One Health 17 (2023) 100577

Contents lists available at ScienceDirect

One Health

journal homepage: www.elsevier.com/locate/onehlt

One Health at gunpoint: Impact of wild boars as exotic species in Brazil - A review

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ARTICLE INFO

Keywords:
Exotic species
Wild boars
One Health
Sus scrofa

ABSTRACT

Wild boars have been listed among the 100 most invasive species worldwide, spreading impacts to all continents, with the exception of Antarctica. In Brazil, a major source of introduction was a commercial livestock importation for exotic meat market, followed by successive escapes and releases to natural ecosystems. Currently found in all six Brazilian biomes, with reports in 11 Brazilian states, wild boars have invaded natural and agricultural areas. Wild boars have been reportedly indicated as hosts and reservoirs of several zoonotic diseases in Brazil, including toxoplasmosis, salmonelosis, leptospirosis, brucellosis, tuberculosis, trichinellosis, and hepatitis E. Wild boars have been also associated with Brazilian spotted fever and rabies, infected while providing plentiful exotic blood supply for native ticks and hematophagous bats. Due to their phylogenetic proximity, wild boars may present ecological niche overlapping and direct disease risk to native white-lipped and collared peccaries. Moreover, wild boars may post an economical threat to Brazilian livestock industry due to restrictive diseases such as Aujeszky, enzootic pneumonia, neosporosis, hemoplasmosis, and classic swine fever. Finally, wild boars have directly impacted in environmentally protected areas, silting up water springs, rooting and wallowing native plants, decreasing native vegetal coverage, disbalancing of soil components, altering soil structure and composition. Wild boar hunting has failed as a control measure to date, according to the Brazilian Ministry of Environment, due to private hunting groups mostly targeting males, intentionally leaving females and piglets alive, disseminating wild boar populations nationwide. Meanwhile, non-government animal welfare organizations have pointed to animal cruelty of hunting dogs and wild boars (and native species) during hunting. Despite unanimous necessity of wild boar control, eradication and prevention, methods have been controversial and should focus on effective governmental measures instead occasional game hunting, which has negatively impacted native wildlife species while wild boars have continuously spread throughout Brazil.

1. Introduction

Wild boars (*Sus scrofa*) were first described by Linnaeus in 1758, and as the same species of domestic and feral pigs, wild boars are the ancestors of ancient and modern swine breeds [1,2], with one of the largest worldwide geographical distributions among terrestrial mammals [3].

Originally, wild boar hunting was considered as primary resource for human subsistence, with their occurrence overlapping the spread of first civilizations on steppes and forests of the Palearctic region [4]. Such human and wild boar distribution crossed from eastern Europe to western Russia [5]. First evidences of wild boar domestication occurred approximately 8500 years ago in Near East, then Europe, later escaping and returning to wildlife [1]. Adult wild boars weigh around 60-80 kg (females) and 75-100 kg (males) [6]. Moreover, litters born with 4–6 piglets through the year in tropical countries, with absence or low wildlife predation and highly adaptative ability, may altogether increase wild boar population up to 150% per year [7].

Despite natural predation and game hunting depletion, including eradication in British Islands, Scandinavia, parts of north Africa, former Soviet Union, and northern Japan, wild boar populations have spread to

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https://doi.org/10.1016/j.onehlt.2023.100577
Received 19 December 2022; Received in revised form 4 June 2023; Accepted 5 June 2023
Available online 8 June 2023

all continents and several oceanic islands, with exception of Antarctica [5]. Not surprisingly, wild boars have been enlisted among the 100 most invasive species worldwide, according to the International Union for Conservation of Nature (IUCN) [8]. Thus, the present review aimed to assess and discuss the One Health impact (human, animal and environmental health) and effectiveness of initial control measures of wild boars in Brazil.

2. Introduction in Brazil

In South America, wild boars have been present for over 100 years, mostly related with hunting purposes in Argentina, then Uruguay and Chile [9]. In Brazil, although isolated records of wild boar exist from the 1960s, the exotic species invasion was acknowledged in the late 1980's and early 1990's, after massive importation of commercial livestock in southern states, followed by releases and escapes to natural ecosystems [7,9]. In subsequent years, more commercial wild boars were imported and/or free-range crossed Brazilian borders mostly from Argentina and Uruguay, and associated with increase of popularity as exotic meat [10,11], along with escape and intentional release associated to game hunting, generating the first free-range Brazilian wild boars populations, with different degrees of crossbreeding with domestic pigs [12,13].

The Brazilian Ministry of Environment currently determines that wild boars or feral pigs should be eradicated in all their forms including

