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Potential Mammalian Vector-Borne Diseases in Live and Wet Markets in Indonesia and Myanmar

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Abstract: Vector-borne diseases spread from wild animals and their associated ectoparasites to humans and domesticated animals. Wildlife markets are recognized as important areas where this transfer can take place. We assessed the potential for spreading vector-borne diseases in two live and wet markets in Myanmar (Mong La, on the Myanmar-China border) and Indonesia (Sukahaji in Bandung on the island of Java) by making an inventory of all live and freshly killed wild mammals for sale. For eight mammal families, we quantified the number of animals on offer, and we used a heatmap cluster analysis to map vector-borne diseases that these families may carry. In Myanmar, we observed large numbers of wild pigs and deer (potentially carrying West Nile and various encephalitis viruses) whereas in Indonesia we observed Old World fruit bats (potentially carrying Chikungunya and encephalitis viruses) and squirrels (potentially carrying West Nile and encephalitis viruses). The trade in Indonesia was dominated by live mammals offered for sale as pets, and only Old World fruit bats and squirrels traded for traditional Asian medicine were killed in the markets. The trade in Myanmar was more geared towards wild meat (e.g., wild pigs, deer, primates) and traditional Asian medicine (squirrels). The combined risks of vector-borne diseases spreading from traded animals to human health highlight the need for an integrated approach protecting public health, economic interests and biodiversity.

Keywords: CITES; conservation; encephalitis; infectious diseases; One Heath; West Nile virus; wildlife trade; zoonosis

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1. Introduction

Vector-borne diseases account for 17% of the estimated global burden of all infectious diseases; their social, health and economic impacts continue to be very high [1]. The incidence of vector-borne diseases in humans, wild and domesticated animals has increased [2] in part due to an increase in the amount of contact between wild animals, their associated ectoparasites on the one hand and humans and domesticated animals on the other. Part of this is facilitated by the intrusion of humans into the domain of wild animals, e.g., due to accelerated land use changes, deforestation and habitat fragmentation, increased access to previously inaccessible areas and an increased globalization of commercial trade in wild animals [3,4]. The latter takes the form of the trade in dead animals, as in the wild meat trade or trade in animal parts for traditional medicine, or it can take the form of trade in

live animals, either for eventual consumption or for decorative purposes, such as to be kept as pets. The emergence of disease in new regions is caused primarily by pathogen movement due to trade and travel [5], whereas local emergence is driven by a combination of environmental changes that affect vectors and wildlife hosts and social changes that affect human exposure to vectors [6]. Vector-borne diseases that were once endemic to specific regions show up in hitherto unaffected regions because of globalization and climate change, and advances in molecular biology during the last three decades have led to the discovery of new vector-borne pathogenic organisms sometimes far outside their region of origin [7–10].

Trade in wildlife provides disease transmission mechanisms at levels that not only cause human disease outbreaks but also threaten livestock, international trade, rural livelihoods, native wildlife populations and the health of ecosystems. Wild mammals, birds, reptiles and amphibians flow daily through trading centers where they are in contact with people and numerous other species of animals (dead and alive, wild and domestic) before they are shipped to other markets, sold locally or released into the wild as part of religious customs meriting release or as unwanted pets [11]. The 2003 SARS-CoV-1 outbreak may have spread from a wildlife market in southern China, similar to the SARS-CoV-2 outbreak [12,13].

In Asia, the main vector-borne diseases of public health importance are malaria, dengue, Japanese encephalitis, chikungunya, African swine fever and West Nile virus amongst others [1,8,10,14,15]. In recent years, especially after the emergence of SARS-CoV-2 (COVID-19) and its links to the Wuhan wet markets in China, there have been calls to ban the sale of exotic animals in markets (e.g., [16]) or to curb the trade in illegal wildlife more effectively as these were seen as main vectors in the emergence of zoonotic diseases [17,18]. It is not 'just' exotic (i.e., non-native) animals or animals that are traded illegally that have the potential to carry diseases harmful to humans, but also includes a wide range of species that are traded legally [19]. Wildlife markets, especially open outdoor ones where wild-caught animals arrive alive and are either sold alive or are slaughtered in the market, bring together wildlife and large numbers of humans in close contact, potentially more so than in settings where the animals are living freely in their natural environment (e.g., a forest) where they may occasionally encounter humans. In Shenzhen, China, 40% (8/40) of wild animal traders had SARS-CoV-1 antibodies in comparison to 5% (1/20) vegetable traders from the same market [20], and similarly among wildlife traders in Guangzhou, China, the highest prevalence of antibodies to SARS-CoV-1 was found among those who traded primarily masked palm civets *Paguma larvata* (16/22, 73%), wild boars *Sus scrofa* (16/28, 57%) and muntjac deer *Muntjacus* spp. (9/16, 56%) [21]. Transmission does occur in markets, but it is not always clear if this is through direct contact or via vectors. In Vietnam, Huong et al. [22] tested for the presence of coronaviruses in rodents, bats and birds along the wildlife trade supply chain and noted that the odds of detecting coronaviruses increased from animals sold by traders (39/188, 21%) to large markets (116/363, 32%) to wild meat restaurants (84/151, 56%). Rather than attempting to eradicate pathogens or the wild species that may harbor them, a more effective method of lowering the likelihood of zoonotic disease transmission is to decrease the contact rate among species, including humans, at the interface created by the wildlife trade. Since wildlife trading in markets functions as a system of scale-free networks with major hubs, these points provide control opportunities to maximize the effects of regulatory efforts [11]. To instigate these control opportunities, it is worthwhile investigating what the potential infectious diseases are that circulate in these wildlife markets [18,23].

