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Parrot Trade and the Potential Risk of Psittacosis as a Zoonotic Disease in Indonesian Bird Markets

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Simple Summary: There are clear links between wildlife trade and emerging infectious diseases including zoonotic diseases. In some cases, this leads to global outbreaks or even pandemics as recently seen with SARS and COVID-19 for instance. One of the first properly documented global pandemics caused by the trade of wildlife at a global level was the Great Parrot Fever Pandemic of 1929/1930. This pandemic was caused by psittacosis, a respiratory disease that can be transmitted to humans from infected birds (once transmitted to humans the disease is known as avian chlamydiosis). We assessed the risk of psittacosis becoming a zoonotic disease in Indonesia's bird markets where a wide range of wild-caught species, including parrots, are traded. In 14 markets on the islands of Java and Bali, we recorded almost 4500 parrots of 21 genera from all parts of the world and these were traded alongside each other. Genera offered for sale together did not cluster into geographic groups, were sold during all months of the year, and for 12/21 genera the presence of psittacosis had been reported in the past. We conclude that the omnipresence of wild-caught parrots from various geographic regions in large numbers within the same bird markets (visited by 100 s of people daily) increases the likelihood that psittacosis is indeed present. This poses a real risk for the zoonotic spread of avian chlamydiosis to humans.

Abstract: Wildlife trade, both legal and illegal, is increasingly recognized as a key factor in the rise of emerging viral infectious diseases, and this is especially apparent in Asia, where large numbers of wildlife are openly offered for sale in bird markets. We here focus on the risk of Psittacosis becoming a zoonotic disease in the wildlife markets of Java and Bali, Indonesia. Psittacosis is particularly prevalent in parrots (hence the name), and the trade in parrots was instrumental in the Great Parrot Fever Pandemic in 1929/1930. Between 2014 and 2023, we conducted 176 surveys of 14 bird markets, during which we recorded 4446 largely wild-caught parrots for sale. On average, each market had nine genera on offer, and the diversity of genera increased with the increasing presence of parrots (up to 16 genera). For most of the bird markets during each survey, parrots from different genera and originating from different parts of the world, were offered for sale alongside each other. Genera offered for sale together did not cluster into natural (geographic) groups. We found no temporal

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difference in the sale of parrots. We conclude that the omnipresence of wild-caught parrots from various geographic regions in large numbers within the same bird markets increases the risk that psittacosis is present and that this poses a real risk for the zoonotic spread of avian chlamydiosis to humans.

Keywords: avian chlamydiosis; Cacatuidae; emerging infectious diseases; Indonesia; ornithosis; Psittaculidae; wildlife trade

1. Introduction

Wildlife trade, both legal and illegal, is increasingly recognized as a key factor in the rise of emerging viral infectious diseases [1–3]. This trade usually involves close contact between humans and wild animals (or their products) during the harvesting, processing, packing and transportation, and at the points of sale (for instance, in wildlife or wet markets). In these markets, diverse wild species are brought in high numbers into close proximity to be sold as pets or slaughtered on the spot for trade as medicines or meat [4], creating the potential for the spread of viral infections [5,6]. These wild animals can be sourced locally, close to the point of sale, or they may have been sourced from hundreds of kilometers away, either from within the country where it is offered for sale or imported from abroad [7,8]. Wild animals are also frequently offered for sale alongside domestic animals with little regard for hygiene or welfare [9,10].

Southeast Asia is one of the global hotspots of emerging zoonotic diseases [11–13]. Within this region, wildlife is commonly traded in open markets, and these markets have been considered 'the perfect storm' for zoonotic disease transmission. Improving our understanding of how pathogens are transmitted and adjusting practices to minimize risk could significantly decrease the likelihood of these pathogens spreading to humans. However, there is still insufficient research on the variety of species sold in markets and the potential for cross-infection of pathogens between these species and humans.

Indonesia, a central player in the Asian bird trade [14], is a crucial geographic area of study due to its diverse bird species traded for various human uses, from entertainment to traditional medicine [15,16]. The trade of birds for human entertainment is the major factor driving an increasing number of Asian species to extinction, with species desired for their singing abilities and/or other attractive attributes, such as their colorful plumage [14]. Much of this trade in birds, and the research into its scope, scale, and conservation implications, has been centered around songbirds (Passeriformes), which are acknowledged to be under immense pressure from both domestic and regional trade, to a level that the current situation has been described as the 'Asian songbird crisis' [14,17]. An increasing awareness of this crisis and the need to better understand trade dynamics have prompted a series of large-scale market surveys across the Southeast Asian region, and most notably in Indonesia [14–18]. These studies, many of which involve full inventories of all bird taxa found in trade, have revealed that songbirds are just one of many orders of birds that are traded in the Southeast Asian bird markets [19–21]. While only a few researchers have made explicit links between the songbird trade and emerging zoonotic diseases, it is vital to acknowledge that avian emerging zoonotic diseases are by no means restricted to songbirds.

The outbreak of COVID-19, its rapid spread around the globe, and the discussions surrounding its origin have brought into focus the risks that human–animal interactions (alongside an ever-increasing closer proximity between humans and wildlife due to habitat loss and degradation) may pose to human health [22,23]. Zoonosis (a disease that is transmitted from an animal to a human) and zooanthroponosis or reverse zoonosis (a disease that is transmitted from humans to other animals) can have serious implications for the health of the individual, including death. Furthermore, disease outbreaks can have a devastating social and economic impact (as indeed seen in the COVID-19 pandemic),

while in general, the risk is low, transmissions of diseases (zoonosis and zooanthroponosis) can occur in any setting where humans and animals come into close contact [24]. In recent years, partially linked to the emergence of COVID-19 and previously SARS [7], there has been a focus specifically on the links between the (illegal) wildlife trade and emerging infectious diseases [25]. While the link between the wildlife trade and SARS has been well established [7,26], the debate surrounding the origin of COVID-19 continues [27,28].

