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Risk Prioritization Tool to Identify the Public Health Risks of Wildlife Trade: The Case of Rodents from Latin America

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Impacts

- Wildlife imported into the United States poses a risk of introducing zoonotic and/or emerging pathogens to humans and animals. Large data gaps exist to properly assess these risks in a quantitative fashion.
- 'Risk prioritization' is a practical tool to identify the highest risk pathogens coming into the country via trade in wildlife. A pilot study evaluating the zoonotic potential of rodents shipped from Latin America proved its usefulness.
- This proposed tool should be further tested/validated in other wildlife trade importation scenarios to help inform policy and to allocate resources accordingly.

Keywords:
Risk prioritization; wildlife trade; rodent-borne pathogen; emerging diseases; risk assessment; zoonoses

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Summary

Wildlife trade (both formal and informal) is a potential driver of disease introduction and emergence. Legislative proposals aim to prevent these risks by banning wildlife imports, and creating 'white lists' of species that are cleared for importation. These approaches pose economic harm to the pet industry, and place substantial burden on importers and/or federal agencies to provide proof of low risk for importation of individual species. As a feasibility study, a risk prioritization tool was developed to rank the pathogens found in rodent species imported from Latin America into the United States with the highest risk of zoonotic consequence in the United States. Four formally traded species and 16 zoonotic pathogens were identified. Risk scores were based on the likelihood of pathogen release and human exposure, and the severity of the disease (consequences). Based on the methodology applied, three pathogens (*Mycobacterium microti*, *Giardia* spp. and *Francisella tularensis*) in one species (*Cavia porcellus*) were ranked as highest concern. The goal of this study was to present a methodological approach by which preliminary management resources can be allocated to the identified high-concern pathogen–species combinations when warranted. This tool can be expanded to other taxa and geographic locations to inform policy surrounding the wildlife trade.

Introduction

It is well established that approximately 60% of emerging infectious diseases are zoonotic and that more than 70% have a wildlife origin (Jones et al., 2008). There are many examples of such diseases (e.g. human immunodeficiency virus, highly pathogenic avian influenza) (Bengis et al., 2004; Morens et al., 2004). Epidemiologically, disease emergence is a result of the dynamic relationship between a disease causing agent, its host, and the environment in which it evolves. In many cases, this relationship is highly influenced by anthropogenic activities or drivers such as land use change, war and famine, climate change, and global trade and travel (Keesing et al., 2010).

Wildlife trade is defined as the sale and/or exchange of wild animal and plant resources, and it can be formal (legal) or informal (illegal) (TRAFFIC, 2014). The economic value of the legal global wildlife trade (including timber

and fisheries) is estimated at US$300 billion annually (Ratchford et al., 2013). The volume of wildlife specimens traded worldwide is substantial. The United States alone imported approximately 1.5 billion live animals between 2000 and 2006 (Smith et al., 2009). This activity has a negative impact on wildlife conservation of threatened species that are traded, pushing certain populations to the border of extinction (Broad et al., 2003). It has also contributed to the emergence (or re-emergence) and spread of infectious diseases (Swift et al., 2007; Karesh and Noble, 2009; Pavlin et al., 2009; Smith et al., 2009, 2012; Travis et al., 2011). These diseases pose a risk for agriculture, native wildlife and public health. One prominent example of the public health risk from wildlife trade importation was the US monkeypox outbreak in 2003. Gambian pouched rats (*Cricetomys gambianus*) infected with monkeypox virus were imported from Africa into the United States via the pet trade and placed in close proximity to native prairie dogs (*Cynomys* spp.), which became infected. The prairie dogs were distributed throughout the country as pets, infecting 71 people in 6 states (Gibbs, 2005; CDC, 2008). After this event, the Centers for Disease Control and Prevention (CDC) and the Food and Drug Administration (FDA) banned the importation of African rodents into the United States.

Public health concerns associated with wildlife trade are reflected by proposed legislative changes such as bill H.R. 669 (2009) proposing a ban of all wildlife imports until a risk assessment could be performed by the US Fish and Wildlife Service (USFWS) for all wildlife species entering the country (Bordallo, 2009). Such an approach may pose economic harm to sectors such as the pet industry, and place substantial burden on importers to provide proof of low risk for importation of individual species. Consequently, agencies could benefit from an accessible, user-friendly, science-based risk assessment tool to aid in the risk evaluation of wildlife imports.

In the vernacular of the World Organisation for Animal Health (OIE), risk assessment is one of the components of the entire risk analysis framework. A formal risk analysis is an unbiased, scientifically based, iterative and transparent process that helps policy decision-making in the face of uncertainty (Jakob-Hoff et al., 2014). The components of a risk analysis are as follows: hazard identification, risk assessment, risk management and risk communication (OIE, 2014). Risk assessment consists of three phases: (i) release – likelihood of a pathogen being released (introduced) into the area of concern; (ii) exposure – likelihood that the species of concern will be exposed to the pathogen once released; and (iii) consequences – the consequence of exposure to the pathogen. Risk analysis applied to disease spread has been used traditionally in the veterinary profession to assess risks related to livestock trade and movements (OIE, 2014). The International Union for Conservation of Nature (IUCN) has also used risk analysis to assess the risk of wildlife translocations and invasive species. In 2014, formal risk analysis guidelines were released that combine both IUCN and OIE methodologies to assess the risk of wildlife diseases in a myriad of situations, including public health impacts (Jakob-Hoff et al., 2014).

The first step when applying the risk analysis framework is to identify the hazards and species of concern (hazard identification). When there are too many hazards to assess, they can be ranked based on their impact (risk), or relevance to the specific problem at hand. This process is called risk prioritization, and some examples can be found in the scientific literature related to the prioritization of foodborne and zoonotic diseases (Kemmeren et al., 2006; Henson et al., 2007; Cardoen et al., 2009; Ruzante et al., 2010; Balabanova et al., 2011; Ng and Sargeant, 2012; Ng and Sargeant, 2013). However, to the authors' knowledge, there are no published reports applying risk prioritization tools to assess the zoonotic risk of wildlife trade into the United States.

Mammals represent a small proportion of the total wildlife imported into the United States compared to other classes (Smith et al., 2009). Within class Mammalia, rodents traded between the United States and Latin America and Caribbean countries (LAC) ranked second in declared rodent importations worldwide, after those imported from Europe to the United States. Between 1999 and 2012, about 100 000 rodents were formally imported from Europe, compared to approximately 15 000 rodents that were formally imported from LAC (Lankau, 2013, Unpublished results). Because of previous experience such as the monkeypox outbreak, some have hypothesized that the importation of rodents from LAC poses a risk for disease introduction into the United States due to the lack of health requirements for importation of this group of animals (CDC, 2013) and their potential to serve as zoonotic disease hosts. Unfortunately, the largest limitation to testing this hypothesis and characterizing the risk is an extreme lack of surveillance data that could be used in risk assessment modelling. Despite this important limitation, the authors believe it is still critical to advance on the development of qualitative and semi-quantitative methodologies to assess risk; these tools are also important for highlighting important data gaps and research priorities. The example of LAC–US rodent import pathway was selected to demonstrate this approach.

The goal of this study was to build a risk prioritization tool to rank zoonotic pathogens from live rodent species endemic to and legally imported from LAC into the United States. Specifically, the question evaluated was: 'What are the highest public health risks of pathogen–rodent species combinations (rodents endemic to LAC, legally and directly

shipped from LAC into the United States) in terms of potential human morbidity and/or mortality (ranging from minor symptoms to death caused by these pathogens)?'.