That is what we set out to do in this study, focusing on mammalian vector-borne diseases in two wildlife markets in Indonesia and Myanmar. We finally place our study in a One Health context where we discuss the impact of wildlife trade on public health and biodiversity in terms of the conservation and socio-economic implications of the observed trade in Indonesia and Myanmar by examining species in trade and their protection status, legality and global conservation status. It is important to stress that we did not set out

to test the actual presence of vector-borne diseases in the mammals we observed in the wildlife markets or indeed of the humans that work and visit these markets; rather our study is perhaps best seen as a theoretical study that sets out to assess the presence of reservoir hosts of vector-borne diseases.

2. Materials and Methods

2.1. Study Areas

We selected two markets where we have worked and collected data over an extended period of time, the first one being Mong La, Myanmar [24–26] and the second being Sukahaji, Indonesia [27–29]. Mong La (population 43,000) is situated in Eastern Shan State on the border with China. It is situated relatively distant within Myanmar (the nearest town is Kentung, population 172,000, at 80 km), but it is well connected to Daluo and is some 100 km from Jinghong (population 205,000) in China (with its own international aiport). The main road through Mong La is part of the R3B route linking Kunming to Bangkok. Developed by Chinese investors, Mong La now focuses on the entertainment industry (nightclubs, brothels, 24-h casinos, exotic meat restaurants) for Chinese visitors [30]. The wet market is situated in the central part of the town and is open each morning.

Sukahaji bird market is in the city of Bandung (population 2.5 million), the capital of the province of West Java. Bandung is well connected to other large cities in Java, including the capital Jakarta (11.3 million), Bekasi (2.5 million) and Tasikmalaya (72,000), and has its own international airport. The market is open 7 days a week and consists of around 75 shops and stalls along Jalan Peta, Suka Asih and Bojongloa Kaler, with additional vendors selling birds along these streets in mobile shops [27–29,31]. Mostly birds are offered for sale, for instance, Chng et al. [27] recorded 3178 wild-caught birds of 154 species on a single day in 2016, but in addition, wild-caught mammals and reptiles are offered every day [28,29].

In both markets the levels of hygiene are low, and of particular relevance is that the presence of still standing water in small pools or puddles is common, thus creating suitable conditions for mosquitoes to remain present.

2.2. Data Acquisition

Myanmar: We visited Mong La on six occasions between 2009 and 2021 (i.e., 6 February 2006; 26 February 2009; 31 December 2013; 6 March 2015; 1 December 2017; 18 January 2021), during which we recorded wildlife that was offered openly for sale in the wet markets and outside nearby wild meat restaurants (there is one cluster of such restaurants along the Mong La River).

A survey was completed within a day, with the morning spent in the wet market and the afternoon surveying the animals that were displayed outside the wild meat restaurants and other outlets that sold wildlife. Vendors were somewhat reluctant in allowing us to take photographs, when it came to live or freshly killed mammals there were no problems in observing and recording.

Indonesia: We surveyed the Sukahaji bird market in Bandung on the island of Java between 2012 and 2021 and selected six visits (similar to Mong La) over this period as a representation of the mammal trade taking place in this market (i.e., 15 April 2012; 27 November 2016; 22 January 2017; 4 February 2018; 6 July 2019; 23 November 2021). A survey lasted a morning or an afternoon, during which, in addition to mammals, birds and reptiles were also recorded. The trade in the bird markets is open, and there were no difficulties recording what was offered for sale.

Here, we focus on mammals, and only the ones that were offered for sale alive or that were obviously newly killed (both whole carcasses and individual body parts). There are no refrigeration facilities in Mong La, and in the sections of the market where wild mammals are offered for sale, there is no running water (this is present in another section where domesticated animals and fish are sold). Animals typically arrive freshly killed in the market in the early morning and are sold on the same day. Animals also arrive alive,

and these are then either sold alive or they are killed when a purchase is made. Some, for instance, Bengal slow lorises *Nycticebus bengalensis*, are slaughtered prior to purchase, but their carcasses are mostly sold on the same day [32].