In light of this, lessons can also be learned from a previous pandemic caused by the trade of wildlife at a global level, i.e., the Great Parrot Fever Pandemic of 1929 and 1930 caused by psittacosis [29]. Psittacosis (also known as ornithosis, when referring to the disease when it affects birds) or avian chlamydiosis (the same disease when it affects humans) consists of a respiratory disease transmitted to humans from infected birds through the inhalation of dried bird droppings and respiratory tract secretions or through direct contact of the bird's beak with the mouth [30]. The etiologic agent is an intracellular gram-negative bacterium *Chlamydia psittaci*. The 1929/1930 outbreak of psittacosis was linked to the then-burgeoning global trade in parrots thus affecting humans in countries on four continents (Denmark, France, Germany, Switzerland and the Netherlands in Europe; Egypt and Algeria in Africa; the USA in North America; Argentina in South America) with the parrots being sourced from at least two continents (South America and Australia). An estimated 800 people were infected during the Great Parrot Fever Pandemic, with around one hundred human deaths reported [29]. While these numbers might appear relatively small, it is crucial to contextualize them within the period when the global human population was only a quarter of its current size, and the world was less globalized (including significantly less international travel). Although psittacosis is a notifiable disease and must be reported to authorities within 48 h in some countries, most countries in the Global South, such as China, India and also Indonesia, have not yet listed psittacosis as a notifiable infectious disease [31]. Current global psittacosis case numbers might be greatly underestimated. For example, between 2018 and 2023, there have been fewer than 100 cases of psittacosis per year in the USA, but this could be an underestimation because of asymptomatic transmission, a paucity of awareness among doctors as to the potential risk of human-to-human transmission, and clinical and laboratory testing issues, resulting in people with psittacosis who do not present with pneumonia often going unnoticed [31].

At least 465 avian species have been found to be infected with psittacosis [32]. Among pet parrots (including cockatoos, parrots, parakeets and lories), *Chlamydia psittaci* is highly prevalent, ranging from 16 to 81% in tested birds [32]. In genetic and phenotypic terms, *C. psittaci* is a heterogeneous species, and a series of genotypes, A to F, varying in their host preference and virulence, have been identified [33]. Genotype A is endemic to parrots and is highly virulent, as is genotype F, although this has also been isolated from turkeys *Meleagris gallopavo* [34]. All genotypes are considered to be readily transmissible to humans.

In summary, psittacosis, particularly genotype A, is highly prevalent in parrots and poses a significant zoonotic risk. The spread of psittacosis, linked to the global wildlife trade, has led to cases of avian chlamydiosis and human fatalities. Extensive data on the trade of wild-caught parrots offer insights into predicting psittacosis risks. Our focus on psittacosis in Indonesia is driven by the country's substantial trade in wild-caught parrots. We aim to assess the impact of trade volume of animals from wild populations and species diversity, factors known to contribute to the risk of disease transmission. We also explore how the parrot trade varies across different bird markets and its implications for zoonotic disease transmission risks, highlighting their roles in possible disease spread.

We test a series of null hypotheses: (1) Bird markets do not differ in the number of parrots or the number of genera they offer for sale; (2) While we expect variation between surveys, over the 10-year study period the number of parrots and the number of genera remains stable; (3) Within each bird market, survey effort has no effect on the mean number of parrots or the number of genera we record; (4) Psittacosis is present in all parrot genera we record in the bird markets as evidenced by prior research; (5) The geographic distance between bird markets is a factor in determining which markets cluster together in terms of

the mean number of birds and the number of genera (so that markets that are geographically closer together are also more similar in terms of number of birds and genera); (6) Genera that occur in certain geographic regions (e.g., eastern Indonesia, South America) cluster together in terms of in which bird market they are recorded.

2. Materials and Methods

2.1. Data Collection in Bird Markets

Java, and to a lesser extent Bali, are densely populated and, although at times congested, have an excellent infrastructure in place to transport both goods and people. Java has a population of over 150 million people living at a density of over 1200 per square kilometer (for Bali, these figures are 4 million and 750 people per square kilometer). Several cities have over one million inhabitants (e.g., Jakarta 10.6 million; Surabaya 2.9 million; Bandung 2.4 million; Semarang 1.7 million). We surveyed 14 bird markets in Java and Bali over the period from 2014 to 2023. Each market was surveyed at least three times (mean 12.6 ± 2.7 times) over a period of 5.2 ± 0.5 years (range 3–9 years). In total, we conducted 176 surveys. COVID-19 had a limited impact on our studies as most bird markets remained open, but travel restrictions and regional lockdowns meant we surveyed fewer cities from 2021 to 2023. Three of the bird markets were situated in the country's capital, Jakarta (Pramuka, Jatinegara and Barito). One was situated in the capital of the province of West Java (Sukahaji in Bandung) in addition to three others in that province (Kerkhof in Garut, Cikurubuk in Tasikmalaya and Plered in Cirebon). Two were in the province of Central Java (Karimata in its capital Semarang and Depok in Surakarta), and one was situated in the Special Region of Yogyakarta (Pasar Satwa dan Tanaman Hias Yogyakarta, known as PASTY). A further three were located in the province of East Java (Splindit in Malang and Bratang and Kupang in the provincial capital Surabaya). Finally, one bird market was situated the capital of Bali, Denpasar (Satria).

Two of the authors (Ab.Ab., V.N.) have regularly visited these bird markets since the early 1990s up until now. As such, we are familiar with their layout, characteristics, and the trade dynamics within and between these markets, allowing us to include a representative sample of the bird markets that are present in these parts of Indonesia. Markets were not selected for their presence of parrots, i.e., we did not survey those bird markets preferentially where we expected to record large numbers or many species of parrots. Hence, there was no relationship between the number of surveys and the quantity and diversity of parrots we recorded (i.e., more surveys in particular bird markets did not necessarily lead to higher quantities or diversity of parrots being recorded than in other bird markets that were surveyed less). Nor was there a significant relationship between the mean number of parrots we observed and survey effort (i.e., markets with many parrots were not surveyed more than markets with few parrots). Consequently, we are confident that the bird markets we surveyed provide a representative overview of the overall trade in parrots in these parts of Indonesia.

Bird markets are open to the public and are open all days of the week, from early morning to early evening (in addition, there are bird markets that are only open on certain days of the Javanese calendar, such as Pon or Wage, but these bird markets are often smaller and were not included here). Traders offer a wide range of bird species bred in captivity and wild-caught bird species for sale, including native species that are legally protected, native species that can be traded in limited numbers and non-native species that are imported into the country. In the larger bird markets (e.g., Pramuka PASTY, Bratang), parrots are typically displayed in the back or in specific sections, but in the smaller bird markets, they are displayed amongst other birds. A survey could last from around two hours for some of the smallest bird markets (e.g., Cikurubuk) to a full day for the largest (e.g., Pramuka).

In Indonesia, all native species of parrots are legally protected and only captive-bred individuals (second generation or above) can be legally traded. Non-native species can be traded, provided they have been imported with the appropriate permits or, again, if they are captive-bred. Parrots are openly offered for sale in the markets, and there was no need

to resort to undercover techniques to record them in the markets. Surveys were conducted by one, two, or occasionally three surveyors. We walked through markets slowly, recording numbers and species either on mobile phones or memorizing numbers and recording them in a notebook directly after leaving the market. Back alleys were not surveyed. We noted species and prices when possible, and photographs were taken opportunistically. We requested asking prices from the vendors without bargaining, and we did not purchase any birds or other wildlife.