The risk prioritization tool developed in this study may have additional applications as a screening tool for other wildlife taxa of concern to governmental and non-governmental agencies and NGOs. It may prove most useful in directing scarce resources in situations with sparse data to prioritize more in-depth research or regulatory methods.

Materials and Methods

Hazard identification

Hazard identification was performed by constructing a database including both wildlife trade data and literature review on species-disease evidence. Once the species of interest were identified, a decision tree was built based on relevant inclusion/exclusion criteria to identify all *potential* rodent-borne hazards (Fig. 1). This allowed for a broad scope of inclusion on first pass, followed by a rigorous ranking procedure to determine the level of relevance to the specific aim of the study.

Data were obtained for the period 2007–2010 from the US Fish and Wildlife Service (USFWS) Law Enforcement Management Information System (LEMIS) (Freedom of Information Act: Data, FOIA) and the 2013–2014 Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) to identify the endemic rodent species legally imported from LAC to the United States. The subsequent literature search matched the common and scientific names of the imported rodent species, in both English and Spanish with various disease search criteria (e.g. salmonellosis AND *Dasyprocta* spp.; parasites AND agoutis, etc.). The literature review was performed using several search engines (Google Scholar, Google, PubMed, OVID Medline, Web of Science) to identify all potential rodent-borne pathogens. The following inclusion and exclusion criteria were applied in an evidence-based manner to match identified rodent spp. with potentially risky pathogens: (i) Is there any evidence that the pathogen is zoonotic? (ii) Is there evidence that the pathogen may be associated with the identified legally traded rodent species endemic to LAC? (For this criterion, any evidence was considered, both natural and experimental infections.) (iii) Is the rodent able to transmit the pathogen (versus a dead-end host)? and (iv) Can the pathogen be directly transmitted to humans? (Fig. 1). Non-directly transmitted pathogens were not included in this study given the requirement for a vector for transmission. In some cases, evidence in a closely related spp., or the same spp., from a different geographic location was considered.

Risk prioritization tool

A semi-quantitative model was built to rank the risk of the zoonotic pathogen–rodent species combinations identified

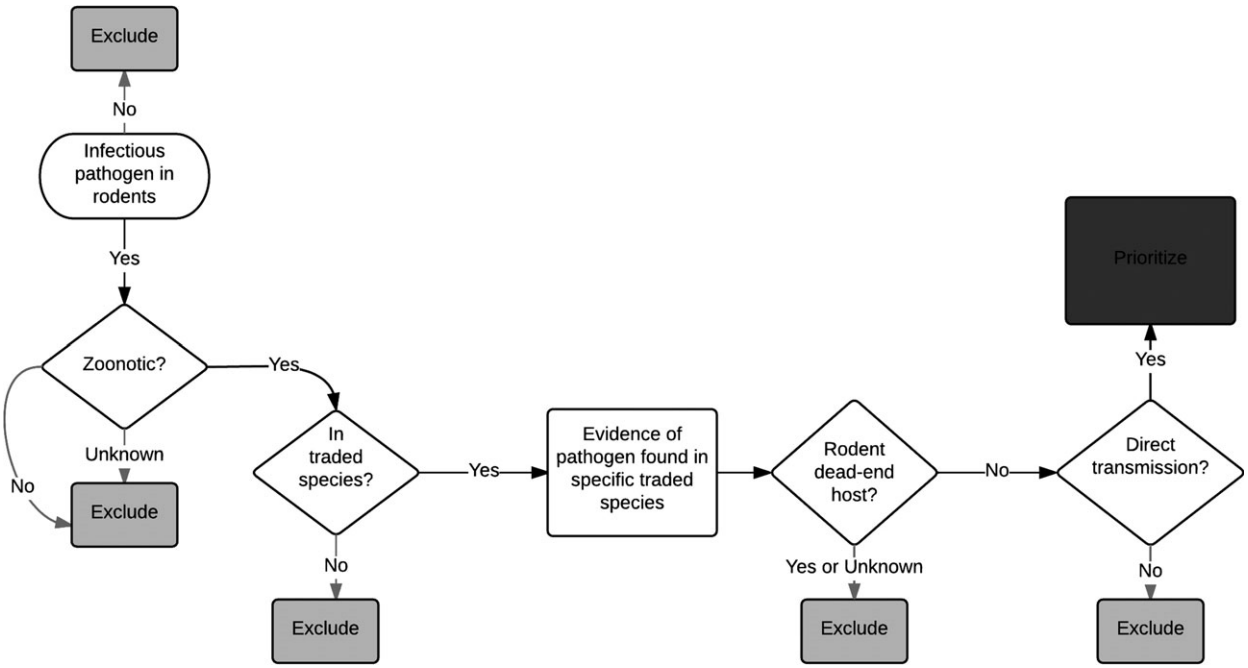

Fig. 1. Inclusion and exclusion criteria applied to the original hazard database during the hazard identification phase.

during the hazard identification process. The components of the model included factors that influenced the likelihood of pathogen presence (release), likelihood of human exposure, and severity (consequences) of the pathogen given disease in humans.

The model was built on the following equations:

$$\text{Overall likelihood} = \text{Likelihood of release} \times \text{Likelihood of exposure} \quad (1)$$

$$\text{Likelihood of release} = [\text{Prevalence} - \text{Clinical signs/Detection} + \text{Number of animals shipped/year}]$$

$$\text{Likelihood of exposure} = [\text{Contact type} + \text{Shedding (duration and frequency)} + \text{Type of transmission}]$$

Table 1 defines and summarizes the factors considered for Equation 1. Due to the limited data available, it was assumed release and exposure factors contribute equally to the overall risk in this evaluation. However, factors should be weighted in a transparent fashion, according to the user's definition of risk in each individual case. The numeric scores assigned to each release and exposure factor were justified based upon available data, peer-reviewed scientific information, or expert interviews. Numeric scores were then related to narrative qualitative terms (low to very high risk). The factor 'Clinical signs/Detection' on equation 1 was added with a negative sign (as a substraction) based on the assumption that if infected animals were inspected at the point of entry and illness discovered, then they should be removed and isolated reducing the overall likelihood of release.

$$\text{Severity(Consequences)} = \text{DALY}\left(\sum S_j \times D_j \times l_j\right) \times \text{Estimated number of households in the United States (not individuals) with imported pet rodents from LAC} \quad (2)$$

where S_j is the severity of the health effect j for a given hazard ranging from 1 (death) to 0 (asymptomatic), D_j is the duration of the health effect j (in days) and l_j is the likelihood of the health endpoint j to be developed by an immunocompetent population ranging from 0 to 1 as percentage of cases.

The total disability-adjusted life year (DALY) is a public health metric (measured in years) used to quantify the impact of premature death and non-fatal health outcomes resulting from disease on a population (Mangen et al., 2013). It estimates the burden of a disease in a population by multiplying the individual health effects after exposure to a certain pathogen (individual DALY value) by the total number of population exposed to the pathogen (total DALY value for a population). This approach has been traditionally used by the World Health Organization (WHO) to evaluate the burden of certain diseases worldwide. The DALY metric has also been used to prioritize foodborne pathogens (Ruzante et al., 2010).

