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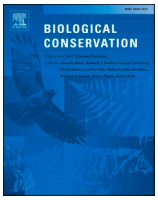

Infectious diseases of interest for the conservation of peccaries in the Amazon: A systematic quantitative review

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ABSTRACT

Infectious diseases are increasingly emerging and spreading globally, ending up being considered a threat to biodiversity. In the Amazon region, repeated disappearance episodes of local populations of white-lipped peccaries have been reported during the last decades. These population crashes remain poorly understood, but current knowledge suggests a potential role of infectious diseases. We conducted a systematic quantitative literature review on infectious diseases affecting suiform species in the Amazon region, analyzing the current knowledge on the topic, and identifying health threats for peccaries. We found that information on the health status of free-ranging peccaries in the Amazon region is scarce, geographically uneven, and mostly cross-sectional. We recommend working with local communities and using alternative participatory sampling methodologies to address the logistical problem of working in this wilderness setting. Furthermore, we emphasize the importance of developing studies with broader geographical coverage and multidisciplinary approaches, especially in areas where episodes of disappearance of white-lipped peccaries have already been observed.

1. Introduction

Over the past decades, infectious diseases have been increasingly emerging and are likely to continue to emerge and spread globally, mostly due to the intensification of anthropogenic activities such as agriculture, urbanization, and the movement of species, along with environmental degradation and climate change (Baker et al., 2022; Keusch et al., 2022). The increasing interactions between wildlife, domestic animals and humans have been key for the dissemination of infectious diseases worldwide (Daszak, 2000; Begou and Kassomenos, 2023). Although infectious diseases have traditionally been considered as natural processes affecting wildlife, it is now clear that anthropogenic activities have been accelerating this process and turning it into a threat to biodiversity (Cunningham et al., 2017). Many of these pathogens can affect susceptible wild hosts, decreasing their populations and, in some cases, leading to their local or, even, global extinction (Smith et al., 2006).

Peccaries are key species of the Amazon ecosystem, favoring the maintenance and regeneration of forests and animal habitats through seed dispersion (Altrichter et al., 2012). They are considered ecosystem engineers due to their role in the dynamics of the abiotic and biotic environment, and one of the main sources of animal protein in rural societies in Latin America (Beck et al., 2010; Sobral et al., 2017). However, repeated episodes of disappearances of local populations of white-lipped peccaries (*Tayassu pecari;* WLP) have been observed since the 1980s in the Amazon region. These disappearances have been followed by a full recovery of the original population after more than a decade (Fragoso, 2004) or even after almost three decades (Fragoso et al., 2022; Taber et al., 2008).

This phenomenon has been occurring in exceptionally large non-fragmented regions of millions of hectares, affecting ecosystem cycles and even food security in indigenous and campesino people in the Amazon; but still remains poorly understood (Fragoso et al., 2016). Although hunting and habitat destruction have been the most studied

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threats, the large populations and the ecology of the species suggest that diseases may be involved in its dynamics (Altrichter et al., 2012; Fragoso et al., 2022). In addition, although white-lipped peccaries inhabit the Amazon region sympatrically with collared peccaries (*Pecari tajacu;* CP), no decline in CP populations have been observed (Fragoso, 1998).

Nowadays, WLP persist only in 21 % of their historical distribution range, and the increasing local extinctions in several countries have driven the IUCN to raise its category from "near threatened" to "vulnerable", and to consider the species as "high risk of extinction in the wild" since 2012 (IUCN, 2022). In recent decades, serological studies in wild peccaries have evidenced the presence of infectious diseases that could impair their health and population dynamics (De Castro et al., 2014; Karesh et al., 1998; Morales et al., 2017; Romero Solorio, 2010), including diseases usually present in domestic livestock (Herrera et al., 2008; Freitas et al., 2009). As such, the lack of a thorough evaluation of the health status of this species, the increase in pig production in the Amazon promoting the interaction between domestic pigs (*Sus scrofa domesticus*) and peccaries (Hohnwald et al., 2019; Serrao et al., 1996), and the scarce information on infectious agents in the suiform interface, highlight the need for a detailed review of the infectious diseases affecting these species in the Amazon region.

The present study aims to perform a systematic quantitative literature review on infectious diseases affecting peccaries and domestic pigs in the Amazon region, in order to identify currently reported health threats for white-lipped peccaries and detect gaps of knowledge for future research directions in Amazonian peccaries' conservation.