Based on our visits, we estimate that on a typical morning, about 50 vendors are present at least several hundred people visit the wet market. In Sukahaji mammals are sold mostly alive for the pet trade; some squirrels and fruit bats are sold for medicine, and these are either sold alive or at the request of the buyer, the vendor will slaughter them on the spot. Sukahaji is open from early morning until late afternoon, and we estimate that, in addition to 150 vendors, up to a thousand people visit the market daily.

While some of the animals in the market, and in particular the carcasses, are sold within one or two days, the live animals especially may not be sold for considerable periods of time, hence increasing the likelihood of diseases spreading from animals to humans.

Greatorex et al. [23] noted that fresh carcasses can carry infective viral pathogens, for instance, by the handling of primate and bat carcasses and by the observation of viral survival without the requirement of a living host that can occur in laboratories for between 24 h and six days at temperatures similar to those found in Myanmar and Indonesia. Smoked, dried, fermented carcasses and carcasses submerged in alcohol (e.g., whole tiger carcasses in 'tiger wine') were excluded due to their unknown potential to transmit pathogens and unknown length of time since death.

2.3. Analysis

While the surveys in Indonesia were complete surveys, that is, we were able to record all openly displayed mammals for sale, data collection in Myanmar was somewhat hampered by the reluctance of some traders to show their wares, and some surveys may have under-recorded the total amount of mammals on offer. By combining the six surveys for Indonesia and Myanmar separately, we overcome this oversight as we are confident that we capture the overall trade in live and freshly killed mammals well (i.e., no new mammal families carrying vector-borne diseases were detected after the third and second survey in Myanmar and Indonesia, respectively).

Given that our knowledge of the presence of vector-borne diseases does not cover individual species very well, the analysis was conducted at the family level. Eight families were included in the analysis: Viverridae (civets), Cercopithecidae (Old World monkeys), Felidae (cats), Suidae (pigs), Cervidae (deer), Sciuridae (squirrels), Pteropodidae (Old World fruit bats) and Rhinolophidae (horseshoe bats).

In terms of vector-borne diseases, we consulted Greatorex et al. [23], Johnson et al. [33] and Morcatty et al. [34]. We added primate malaria to the list of vector-borne diseases (zoonotic malaria caused by *Plasmodium knowlesi* is particularly common in Southeast Asia: [35]). There is evidence of infections of *P. knowlesi* in captive long-tailed macaques *Macaca fascicularis* [36] (Table 1).

Table 1. Vector-borne diseases considered as having the potential to spread to humans in and around wet and wildlife markets. Direct contact indicates the disease can also spread directly to humans by contact with blood or other bodily fluids, in addition to through a vector.

Vector-Borne Disease	Transmission [1]	References
Crimean-Congo hemorrhagic fever virus	*Hyalomma* ticks/direct contact	[37–39]
Chikungunya virus	*Aedes* (daytime) mosquitoes	[8,40,41]
Dengue virus	*Aedes* (daytime) mosquitoes	[42,43]
Japanese encephalitis virus	*Culex* (evening) mosquitoes	[9,44,45]
Tick-borne encephalitis virus complex	*Ixodes* ticks	[44,46,47]
West Nile virus	*Culex* (evening) mosquitoes	[15,48,49]
Western equine encephalitis virus	*Aedes* (daytime) mosquitoes	[50–52]
Yellow fever virus	*Aedes* (daytime) mosquitoes	[10,53,54]
Primate malaria	*Anopheles* (evening/night) mosquitoes	[55–58]
Dabie banda virus	Ticks/direct contact	[59–62]

[1] For mosquitoes, daytime refers to species that have a preponderance to be active during the day whereas evening refers to those species that become more active after sunset.

We created a presence-absence matrix for these seven families and their potential vector-borne diseases for both Myanmar and Indonesia, provided there was at least one detection. Values were based on the pooled number of animals or whole animal equivalents that we observed. These values were then used to generate a heatmap using ClustVis [63]. ClustVis uses several R packages internally, including ggplot2 for the principal component analysis (PCA) plot, pheatmap (R package version 0.7.7) for plotting heatmap and PCA. We used the default setting for the PCA analysis, i.e., a Singular Value Decomposition with imputation. For data pre-processing the unit variance scaling method divides the values by standard deviation so that each row has variance equal to one [63].

3. Results

3.1. Observations in the Markets

In Myanmar we observed at least 16 species of the seven recorded families; numbers for individual species were low (i.e., rarely more than ten individuals) but the sale of animals happened at a high rate (i.e., few animals stayed for long in the markets, and new ones came in regularly).