In this study, it was adapted to assess the severity of zoonotic pathogens from imported rodents in humans. Specifically, the DALY values were estimated to evaluate morbidity outcomes but not mortality, except for the combination *Lyssavirus* (rabies)–*Cavia porcellus*, where death in humans is well documented. In three instances (*Salmonella enterica* spp.–*Cavia porcellus*, *Salmonella enterica* spp.–*Dasyprocta* spp. and *lymphocytic choriomeningitis virus*–*Cavia porcellus*), the DALY was estimated by weighing the individual effect of two distinct group of clinical symptoms (gastrointestinal symptoms, and bacteremia for the first two, and flu-like symptoms plus meningitis for the latter). A web-based software developed by the US Food and Drug Administration (FDA) (iRisk 1.0) to rank microbial and chemical hazards in food was used to estimate the weighted DALY values (FDA-iRisk, 2014).

A subjective scale was applied to estimate the values of the severity component (S_j). This scale ranged from 0 (asymptomatic) to 1 (death): 0.1: very mild symptoms such as local inflammation or mild cold; 0.3: flu-like symptoms including headaches, nausea, aches; 0.5: severe symptoms, respiratory or gastrointestinal; 0.7: very severe respiratory, gastrointestinal or neurological symptoms; 0.9: extremely severe symptoms, including encephalitis or complicated cardiovascular symptoms; and 1: death possible. The duration of the health effect (D_j) was converted from days to years by the iRisk software.

Once the individual DALY values were obtained for each pathogen, they were multiplied by the population at risk. For this study, the population at risk was the number of households with pet rodents imported from LAC (and endemic to LAC). To estimate households at risk, the total number of rodents imported (and endemic) from LAC per year was obtained from LEMIS USFWS database (2007–2010). Then, it was assumed that one household in the United States would receive one imported (and endemic) rodent from LAC. There were about 1230 imported rodents for that period, so the estimated population at risk would be 1230 US households. For equations 1 and 2, data found in the scientific literature were the first choice to inform the model, followed by expert opinion. Finally, 'total risk score' was calculated (Equation 3) for each pathogen–rodent species combination and ranked (highest–lowest risk score).

$$\text{Risk Score} = \text{Likelihood} \times \text{Severity} \quad (3)$$

In anticipation that there would be major data gaps in the scientific literature, we supplemented our data using an expert elicitation process. Twenty-three experts were polled from professional organizations, NGOs, academia or

Table 1. Factors considered in Equation 1 of the risk prioritization model

Factor	Definition*	Assumptions	Scores†
Prevalence	Endemic prevalence (number of infected rodents with the specific pathogen from the total population at risk).	The prevalence assumed for most of the wildlife pathogens identified is low (considered rare events). This is why prevalence of 1–10% was given a medium score.	Low = 1 (<1%) Medium = 2 (1–10%) High = 3 (11–50%) Very high = 4 (51–100%)
Clinical signs/ Detection	Clinical signs refer to any manifestation of disease present in the infected rodents. Detection of the infected rodent would occur at the port of entry through an inspection or health assessment.	If an infected rodent showed clinical signs, the detection was high, and risk was low. If the rodent did not show clinical signs, the detection was low. All the pathogen–rodent species combinations were given a low detection score, given the lack of required inspections.	Low = 1 Medium = 2 High = 3
Number of animals shipped/year	Number of rodents from the species of concern shipped to the United States on an annual basis.	It was assumed that the higher number of animals being imported, the higher the risk.	*Coendou prehensilis*: ~12 animals/year = 1 *Dasyprocta* spp.: ~18 animals/year = 2 *Cavia porcellus* ~1200 animals/year = 3
Contact type	Type of human contact with the rodent.	It was assumed that in lab/research facilities the personal protection equipment (PPE) would be more strict (lower risk) than at a zoo, or than if the rodent was used as a pet, where PPE would be non-existent (higher risk).	Low = 1 (Lab/Research) Medium = 2 (Zoo) High = 3 (Pet)
Shedding factor (Duration)	Length of time that the rodent was likely to shed the pathogen.	It was assumed that the risk would be higher if the shedding duration was longer.	Weeks = 1 Months = 2 Lifelong = 3
Shedding factor (Frequency)	Rate at which the rodent was likely to shed the pathogen.	It was assumed that the risk would be higher if the shedding was constant.	Rare intermittent = 1 Frequent intermittent = 2 Constant = 3
Type of transmission	Route of human exposure to the pathogen of concern.	It was assumed that the contact frequency was less likely to occur for blood contact (lowest risk), and most likely for environmental (highest risk).	Blood contact = 1 Direct contact (skin, scratch, bite) = 2 Faecal–oral = 3 Aerosol = 4 Environmental (water, food, bedding, fomites) = 5

*The definitions of these factors are specific for the case of zoonotic pathogens from rodents imported from LAC into the United States.
†The numeric scores assigned to each factor were chosen based on prior knowledge of the epidemiology and pathogenesis of zoonotic diseases (prevalence, shedding duration and frequency, and type of transmission) and of wildlife trade (detection, contact type, and number of animals shipped per year, which was extracted from the USFWS LEMIS 2007–2010).

governmental agencies. They were selected based upon their demonstrated expertise on the ecology or pathogenesis of one or more rodent-borne diseases from the hazard list. The content of the survey was sent to the University of Minnesota Institutional Review Board for their review, and an exempt status was granted meaning that no personal data were used in the study. Survey Monkey® was used to build an eight-question survey to characterize specific expertise (on a scale of 1–4, 1 being Minimal Knowledge/ Experience, four Extensive Experience), host–pathogen prevalence, shedding and severity of illness in humans (Appendix 2). Experts were also asked about the certainty of their answers using a scale that ranged from 1 to 3 (1: Uncertain; 2: Moderately certain; 3: Certain). When there large discrepancy occurred between expert opinions, answers were averaged. When answers involved a numeric range, the highest end was used based on the precautionary principle. The precautionary principle asserts that the burden of proof for potentially harmful actions by industry or government rests on the assurance of safety and that when there are threats of serious damage, scientific uncertainty must be resolved in favour of prevention (Goldstein, 2001). Given the uncertainty around the published data and the expert opinion, especially in regard to prevalence, a

sensitivity analysis was explored to account for some of this variability.

Results

Hazard identification

Four legally traded rodent species during the study period (2007–2010) were identified (*Cavia porcellus, Coendou prehensilis*, *Cuniculus paca* and *Dasyprocta* spp.). A total of 171 literature sources were evaluated (142 peer-reviewed articles, four books and 25 technical reports), resulting in 329 rodent-borne pathogens worldwide. Of the 329 infectious pathogens, 156 were zoonotic, and there was some evidence (including experimental) that the rodent species endemic and traded from LAC could be infected with 39 of these pathogens (Appendix 1, Table S1). One of the rodent species, *Cuniculus paca*, was excluded from the analysis, as there was no evidence of any zoonotic pathogen in this species. For the 39 pathogens, rodents were not a dead-end host for 35. Ultimately, 16 pathogens met the last criterion of being directly transmitted from rodents to humans (Appendix S1, Table S2). The final 16 pathogens and three rodent species combinations were ranked using the risk prioritization tool (Fig. 2).