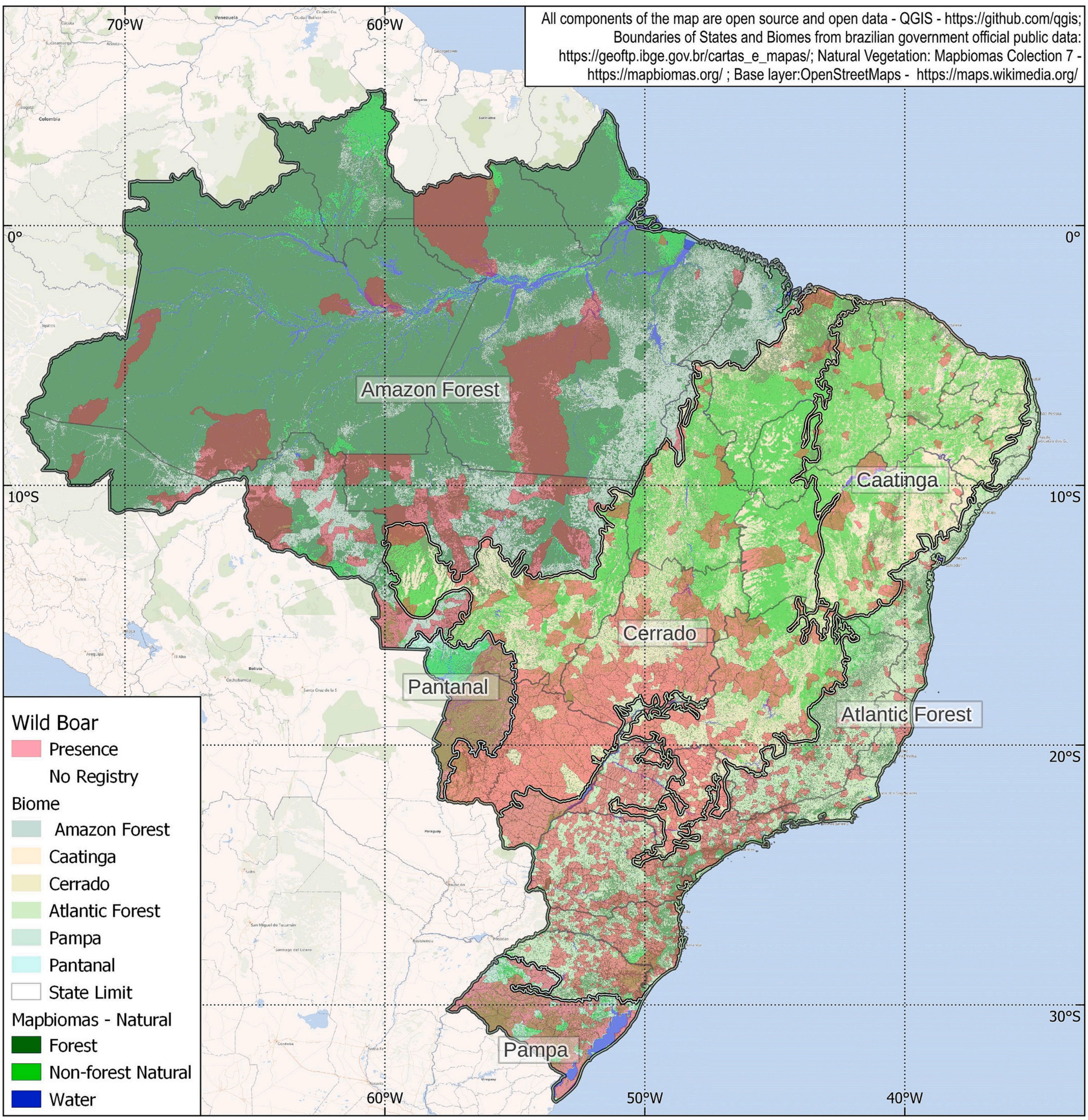

Fig. 1. Wild boar occurrence throughout Brazilian biomes, according to the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), 2019.

native, domesticated, sylvatic or mixed, in all lineages, breeds and crossing levels with domestic pigs, with exception of the Montero pigs, which have non-related origin in the central-western Brazil [14]. Wild boars have shown an accelerated increase in the last 30 years, and found in all six Brazilian biomes, particularly in the Cerrado, Atlantic Rainforest and Pampa, with reports in 1152/5568 (20.7%) cities, including all states of southern, southeastern and central-western regions (Figs. 1 and 2, Supplementary material 1) [9,15]. The few estimative revealed that wild boar abundance may range from 3/km^2 in the southern Santa Catarina state up to 16/km^2 individuals at the Mantiqueira Mountains, which covers southeastern states of São Paulo, Minas Gerais and Rio de Janeiro [16].

3. Impact on human health

Wild boars have been indicated as hosts and reservoirs of several zoonotic diseases, including toxoplasmosis [17], salmonellosis [18], leptospirosis [19], brucellosis [20] and tuberculosis [21], enzootic pneumonia [22], *Pneumocystis* spp. pneumonia [23], hepatitis E virus, influenza A virus, trichinosis [24–26] and sarcocystosis [27] in Brazil and other South American countries [28]. In addition, wild boars in Brazil have been also associated with Brazilian spotted fever [29] and rabies [30], providing blood meals for ticks and hematophagous bats (Table 1).

Mycobacterium bovis DNA was detected in organ tissues of wild boars in southern Brazil, with 27.9% animals and 4.3% organs with tuberculosis-like histological lesions [31], with isolates from five wild