2.2. Selection of Species and Analysis at the Genus Level for Disease Risks

We included all species of parrot, irrespective of whether they were native to Indonesia or not. Taxonomy and geographic origin of species and genera follows de Hoyo (2020) [35]. Indonesia has 83 species of parrot that are native to the country, including 7 species of cockatoos (family Cacatuidae) and 66 species of Old-World parrots (family Psittaculidae) [35]. In Indonesia, all native parrot species are legally protected and no wild-caught individuals are allowed to be sold in the bird markets.

The parrot species recorded are not uniformly distributed across all surveyed locations, with related parapatric species or congeners that alternated across geographical regions. To address this, we pooled taxonomic species into their respective genera, allowing for a more comprehensive analysis of disease risk factors and provide a clearer picture of the potential disease risks associated with different parrot genera in Indonesia.

Identification of parrots was performed in the bird markets. For species that were not readily identifiable, we asked vendors about species names and origin, and occasionally we took photographs for later identification. Very young birds (chicks, fledglings) or birds that had lost parts of their plumage during transport or storage, were only identified at the genus level.

We excluded Lovebirds *Agapornis* spp., Budgerigars *Melopsittacus undulatus*, and Cockatiels *Nymphicus hollandicus*, as these species are captive-bred within Indonesia in large numbers. More importantly, these parrots are frequently sold in standard pet shops throughout the county, and where they are present in bird markets, especially for lovebirds, they are sold by vendors and shops that specialize in these species without other birds (including other parrot species) on offer. Hence, by and large the trade in these three species is spatially separated from the trade in other parrot species.

2.3. Prevalence of Psittacosis from the Literature

For all the genera recorded in the bird markets, we compiled data from the literature about the prevalence of psittacosis (this was mostly based on testing for antibodies or other positive markers). We used Google Scholar to locate these publications, with searches conducted in October and December 2023, using the name of the genus we detected in our market surveys (e.g., *Cacatua*) and psittacosis or avian chlamydiosis as key words. In addition, we searched for 'parrot' and 'psittacosis' and 'parrot' and 'avian chlamydiosis'. Most of the searches resulted in English language articles or reports, but any report in French, Spanish, Portuguese, Dutch, German, Malay and Indonesian would have been suitable for inclusion. For each study we recorded the sample size (i.e., the number of individual parrots of a particular genus that was tested) and the number of positive samples. For analysis we pooled these samples and present the overall percentage of birds within a genus that tested positive.

2.4. Statistical Methods

We conducted most of the analysis at the genus level; for the genera we recorded in the bird markets we found a mean of 2.0 ± 0.3 species per genus; range 1–7). With the aim of representing which are the most popularly traded psittacine and their respective bird markets, a weighted matrix was created to record the number of animals traded in each bird market. From this, a chord diagram was created using the Circlize package [36].

For the heatmap analysis, we created a 14 by 21 presence–absence matrix for the parrot genera and the bird markets. Values were based on the average number of individuals that we observed over the course of the surveys. These values were then used to generate a heatmap using ClustVis [37]. ClustVis uses several R packages internally, including ggplot2 for the principal component analysis (PCA) plot, heatmap (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 a variance equal to one [37].

For the temporal analysis, we focused on one bird market, Sukahaji in Bandung, which was surveyed 29 times between 2014 and 2022. For each survey, we tallied the number of species and number of individual parrots. From the second survey onwards, we recorded the number of new species that had not been recorded during previous surveys to arrive at a cumulative number.

Prices were collected in Indonesian rupiah; these were adjusted for inflation to June 2023 (for instance, IDR10,000 in June 2014, when adjusted to June 2023, equals IDR13,340), and this was then converted to US dollars at June 2023 rates (with IDR10,000 equaling USD0.67).

We used parametric statistics (one-way Anova, Pearson's product-moment correlation) and prior to analysis we checked whether our data were normally distributed, and if not, we log-transformed the data to approach a normal distribution more closely (which it did). When comparing multiple groups in addition we checked whether the variances between groups were similar. We accept significance when $p < 0.05$ in a two-tailed test. All statistical analyses were performed using R v 4.3.0, and we report means $\pm$ SE.

3. Results

3.1. General Findings

Combing data from all the bird markets, we recorded at least 41 species of parrot from 21 genera, with a total of 4446 parrots recorded (211.7 $\pm$ 87.7 birds per genus; range 2–1288). In the majority of markets, we recorded between 100 to 400 parrots, with the exception of Pramuka, where we observed significantly more. Out of the 21 recorded parrot genera, the market that traded the highest number of specimens was Pramuka, with a total of 1810 individuals. Pramuka also had the highest diversity of genera, with a total of 16 genera and at least 32 species recorded.

We did not find a significant relationship between survey effort and the mean number of parrots we observed (Pearson's R = -0.344, $R^2 = 0.118$, $p = 0.229$) nor did we find a significant relationship between survey effort and the number of genera recorded (Pearson's R = 0.252, $R^2 = 0.06$, $p = 0.385$). In bird markets where more individual birds were recorded, either in absolute numbers or as the mean number of birds per survey, we also recorded more parrot genera (total birds: Pearson's R = 0.779, $R^2 = 0.607$, $p = 0.001$; mean number of birds: Pearson's R = 0.544, $R^2 = 0.296$, $p = 0.04$).

Our study spanned ten years (2014–2023); on average, each bird market was monitored in five of these years, ranging from having surveys performed in three to nine years. There was no significant relationship between the number of years monitoring took place and the mean number of parrots that were recorded (Pearson's R = 0.234, $R^2 = 0.06$, $p = 0.381$) or the total number of genera that were recorded (Pearson's R = 0.466, $R^2 = 0.218$, $p = 0.09$) and hence it appears that the trade in parrots, in terms of number of birds and number of genera for sale, has remained stable over this period.

From the literature we found a high rate of positive tests of psittacosis based on relatively large sample sizes in the following genera: *Trichoglossus*, *Ara*, *Amazona*, and *Psittacula*. Sometimes equally high levels of prevalence, but based on smaller sample sizes, were found in the following genera: *Aprosmictus*, *Aratinga*, *Eos*, and *Lorius*. We found low levels of positive tests despite relatively large sample sizes in *Cacatua* and *Platycercus*. Overall, of the 529 parrots that were reportedly tested, 111 tested positive for psittacosis, i.e., 21% (Table 1). The studies reporting on psittacosis came from a number of different

countries, included wild parrots as well as ones from captive settings; none were specific to bird markets and none came from Indonesia.