2. Materials and methods

We conducted a search in English-language in the online databases Scopus and Pubmed, with a date range from the 1st of January 1990 to the 28th of February 2022. We used keywords related to the host species (peccaries, swine, and pigs), the political units of each country composing the Amazon region (Brazil, Perú, Colombia, Venezuela, Ecuador, Bolivia, Suriname, Guyana, and French Guyana), and pathogen or disease-associated terms. Given that the bibliography related to diseases in the Amazon is not broad, we conducted an additional search through Google Scholar in English language. This allowed us to identify studies published in journals not indexed in the *Journal Citation Reports* (JCR), academic theses, dissertations, and congress presentations or summaries, using the same previous search terms combined or as a search refining term to improve result outputs. Since non-English-language studies are numerous in biodiversity and conservation topics in South America, we also conducted additional searches in Spanish and Portuguese in Google Scholar. The search algorithms are presented in Supporting information 1.

We evaluated each entry obtained in the different searches based on the title, abstract, and details of the document to evaluate the research

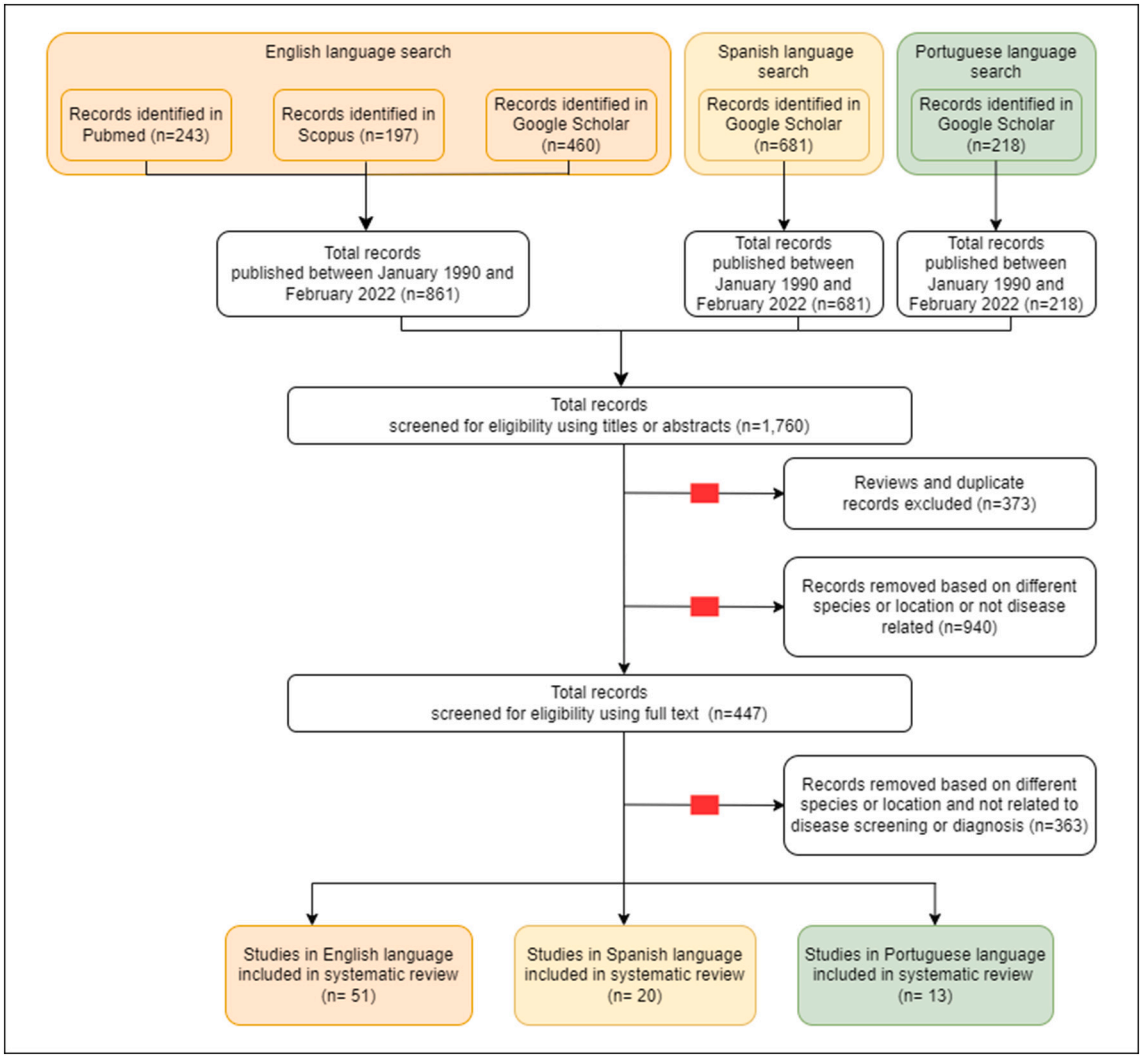

Fig. 1. Conceptual diagram of the identification of studies on infectious diseases affecting suids in the Amazon region, and selection process for the inclusion in the systematic review using PRISMA (Preferred Reporting Items for Systematic review and Meta-Analysis).

topic, correct location in the Amazon region and correct host species, in order to decide the inclusion in our database. We also excluded general review papers from the database to avoid reporting duplicate data (Fig. 1).

We reviewed the content of each study and used it to construct a database by recording the following general information: species reported, sample size, location, year of study, year of publication, pathogens studied, laboratory and diagnostic methods, results, and additional notes when needed. We also classified the selected bibliography into the category 'Conservation Medicine' if they investigated the impact of infection or disease on wildlife populations, the category 'Zoonosis' when they were focused on the transmission or affection of pathogens to humans, and 'Production' when investigating the impact of diseases on livestock.