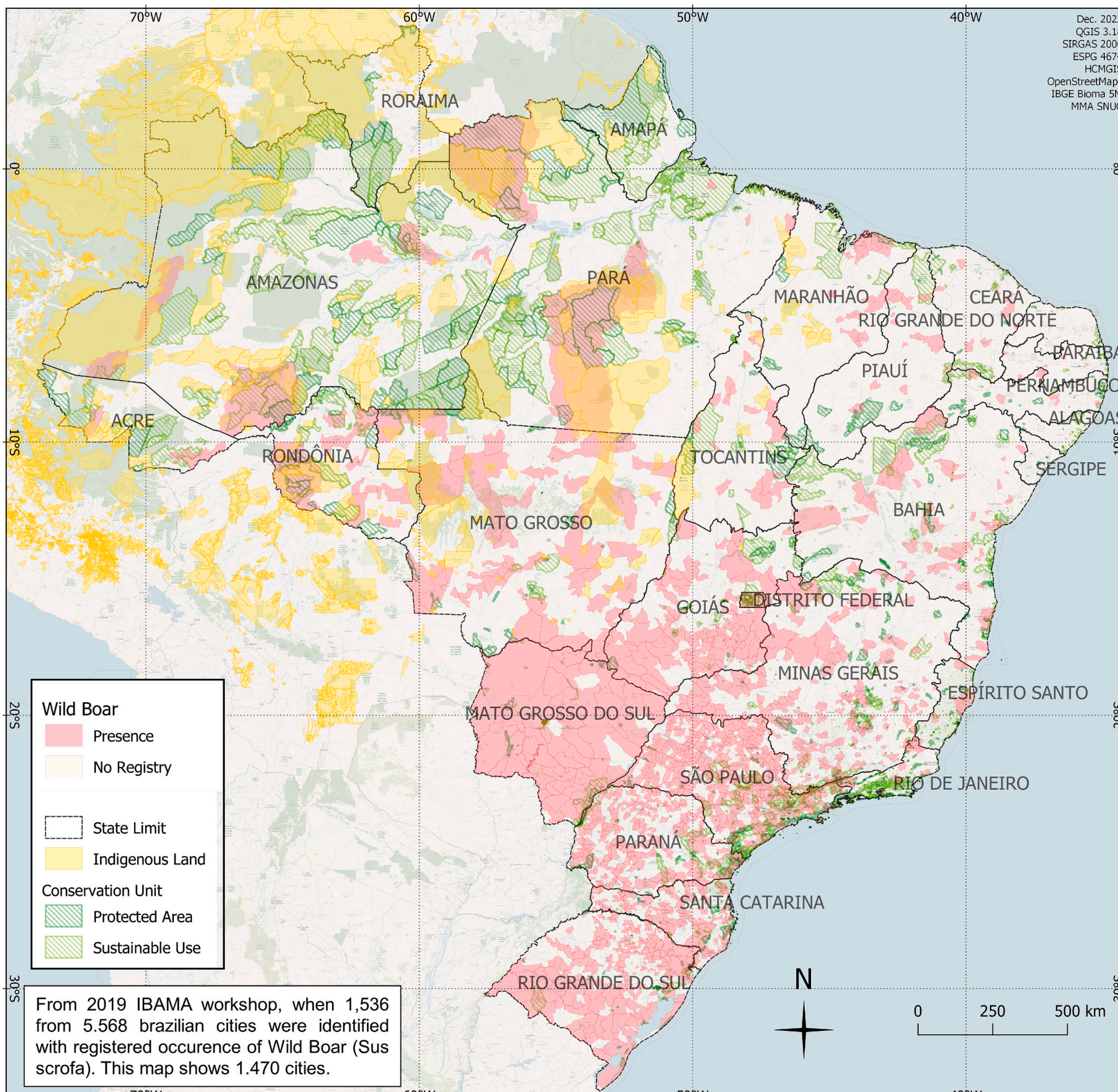

Fig. 2. Wild boar occurrence throughout Brazilian states, the indigenous land, protected areas and for sustainable use, according to the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), 2019.

Table 1
Wild boar impact on human health in South America- Brazil.

Causative agent	Diagnostic method/sample	Frequency of seropositive or positive	Comments	Year/local of study/ reference
Toxoplasma gondii	Modified agglutination test (MAT)/serum	15/71 (21.1%)	A total of 49/157 (31.2%) hunting dogs and 15/49 (32.7%) hunters were seropositive by indirect immunofluorescent antibody test (IFAT)	2016–2018/ southern and central-western Brazil [17]
Salmonella spp.	Histological and microbiological analysis/ intestine and lung	20/40 (50.0%) with lesions.	*Salmonella enterica* was isolated from a large intestine	2002/Brazil [18]
Leptospira spp.	MAT/serum	9/74 (12.2%)	A total of 16/170 (10.6%) hunting dogs were seropositive for at least one serovar; all hunters 0/49 (0.0%) were seronegative	2016–2018/ southern and central-western Brazil [19]
Leptospira spp.	MAT	8/8 (100%)		2009/Colombia [49]
Brucella spp.	Rose Bengal test (RBT) for screening, and standard tube agglutination test (STAT) and the 2-mercaptoethanol test (2MET) as confirmatory tests/serum	0/86 (0.0%)	All 0/170 (0.0%) hunting dogs and 0/49 (0.0%) were seronegative.	2016–2018/ southern and central-western Brazil [20]
Brucella spp.	ELISA/serum	0/6 (0.0%)	–	2009/Colombia [49]
Mycobacterium spp.	Isolation and PCR/lungs, liver, spleen, kidneys and lymphnodes	15 isolates *Mycobacterium* spp. in 13 wild boars sampling	The isolates were classified as *M. tuberculosis* (33.3%), *M. colombiense* (33.3%), *M. avium* subsp. *hominissuis* (13.3%), *M. parmense* (13.3%) and *M. mantenii* (6.66%)	2021/southern Brazil [21]
Hepatitis E virus	ELISA/serum	8/61 (13.1%)	–	2017–2018/ southern Brazil [28]
Influenza A virus	ELISA/serum	6/61 (9.8%)	–	2017–2018/ southern Brazil [28]
Influenza A virus	PCR/lung	11/60 (18.3%) positive wild boars	Chronic diffuse bronchopneumonia was observed in all samples	2011/southern Brazil [106]
Rickettsia spp.	immunofluorescent-antibody assay (IFA)/serum	58/80 (72.5%)	24/170 (14.1%) hunting dogs and 5/34 (14.7%) hunters were seropositive for *Rickettsia* spp. Wild boars may be carrying and spreading capybara ticks, important to BSF transmission in Brazil	2016–2018/ southern and central-western Brazil [29]
Rabies virus	Rabies-modified rapid fluorescent focus inhibition test/serum	9/80 (11%)	A total of 43/49 (88%) hunters lacked immune protective titers (0.50 IU/mL). Images obtained by camera trap (n = 11,112) revealed vampire bats blood feeding in 13/94 (14%) wild boars from State Park	2016–2018/ southern and central-western Brazil [30]
Trichinella spp.	ELISA, artificial enzymatic digestion/serum; diaphragm, tongue, and or masseter muscles	7/115 (6.1%) seropositive; tissue samples from all 37 wild boars were negative	–	2018–2020/ southeastern Brazil [24]
Trichinella spp.	ELISA, artificial enzymatic digestion/Serum; muscle juice	3/125 (2.4%) seropositive; 5/304 (1.64%) positive meat juice	–	2014–2018/ Argentina [25]
Trichinella spiralis	PCR/meat	5/278 (1.8%) positive wild boars	–	2009–2014/Chile [26]
Sarcocystis spp.	Light microscopy and PCR/muscle	116/240 (48.3%) were positive by light microscopy; 110/240 (45.8%) by PCR	–	Argentina [27]
Pneumocystis spp.	Immunohistochemistry (IHQ)/skin, tonsils, spleen, lymph nodes, intestines, liver, stomach, kidneys, heart and the central nervous system	39/78 (50%) positive wild boars	16/78 (20.5%) wild boars coinfected by *Pneumocystis* and porcine circovirus type 2	2005–2008/ southern Brazil [23]