Risk prioritization tool

The results of the risk prioritization are presented by numeric rank in Table 2. Results from this table are based on an averaged prevalence estimated with the existent data (published and expert opinion). Scores for the likelihood of release/exposure (Equation 1) ranged from a maximum of 78 (*Cryptosporidium* spp. in *Cavia porcellus*) to a minimum score of 18 (*Campylobacter jejuni* in *Coendou prehensilis*). Scores for the DALY values severity/consequence (Equation 2) ranged from a maximum of 212.3 (*Mycobacterium microti* in *Cavia porcellus)* to 0.1 (*Trixacarus caviae* in *Cavia porcellus* and *Trichophyton mentagrophytes* in *Cavia porcellus*). The highest ranked pathogen according to Equation 3 was *Mycobacterium microti* in *Cavia porcellus* with a risk score of 9341, followed by *Giardia* spp. in *Cavia porcellus* with a risk score of 2426 and *Francisella tularensis* in *Cavia porcellus* with a risk score of 1651. The lowest ranked pathogens were *Trichophyton mentagrophytes* in *Cavia porcellus* (6.5) and *Trixacarus caviae* in *Cavia porcellus* (5.9).

The expert elicitation response rate was 22%. The largest reason for lack of response was lack of knowledge regarding specific questions integral to the research question at task (questions were related to prevalence, shedding and/or clinical symptoms in humans). Of those responding, most were 'uncertain' (highest uncertainty ranked) about the majority of their responses. Others felt they were unqualified to answer specific pathogen–species questions, or human medical questions. Results from the sensitivity analysis on the uncertainty of prevalence estimates are shown in Table 3. Using all the prevalence values obtained from the literature and expert opinion for the pathogens in the

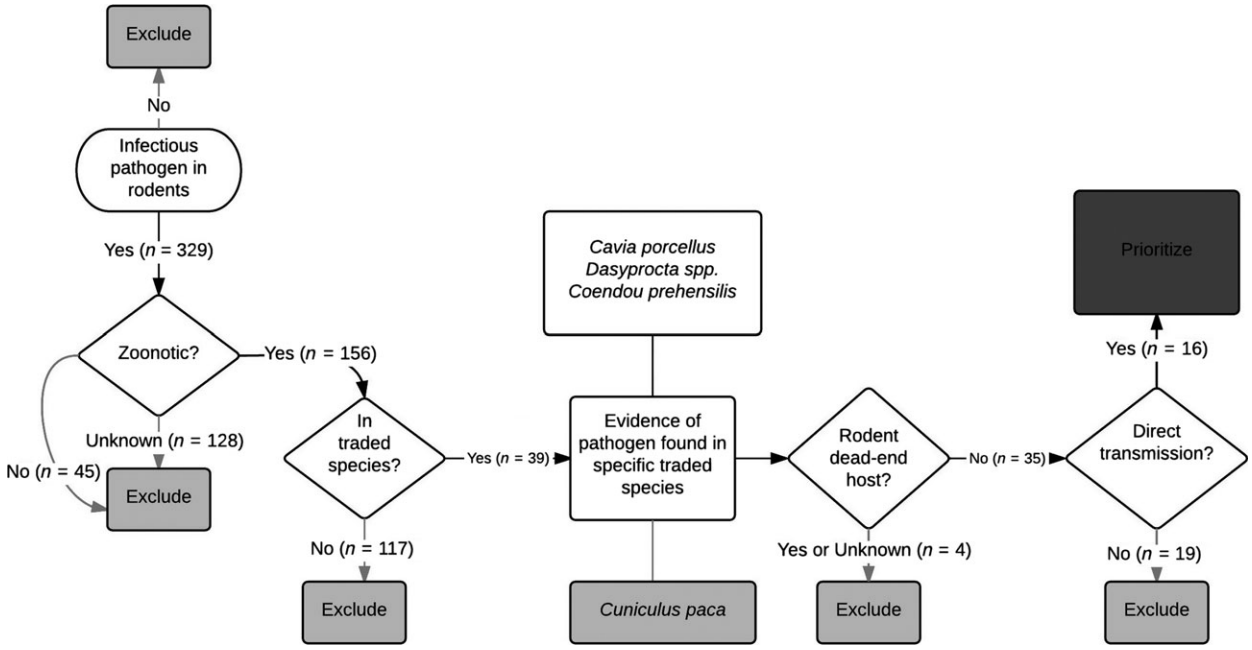

Fig. 2. Results from the hazard identification process. Sixteen pathogens met all the inclusion criteria (dark box), and 313 did not meet the inclusion criteria and were not assessed further (grey boxes).

Table 2. Final risk scores estimated for all the zoonotic pathogens–rodent species combinations using the averaged prevalence

Pathogen/Rodent species	Likelihood of Release and Exposure	Severity DALY* (years) x Number of households owning an imported pet rodent from LAC	Risk Score	References
Mycobacterium microti/Cavia porcellus	[(2†) – (1) + (3)] x [(3) + (2†) + (1) + (5)] = 44	(0.7 × 300/365 d × 0.3†) = 212	9341	Panteix et al., 2010;
Giardia/Cavia porcellus	[(4) – (1) + (3)] x [(3) + (2) + (2) + (5)] = 72	0.5† × 40/365 d† × 0.5) = 34	2426	Gressler et al., 2010; cfsph.iastate Kilonzo et al., 2013;
Francisella tularensis/Cavia porcellus	[(3†) – (1) + (3)] x [(3) + (1) + (1†) + (5)] = 50	(0.7† × 20/365 d† × 0.7) = 33	1651	Bell and Stewart, 1975; Christova, 2004
Salmonella enterica spp./*Cavia porcellus*	[(3†) – (1) + (3)] x [(3) + (3†) + (2) + (3)] = 55	[1) Gastrointestinal symptoms: (0.5† × 7/365 d × 0.9)] + [2) Bacteriemia: (0.9 × 15/365 d × 0.1)] = 16	880	Bartholomew et al., 2014; Public Health Agency of Canada, 2011
Cryptosporidium/Cavia porcellus	[(4) – (1) + (3)] x [(3) + (3) + (2) + (5)] = 78	(0.5 × 15/365 d × 0.3)	591	Ludwig and Marques, 2011; Chaochao et al., 2009; Kilonzo et al., 2013; cdc.gov CDC, 2012 Ramirez et al., 2004;
Cryptosporidium/Coendou prehensilis	[(4) – (1) + (1)] x [(3) + (3) + (2) + (5)] = 52	(0.5 × 15/365 d × 0.3) = 8	393	Chaochao et al., 2009; Kilonzo et al., 2013; Ramirez et al., 2004; cdc.gov cdc.gov/mmwr
Salmonella enterica spp./*Dasyprocta leporina*	[(1) – (1) + (2)] x [(3) + (3) + (2) + (3)] =22	[1) Gastrointestinal symptoms: (0.5† × 7/365 d × 0.9)] + [2) Bacteriemia: (0.9 × 15/365 d × 0.1)] = 16	352	Adesiyun et al., 1998; CDC, 2015 Bartholomew et al., 2014; Public Health Agency of Canada, 2011
Enterocytozoon bieneusi/Cavia porcellus	[(2) – (1) + (3)] x [(3) + (3) + (3†) + (5)] = 56	(0.3 × 30/365 d† × 0.2†) = 6	339	Didier et al., 1998; Matos et al., 2012; Weese and Fulford, 2011;
Pasteurella multocida/Cavia porcellus	[(4†) – (1) + (3)] x [(3) + (2†) + (2†) + (2)] = 54	(0.3 × 20/365 d† × 0.3†) = 6	327	Chomel, 1992;
Yersinia pseudotuberculosis/Cavia porcellus	[(2†) – (1) + (3)] x [(3) + (3) + (1†) + (3)] = 40	(0.3 × 20/365 d† × 0.4†) = 8	323	Chomel, 1992; Suckow et al., 2011;
lymphocytic choriomeningitis virus/Cavia porcellus	[(2†) – (1) + (3)] x [(3) + (2†) + (2†) + (4)] = 44	[1) Flu-like symptoms: (0.3 × 7/365 d × 0.05)] + [2) Meningitis: (0.9 × 365/365 d × 0.005)] = 6	260	Bonthius, 2012; CDC, 2014a CFSPH, 2010 Childs et al., 1992;