Two-thirds of the animals or animal equivalents were freshly killed whereas the remaining third of the animals were alive when first observed. Most of the animals we focus on were traded within the eastern and north-eastern side of the wet market, with smaller numbers displayed in front of the wild meat restaurants a few 100 m further to the east. Animals were kept in small cages or tethered. Butchering was not in the most basic of hygienic conditions, with no facilities for cleaning or preventing cross-contamination. Carcasses of animals would arrive in the morning and were left out in the open, with often only a piece of cardboard as protection.

Fewer species were observed in Indonesia with four of the seven recorded families, but numbers were higher, especially for the Sciuridae and the Pteropodidae. All but three of the individuals we observed were alive (Table 2).

Table 2. Individuals of eight mammal families (Cercopithecidae, Felidae, Viverridae, Suidae, Cervidae, Sciuridae, Pteropodidae, Rhinolophidae) * recorded in two live and wet markets in Myanmar and Indonesia. Key to global conservation status: CR = Critically Endangered; EN = Endangered; VU = Vulnerable.

FAMILY, Species [Conservation Status]	Mong La, Myanmar		Bandung, Indonesia	
	Live	**Dead**	**Live**	**Dead**
CERCOPITHECIDAE				
Northern pig-tailed macaque *Macaca leonina* [VU]	2			
Assamese macaque *M. assamensis*	2			
Rhesus macaque *M. mulatta*	9			
Long-tailed macaque *M. fascicularis* [EN]			10	
Macaque *Macaca* spp.		3		
Phayre's langur *Trachypithecus phayrei* [EN]		1		
Ebony langur *T. auratus* [EN]			4	
FELIDAE				
Leopard *Panthera pardus* [VU]		1		
Clouded leopard *Neofelis nebulosa* [VU]		2		
Asian golden cat *Catopuma temminckii*		1		
Leopard cat *Prionailurus bengalensis*	2	1	3	
Jungle cat *Felis chaus*	1			
VIVERRIDAE				
masked palm civet *Paguma larvata*		2	2	
Asian palm civet *Paradoxurus hermaphroditus*	1	4	20	
SUIDAE				
Eurasian wild pig *Sus scrofa*		11		
CERVIDAE				
Sambar *Rusa unicolor* [VU]		13		
Large deer		2		
Northern red muntjac *Muntiacus vaginalis*	11	26		
SCIURIDAE				
Pallas's squirrel *Callosciurus erythraeus*	2	1		
Plantain squirrel *C. notatus*			66	2
Squirrel *Callosciurus* spp.	2	10		
Red-cheeked squirrel *Dremomys rufigenis*	3			
Flying squirrel		2		
PTEROPODIDAE				
Large flying fox *Pteropus vampyrus*			50	1
RHINOLOPHIDAE				
Small bat		5		

* Other families recorded included the slow lorises Lorisidae (Myanmar: Bengal slow loris *Nycticebus bengalensis* [EN] live 30, dead 47; Indonesia: Javan slow loris *N. javanicus* [CR]: live 2).

While Sukahaji bird market stretches out over a large area, almost all outdoors and some along the roads leading to the market, vendors selling mammals are mostly concentrated in the central part of the market. The live animals were mostly kept in cramped conditions, in tiny cages stacked on top of each other, domestic and wild-caught animals separate but in close contact. Squirrels were kept 5 to 20 in a cage without any water, food or shelter; fruits bats were kept in similar conditions. As in Mong La, cages are often stacked on top of each other, and levels of hygiene are very low. Occasionally large fruit bats and plantain squirrels that were bought for traditional medicinal purposes would be slaughtered in the market. Figure 1 illustrates the conditions in the markets (Figure 1).