Table 1. Prevalence of psittacosis in native and non-native parrot genera that were recorded in the bird markets in Java and Bali, Indonesia.

Genus	Percentage Tested Positive (Combined Sample Size)	Reference
Lorius	50 (2)	[32]
Psittacula	33 (103)	[32–36]
Trichoglossus	58 (12)	[35]
Cacatua	4 (156)	[32,35]
Platycercus	9 (112)	[34,35]
Ara	48 (50)	[34,36]
Amazona	35 (52)	[34,36]
Aprosmictus	50 (2)	[36]
Psittacus	20 (20)	[36]
Aratinga	50 (6)	[36]
Eos	50 (2)	[36]
Eclectus	17 (12)	[32,34,36]

3.2. Links between Bird Markets and Genera

Three genera (*Eos*, *Loriculus*, and *Trichoglossus*) were traded and co-occurred in all studied bird markets, with a higher overall quantity of specimens. *Eos* had the highest number of recorded specimens with 1281, followed by *Loriculus* with 1079, and *Trichoglossus* with 1051. The cord diagram reveals the interconnections between recorded parrot genera and sampled bird markets showing that (a) on average, each genus was recorded in 5.8 ± 1.1 markets and (b) each bird market had 8.8 ± 0.9 genera for sale over the course of the survey (Figure 1). These means, however, are heavily skewed due to (1) three genera that were recorded in all 14 markets, (2) the six genera that were recorded in only one bird market, and (3) the three markets where a high diversity of genera was offered for sale (i.e., Pramuka with 16 genera, Sukahaji with 13 and Barito with 12). Overall, there was a clear, positively significant relationship between the number of genera and the total number of individuals recorded in a bird market (Pearson's R = 0.783, R^2 = 0.61, p = 0.0009). Additionally, there was a significant relationship between the number of bird markets in which a genus was present and the total number of individuals of that genus that was recorded (Pearson's R = 0.924, R^2 = 0.85, p = 0.0001).

The heatmap (Figure 2) shows three distinct bird market clusters, each grouping four or five markets, i.e., (1) Bratang, Jatinegara, Pasty and Splindit; (2) Satria, Pramuka, Karimata and Kupang; (3) Kerkhof, Sukahaji, Cikurubuk and Plered. The third cluster comprises markets in the province of West Java, but the other two clusters contain markets in western, central and eastern Java. The one wildlife market in Bali clusters closest to one in Central Java. In terms of clustering of genera, several smaller clusters are recognizable, e.g., the three large-billed genera of *Eclectus*, *Psittinus* and *Tanygnatus* (the latter of which has been synonymized with *Psittinus*: Ref. [38]) or the two South American genera of *Myiopsitta* and *Aratinga* with the Australian *Platycercus*. One large cluster of mainly eastern Indonesian genera (*Loriculus*, *Eos*, *Trichoglossus*, *Calcopsitta*, *Lorius*, *Charmosyna* and *Cacatua*) is also recognizable in the heatmap (Figure 2).

3.3. Temporal Patterns

Over the period from April 2014 to March 2022, we made 29 visits to Sukahaji bird market in Bandung. On every occasion we recorded parrots for sale (a total of 13 genera and 18 species) (Figure 3). On average, during each individual survey 3.5 ± 0.4 species and 13.0 ± 3.4 individual parrots were recorded (or 3.5 ± 0.7 individuals/species), with the smallest number of parrots recorded being a single parrot, and the largest number recorded being 101 parrots of five different species. As with the between-market surveys,

in Sukahaji we found a clear positive relationship between the number of genera and the number of individuals detected during individual surveys (Pearson's R = 0.708, R^2 = 0.50, p = 0.0001). Hence, when more individual parrots are offered for sale, there is also increased species diversity.