Table 2. (Continued)

Pathogen/Rodent species	Likelihood of Release and Exposure	Severity DALY* (years) x Number of households owning an imported pet rodent from LAC	Risk Score	References
Campylobacter jejuni/Dasyprocta leporina	[(2) – (1) + (2)] x [(3) + (1) + (2†) + (3)] = 27	(0.7 × 10/365 d† × 0.4†) = 9	255	Adesiyun et al., 1998; Meerburg and Kijlstra, 2007; University of Rochester Medical Center, 2014
Streptococcus zooepidemicus/Cavia porcellus	[(2†) – (1) + (3)] x [(3) + (3†) + (3†) + (4)] = 52	(0.1 × 25/365 d† × 0.5†) = 4	219	Fulde and Valentin-Weigand, 2013;
Campylobacter jejuni/Coendou prehensilis	[(2†) – (1) + (1)] x [(3) + (1) + (2†) + (3)] = 18	(0.7 × 10/365 d† × 0.4†) = 9	170	Meerburg and Kijlstra, 2007; University of Rochester Medical Center, 2014
Bordetella bronchiseptica/Cavia porcellus	[(4) – (1) + (3)] x [(3) + (3) + (1†) + (5)] = 72	(0.1 × 10/365 d × 0.3) = 1	73	Baskerville et al., 1982; Charles River Laboratories International, 2009 School of Veterinary Medicine, University of Wisconsin, Madison, 2004 Woolfrey and Moody, 1991;
Mycoplasma caviae/Cavia porcellus	[(2) – (1) + (3)] x [(3) + (2†) + (1†) + (2)] = 32	(0.1 × 15/365 d × 0.4†) = 2	65	Hill, 1971; Merck Manuel, 2011;
Lyssavirus/Cavia porcellus	[(1) – (1) + (3)] x [(3) + (3) + (3) + (2)] = 33	(1 × 10/365 d × 0.02) = 0.7	22	CDC, 2011 Eidson et al., 2005; Rupprecht et al., 2002;
Trichophyton mentagrophytes/Cavia porcellus	[(2†) – (1) + (3)] x [(3) + (2†) + (2†) + (5)] = 48	(0.1 × 4/365 d† × 0.1†) = 0.1	6.5	CDC, 2014b
Trixacarus caviae/Cavia porcellus	[(2†) – (1) + (3)] x [(3) + (2) + (1) + (5)] = 44	(0.1 × 4/365 d† × 0.1†) = 0.1	5.9	Merck Manuel, 2011

*The total DALY value (years) was multiplied by the assumed number of households in the United States that owned imported pet rodents of the species of concern for this study per year (inferred from USFWS LEMIS 2007–2010), which was estimated as 1230.
†Expert elicitation.

Table 3. Sensitivity analysis on prevalence uncertainty.

Pathogen/Rodent species	Prevalence Scores	Likelihood of release and exposure	Severity	Risk score
Mycobacterium microti/ *Cavia porcellus*	1, 2, 3†	33–55	212	7006–11 677
Giardia/*Cavia porcellus*	4‡1, 2†	36–72	34	1213–2426
Francisella tularensis /*Cavia porcellus*	2, 3†	40–50	33	1321–1651
Cryptosporidium/ *Cavia porcellus*	4‡	78	8	591
Salmonella enterica spp./ *Cavia porcellus*	1, 3†	33–55	10	344–574
Cryptosporidium/ *Coendou prehensilis*	4‡	52	8	394
Enterocytozoon bieneusi/ *Cavia porcellus*	2‡ 1, 2†	42–56	6	255–340
Pasteurella multocida/ *Cavia porcellus*	2, 4†	36–54	6	218–328
Yersinia pseudotuberculosis/ *Cavia porcellus*	2†	40	8	323
lymphocytic choriomeningitis virus/*Cavia porcellus*	2, 3†	44–55	6	260–324
Campylobacter jejuni/ *Dasyprocta leporina*	2‡† 1, 3†	18–36	9	170–340
Salmonella enterica spp./ *Dasyprocta leporina*	1‡ 2†	22–33	10	230–345
Streptococcus zooepidemicus/ *Cavia porcellus*	2, 4†	52–78	4	219–329
Campylobacter jejuni/ *Coendou prehensilis*	1, 2, 3†	9–27	9	85–255
Bordetella bronchiseptica/ *Cavia porcellus*	4‡ 2†	48–72	1	48–73
Mycoplasma caviae/ *Cavia porcellus*	2‡† 3†	32–40	2	65–81
Lyssavirus/*Cavia porcellus*	1‡	33	0.7	22
Trichophyton mentagrophytes/ *Cavia porcellus*	1, 2, 3, 4†	36–72	0.1	5–10
Trixacarus caviae/ *Cavia porcellus*	2‡†	44	0.1	5.9

†Expert elicitation.
‡Published evidence.

selected species, a very similar ranking list was obtained compared to the one shown in Table 2 using averaged prevalence.

Discussion

It is apparent that wildlife trade poses a risk for public health through the potential introduction and/or reintroduction of zoonotic pathogens into the United States (Swift et al., 2007; Karesh and Noble, 2009; Pavlin et al., 2009; Smith et al., 2009, 2012; Travis et al., 2011). Ongoing concern about the risk has prompted suggested regulatory changes without adequate scientific evidence for decision-making. Therefore, agencies and other regulatory stakeholders are in need of user-friendly, scientific tools to assess public health risks of imported wildlife species to assist in allocation of resources and policy decisions.

A risk prioritization tool can prove useful for identifying pathogen–species combinations that might pose a zoonotic risk through a scoring system. This approach is widely used in food safety to rank foodborne and zoonotic pathogens risks in a region or a country (Kemmeren et al., 2006; Henson et al., 2007; Ruzante et al., 2010; Ng and Sargeant, 2012; Ng and Sargeant, 2013). In this study, zoonotic pathogens that may be carried by legally traded rodents endemic to LAC were assessed, and the highest risk

pathogen–rodent species combinations were identified. Final risk score was estimated as a function of likelihood for the pathogen to be present in the species, and if potential for presence exists, severity of the human disease. Severity was estimated by computing DALY values, a public health metric, which was uniquely adapted here to assess zoonotic risk (in terms of consequence) of wildlife trade in the United States. Due to limited data, only immunocompetent adults were considered. DALY values would have likely differed if immunosuppressed adults or children were assessed instead, especially given relatively high rates of contact between children and exotic pets in the United States.