When a thesis or congress presentation was later published as an article, the information was considered only from the research article. When information was partially published in an article (for example, some but not all pathogens were published in a research article), the unpublished information was considered directly from the thesis.

3. Results

A total of 84 publications met our inclusion criteria, including 62 research articles, 16 research theses and six congress/conference presentations. Of these 84 publications, five theses and two congress presentation were discarded because their results were also present in other publications, reducing the total number of publications assessed in this systematic review to 77 (Supporting information 2).

3.1. Species and sampling design

Domestic pigs were the most studied suiform species, being reported in 35 (45.5 %) of the retrieved studies. The CP were included in 31 (40.3 %) of these studies, and WLP in 23 (29.9 %), including 12 mixed-species studies. Overall, 47 (61 %) reports involved captive animals (35 studies on domestic pigs, ten on CP, one on WLP, and one involving both peccary species); while 29 (37.7 %) involved free-ranging animals (ten on WLP, nine on CP, and ten on both peccary species). Only one study (1.3 %) involved both captive and free-ranging animals and considered CP and WLP. The number of animals sampled varied depending on the species. Studies involving peccaries presented sampling sizes ranging from one to 125 individuals, with a median sample size of eleven individuals (Q1: 3; Q3: 42); while the sample size in studies involving domestic pigs ranged from six to 1070 individuals, with a median size of 109.5 (Q1: 63; Q3: 179).

3.2. Pathogens

Eighty pathogens were studied in domestic pigs and peccaries, including 35 (43.8 %) parasites, 25 (31.3 %) bacteria and 20 (25.0 %) viruses. *Toxoplasma gondii* (15.6 %, 12/77 studies) and *Leptospira* spp. (11.7 %, 9/77 studies) were the most studied pathogens. Other reported pathogens were *Streptococcus* spp. (6.5 %, 5/77 studies), Hepatitis E virus (6.5 %, 5/77), Aujeszky disease virus (5.2 %, 4/77 studies), *Brucella* spp. (5.2 %, 4/77 studies) and *Trypanosoma* spp. (5.2 %, 4/77 studies), among others.

Of the 42 studies including peccaries, the most studied pathogens were *Leptospira* spp. (14.3 %, 6/42 studies), *T. gondii* (14.3 %, 6/42 studies), *Brucella* spp. (9.5 %, 4/42 studies), Aujeszky disease virus (9.5 %, 4/42 studies), and *Trypanosoma* spp. (9.5 %, 4/42 studies). While regarding the 35 studies in domestic pigs, the most studied pathogens were *T. gondii* (8.6 %, 6/35 studies), Hepatitis E virus (14.3 %, 5/35 studies), *Leptospira* spp. (8.3 %, 3/35 studies), and *Taenia solium* (8.3 %, 3/35 studies).