boar tissue isolates classified as *M. tuberculosis*, *M. colombiense*, *M. avium* subsp. hominissuis, *M. parmense* and *M. mantenii* [21]. Despite wild boars have been indicated as reservoirs of *Brucella suis* and *Brucella abortus* for both livestock and wildlife species [32,33], all wild boars, hunting dogs, and hunters sampled from three Brazilian regions were seronegative to *Brucella* spp., suggesting a low circulation of *Brucella* spp. in wild boars, hunting dogs, and hunters in these areas [20].

Overall, anti-*T. gondii* seropositivity was observed in 21.1% wild boars, 31.2% hunting dogs and 32.7% hunters of two Brazilian areas [17]. Despite the seroprevalence within national and international range, wild boars were less exposed to infection than hunting dogs and hunters, showing that wild boars alone may provide a biased basis for public health concerns [18]. Probably due to presence of infected domestic cats, higher prevalence was observed in captured than in free-range wild boars, and from anthropized than from natural areas [17]. Regardless, consumption of raw or undercooked meat of free-range wild boars should always be considered a major risk factor for toxoplasmosis [17]. However, toxoplasmosis studies have shown positivity variation according to wild boar sampling locations, with 27.0% in a combined serology-molecular survey from five different Brazilian states [34], and 76.9% in the São Paulo state [35].

Despite all hunters examined in a study were seronegative for *Leptospira* spp., 12.2% wild boars and 10.6% hunting dogs were seropositive for at least one serovar, with higher seropositivity in wild boars from natural than anthropized areas [19]. Leptospiral serovars included Patoc, Canicola, and Minis were found in wild boars, while Pyrogenes, Pomona, Icterohaemorrhagiae, Shermani, Patoc, and Canicola were found in hunting dogs, such reservoir species may bring sylvatic leptospiral serovars to human settings [19].

A surprising wild boar transmissible disease the Brazilian Spotted Fever, the deadliest tick-borne pathogen worldwide, with 72.5% wild boars, 14.1% hunting dogs and 14.7% hunters seropositive to at least one *Rickettsia* species [29]. Besides serology, 42.2% ticks from wild boars were identified as *Amblyomma sculptum*, 57.4% as *Amblyomma brasiliense*, 0.24% larvae of *Amblyomma* spp. and 0.06% nymph as *Amblyolmma dubitatum*, with all hunting dog ticks as *Amblyomma aureolatum* and all hunter ticks as *A. sculptum* [29]. As the only significant association with rickettsial seropositivity was the increased risk of female wild boars, probably due to environmental exposure, hunters and hunting dogs may undergo a randomly exposure in each incursion [36]. In such scenario, wild boar hunting may increase likelihood of human infection to rickettsial and other tick-borne pathogens, as wild boars may be carrying and spreading infected *Amblyomma sculptum* ticks from capybaras to different ecosystems [29]. Despite wild boar ability to infect ticks and its role on *Rickettsia* spp. transmission cycle remains to be fully established, incursion into tick habitats may lead to biting, infection, transmission and spreading of *Rickettsia* spp. and other tick-borne diseases [29,36].

Rabies may be the most threating zoonosis that wild boars may spread in Brazil, as one of the deadliest diseases worldwide. In a recent study, 11.2% of wild boars in Brazil presented serum titers for rabies exposure, likely due to contact with contaminated saliva of vampire bats or from infected carcass consumption [30,37]. Meanwhile, 87.8% of corresponding hunters lacked immune protective titers [30]. Thus, Brazilian wild boars exposed to rabies may play an important role in the sylvatic rabies cycle by indirectly providing a blood supply for vampire bats, along with directly transmission of rabies virus to hunters and hunting dogs [30]. These findings have suggested that hunters, park rangers, researchers and other wild boar contacting individuals may be potential risk groups for contracting rabies, as workers ́health occupations who should receive mandatory pre-exposure rabies vaccination [30].

