animal-human transmission route was categorized as "Direct contact"; "Indirect contact"; "Foodborne"; "Waterborne"; "Vector" following the definition by the US CDC Zoonotic Disease. Aquatic snails, in spite their potential role in the pathogen transmission between animals and humans, are regarded as intermediate hosts instead of vectors in this study.

• **(potential) Wild and Domestic Animal Hosts**: In order to make the table accessible and practical for monitoring purposes, common names of animals were used, instead of the scientific names. The list is not meant to be an exhaustive list of all potential animal hosts. It is difficult to determine which animal species are capable of natural infection with a certain disease, especially in wild animals where surveillance is often inadequate. Where data from China is available, the species and taxa of infected wild animal species was included. In addition, the most specific taxa of animal hosts from research in other countries and intergovernmental agencies' reports was recorded. For the majority of diseases, the role of listed potential wild animal hosts in the transmission of pathogen to humans and/or domestic animals will require further investigation.

4.3. A transdisciplinary approach for One Health

The present review considers the scope of government-level operations and coverage as a path for timely policy decisions, and a framework for emerging pathogens and zoonotic disease detection, response, and prevention. Similar attention should also be paid to non-government activities and research that are needed to ensure the effective implementation of strategies. Understanding the human–animal–environment interaction and its relationship to pathogen spillover risk in a sociocultural context provides a foundation for developing effective risk mitigation strategies. Although the current zoonotic disease management is oriented to human health and the animal industry, interdisciplinary consideration is required to reduce reverse zoonotic transmission risks to protect wild animal health. The integration of ecology and evolution that recognizes the dynamics between animal hosts and pathogens within environmental contexts, and the application of social and behavioral science to identify the at-risk human-animal interaction in the animal trade value chain will better inform disease management measurements in wild animal populations and animal production systems. This is relevant for decisions about appropriate treatment of existing wild animals in captive production and trading systems, with challenges that have been posed in the closures of the mink farming industry in Europe in response to COVID-19 [89]. Effective disease risk monitoring and management in animal populations also relies on skilled human capital and techniques that require investments in training and education across multiple disciplines [90,91].

Across both government and non-government stakeholder groups, a greater understanding of the relevance of emerging and zoonotic disease threats can motivate risk management and reinforce the need for coordinated sustainable development efforts in China. Attention to the direct and indirect impacts of known and novel disease threats can help to target entry points for intervention and identify areas where stopgap measures may be rapidly needed as part of COVID-19 recovery. The gaps identified in the existing landscape of policy responses, animal management, and disease and pathogen monitoring provide a basis for authorities to review their mandates and systems and contribute to an overall national strategy. A One Health platform supported by multiple sectors to provide insight and coordination for disease emergencies and routine operations has the potential to substantially address these gaps.

Authors' contributions

All authors contributed equally to the development of this study. H.L. & P.D. contributed to the conception and design of the study. H.L., Y.C., and C.C.M. conducted review and analysis of literature and policy information. H.L. and C.C.M. developed the first draft of the paper. P.D., H.T., A.A.C., and M.D.F. advised on manuscript writing and reviewed the paper. All authors read and approved the final manuscript.

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Declaration of Competing Interest

The authors declare there is no conflict of interest.

Appendix A. Supplementary data

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