Results from both approaches (averaged prevalence and sensitivity analysis) ranked *Mycobacterium microti–Cavia porcellus* as the pathogen–species combination of highest risk, followed by *Giardia* spp. (giardiasis)–*Cavia porcellus*, and *Francisella tularensis* (tularaemia)–*Cavia porcellus*. These results were expected for the specific research question evaluated in this study using the methodology applied. The ultimate goal of the study was to assess the human health consequences in the United States after rodent exposure. Likelihood scores for release and exposure were very similar for most of the pathogen–species combination (most of the scores ranged from 40 to 56). This was mainly due to the fact that i) all of them were scored the same for the factor 'Clinical signs/Detection', because there are no required regulations to inspect imported rodents from Latin America into the United States; ii) *Cavia porcellus* was the most common species, and thus, the score for the factor 'number of animals shipped/year' was almost the same for most of the combinations evaluated; iii) the score for the factor 'contact type' was shared among all of them; and iv) the variability among the rest of the scores was small. However, the scores for Equation 2 (severity of disease in humans) varied greatly from 0.1 to 212 (100× increase) due to the difference in duration and severity of the clinical symptoms among the diseases. Thus, final risk score was mainly influenced by Equation 2 (severity of disease in humans). The three pathogens identified with the highest risk score showed the longest duration of clinical symptoms reported once affecting humans, raising the severity score and thus the final risk score. For example, *M. microti* infections in humans may affect both immunocompetent and immunocompromised persons and may be difficult to detect and resolve, causing chronic illness (van Soolingen et al., 1998; Emmanuel et al., 2007). Similarly, tularaemia *(F. tularensis)* can cause chronic and severe disease in humans. Given the limited published data available, it was sometimes necessary to rely on the expert opinion gathered, for which there were few expert responses, most providing a low level of certainty. This highlights the critical need for more peer-reviewed wildlife disease data.

The usefulness of a risk prioritization tool is to allocate additional resources on the identified higher risk pathogen–rodent species, such as performing a risk assessment, acquiring new experimental data, and establishing specific risk management guidelines if warranted. As mentioned previously, the methodology applied resulted in a relative risk ranking, as opposed to an overall risk. New experimental data are needed in areas such as the evaluation of the zoonotic potential of pathogens (n = 128), the need to understand whether the traded rodent species serve as dead-end hosts for certain pathogens, and the need to obtain data on prevalence of in source populations, as well as in hosts that come into contact with evaluated species in the pet trade (such as was the case with prairie dogs in the United States acquiring monkeypox from imported African rodents).

Even though the comparison with other published studies on the prioritization of zoonotic pathogens is usually difficult due to the different approaches and factors considered, it is possible to contrast some of the main findings. Ng and Sargeant (2012) established a disease priority list for the United States and Canada based on public perception of which zoonotic diseases showed the highest risk (out of 62 total), considering all animal taxa. The study used a randomized survey among health professionals to estimate the disease criteria (21 in total) and the weighted scores for each. For the United States, Creutzfeldt–Jakob disease (prion-caused) was assigned the highest risk score followed by rabies (*Lyssavirus*) and Nipah virus encephalitis (caused by *Nipah virus*). Tularaemia (caused by *Francisella tularensis*) was ranked eighth, and giardiasis (*Giardia* spp.) ranked 33rd. The study used extensive criteria for disease prioritization including animal–human and human–animal transmission and exposure, disease prevalence in the region and economic factors. The research question in our study was narrowed to exclusively human exposure, thus limiting the number of disease criteria. However, most of the criteria used for human exposure (case-fatality, severity, duration, transmission) were also included in our study and estimated in more detail using the DALY approach. Despite the different approach taken by Ng and Sargeant (2012), as it was applied to all animal taxa, two of the three highest ranked zoonotic pathogens in our study were listed within the 50% of the pathogens in Ng's study. The main benefits of using a semi-quantitative tool are the flexibility, simplicity, quickness, and easiness to implement by policymakers to respond to different wildlife trade scenarios without the need to carry out data and cost-intensive research studies. Additionally, the introduction of DALY values into the tool adds an in-depth evaluation of the public health impact not used before for human–wildlife health interactions.

Other studies have specifically evaluated which zoonotic pathogens are more likely to be introduced into the United States through wildlife species. Pavlin et al. (2009) identified 30 zoonotic pathogens in the literature from several imported wild species. Among them, *lymphocytic choriomeningitis virus*, *Lyssavirus* and *Francisella tularensis* coincided with our study.

To develop the risk prioritization tool, some assumptions were made. For Equation 1 (likelihood of release and exposure), a decision was made by the authors to assign scores to the factors involved in the equation from 1 to 5 based on the available scientific evidence. For both Equation 1 and Equation 2 (severity), the estimated values were also based on available scientific literature, and on expert opinion when data were not available. The experts consulted through the survey reported a certain level of uncertainty for their final risk score estimations (Equation 3), which could be considered one of the limitations of this study. The data gaps encountered in this process may or may not be unique to the rodent trade. The information available for wildlife trade is still very scarce, including the zoonotic potential. Once new data are available, this risk prioritization case study can be updated, advancing the accuracy of the results. Information obtained from this study proves useful to make preliminary recommendations regarding data gaps. The management guidelines in better informed case studies would target the highest ranked pathogens, and the human population that would be in contact with the imported animals (mainly pet owners in this case), to avoid or at least minimize the chance of zoonotic transmission.

Guidance for policymakers would include the establishment of critical control points, with a focus on the top-ranked pathogens first, if warranted. In general, these would be at the source (need for a health inspection and/or health testing prior to shipment), at the port of entry in the United States (need for health inspection, testing for those pathogens when feasible, and/or quarantine before distribution), and at distribution (need for more information about the end point; providing education to consumers).

The risk prioritization tool can be replicated for the remaining wildlife species that are brought in legally (and in some cases where enough information is available – illegally) into the United States, from different parts of the world. The specific problem to evaluate can be changed depending on the end goal. For example, instead of assessing the public health impact, the process can be focused on the impact to agriculture, or to the health of native wildlife species, and the factors included can be weighted accordingly. Applying this process to other wildlife trade species will not only help to establish management guidelines, but it will also help in identifying critical areas of research where data are lacking.

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References

Adesiyun, A. A., N. Seepersadsingh, L. Inder, and K. Caesar, 1998: Some bacterial enteropathogens in wildlife and racing pigeons from Trinidad. *J. Wildl. Dis.* 34, 73–80.

Balabanova, Y., A. Gilsdorf, S. Buda, R. Burger, T. Eckmanns, B. Gärtner, and G. Krause, 2011: Communicable diseases prioritized for surveillance and epidemiological research: results of a standardized prioritization procedure in Germany, 2011. *PLoS One* 6, e25691. doi:10.1371/journal.pone.0025691.

Bartholomew, M. L., R. T. Heffernan, J. G. Wright, R. F. Klos, T. Monson, S. Khan, E. Trees, A. Sabol, R. A. Willems, and R. Flynn, 2014: Multistate Outbreak of *Salmonella enterica* Serotype Enteritidis Infection Associated with Pet Guinea Pigs. *Vector Borne Zoonotic Dis.* 14, 414–421.

Baskerville, M., A. Baskerville, and M. Wood, 1982: A study of chronic pneumonia in a guineapig colony with enzootic *Bordetella bronchiseptica* infection. *Lab. Anim.* 16, 290–296.

Bell, J. F., and S. J. Stewart, 1975: Chronic shedding tularemia nephritis in rodents: possible relation to occurrence of *Francisella tularensis* in lotic waters. *J. Wildl. Dis.* 11, 421–430.