In a recent comprehensive study, serum from wild boar from the southern Brazilian state of Santa Catarina were screened for a series of pathogens and 52.4% were seropositive for porcine circovirus type 2 (PCV2), 21.3% for *Leptospira* spp., 13.1% for hepatitis E, 9.8% for influenza A virus, with no seropositivity for *Brucella* spp. and classical swine fever virus [28]. Additionally, 2.9% wild boars were seropositive for eastern equine encephalitis virus (EEEV), indicating exposure of free-range wild boars from central-western Brazil, although with uncertain role on viral transmission [38]. Despite no confirmed presence of parasite, 6.1% wild boars were seropositive in ELISA for *Trichinella* spp., suggesting the occurrence wild cycle related to wild boars in Brazil [24].

4. Impact on native and livestock animal health

Wild boars have been phylogenetically close to domestic pig species (*Sus scrofa domesticus*) within the Suidae (swine) family and related to the Tayassuidae (peccaries) family to the nonruminating ungulates into the Suina clade or suborder within the order Artiodactyla. Thus, pathogen transmission may increase by free-range wild boar movement in Brazil, overlapping commercial and backyard swine production, and Tayassuidae wildlife Brazilian native species such as white-lipped (*Tayassu pecari*) and collared (*Pecari tajacu*) peccaries [39].

Due to their phylogenetic proximity, wild boars may present ecological niche overlap with white-lipped and collared peccaries in their ecosystems, forcing these native species to change their dietary habits and habitats and run to open-fields of grain cultivations, as observed in southern Brazil [9,29,40]. Besides mountain lions and jaguars hunt wild boars, they may not kill adult animals and enough quantity to stop the population growth [41,42].

As for the swine industry, wild boars have already been indicated as of high risk of contact and disease transmission to commercial farms and subsistence backyard herds of domestic pigs in central-western Brazil [43]. Not surprisingly, Aujeszky disease, caused by a herpes virus with major economic losses to swine industry worldwide, has been already isolated in wild boar tissues, indicating a role as disease amplifiers [44]. Out of a total of 94 free-ranging wild boars (*Sus scrofa*) from two different Brazilian biomes, 1/36 (0.03%) from central-western Brazil was seropositive for antibodies against pseudorabies virus (PRV), exposing livestock and free-range peccaries and other wildlife species in these areas [45]. In fact, an early study conducted in São Paulo state, southeastern Brazil with farmed wild boars before nationwide prohibition had already found an overall prevalence of 30.7% seropositive wild boars, which may have affected the Brazilian national pseudorabies eradication program [46] (Table 2).

Wild boars have been associated with swine enzootic pneumonia, characterized by high morbidity, growing delay and economical losses, with similar risk factors to domestic pigs, as wild boars may play a reinfecting role on disease transmission for domestic pigs and commercial farms [22]. A total of 65.9% wild boars of Parana state, southern Brazil were serologically positive for *Mycoplasma hyopneumoniae*, the causative agent of enzootic pneumonia [22].

A comprehensive survey in Rio Grande do Sul state, far-southern Brazil has shown that 57.5% wild boars had at least one pathogen, with 2.5% for porcine circovirus 2 (PCV2), 53.8% for Torque teno Sus virus 1a (TTSuV1a), 5.0% for 1b (TTSuV1b), 3.8% for *Pasteurella multocida*, 1.3% for *Actinobacillus pleuropneumoniae*, 3.8% for *Glaesserella parasuis*; all samples were molecularly negative for *Mycoplasma hyopneumoniae* and Influenza A virus (IAV) [47]. Also in Rio Grande do Sul, bronchi and bronchioles of 60% studied wild boars have shown *Metastrongylus* spp. parasitism, which may cause bronchopneumonia, dyspnea and debility in domestic pigs and peccary [48].

Classical swine fever has been another concern for animal sanitary surveillance, as free-range wild boars may increase disease spreading, with positive animal reported in Colombia [49,50]. As southern, southeastern, and central-western Brazilian regions have been declared as disease-free by the Ministry of Agriculture and Livestock, concern of swine sanitary status for exportation has been of economic importance [51]. As expected for southern Brazil, all 61 sampled wild boars have tested seronegative for classical swine fever virus in a previous study [28]. Porcine lymphotropic herpesvirus (PLHV) can cause lymphoproliferative disorders and were reported infecting 96% wild boars in Parana State, southern Brazil [52]. *Pneumocystis* spp. can lead to pneumonia, especially in young swine, and were detected in 50% wild boars of southern Brazil [23]. Porcine circovirus 2 and 3 virus are recognized to cause multiple disease conditions in swine and were detected in 57.7% wild boars from southern Brazil [53], and also detected in 67% animals in Colombia [49]. Also in Colombia, 67% wild boars were seropositive to vesicular stomatitis virus, considered endemic in South America [49].

Not only swine but also cattle farms may be at risk of diseases, as a recent wild boar study in Brazil has shown that 8.9% hunting dogs were seropositive to the protozoan *Neospora caninum*, an important cause of abortion in cattle with domestic dogs serving as the definitive hosts [54]. In addition, cultivated tissue samples of slaughtered wild boars from the São Paulo state resulted in four intermediately virulent type *Rhodococcus equi* isolates, which may cause pneumonia in foals, lymphadenitis in pigs and HIV-positive patients [55].

Hemotropic mycoplasmas (hemoplasmas) may also be a problem, since 58.5% wild boars and 59.1% dogs were positive by qPCR for at least one hemoplasma, with all hunters negative [56]. Dogs with high hunting frequency were 2.4 more likely to be infected [56]. Sequencing revealed a probable novel *Hemoplasma* species in wild boars [56]. Although exposure to *Hemoplasma* species was present, the study herein found no evidence of cross-species transmission [56]. In addition, a molecular vector-borne survey has found that wild boars may act as a potential spreader of tick-borne pathogens such as *Ehrlichia* spp., *Bartonella* spp., hemotropic mycoplasmas, and *Cytauxzoon*, posting high health concerns, particularly to humans, horses, rodents, pigs, and cats [57].