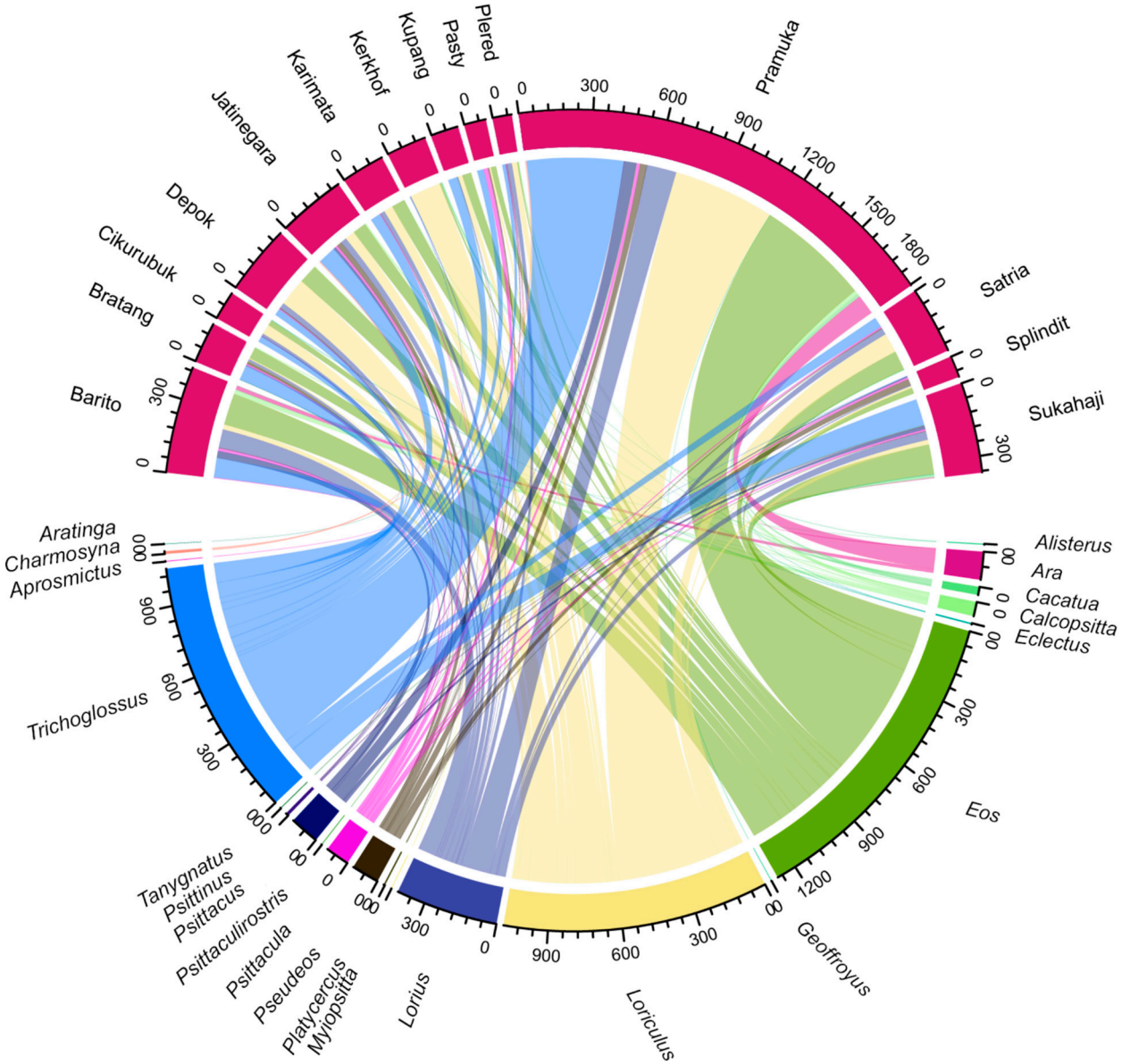

Figure 1. Cord diagram mapping the interconnections between wildlife markets in Java and Bali, Indonesia (upper half circle) and recorded parrot genera (lower half circle).

The variation (number of individuals, number of species, number of genera) between surveys was large. We found no temporal difference in the number of parrots we recorded, i.e., 8.2 ± 2.5 parrots/survey in January–April, 36.9 ± 15.0 in May–August and 5.7 ± 1.7 in September to December (one-way Anova, $F_{2,26}$ = 2.66, p = 0.089).

3.4. Origins

Only a few species of parrot have Java included as part of their natural range, i.e., Red-breasted Parakeet *Psittacula alexandri*, Javan Hanging Parrot *Loriculus pusilus* and Blue-crowned Hanging Parrot, *L. galgulus* (feral populations). The three species are also found in Bali. In addition, the Yellow-crested Cockatoo *Cacatua sulphurea* occurs on offshore

islands of Java or Bali (e.g., Masakambing, administratively part of the province of East Java and Nusa Penida, administratively part of Bali). All four species were recorded during our trade surveys. Within Indonesia, the red-breasted parakeet has its main distribution range on Java and Bali and their offshore islands, and the Javan hanging parrot is endemic to Java and Bali, thus, we would expect that the birds we observed in the markets were sourced locally. The other two species are not endemic to Java and Bali, and they may have been sourced from elsewhere within Indonesia (e.g., Blue-crowned Hanging Parrot from Sumatra and Yellow-crested Cockatoo from eastern Indonesia).

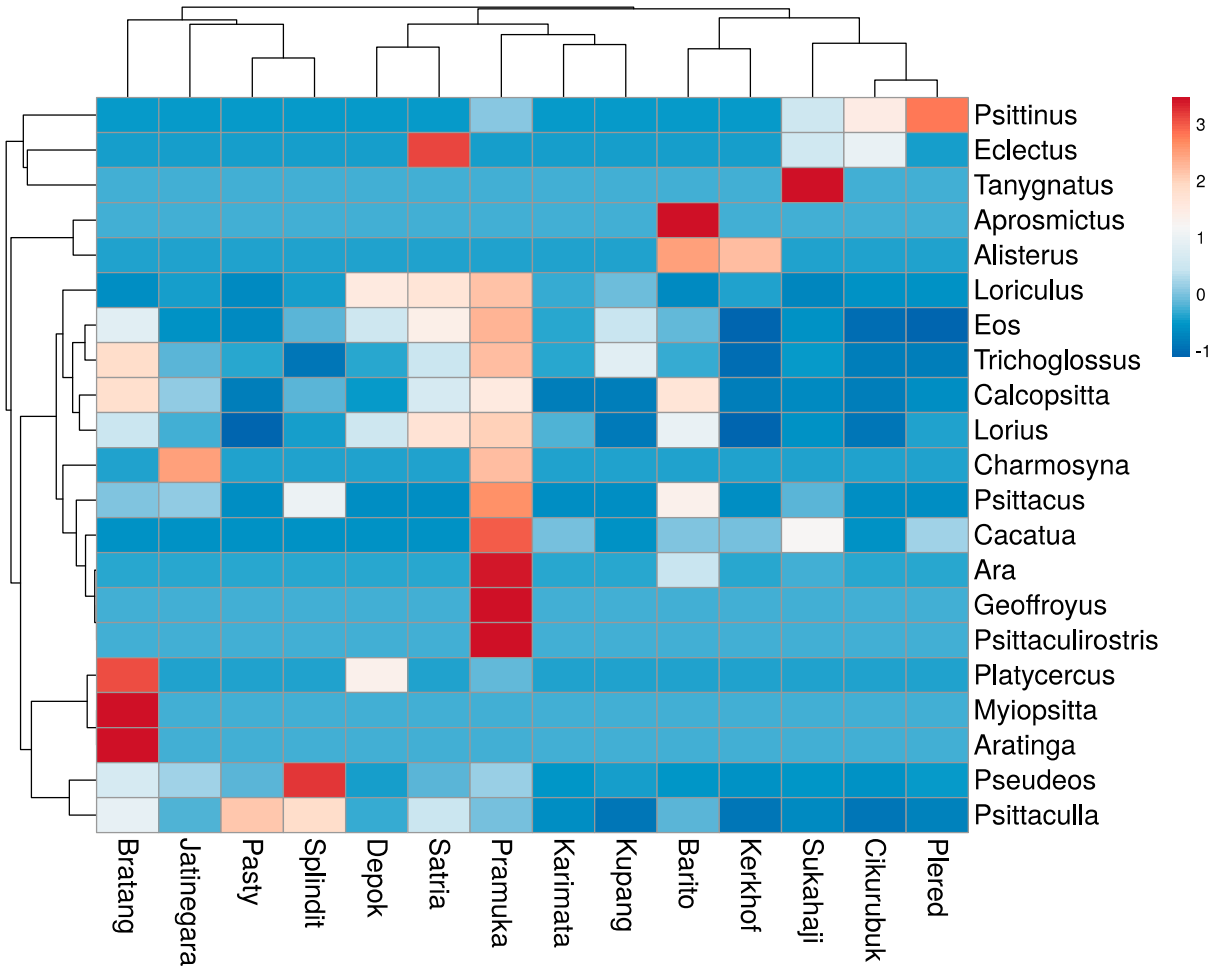

Figure 2. Heatmap of parrot genera recorded in 14 wildlife markets in Java and Bali between 2014 and 2023 based on the mean number of birds observed per survey. The values are relative, with red indicating the highest values and pale blue the lowest. The dendrograms on the left represent the clustering of genera, whereas the dendrogram on the top indicates the clustering of markets.