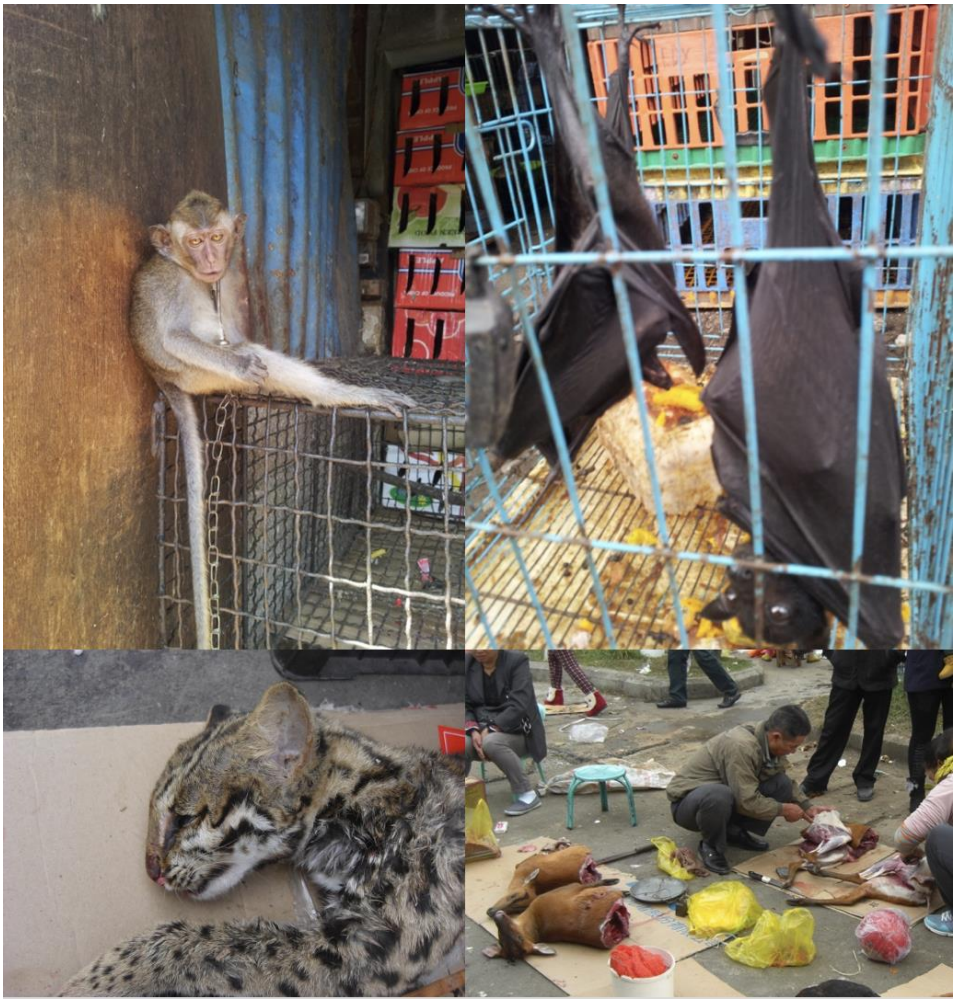

Figure 1. Wildlife observed in trade in Indonesia (**top**) and Myanmar (**bottom**), clockwise from top left: long-tailed macaque (*Macaca fascicularis*); large flying fox (*Pteropus vampyrus*); northern red muntjac (*Muntiacus vaginalis*); leopard cat (*Prionailurus bengalensis*).

3.2. Vector-Borne Diseases and Mammals in Markets

Indonesia: In the ClustVis heatmap analysis the first PC axis explained 45.9% of the variation and the second explained 25.3%. PC1 was associated with high loadings for Crimean-Congo hemorrhagic fever virus (0.57) and West Nile virus (0.58). PC2 was associated with low loadings for Japanese encephalitis virus (−0.49), Chikungunya (−0.45) and Primate malaria (−0.45). Regressing PC1 against PC2 allowed for clear identification of most families, albeit that the Pteropodidae and Suidae showed considerable overlap (Figure 1). When considering families, the cluster analysis (indicated by the dendrograms on the top and left side of the heatmaps) shows two clusters, one grouping Sciuridae and Cercopithecidae, and the second with the other four families, i.e., Phinolophidae, Pteropodidae, Cervidae, Suidae and Felidae. In terms of vector-borne diseases, we recognise two clusters, i.e., (1) Chikungunya and Japanese encephalitis virus and (2) the remaining vector-borne diseases.

Myanmar: PC1 explained about two-fifths of the variation (37.6%) and PC2 explained a little less (30.2%). PC1 was associated with high loadings for CCHFae (0.62) and TBEVC (0.48). PC2 was associated with low loadings for West Nile virus (−0.62) and Dalie banda virus (−0.56). Regressing PC1 against PC2 allowed for clear identification of most families, with both Scuiridae and Cervidae separating considerably (Figure 2). In terms of families in the cluster analysis, the Pteropodidae, Rhinolophidae and Cervidae formed one cluster, and the remaining five families formed a second (with an early split for the Suidae and

Scuiridae). The pattern of clustering for the vector-borne diseases was less clear, with three equal groupings (Figure 2).