Thirty-seven pathogens were reported in CP, 29 in WLP, and 19 in domestic pigs. In CP, *Leptospira* spp. was the most reported pathogen (10.8 %, 4/37 studies). In WLP, the most reported pathogens were *T. gondii* (13.8 %, 4/29 studies) and Aujeszky's disease virus (10.3 %, 3/29 studies). In domestic pigs, the most reported pathogens were Hepatitis E virus (26.3 %, 5/19 studies) followed by *T. gondii*, *Leptospira* spp., and *T. solium* (each 15.8 %, 3/19 studies). The total list of pathogens and prevalence/seroprevalence compiled in this literature review can be found in Table S1.

Of the 80 pathogens studied, 24 pathogens were not found in suiform species in the Amazon region, including African swine fever virus, Classical swine fever virus, Foot and Mouth disease virus and *Mycobacterium tuberculosis*, among others (see Table S1 for the full list of undetected pathogens).

Out of the 77 evaluated studies, 43 (55.8 %) focused on the 'Zoonosis' category, 26 (33.8 %) on the 'Conservation Medicine' category, and 22 (28.6 %) on the 'Production' category. The combination of two or all three focus of study was detected in 13 (16.9 %) studies.

3.3. Diagnostic testing performed and study types

Diverse methodologies were reported for pathogen diagnosis and surveillance over the last three decades, showing a notable increase in the use of molecular biology techniques (Fig. 2). Twenty-eight (36.4 %) studies used molecular methods for pathogens' RNA/DNA identification and characterization (for example PCR and sequencing), while 25 (32.5 %) included serologic diagnostic testing (for example Enzyme-Linked Immunosorbent Assay, microscopic agglutination tests and Immunofluorescence antibody tests). Seventeen (22.1 %) studies contained diagnosis of pathogens based on direct microscopy, histopathology and diverse culture techniques. Complementary clinical evaluations were only reported in 2 (2.6 %) studies. Seven (9.1 %) studies included a combination of two or more methodologies. Specific laboratory techniques are shown in Table S2.

Most of the studies (56/77; 72.7 %) were cross-sectional, while two were longitudinal (2.6 %), and nineteen (24.7 %) did not report research period information. Ten studies (13.0 %) encompassed two different sampling periods, and six (7.8 %) were based on long periods of sampling (>three years).

3.4. Study location

The reviewed studies were performed in the Amazonian regions of Brazil (63.3 %, 49/77), Peru (28.6 %, 22/77), Bolivia (2.6 %, 2/77), French Guyana (2.6 %, 2/77), Colombia (1.3 %, 1/77), and Ecuador (1.3 %, 1/77). The most sampled provinces/states were Pará (Brazil,

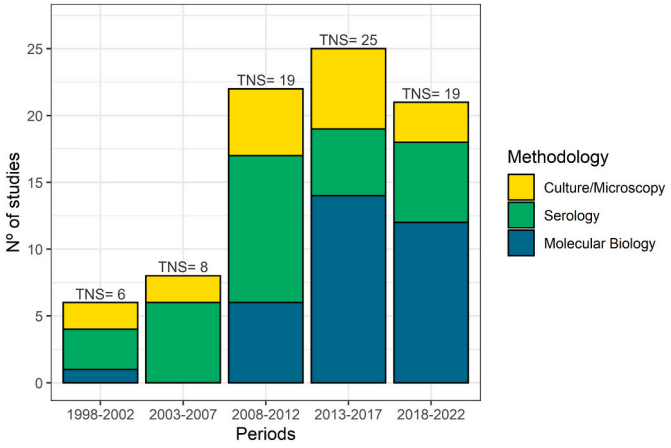

Fig. 2. Diagnostic methods and techniques used in the studies included in the review (n = 77) on infectious diseases affecting suids in the Amazon region, distributed by period between 1998 and 2022 (not mutually exclusive). TNS: Total number of studies.

29.9 %, 23/77), Mato Grosso (Brazil, 29.9 %, 23/77), and Madre de Dios (Peru, 14.3 %, 11/77) (Fig. 3).