Bengis, R. G., F. A. Leighton, J. R. Fischer, M. Artois, T. Morner, and C. M. Tate, 2004: The role of wildlife in emerging and re-emerging zoonoses. *Rev. Sci. Tech. Off. Int. Epiz.* 23, 497–512.

Bonthius, D. J., 2012: Lymphocytic choriomeningitis virus: an underrecognized cause of neurologic disease in the fetus, child, and adult. *Semin. Pediatr. Neurol.* 19, 89–95.

Bordallo, M., 2009: HR 6311, the Non-native Wildlife Invasion Prevention Act. Congress. House. United States. Committee on Natural Resources. Subcommittee on Fisheries. (Vol. 4). USGPO.

Broad, S., T. Mulliken, and D. Roe, 2003: The nature and extent of legal and illegal trade in wildlife. In: Oldfield, S. (editor), The Trade in Wildlife: Regulation for Conservation, pp. 22. Earthscan Publications. London, UK.

Cardoen, S., X. Van Huffel, D. Berkvens, S. Quoilin, G. Ducoffre, C. Saegerman, and K. Dierick, 2009: Evidence-based semiquantitative methodology for prioritization of foodborne zoonoses. *Foodborne Pathog. Dis.* 6, 1083–1096.

Centers for Disease Control and Prevention, 2008: Monkeypox. Available at: http://www.cdc.gov/ncidod/monkeypox/index.htm(accessed on 25 March 2014).

Centers for Disease Control and Prevention, 2011: Rabies. Available at: www.cdc.gov/rabies(accessed on 15 May 2014).

Centers for Disease Control and Prevention, MMWR 2012: Cryptosporidiosis Surveillance, United States, 2009-2010 and

Giardiasis Surveillance, United States, 2009-2010. Available at: http://www.cdc.gov/mmwr/pdf/ss/ss6105.pdf(accessed on 15 May 2014).

Centers for Disease Control and Prevention, 2013: Bringing an Animal into the United States. Available at: http://www.cdc.gov/animalimportation/bringinganimaltous.html, (accessed on 25 March 2014).

Centers for Disease Control and Prevention, 2014a: Fungal Diseases. Available at: http://www.cdc.gov/fungal/diseases/dermatophytes/index.html (accessed on 15 May 2014).

Centers for Disease Control and Prevention, 2014b: Lymphocytic Choriomeningitis (LCM). Available at: http://www.cdc.gov/vhf/lcm/symptoms/index.html, (accessed on 15 May 2014).

Centers for Disease Control and Prevention, 2015: Salmonella homepage. Available at: http://www.cdc.gov/salmonella/ (accessed June 2015).

Chaochao, L. V., L. Zhang, R. Wang, F. Jian, S. Zhang, C. Ning, H. Wang, C. Feng, X. Wang, X. Ren, M. Qi, and L. Xiao, 2009: *Cryptosporidium* spp. in wild, laboratory, and pet rodents in China: prevalence and molecular characterization. *Appl. Environ. Microbiol.* 75, 7692–7699.

Charles River Laboratories International, 2009: *Bordetella bronchiseptica*- Technical sheet. Available at: http://www.criver.com/files/pdfs/infectious-agents/rm_ld_r_bordetella_bronchiseptica.aspx(accessed 15 May 2014).

Childs, J. E., G. E. Glass, G. W. Korch, T. G. Ksiazek, and J. W. Leduc, 1992: Lymphocytic choriomeningitis virus infection and house mouse (*Mus musculus*) distribution in urban Baltimore. *Am. J. Trop. Med. Hyg.* 47, 27–34.

Chomel, B. B., 1992: Zoonoses of house pets other than dogs, cats and birds. *Pediatr. Infect Dis. J.* 11, 479–487.

Christova, I., T. Velinov, T. Kantardjiev, and A. Galev, 2004: Tularaemia outbreak in Bulgaria. *Scand. J. Infect. Dis.* 36, 785–789.

Didier, E. S., K. F. Snowden, and J. A. Shadduck, 1998: Biology of microsporidian species infecting mammals. *Adv. Parasitol.* 40, 283–320.

Eidson, M., S. D. Matthews, A. L. Willsey, B. Cherry, R. J. Rudd, and C. V. Trimarchi, 2005: Rabies virus infection in a pet guinea pig and seven pet rabbits. *J. Am. Vet. Med. Assoc.* 227, 932–935.

Emmanuel, F. X., A. L. Seagar, C. Doig, A. Rayner, P. Claxton, and I. Laurenson, 2007: Human and animal infections with Mycobacterium microti, Scotland. *Emerg. Infect. Dis.*, 13, 1924.

Food and Drug Administration, 2014: FDA-iRisk 1.0- Technical Documentation. Available at: https://irisk.foodrisk.org/ (accessed on October 2013).

Fulde, M., and P. Valentin-Weigand, 2013: Epidemiology and pathogenicity of zoonotic streptococci. In:Singh Chhatwal, G. (ed.) Host-Pathogen Interactions in Streptococcal Diseases, pp. 49–81. Springer-Verlag Berlin, Heidelberg.

Gibbs, E. P., 2005: Emerging zoonotic epidemics in the interconnected global community. *Vet Rec.* 157, 673.

Goldstein, B. D., 2001: The precautionary principle also applies to public health actions. *Am. J. Public Health* 91, 1358–1361.

Gressler, L. T., A. S. da Silva, M. K. da Silva, A. A. Tonin, and S. G. Monteiro, 2010: Gastrointestinal parasites of cavy (*Cavia aperea aperea*) in southern Brazil. *Res. Vet. Sci.* 89, 206–208.

Henson, S., J. A. Caswell, J. A. Cranfield, A. Fazil, V. Davidson, S. Anders, and C. Schmidt, 2007: A multi-factorial risk prioritization framework for food-borne pathogens. University of Massachusetts, Amherst. Available at SSRN 989768.

Hill, A., 1971: *Mycoplasma caviae*, a new species. *J. Gen. Microbiol.* 65, 109–113.

Jakob-Hoff, R. M., S. C. MacDiarmid, C. Lees, P. S. Miller, D. Travis, and R. Kock. 2014: Manual of Procedures for Wildlife Disease Risk Analysis. OIE (World Organisation for Animal Health), Paris, France.

Jones, K. E., N. G. Patel, M. A. Levy, A. Storeygard, D. Balk, J. L. Gittleman, and P. Daszak, 2008: Global trends in emerging infectious diseases. *Nature* 451, 990–993. doi:10.1038/nature06536.

Karesh, W. B., and E. Noble, 2009: The bushmeat trade: increased opportunities for transmission of zoonotic disease. *Mt Sinai J. Med.* 76, 429–434.

Keesing, F., L. K. Belden, P. Daszak, A. Dobson, C. D. Harvell, R. D. Holt, P. Hudson, A. Jolles, K. E. Jones, and C. E. Mitchell, 2010: Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature* 468, 647–652.

Kemmeren, J. M., M. J. J. Mangen, Y. T. H. P. Van Duynhoven, and A. H. Havelaar, 2006: Priority Setting of Foodborne Pathogens: Disease Burden and Costs of Selected Enteric Pathogens. Rijksinstituut voor Volksgezondheid en Milieu RIVM, National Institute for Public Health and the Environment, Ministry of Health, Welfare and Sport, Bilthoven, the Netherlands.