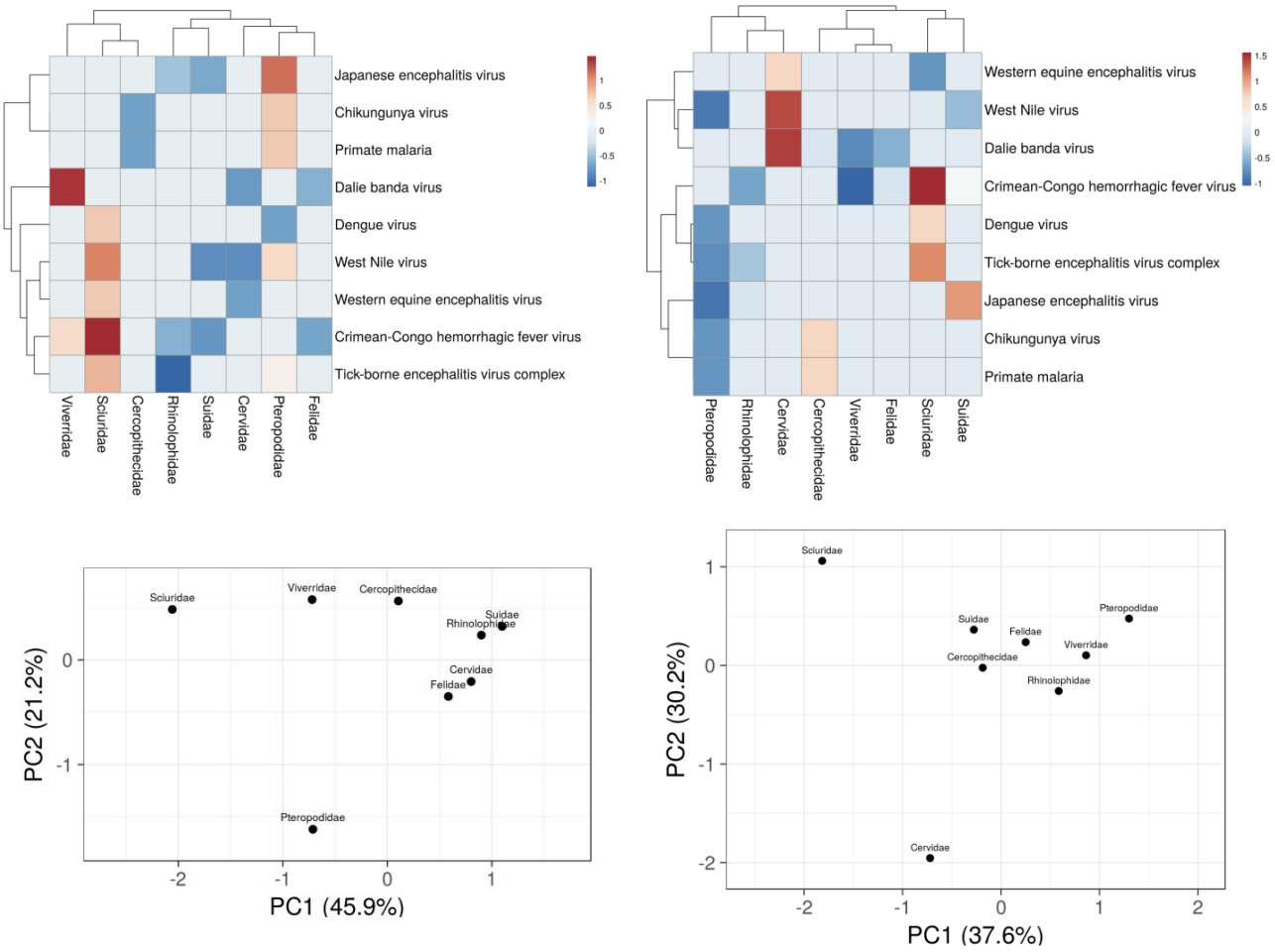

Figure 2. Top: Heatmaps of potential vector borne diseases in various mammal families recorded in wildlife markets in Indonesia (**left**) and Myanmar (**right**). The values are relative with red indicating the highest values and pale blue the lowest. The dendrograms on the left represent the clustering of potential vector-borne diseases whereas the dendrogram on the top indicates the clustering of mammal families. Bottom: Associated principal component plots showing the position of the eight mammal families, with the values between brackets indicating the amount of variation explained by PC1 and PC2, respectively.

4. Discussion

4.1. Vector-Borne Diseases, Mammals and Wildlife Trade

We show that there is a consistent and open trade in live (Indonesia and Myanmar) and freshly killed (Myanmar) wild mammals under conditions that have the potential to spread vector-borne diseases. In other parts of Indonesia, there are markets where, just like in Mong La, live and/or freshly killed mammals are openly offered for sale, including Genyem, Nimbokrang, Manokwari and Sorong (Papua), Jambi, Maura Tebo (Sumatra) and Modoinding, Pompasa Baru, Motoling, Kawangkoan and Tomohan (Sulawesi) [63–69]. Similarly, in other Myanmar wildlife markets, live and freshly killed mammals are offered for sale, including in Muse, Putao, Dagon, Kyaiktiyo, Tachilek and Three Pagoda Pass [70–72].

In all these places, trade happens in public markets that are open daily (or at least several times a week) and that are visited by hundreds if not thousands of people on a daily basis. Assuming our surveys were representative for the trade on any given day in the two

markets we monitored, our observations suggest that annually some 7500 live individuals of these seven mammal families are traded in Sukahaji bird market on an annual basis (or 9000 if we include the Lorisidae and the Viverridae). We arrive at comparable numbers for Mong La: 6250 live or freshly killed individuals of these seven mammal families (or 11,250 including the Lorisidae and the Viverridae), adding that a large additional trade in Mong La comprises animal parts rather than live or freshly killed animals [17–19].