Besides their impact as source for infectious diseases in livestock (swine fever, Aujeszky, brucellosis and trichinellosis), and in humans (spotted fever, rabies, hepatitis E, tuberculosis, leptospirosis) [58], wild boars have also threatened wildlife conservation and biodiversity due to transmissible diseases to Brazilian native species. First, Tayassuidae family members such as Brazilian collared and white-lipped peccaries are closely related to wild boars and may acquire livestock swine diseases. Also, wild boars may harbor and spread herbivore diseases such as foot and mouth disease virus (FMDV) infection, which may affect several

Table 2
Wild boar impact on native and livestock animal health in South America- Brazil.

Causative agent	Diagnostic method/sample	Frequency of seropositive or positive	Comments	Year/local of study/reference
Pseudorabies virus (PRV)	ELISA/serum	1/36 (0.03%)	–	2016–2018/ central-western Brazil [45]
Pseudorabies virus (PRV)	ELISA/serum	110/358 (30.7%)	–	1998–2001/ southeastern Brazil [46]
Pseudorabies virus (PRV)	in-house serum neutralization/serum	0/15(0.0%)	–	2009/Colombia [49]
Eastern, Western, and Venezuelan Equine Encephalitis Viruses	microplate serum neutralization test/serum	3/102 (2.9%) wild boars were seropositive for antibodies against eastern equine encephalitis virus	All 170 hunting dogs and 49 hunters were seronegative. Wild boars can be used as sentinels for eastern equine encephalitis virus activity.	2016–2018/ central-western Brazil [38]
Neospora caninum	In-house indirect immunofluorescence test (IFAT)/serum	All 98 wild boars were seronegative	15/168 (9%) hunting dogs were positive, and all 49 hunters were seronegative.	2016–2018/ southern and central-western Brazil [54]
Hemotropic mycoplasmas (hemoplasmas)	qPCR/blood	38/65 (58.5%)	94/159 (59.1%) positive hunting dogs. All 25 hunters were negative. Sequencing revealed *Mycoplasma parvum* and *M. suis* infection in wild boars, and *M. haemocanis* in dogs.	2016–2018/Brazil [56]
Hemotropic mycoplasmas (hemoplasmas)	PCR/blood and ticks	88.06% of blood samples and 8.69% of ticks were positive	*Mycoplasma suis* and *Mycoplasma parvum*	southeastern Brazil [57]
Cytauxzoon felis	PCR/blood and ticks	All blood and tick samples were negative	–	southeastern Brazil [57]
Anaplasma spp.	PCR/blood and ticks	5.97% blood samples and 50.54% ticks were positive	–	southeastern Brazil [57]
Ehrlichia spp.	PCR/blood and ticks	9.24% of ticks were positive	–	southeastern Brazil [57]
Porcine circovirus 2 (PV2) and 3 (PV3)	PCR/heart, kidneys, liver, lung, lymph nodes, spleen, and tonsils	15/26 (57.7%) positive for PV2 and PV3	–	southern Brazil [53]
Porcine circovirus	ELISA/serum	2/3 (67%)	–	2009/Colombia [49]
Pneumocystis spp.	Immunohistochemistry (IHQ)/skin, tonsils, spleen, lymph nodes, intestines, liver, stomach, kidneys, heart and the central nervous system	39/78 (50%) positive wild boars	16/78 (20.5%) wild boars coinfected by *Pneumocystis* and porcine circovirus type 2	2005–2008/Brazil [23]
Torque teno Sus virus 1a (TTSuV1a) and and 1b (TTSuV1b)	PCR/lymph nodes	43/80 (53.8%) positive for TTSuV1a, 5.0% (4/80) positive for TTSuV1b	Histological analysis: Bronchopneumonia, vascular congestion, hemorrhage, edema, emphysema, fibrosis, follicular hyperplasia and presence of *Metastrongylus* sp. in TTSuV1a positive wild boars. Chronic bronchitis and presence of Metastrongylus sp. in TTSuV1b positive wild boars.	2013–2015/ southern Brazil [47]
Influenza A virus	hemagglutination inhibition (HI) assay; PCR/lung, lymph nodes; serum	16/45 (35.5%) seropositive; all negative by PCR	–	2013–2015/ southern Brazil [47]
Pasteurella multocida	PCR/lung	3/79 (3.8%)	Histological analysis: emphysema and vascular congestion	2013–2015/ southern Brazil [47]
Actinobacillus pleuropneumoniae	PCR/lung	1/79 (1.3%)	–	2013–2015/ southern Brazil [47]
Glaesserella parasuis	PCR/lung	3/79 (3.8%)	Histological analysis: Chronic bronchitis, bronchitis, bronchiolitis, emphysema and presence of *Metastrongylus* sp.	2013–2015/ southern Brazil [47]
Mycoplasma hyopneumoniae	PCR/lung	All 79 wild boars were negative	–	2013–2015/ southern Brazil [47]
Mycoplasma hyopneumoniae	ELISA and immunohistochemistry (IHC)/ serum and lung tissue fragments	58/88 (65.9%) seropositive, 13/27 (48.1%) positive wild boars	Only wild boars with enzootic pneumonia-like macroscopic lesions have tissues sampled.	2017–2019/ southern Brazil [22]
Rhodococcus equi	PCR/ lymph nodes	4/120 (3.3%) positive lymph nodes from slaughtered wild boars	Presence of lesions (enlargement, granuloma, purulent focus, fibrosis, calcification, caseation, nil lesions) in positive lymph nodes. Isolates strains presented intermediately virulent type 8	2008–2009/ southeastern Brazil [55]
Classical swine fever virus	ELISA/serum	All 6 wild boars were seronegative.	–	2017–2018/ southern Brazil [28]
Classical swine fever virus	neutralizing peroxidase-linked antibody/ serum	1/15 (7%)	–	2009/Colombia [49]