In total, 27 of the species and 12 of the genera we recorded have a natural distribution range that includes eastern Indonesia, i.e., the region east of Wallacea (e.g., Australia, Oceania) or north (e.g., the Philippines). Three of the genera (*Loricullus*, *Psittaculla*, *Psittinus*) include species that are found in western Indonesia, as well as parts of mainland Southeast Asia. For these 15 genera, we expect that most of the individuals we observed in the markets were sourced from Indonesia rather than from other countries.

Species belonging to three genera are native to South and Central America (*Ara*, *Myiopsitta*, *Aratinga*) and one in Australia (*Platycercus*) (Table 2), and individuals of these taxa we observed in the markets have either been imported or, perhaps in smaller numbers, were captive-bred in Indonesia. One genus (*Psittacus*), including two species, is only found in Africa and given that this species has been exported in very large numbers out of various

African range countries [38], we expect that the individuals we observed in the Indonesian markets were imported rather than captive bred locally. We did not obtain firm information on to what extent the parrot trade we observed is part of a larger global network of parrot trade (which in itself would have additional global health implications). Some of the larger traders in some of the larger markets (e.g., Pramuka in Jakarta), and especially the ones that offered non-native species for sale, may be part of a global network, but it appears that the majority of traders in the bird markets cater largely if not exclusively for a domestic clientele.

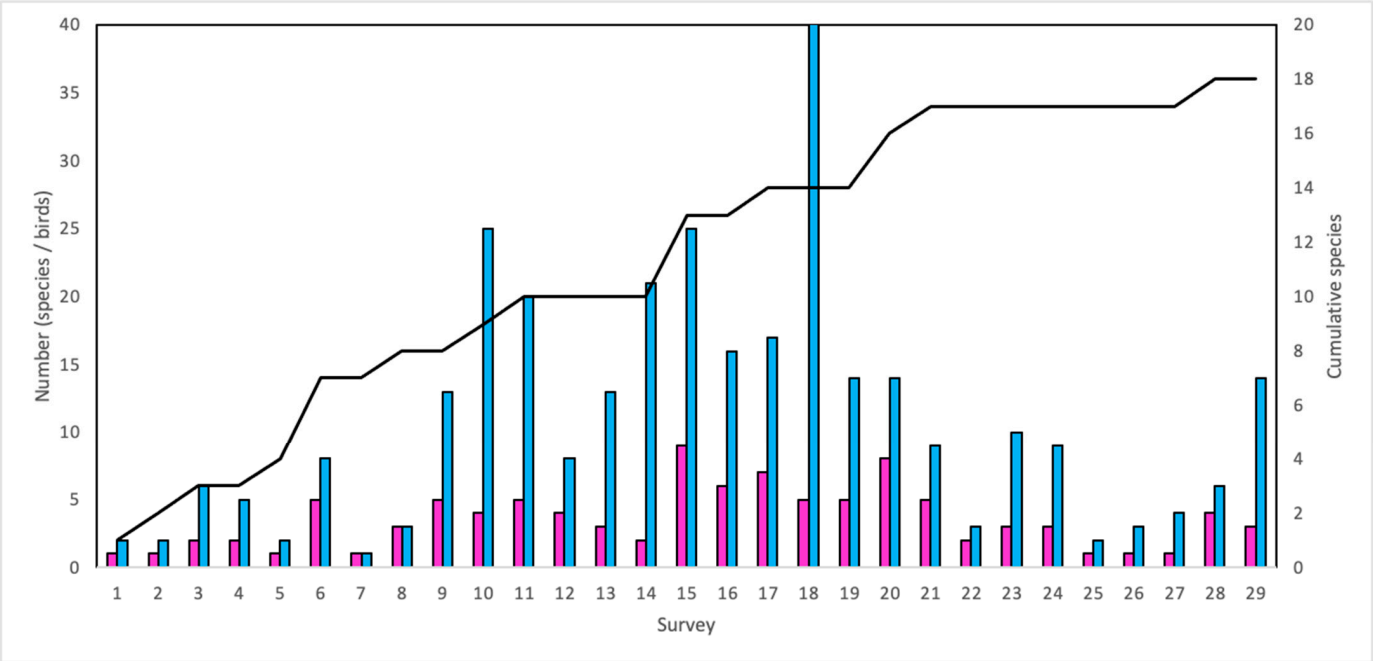

Figure 3. Temporal variation in the number of parrot species (pink bars) and number of individuals (blue bars) recorded during 29 surveys of Sukahaji bird market in Bandung, West Java, Indonesia, between 2014 and 2022. The grey line represents the cumulative number of species that were recorded, peaking at 18 species. The bar at survey 18 extends to 101 birds.

Table 2. The geographic origin of the parrot species (and genera) recorded in bird markets in western Indonesia (Java and Bali) over the period 2014–2023, showing that most likely these have been sourced from other parts of Indonesia and from abroad (see text for details). Data on geographic origin taken from del Hoyo (2020) [35].

Origin	Genera (Species)	Individual Parrots
South and Central America	3 (6)	115
Australia	1 (2)	5
Africa	1 (2)	119
Western Indonesia	3 (5)	1188
Eastern Indonesia	12 (27)	2978

For an illustration of the parrot trade in bird markets in Indonesia we refer to Figure 4.

Figure 4. Parrot trade in Indonesia showing the species that are offered for trade and the conditions in which they are traded, from left, clockwise: Chattering Lory *Lorius garrulus* and Black Lory *Chalcopsitta atra*; African grey parrot *Psittacus erithacus*; bird market with Moluccan Red Lory *Eos bornea* and Dusky Lory *Pseudeos fuscata*; Black-capped Lory *Lorius lory*, Dusky Lory, Brown Lory *Chalcopsitta duivenbodei*, Chattering Lory and Eclectus Parrot *Eclectus roratus*; bird market; the photo in the center depicts a Moluccan Red Lory. Credit: Katey Hedger, Vincent Nijman and Abdullah Abdullah.