3.5. Publication format

Forty-nine (63.6 %) studies were published in English, including 45 articles and 4 congress presentations. Sixteen (20.7 %) were published in Spanish, comprising 10 articles and 6 theses, and 12 (15.6 %) in Portuguese, including 7 articles and 5 theses. The 62 research articles were published in 41 different journals; in particular, 44 (70.9 %) articles were published in journals indexed in the JCR and 18 (29.5 %) articles were published in journals not indexed in the JCR. The reviewed articles were mostly published in the journals '*Revista Brasileira de Parasitologia Veterinária*' (9.7 %, 6/62), '*Revista de Investigaciones Veterinarias del Perú*' (6.5 %, 4/62), '*Acta Scientiae Veterinariae*' (4.8 %, 3/62), and '*International Journal for Parasitology: Parasites and Wildlife*' (4.8 %, 3/62). Moreover, eleven theses were defended in eight different universities, being the Universidade de São Paulo (Brazil) (18.2 %, 2/11) the highest representative. Four theses were from undergraduate studies (36.4 %), four from master studies (36.4 %), and three from doctoral dissertations (27.3 %) (Table S3).

4. Discussion

In the lasts 50 years, the increase of human population and anthropogenic activities, including deforestation, intensive farming, illegal and poorly regulated wildlife trade, and climate change, have promoted an unprecedented habitats' destruction and biodiversity loss worldwide (Mace et al., 2005). Wildlife population declines may be caused by single or multiple synergic elements, and diseases should always be considered as potential synergic factors (Preece et al., 2017). Although pathogens have been proven to be related with the collapse of various wild species (Smith et al., 2006), infectious diseases have been hardly ever studied as a factor in the decline of white-lipped peccary populations in the Amazon region. In the present work, we reviewed the scientific literature on infectious diseases of domestic pigs and peccaries in the Amazon region, aimed to the identification of health threats for peccaries, especially WLP, and to identify future research directions for the Amazonian peccaries' conservation.

The available information related to diseases in free-ranging wild species listed as Vulnerable or Endangered by the IUCN is still very limited and has been focused on few pathogens in selected wild host species (Martinez-Gutierrez and Ruiz-Saenz, 2016; Scheele et al., 2019). At the view of the results of our review, studies on diseases affecting the health of wild peccaries have received limited attention. We also detected a lack of inter and multi-disciplinary studies encompassing infectious diseases. Preventing and managing emerging diseases in wildlife demand an interdisciplinary approach such as the One Health initiative, which recognizes health issues at the complex human, animal and environmental interface (Harrison et al., 2019; Trilla, 2020). Studies that consider different approaches such as ecology, environment, human population and activities are mandatory to face the conservation of WLP (Jori et al., 2009; Romero Solorio, 2010).

Our review highlighted a notably higher number of studies in captive animals than in free-ranging wild individuals. In fact, domestic pigs were the most studied suiform species. Some probable causes of the relative lack of studies in free-ranging peccaries are the costs of field studies, the difficulty of field work in the Amazonian forests, the scarce funding for disease studies for Amazonian wildlife, and the need for transdisciplinary expertise and resources to ensure ethical and appropriate sampling (Wobeser, 2007). In that sense, the collaborative working with local hunters have been proven a useful strategy, allowing the access to a larger biological sampling in terms of species and individuals (Aston et al., 2014; Morales et al., 2017). In addition, more inexpensive strategies, such as filter paper, allows a convenient sample collection and preparation, especially when working in remote areas such as the Amazon region (Aston et al., 2014). Considering the difficulties of sampling procedures and logistics in wild species in the