The risk to human health differs greatly between markets. Lin et al. [73] concluded that wildlife markets that have the highest levels of risk are (1) those that offer higher disease risk taxa such as rodents, primates and bats; (2) those that sell live wild-caught animals and where slaughter takes place in these markets; (3) those with poor hygiene conditions, including the improper storing of carcasses and low levels of cleaning; (4) those that are larger, including the number of vendors, number of animals for sale and number of customers; (5) those where animals are kept at high density in cramped conditions with cages stacked on top of each other and where frequent interspecies mixing takes place and (6) those markets that sell animals that were sourced at considerable distances and that have long supply chains. We note that both Mong La and Sukahaji meet most if not all of these six criteria.

While we have no data on the actual transmission of diseases in wildlife markets in either Myanmar or Indonesia, it may be worth speculating how this could happen in practice. Focusing on primate malaria in Indonesia, as an example, humans may get infected if bitten by an *Anopheles* mosquito that previously fed on either a long-tailed macaque, a pig-tailed macaque *M. nemestrina* or a *Presbytis* langur, as these are known to suffer from primate malaria [55]. These species often live in different types of forests (in Java, long-tailed macaques live more along the forest edge, whereas grizzled langur *P. comata* lives more in the interior; pig-tailed macaques are not found on Java; a similar pattern is found on Sumatra, with pig-tailed macaques being more terrestrial than the other two species) at low densities (i.e., up to three or four individuals per hectare at the most) and generally rarely come in contact with humans. In these setting, for instance along a forest edge, an *Anopheles* mosquito that has bitten one of these primates is much more likely to bite another primate than a human. In the markets, these three species can be found in very close proximity in cramped conditions at a 'density' that is much higher than in the wild, but unlike in the wild, they now come in daily contact with 100s if not 1000s of people. Any mosquito that bites a primate is more likely to subsequently bite a human rather than a primate. For other vector-borne diseases, the likelihood of transfer from one species to another in the markets is less clear, as some mosquitoes are very specific in the species they feed on (making it less likely that humans will be bitten, even if they are present in high densities and in large numbers).

While here we focus on the trade in wild-caught mammals and the potential they have for carrying and transmitting vector-borne diseases of humans, in these same markets, there is a parallel trade in domestic mammals that equally have the potential to be of zoonotic concern [74]. In Myanmar, this takes the form of domestic dogs being sold for meat, and in Indonesia, it takes the form of a wide range of domestic mammals sold for the pet trade, including rabbits, dogs and cats. In both markets, free-ranging cats and dogs are found (dogs more so in Myanmar, cats more so in Indonesia), and numerous rats are found in both. We focused on the potential of vector-borne diseases spreading from wild mammals in trade rather than the actual spread, but it is important to note that many of the diseases we focused on have indeed been recorded in Myanmar, Indonesia and/or neighbouring countries [1,35,36,75–93].

The main differences in terms of species composition between Indonesia and Myanmar was the higher number of Sciuridae (11.3 vs. 1.3 animals survey^{-1}) and Pteropodidae (8.3 vs. 0) and the absence of Rhinolophidae, Cervidae and Suidae in Indonesia. Compared to a similar study conducted in seven wildlife markets in Laos [23], in Myanmar, we observed markedly more Cervidae (8.7 vs. 1.1 animals survey^{-1}), Suidae (1.8 vs. 0.4) and Felidae (1.3 vs. 0.2), an equal number of Rhinolophidae (0.8 vs. 0.6) but fewer Sciuridae (1.3

vs. 4.0). Comparing the findings in Laos with that of Indonesia, we observed markedly more Sciuridae (11.3 vs. 4.0 animals survey^{-1}), Pteropodidae (8.3 vs. 2.6) and, to a lesser degree, Felidae (0.5 vs. 0.2). In Laos, no Cercopithecidae were observed, and the only primates for sale were Lorisidae (0.1 animals survey^{-1} vs. 0.3 in Indonesia and 3.7 in Myanmar).

4.2. A One Health Approach to Mitigating the Risk of Zoonotic Diseases

We here discuss the conservation and socio-economic implications of wildlife trade by focusing on the legality of the trade and protection status of traded wildlife. There are likely to be multiple causes of novel disease emergence, including vector-borne diseases, but the transport of pathogens, often in infected hosts, by humans as part of economic activities is a major driver of this. Natural biodiversity may limit the exposure, impact and opportunities for pathogen spillover of many zoonotic pathogens through a dilution or buffering effect [94]. A One Health approach refers to approaches to tackling zoonotic diseases that consider multiple components that increase the likelihood of the emergence and spread of these diseases. This does include biodiversity and the use of animals as well as socio-economic, cultural, political and legislative drivers that either promote or restrict this spread [65].