4. Discussion

4.1. General Findings

Through our surveys, we recorded over 4000 mainly wild-caught parrots from 21 genera for sale in the bird markets located in Java and Bali. Parrots were found in all of the 14 bird markets surveyed, with the larger markets containing large numbers of parrots from different genera for sale on every survey. Java and Bali are home to only three or four parrot species—each of which were observed for sale—and therefore the majority of parrots must have been transported over significant distances. This includes parrots imported from Africa, South America, and Australia, but even those originating from eastern Indonesia would have been transported over 1000 s of kilometers, involving either long boat journeys, flights and/or distances covered by car or truck. Our observations suggest that the sampled bird markets, especially the smaller ones, primarily cater to the domestic market. To gain a deeper understanding of the potential for disease spread beyond Indonesia's borders, future research could focus on available data from the parrot trade export network, exploring the associated risks with the exportation of birds to other countries.

The bird markets that presented the largest number of parrots for sale were Pramuka and Barito in Jakarta, Sukahaji in West Java and Satria in Bali. Within our study area, Pramuka is our westernmost market and Satria the easternmost, and thus the trade in parrots does not appear to be concentrated to one specific region. Three genera (*Eos*, *Trichoglossus* and *Loriculus*), from different parts of Indonesia, were recorded in each market and form the bulk of the Indonesian parrot trade.

Whilst we were not able to test parrots for the presence of psittacosis in the wildlife markets in Java and Bali, there is sufficient evidence from previous studies to show that

the majority of the genera we recorded have tested positive previously for the disease (see our Table 1). This includes the taxa we frequently recorded in the bird markets in Java and Bali, i.e., the genera *Trichoglossus*, *Cacatua*, *Platycercus*, *Ara*, *Amazona*, *Aprosmictus*, *Psittacus*, *Aratinga*, *Eos*, *Lorius*, *Eclectus*, and *Psittacula* [39–41]. It is therefore reasonable to assume that, given that when tested high proportions of parrots test positive for psittacosis, the prevalence in the bird markets is not negligible. We did not find evidence to support for the presence of psittacosis within all genera we recorded, however, we suspect that this is due to the paucity of testing these parrots, especially within Indonesia. In addition to parrots, there are several other bird species that may carry Chlamydiosis and other pathogens and are often traded alongside the parrots. For instance, surveys conducted in 2016 reported on the presence of approximately 16,000 wild-caught birds from more than 200 species in three Jakarta bird markets alone, which increases further the risk of disease spreading [18,42].

4.2. Disease Transmission Implications

The COVID-19 pandemic, and especially its links to wet markets and the live wildlife trade, has led to a renewed interest in the Great Parrot Fever Pandemic, psittacosis and avian chlamydiosis, including previous research [43–52]. One of the lessons from this renewed interest is that while the global incidence of avian chlamydiosis infection is apparently low [53] there is a significant likelihood of human-to-human transmission of psittacosis [54]. In November 2012, an outbreak of human psittacosis was observed at the New Territories North Animal Management Centre in Hong Kong, resulting in the infection of six staff members. Subsequently, several medical personnel and family members who had been in close proximity to the patients during their hospitalization also exhibited comparable symptoms to those infected [55].

Disease risk associated with the trade in parrots is further compounded by poor animal husbandry conditions. Animals that are caught for the wildlife trade are usually highly stressed and transported in very cramped conditions in close proximity to many other animals [9,56,57], thus, increasing opportunities for disease transmission. For example, a large wildlife confiscation in the Philippines involved 312 Indonesian birds (and marsupials), many of which were malnourished, in poor condition and experienced progressive morbidity and mortality [58]. In an examination of five of the confiscated birds (Sulphur-crested Cockatoos *Cacatua galerita*, Black Palm Cockatoos *Probosciger atterimus*, Moluccan Cockatoos *C. moluccensis*), they found that four birds had aspergillosis (a fungal disease), and all birds suffered severe haemorrhagic enteritis [59].

The spatial-temporal dynamics observed in the parrot trade are crucial elements that could influence the risk of disease transmission. The persistent trade over the years, all year-round are combined with variated origin of parrots traded, including both western and eastern Indonesia, as well as international sources such as South and Central America, Australia, and Africa. This temporal persistence and spatial diversity in the origin of parrots in the trade is indicative of the extensive network that supports the movement of these birds across regions, underscores the potential for disease introduction and spread.

4.3. Study Limitations

In an ideal world we would have like to be able to test for the presence of psittacosis in each of the almost 4500 parrots we observed in the bird markets over the ten-year study period; and additionally to have tested as many of the parrot sellers and (potential) customers for the presence of avian chlamydiosis. This was not possible for various reasons, and we had to design our study in a way that was both practical and feasible. Hence, to ascertain the establishment of psittacosis in the parrot genera we observed in the markets we had to refer back to published research, where we found a substantial number of confirmed cases a large number of studies. Although we acknowledge that our research lacks specific cases from Indonesia, other researchers working on parrots in Indonesia (either in the wild, in zoos or in the pet trade) also have struggled to test for psittacosis likewise have not done this (or if they have, this remains unpublished). It is important

to note that the availability of confirmed cases of pathogens, especially in wild animals on a large scale, is rare as surveillance in the wild is not commonly done. The use of available notified cases, whether in humans or wild animals, to extrapolate the risk of diseases to other areas is a commonly employed approach, even in more complex modelling scenarios [60,61].

In Indonesia, psittacosis is not a notifiable disease and hence there is no obligation when detected to report this to the authorities, and as elsewhere in the Global South, psittacosis case numbers in Indonesia, most certainly are underestimated [31]. Asymptomatic transmission, a general lack of awareness among doctors as to the potential risk of human-to-human transmission, and lack of clinical and laboratory testing options, are a few of the reasons for this underestimation [31]. Our review implies that psittacosis is prevalent enough to be a global concern and likely widespread, making it improbable that Indonesian bird markets are exempt from its occurrence. Although we did not conduct specific tests on the parrots involved in the monitored trade to establish a direct link between psittacosis transmission and the bird markets surveyed, the evidence from our review and the broader global context strongly suggests a substantial risk of disease transmission. Therefore, our study draws attention to the historical prevalence of psittacosis in parrots, raising pertinent concerns about the market conditions that foster the spread of communicable diseases, influenced by factors such as hygiene conditions, the high diversity and density of parrot species within markets and long transportation routes of individuals until they reach the market. Given that these markets can host non-indigenous wild-caught species, transported over long distances, the potential for diseases like psittacosis to enter and spread across the bird markets is likely, demanding further investigation. Furthermore, the prevalence of psittacosis in Indonesian bird markets could be heightened because of the presence of domesticated parrot species (e.g., lovebirds, Budgerigars and Cockatiels) that are offered alongside the wild-caught ones. We did not systematically record these as our research interests are mostly focused on wild birds [10,12,15,19–21,42] but diseases may not distinguish between 'wild' and 'domestic' and for future studies we recommend the inclusion of domestic species alongside wild ones.