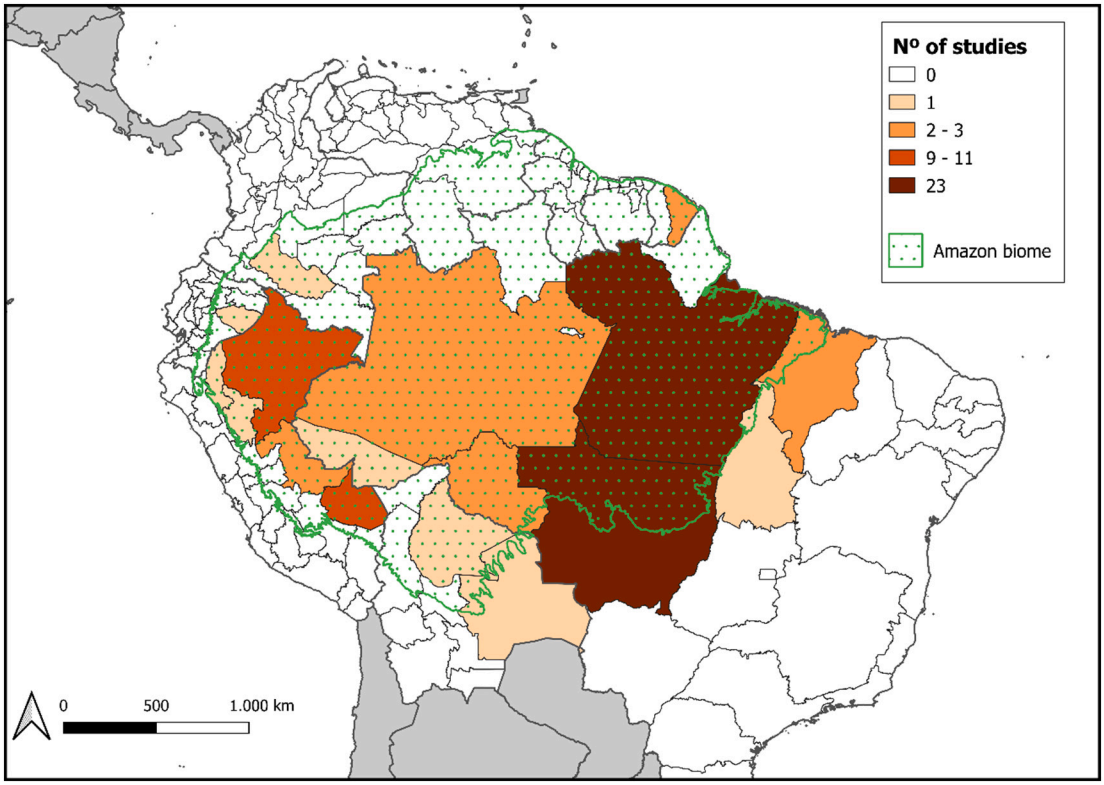

Fig. 3. Locations of studies on infectious diseases affecting swine and peccaries in the Amazon region. Provinces or states are colored according to the number of the studies included in the review (n = 77).

Amazon, studying the declines in WLP population represents a challenge. Additionally, in areas where population declines occurred, individuals may be hardly detected due to the consequent low animal density.

From the perspective of disease prevention, studies on infectious diseases in captive peccaries and domestic pigs from the Amazon region can be a cornerstone for the evaluation of the risk of disease spreading from captive suiforms to free-ranging peccaries. In the rural Amazon, pigs raised for subsistence are usually not confined, housed in the backyard without biosecurity conditions, and having direct access to the natural environments of the Amazon rainforest (Hohnwald et al., 2019; Labruna et al., 2002), therefore increasing the probability of contact with populations of wild peccaries.

Although WLP disappearances have been documented in several Amazon regions of Brazil, Peru, Ecuador, Bolivia, French Guyana, Guyana, and Colombia (Fragoso et al., 2022), most studies on infectious diseases were performed in only three of these regions, in Brazil and Peru. This uneven and disproportionate localization of studies depicts an incomplete representation of the Amazon region and limits the knowledge on the variability of diseases in the current distribution of peccaries. In some regions, studies reported the presence of specific pathogens in all three suiform species, providing initial information on the diseases at the interface of these species in the Amazon region. This knowledge facilitates sampling procedures and logistics in areas where sampling wildlife is highly complicated, or in locations where WLPs have disappeared. However, in other regions, information on a specific pathogen was only available for one species.

Regarding the type of studies carried out, most of the studies were cross-sectional surveys, offering a snapshot of a single moment in time, and not providing enough information on causes, effects, and risks in a disease-population relationship (Thelle and Laake, 2015; Wobeser, 2007). Cohort, case-control, and longitudinal studies may be more relevant to understand the impact of infectious diseases on WLP populations. Moreover, we reviewed a notable number of studies that did not report information on the sample period, hampering the association of the results with a specific event or conditions of the population.

In this review, the difference between the number of studies focused on the conservation of both peccaries and those describing the presence of zoonotic agents was also striking. The higher number of studies focusing on zoonotic agents is probably driven by the fact that subsistence hunting is a wide-spread practice in tropical forests, and, in the Amazon, wild meat represents a significant source of animal protein and income for rural and indigenous communities (El Bizri et al., 2020; Torres et al., 2018), and can even be found in urban markets (Mayor et al., 2021). This condition increases the probability of exposure for Amazonian societies to threads related to food security and zoonosis.