(continued on next page)

Table 2 (*continued*)

Causative agent	Diagnostic method/sample	Frequency of seropositive or positive	Comments	Year/local of study/reference
Porcine lymphotropic herpesvirus (PLHV)	PCR/lung	48/50 (96%) positive wild boars	Lung and spleen fragments were obtained from six fetuses, all negative	2017–2019/ Southern Brazil [52]
Vesicular stomatitis virus	In-house serum neutralization test/serum	4/6 (67%)	–	2009/Colombia [49]
Brucella spp.	Rose Bengal test (RBT) for screening, and standard tube agglutination test (STAT) and the 2-mercaptoethanol test (2MET) as confirmatory tests/ serum	0/86 (0.0%)	All 0/170 (0.0%) hunting dogs and 0/49 (0.0%) were seronegative	2016–2018/ Brazil [20]
Brucella spp.	ELISA/serum	0/6 (0.0%)	–	2009/Colombia [49]
Metastrongylus spp.	Microscopy/Lungs, bronchi, trachea, and intestines	24/40 (60%) with *Metastrongylus* spp. in bronchi and bronchioles samples	–	2010–2011/ Southern Brazil [48]
Porcine cytomegalovirus	PCR/tonsils	35/62 (56%)	–	2016–2019/ Argentina [107]
Trichinella spp.	ELISA; artificial enzymatic digestion/serum; diaphragm, tongue, and or masseter muscles	7/115 (6.1%) seropositive; all tissue samples for 37 wild boars were negative	–	2018–2020/ southeastern Brazil [24]
Trichinella spp.	ELISA, artificial enzymatic digestion/ Serum;muscle juice	3/125 (2.4%) seropositive and 5/304 (1.64%) meat juice samples	–	2014–2018/ Argentina [25]
Trichinella spiralis	PCR/meat	5/278 (1.8%) positive wild boars by PCR	–	2009–2014/Chile [26]
Sarcocystis spp.	Light microscopy and PCR/muscle	116/240 (48.3%) were positive by light microscopy;110/240 (45.8%) by PCR	–	Argentina [27]

native ungulate Brazilian species including deer and tapirs [59]. Although wild boars have presented antibodies for canine distemper virus (CDV) following a distemper outbreak [60], which may be life-threatening to native Brazilian carnivores, such role remains to be fully established and should be further investigated. In addition, as omnivore predators, wild boars may prey on native reptiles, amphibians, small mammals, and large mammal newborns including deer, anteaters, and capybaras.

5. Impact on biodiversity

Wild boars have been placed among the most invasives species worldwide, along with rats, domestic dogs, and domestic cats [61]. Predation, competition for limited resources and introduction of diseases have been among the direct deleterious effects related to biological invasion of exotic species with high adaptative capacity such as wild boars [62]. A study of wild boar diet by analyzing stomach contents has shown biodiversity implications by seasonal, circadian, broad, and highly adaptative diet on three Brazilian ecoregions including Pampa, Araucaria Forest, and Pantanal forest–grasslands [63].

Wild pigs have developed highly damaging behaviors, causing deep negative impacts in natural ecosystems, including taxonomic groups often minimally threatened by other invasive mammalian species, such as herpetofauna and plants [64,65]. This invasive species may also modify the ecological niche of several native animal and plant species by direct destruction, consumption, wallowing in nestles of frogs, flies, small rodents and birds [66]. As opportunistic omnivores, the high dietary versatility has included insects, larvae, amphibians, reptiles, small mammals, birds, and carcasses in decomposition, besides seeds and roots of endangered plant species [67].

A previous study has quantified wild boar impact in native and non-native distribution areas measuring the taxa and taxonomic groups endangered, and based on the IUCN Red List [5]. Wild boars have threatened 672 taxa in 54 different countries worldwide, including 14 species that have directly been driven to extinction, particularly in non-native range of wild boars [5]. Although this study has assessed the impact in Australia, North America and Europe [5], it did not include South America as endangered area. Not surprisingly, another study has shown that 28% of ecological niches were unfilled in Neotropical region after wild boar invasion, suggesting that the impact of wild boar in such areas may be currently higher than in other regions worldwide [68]. The ongoing population growth in South America, particularly in Brazil, has been associated with wild boar farming and escape, game-hunting practices and cross-country dispersion [7].

Brazil borders 10 of 12 South American countries, with the exception of Ecuador and Chile. In addition, out of the six Brazilian biomes, five are shared with other contiguous countries, with exception of Caatinga. Despite being a long Atlantic Ocean seashore in the east, Pampa and Atlantic Forest biomes spread to Uruguay, Paraguay, and Argentina in the south; Cerrado and Pantanal biomes to Paraguay and Bolivia at west; and the biggest Brazilian biome, the Amazon Forest reaches up north Bolivia, Colombia, French Guiana, Guyana, Peru, Suriname, and Venezuela (Fig. 1). Found in all Brazilian biomes, wild boars have been already reported in Colombia, Argentina, Uruguay and Chile, expectedly invading ecoregions overlaying Bolivia and Paraguay [69]. As invasive wild pigs across the contiguous USA from 1982 to 2012 were driven by higher habitat heterogeneity and limited only by cold temperatures and water scarcity [70], widespread may be faster in South American biomes, which provide access to multiple key resources including biodiversity, water, forage, and shelter.