Kilonzo, C., X. Li, E. J. Vivas, M. T. Jay-Russell, K. L. Fernandez, and E. R. Atwill, 2013: Fecal shedding of zoonotic food-borne pathogens by wild rodents in a major agricultural region of the central California coast. *Appl. Environ. Microbiol.* 79, 6337–6344.

Ludwig, R., and S. M. T. Marques, 2011: Occurrence of *Cryptosporidium* spp. oocysts in mammals at a zoo in southern Brazil. *Ibero-Latinoamericana de Parasitología.* 70, 124.

Mangen, M. J. J., D. Plass, A. H. Havelaar, C. L. Gibbons, A. Cassini, N. Mühlberger, A. van Lier, J. A. Haagsma, R. J. Brooke, T. Lai, C. de Waure, P. Kramarz, M. E. Kretzschmar, and BCoDE consortium, 2013: The pathogen-and incidence-based DALY approach: an appropriated methodology for estimating the burden of infectious diseases. *PLoS One* 8, doi:10.1371/journal.pone.0079740.

Matos, O., M. L. Lobo, and L. Xiao, 2012: Epidemiology of *Enterocytozoon bieneusi* infection in humans. *J. Parasitol. Res.* 2012, 1–19. doi: 10.1155/2012/981424.

Meerburg, B. G., and A. Kijlstra, 2007: Role of rodents in transmission of Salmonella and Campylobacter. *J. Sci. Food Agr.* 87, 2774–2781. doi:10.1002/jsfa.3004.

Morens, D. M., G. K. Folkers, and A. S. Fauci, 2004: The challenge of emerging and re-emerging infectious diseases. *Nature* 430, 242–249. doi:10.1038/nature02759.

Ng, V., and J. M. Sargeant, 2012: A quantitative and novel approach to the prioritization of zoonotic diseases in North America: a public perspective. *PLoS One* 7, doi:10.1371/journal.pone.0048519.

Ng, V., and J. M. Sargeant, 2013: A quantitative approach to the prioritization of zoonotic diseases in North America: a health professionals' perspective. *PLoS One* 8, doi:10.1371/journal.pone.0072172.

OIE, 2014: Risk Analysis. Terrestrial Animal Health Code, 23rd Edn, Vol I, Section 2, OIE, Paris, France. ISBN: 978-92-9044-934-8.

Panteix, G., M. C. Gutierrez, M. L. Boschiroli, M. Rouviere, A. Plaidy, D. Pressac, H. Porcheret, G. Chyderiotis, M. Ponsada, K. Van Oortegem, S. Salloum, S. Cabuzel, A. L. Banuls, P. Van de Perre, and S. Godreuil, 2010: Pulmonary tuberculosis due to *Mycobacterium microti*: a study of six recent cases in France. *J. Med. Microbiol.* 59, 984–989. doi:10.1099/jmm.0.019372-0.

Pavlin, B. I., L. M. Schloegel, and P. Daszak, 2009: Risk of importing zoonotic diseases through wildlife trade, United States. *Emerg. Infect. Dis.* 15, 1721–1726. doi:10.3201/eid1511.090467.

Public Health Agency of Canada, 2011: *Salmonella enterica* spp. Available at: http://www.phac-aspc.gc.ca/lab-bio/res/psds-ftss/salmonella-ent-eng.php(accessed on 15 July 2014).

Ramirez, N. E., L. A. Ward, and S. Sreevatsan, 2004: A review of the biology and epidemiology of cryptosporidiosis in humans and animals. *Microbes Infect.* 6, 773–785. doi:10.1016/j.micinf.2004.02.021.

Ratchford, M., B. Allgood, and P. Todd, 2013: Criminal Nature: The Global Security Implications of The Illegal Wildlife Trade. International Fund for Animal Welfare (IFAW), Washington DC.

Rupprecht, C. E., C. A. Hanlon, and T. Hemachudha, 2002: Rabies re-examined. *Lancet Infect. Dis.* 2, 327–343. doi:10.1016/S1473-3099(02)00287-6.

Ruzante, J. M., V. J. Davidson, J. Caswell, A. Fazil, J. A. L. Cranfield, S. J. Henson, S. M. Anders, C. Schmidt, and J. M. Farber, 2010: A multifactorial risk prioritization framework for foodborne pathogens. *Risk Anal.* 30, 724–742. doi:10.1111/j.1539-6924.2009.01278.x.

School of Veterinary Medicine, University of Wisconsin, Madison, 2004: *Bordetella bronchiseptica* as a zoonotic agent. Available at: http://www.vetmed.wisc.edu/pbs/zoonoses/Bordetella/bordetellaindex.html (accessed on 15 July 2014).

Smith, K. F., M. Behrens, L. M. Schloegel, N. Marano, S. Burgiel, and P. Daszak, 2009: Reducing the risks of the wildlife trade. *Science* 324, 594.

Smith, K. M., S. J. Anthony, W. M. Switzer, J. H. Epstein, T. Seimon, H. Jia, M. D. Sanchez, T. T. Huynh, G. G. Galland, and S. E. Shapiro, 2012: Zoonotic viruses associated with illegally imported wildlife products. *PLoS One* 7, doi:10.1371/journal.pone.0029505.

van Soolingen, D., A. G. Van Der Zanden, P. E. De Haas, G. T. Noordhoek, A. Kiers, N. A. Foudraine, and J. D. van Embden, 1998: Diagnosis of *Mycobacterium microti* infections among humans by using novel genetic markers. *J. Clin. Microbiol.* 36, 1840–1845.

Suckow, M. A., K. A. Stevens, and R. P. Wilson, 2011: The laboratory rabbit, guinea pig, hamster, and other rodents. Academic Press, San Diego, CA, USA. ISBN 0123809215978 0123809216

Swift, L., P. R. Hunter, A. C. Lees, and D. J. Bell, 2007: Wildlife trade and the emergence of infectious diseases. *EcoHealth* 4, 25–30. doi:10.1007/s10393-006-0076-y.

The Center for Food Security and Public Health, 2010: Lymphocytic ChoriomeningitisAvailable at: http://www.cfsph.iastate.edu/Factsheets/pdfs/lymphocytic_choriomeningitis.pdf (accessed 14 May 2014).

The Merck Veterinary Manual. 2011: Guinea Pigs. Available at: http://www.merckmanuals.com/vet/exotic_and_laboratory_animals/rodents/guinea_pigs.html (accessed on 15 May 2014).

Traffic. 2014. Available at: http://www.traffic.org/trade/(accessed on 15 May 2014).

Travis, D. A., R. P. Watson, and A. Tauer, 2011: The spread of pathogens through trade in wildlife. *Rev. Sci. Tech. Off. Int. Epiz.* 30, 219.

University of Rochester Medical Center, 2014: Zoonoses. Available at: http://www.urmc.rochester.edu/animal-resource/occupational-health/zoonoses.aspx(accessed on 15 July 2014).

Weese, J. S., and M. B. Fulford, 2011: Companion animal zoonoses. Wiley Online Library, Ames, IA, USA.

Woolfrey, B. F., and J. A. Moody, 1991: Human infections associated with *Bordetella bronchiseptica*. *Clin. Microbiol. Rev.* 4, 243–255.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Table S1. Complete list of the zoonotic pathogens identified in the legally traded species from Latin America (n = 39).

Table S2. Pathogens and rodent species list meeting all inclusion criteria (n = 16) during the hazard identification process.

Appendix S2. Survey questions and answers from the expert elicitation process conducted using Survey Monkey®.