All research studies that carry out biological collections need to have prior authorizations from ethics committee form institutional participants, and collection authorizations from each corresponding public sectors. For instance, in Brazil, the responsible public institutions for the authorizations of wildlife biological collection is the Instituto Chico Mendes de Conservação da Biodiversidade of the Ministry of the Environment, and in Peru, the Servicio Nacional Forestal y de Fauna Silvestre belonging to the Ministry of the Agriculture, and the Servicio Nacional de Áreas Naturales Protegidas of the Ministry of the Environment. In addition, the conduction of comprehensive and holistic studies within the One Health framework frequently requires the integration of other interfaces (humans, domestic animals and/or environment) that will each need authorizations from public sectors. To these must be added the permits for the export of biological samples when needed, and the parallel importation authorizations by the receptor government, which includes compliance with the requirements of the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity, authorizations by national Animal Health departments, and finally the particular requirements of conveyors and courier companies. We argue that export permits could be avoided by improving the availability of appropriate technology with comparable costs in local countries. Overall, obtaining prior authorizations is a highly expensive in terms of time, economy and human efforts. Definitely, although it is essential to control the activities that are carried out with local biodiversity, from the point of view that research should help improve the sustainability of that biodiversity, we claim a smart process for the obtention of all required authorizations.

Among the pathogens studied in the reviewed studies, *T. gondii* and *Leptospira* spp. were the most reported. Although these diseases do not pose a threat to animal populations, they are important foodborne pathogens. *Toxoplasma gondii* has an average prevalence of infection of 30 % in human Amazon communities, even reaching 100 %, and Leptospirosis is among the main zoonotic causes of morbidity throughout the world, especially in tropical regions (Costa et al., 2012; Dubey, 2010; Sobral et al., 2005). Additional pathogens reported in domestic pigs are related to livestock production or zoonosis (e.g. Hepatitis E and *Taenia sollium*). These pathogens represent major public health and food safety problems worldwide especially in rural tropical and subtropical regions, where they also affect the economy of producers (Dalton et al., 2008; Del-Brutto et al., 2017).

Aujeszky disease virus and *Brucella* spp. were also reported in peccaries (Mayor et al., 2006; Romero Solorio, 2010). Aujeszky's disease causes a wide array of organ disorders, generating mortalities of 100 % in newborn pigs and 30 % in older piglets (Zuckermann, 2002). Brucellosis is one of the most common zoonoses in the world and is also present in wild species (Paulin and Ferreira Neto, 2003). In Brazil and Peru, bovine brucellosis is endemic in several states and regions (Megid et al., 2005; Pappas et al., 2006; Poester et al., 2009), and causes important reproductive problems, including infertility and abortions that can reach up to 80 % (Duncan, 1990). These diseases can impair the population dynamics of large herds of WLP. However, due to the low number of animals sampled and the lack of longitudinal studies, the potential impact of Aujeszky's disease or brucellosis on peccaries has not yet been assessed (Martins De Castro et al., 2014; Romero Solorio, 2010).

Finally, we found that studies in local official languages (Spanish or Portuguese) accounted for a third of the studies. This information generated by local professionals and in the local language has a crucial role in providing information on biodiversity and conservation, and advising local policies (Amano et al., 2021). This evidences that non-English-language studies must be considered when reviewing topics related to biodiversity and conservation in the Amazon.

5. Conclusions

Infectious diseases are probably involved in the emergence of repeated local episodes of disappearance of WLP populations in the Amazon region. However, the impact of infectious diseases on the decline of peccary populations has not yet been evaluated. The few research studies and the experimental design have not been sufficient to address this problem.

In further research efforts, it is important to both increase the number of studies focused on the impact of infectious diseases on the conservation of Peccaries' species, and to develop studies with broader geographical coverage, in coordination with different local research groups and including multidisciplinary approaches. We encourage the implementation of more cost-efficient sampling methods and culturally friendly. Likewise, studies on infectious diseases in local and regional captive peccaries and domestic pigs in the Amazon region can be forward revealing potential emerging pathogens.

Data accessibility statement

No new data were generated for this article.

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Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2022.109867.

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