Both Indonesia and Myanmar have recognised that certain species should not be traded commercially and both countries have lists of species that are legally protected (including many of the cats, primates and deer that we observed in the markets). Harvest and trade in other species is regulated though quota systems or seasonal closures. Seven of the species we observed in trade, alive or freshly killed, are listed as globally threatened with extinction. These include two species of macaques and two species of langur, one of each taxon observed in Myanmar and one of each taxon observed in Indonesia, as well as two species of wild cat and a deer in Myanmar (Table 1). It is disconcerting to see these species openly in trade; both Myanmar and Indonesia carry a global responsibility to ensure the last remaining populations of these species are safeguarded from any human harm.

Mong La is situated in 'Special Region 4' and is strategically situated across the border from Daluo in China. It is controlled by an autonomous ruler (Lin Min Xiang) and the Myanmar central government has limited authority [30]; it is a de facto Chinese enclave in Myanmar. Many of the species, including the parts of high-profile ones such as tigers *Panthera tigris*, elephants, rhinos and pangolins *Manis* spp, are openly offered for sale [24–26]. Several of the species we discuss here, including most of the wild cats, are formally protected in Myanmar, and much of the trade we observed is illegal under the country's legislation (the cross-border trade in these animals furthermore would be in violation of several regional treaties and international conventions Myanmar has signed).

The commercial trade in wildlife taken from the wild in Indonesia is strictly regulated through a harvest quota system [29]; while some of the species we observed in trade, such as many of the squirrels and some of the primates are not legally protected, their trade would have almost certainly have been in violation of Indonesia's harvest regulations. The ebony langurs and leopard cats we observed in Sukahaji bird market are protected under Indonesian law and cannot be traded [29]. As such the majority of the trade we observed in Indonesia is therefore illegal under the country's national legislation. However, Sukahaji bird market, just like many other markets in Indonesia, has been operating in the same location and are open daily, so the public display of legally protected species clearly is not of concern to local traders and the local (or indeed national) authorities.

It has been long recognised that there are clear links between wildlife trade and the risk of spreading zoonotic diseases, especially as trade becomes more globalised [2,4,11,17,95–98]. Specifically focusing on reducing the risk of vector-borne diseases spreading from wildlife to humans, with urgency we implore the traders' organizations that run Sukahaji and Mong La markets to focus on increasing the levels of hygiene in all parts of the trade (transport, storage, display, handling, selling) and to cease trading those species for which they have no permission to trade. Other mitigation strategies should focus on the general cleanliness

of the area, ensuring that there are no still-standing water sources available for mosquitoes to breed in and properly cleaning the market prior to closure for the night (something that is not done at present). Among the measures are the obvious improvement of standards of hygiene and sanitation in these markets, which may include avoidance of keeping animals in overpopulated cages and regular cleaning and disinfection of animal enclosures, pest control and waste management with special attention to animal urine, faeces and other secretions [34].

For a comprehensive analysis of risks, information should become available on the pathogen loads in traded animals, the transmission risks at different contact points and the origins of the animals in trade. Periodic zoonotic surveillance (noting which wild-caught mammalian species are present in the market), ideally in combination with clinical testing, may result in the early detection of the occurrence of main pathogens, allowing the prevention of outbreaks in both humans and animals [99,100]. Such a functional early alert system may attenuate the health, social and economic impacts of epidemics and pandemics [101]. The guidance from the World Health Organization [102] is to concentrate on live species in food markets, but by extension, this also concerns the sale of live animals for other purposes, including the pet and medicinal trade. The development and implementation of campaigns for market traders, stallholders, consumers and the general public that can bring information about the risks of transmission of zoonotic pathogens at the human–animal interface, safety practices in handling and keeping live wild animals and what to consider when selling or buying an animal in order to reduce the likelihood of spreading zoonotic diseases [34,102].

More broadly speaking, given that a substantial proportion of the trade in the markets in Myanmar and Indonesia comprises legally protected species that cannot be bought or sold, and given that the trade in other, non-protected, species violates other national regulations, and given that in the case of Mong La, a large part of the trade is to meet the demand from across the border in China and is traded in violation of CITES regulations, and given that previous law enforcement actions, if any, must have been wholly ineffective in curbing this illegal trade, we urge the authorities to either completely shut down these two markets, or, at a minimum, to permanently prevent the sale of wild-caught animals. In most wildlife markets in Myanmar and Indonesia, and for most vendors in these markets, the sale of wild-caught mammals is not the main source of revenue (i.e., most sell only domestic mammals or sell a combination of wild-caught *and* domestic animals). The latter option (to ban the sale of wild-caught animals) would have, in our view, limited impact on the livelihoods or financial security of most traders, as the majority of traders could switch to focusing exclusively on domestic or captive-bred individuals.

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