Our study was largely observational and we focused on a relatively large number of bird markets that were visited infrequently over a prolonged period of time. A higher number of visits to certain markets that were surveyed only a few times (and perhaps a more equitable distribution of visits to these markets) may have resulted in slightly different patterns of trade. Equally, spending more time in these markets may have led to deeper insights into how the parrot trade in this part of Indonesia operates, what trade networks are involved and from where exactly the parrots are sourced. The latter extends to gaining insight into what extent the Indonesian parrot trade is part of a larger global network, where parrots are exported, imported and re-exported from. Our primary objective, however, is for our work to serve as a crucial early warning, and we propose that future research, incorporating direct testing of traded parrots, can yield more concrete data. Despite the absence of such testing in our study, it serves as underscoring the imperative for further investigations into the health implications of the parrot trade.

4.4. Conservation and Management Implications

Globalization has facilitated the expansion of bird markets, allowing for easier transmission of infected animals across borders [62]. Therefore, globalization may act as a catalyst for the spread of diseases such as psittacosis due to the greater accessibility and frequency of international travel, which not only increasing the risk of human exposure to infected animals but also leading to the wider dissemination of contaminated products. The interconnectedness brought about by this phenomenon complicates the containment of psittacosis, making it more challenging to control compared to past outbreaks of zoonotic diseases [63]. Regulatory inconsistencies between countries further exacerbate the situation, with different nations having varying standards for animal health and biosecurity—from strict to no standards—making it difficult to implement uniform containment measures

and leading to gaps in disease surveillance and control [64]. Likewise, within countries, including Indonesia, there may be differences in both regulations and implementation of agreed policies that hamper disease surveillance and control.

The risk of zoonotic disease in parrots poses challenges not only from a public health and disease risk perspective but also from a conservation perspective. Twenty-nine percent of extant parrots are classified on the IUCN Red List as threatened, and more than half of all parrot species are in decline [65,66]. The spread of such diseases could further threaten these already at-risk populations, particularly if novel pathogens are introduced from abroad through trade. Parrots imported for the pet trade have been known to escape and establish non-native populations, for example, the Alexandrine Parakeet *Psittacula eupatria* in Europe, parts of the Middle East, Japan and Singapore [67], Ringnecked Parakeets (*P. krameri*) in the UK (originating from Africa and South Asia). Escapees of infected parrots could pose substantial risks to indigenous wildlife populations, as documented in countries such as the USA (Hawaii) [68] and New Zealand [69].

In Indonesia, parrots stand as the second most trafficked group of birds, following songbirds [70]. A relevant 84% of the species and 80% of the genera documented in the sampled markets naturally inhabit Indonesia (accounting for 71% of the total individuals recorded). This highlights the profound conservation ramifications of the parrot trade with a substantial impact on Indonesia. The Wallacean parrots, in particular, are among the most threatened globally [71] and were constantly recorded in trade. Those wild populations are already significantly impacted by parrot trade and underscore the urgency of not only controlling the trade's impact but also preventing the introduction of diseases that could further jeopardize the already vulnerable wild populations.

In the aftermath of the COVID-19 pandemic, there is a growing awareness of the health risks associated with the trading of wildlife and the need to mitigate these risks [72]. Efforts to reduce the potential spread of zoonosis in these bird markets will need to consider the risks of novel disease introduction from wild-caught birds, the spread of disease between parrots and other animals, the risk to human health and the risk to wild populations. Compendium of measures to control *Chlamydia psittaci* infection among humans (avian chlamydiosis) and pet birds (psittacosis) provides essential guidelines for public health officials, the pet bird industry, and others involved in managing these diseases and safeguarding public health [73]. Some strategies can help to effectively monitor and manage the risk of psittacosis and other diseases in the parrot trade. The inclusion of regular health screenings and genetic testing to identify pathogenic strains will promote disease surveillance [74,75]. Combined with identification of possible sources of pathogens, enhancing biosecurity measures in bird markets through separation of different bird species, control of market density, and maintenance of good sanitary conditions can reduce cross-species transmission risks [76]. Additionally, public awareness campaigns serve as an essential tool for educating both bird traders and the general public about zoonotic diseases and promoting best practices in bird handling [77].

It is also important to recognize that zoonosis risk is not limited to illegal wildlife trade but is also a threat embedded in legal trade [72]. More than 16 million live CITES-listed parrots in 321 species were legally traded globally between 1975 and 2016 [66]. Stricter controls on the import and export of wild birds are crucial to prevent the spread of non-native diseases and overharvesting of wild populations [78]. Ultimately, establishing robust national and international disease control mechanisms and adopting a One Health approach, which considers the interplay of human, animal, and environmental health, is critical for tackling diseases like psittacosis in the intricate context of wildlife markets [79].

5. Conclusions

The Great Parrot Fever Pandemic of 1929 and 1930 was incontrovertibly linked to the then burgeoning global trade in parrots, with 1000 s of birds being shipped from one country and one continent to the next. People from all over the world were infected and around one hundred people died [76]. Lessons could and should have been learned

from this but this has not happened universally. We focused on the open bird markets in western Indonesia as these seem to be places where the conditions for the next outbreak of psittacosis (and avian chlamydiosis) are ideal: dozens of parrots are present among 1000 s of other wild-caught birds, in cramped and stressful conditions, with poor ventilation and hygiene, and in the presence of 100 s or 1000 s of people visiting these markets daily. During our surveys of 14 of these markets we indeed recorded 1000 s of parrots from a large number of species that included both locally caught species, species that were caught in other parts of Indonesia, and ones that were shipped in from South America, Australia, Africa or mainland Asia. While we were not able to test individual birds in the markets, for 12/21 parrot genera we found evidence from previous studies of a high prevalence of psittacosis (i.e., around a fifth of the birds tested positive). Hence, there is every reason to assume psittacosis is present in the Indonesian wildlife markets. While psittacosis is not yet classified as a severe disease for humans today, its potential impact on vulnerable people and wild avian populations underscores its significance as a threat to animal health, public health, and food safety. This necessitates a controlled response and measures to mitigate risk of zoonotic disease transmission (there are frameworks and protocols in place for this already [76–80] and in an Indonesian context this could follow to what has been argued for the wildlife trade linked to tourism: Ref. [81]). We did not see any evidence of this during our 176 surveys of these bird markets, and this is something that should cause concern from a public health perspective and is something that needs to be addressed.

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