6. Impact on plant health

The international One Health initiative has recently advocated that plant (photosynthetic organisms) health should be considered a separate standalone health issue from environmental health, as destruction of (native) plant species may itself impact the local micro-ecosystem health including invertebrate animals and other plants, along with biodiversity, human and animal health, and impact on environmental health [71]. Despite the recent wild boar invasion (less than eight years) in certain southern Brazil areas, seed dispersion and sprouting of Araucarias, a top endangered native pine tree, may be directly impaired by over-consumption by wild boars [72,73]. As *Araucaria* seed dispersion relies mostly on underground hides by agoutis and jays for later meals, excessive wild boar intake may disrupt the *Araucaria* life cycle, as no native large granivore is found in that ecosystem [73,74]. In addition, less availability of *Araucaria* seeds may compromise native animal (vertebrate and invertebrate) species in such fragile balance, already impacted by anthropic activities [73,75]. On the other hand, given wild boar are omnivorous and rely on native vegetation for shelter and food [76], frugivory and seed dispersal of other plant species is occurring, including native and exotic plants [77].

7. Impact on environmental health and agriculture

Along with land use and greenhouse gases, introduction of exotic species has been among the top three main risk factors for biodiversity [78]. Wild boars have been reported in at least 46 national or state conservation units, defined as areas of relevant value for native biological diversity preservation [15]. Large exotic species as wild boars in such preserved areas may be more difficult to control due to resistance of capture by trapping and slaughter by firearm [14]. In addition, soil rooting habits of wild boars may result in decrease of vegetal coverage, micro-arthropod richness and abundance, disbalance of soil components as phosphorus, nitrogen, magnesium, manganes and zinc, causing soil sedimentation, altering soil structure and composition in both natural preserved and agricultural areas [79,80].

A study has reported stomach contents of 106 wild boars from landscape agriculture area in São Paulo State, southeast Brazil. Stomach contents were mainly composed by corn (41%) and sugarcane (28.5%), in addition to vegetal (27%), and vertebrates and invertebrates matter (4%) [76]. Despite food availability in natural ecosystems, easy access to crops of corn, barley, wheat, soybean, rice, rye and oat may provide abundant food source for wild boars, leading to population growth along with crop damages and farming losses [76].

As free-range, wild boar males and females have distinct behavior, with females and piglets in hidden groups, males tend to solitary habits, with aggressive behavior, particularly during mating [81]. In such scenario, state and national preservation units may serve as protective nursery areas for wild boars with prohibited hunting as observed in southern Brazil, with males being hunted while crossing surrounding agricultural areas [17,29]. Wild boars have been adapted their habits accordingly local environmental conditions, specially associated with anthropogenic presence that may modify the effects of exotic species on the native ecosystem [82]. Finally, it is important to understand that effects of invasive species can begin with small modifications in the behavior of native species, and it is difficult to evaluate what effect this will have on the biological dynamics of the environment [5].

8. Wild boar hunting as population control measure

In 2013, considering the prior definitions of harmful invasive exotic and synanthropic fauna by the Normative Instruction 141/2006, the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) published the Normative Instruction 03/2013, which terminated wild boar commercial farms and allowed hunting for population control [14]. Hunters were registered and hunting periodically informed four times per year, with prohibition of live animal transportation and trading of wild boar meat, leather and other derivate products. As hunting has been never allowed in Brazil, wild boars were the first animal species for hunting in history, leading to a frenzy of hunting groups, mostly using hunting dogs for wild boar sniffing and capture [14,84,85]. Not surprisingly, illegal hunting has skyrocketed in recent years, as hunters have target also native peccaries, capybaras, wild cats and even jaguars [86].

Launched in 2017, the National Plan of Wild Boar Prevention, Control, and Monitoring in Brazil aimed to prevent the wild boar territorial expansion, its health, environmental, social and economic impacts, primarily protecting the natural ecosystems and biodiversity [87]. In agreement with the Brazilian Federal Council of Veterinary Medicine, wild boar control should be made in a humanitarian manner, with appropriated equipment and ensuring reduction of damages in conservation units and natural ecosystems. In response to the national hunting regulations, the São Paulo state issued the Law 16,784/2018, which prohibited hunting "in all forms, under any pretext and for any purpose" [89].

A recent study conducted in partnership with the Brazilian Ministry of Agriculture and Livestock has found that use of dogs to prevent crop damage and wild boar shooting as sport hunting were likely ineffective, requiring a governance to deal with all the involved aspects in wild boar control, environmental impacts, and health risks [90].

9. Animal welfare controversy

Non-governmental organizations of animal welfare and protection nationwide have started questioning the use of hunting dogs for wild boar sniffing and apprehension [91]. As argued, hunting dogs continuously underwent animal cruelty due to stressful transportation, in cages with no water, food or space for rest, lack of hygiene, fight wounds and potential death, and exposure to diseases already mentioned above [85]. As hunting dogs are also exotic fauna in Brazil, such activities may lead to native fauna predation as birds and small rodents, contributing for biodiversity damages [85]. Moreover, animal protection organizations have pointed to a series of hunter deaths due to accidental shots during incursions [86]. In 2019, the IBAMA published the Normative Instruction 12/2019, which allowed dog use for the hunting activities, consigering animal welfare regulation [108]. Finally, Brazilian society has strongly criticized the contemporary approach of biosecurity against exotic animal species, relying on a military mode of "man versus wild boar" thinking, stimulating individual gun purchase and hunting for control [92].

Hunters have complained about the federal government bureaucracy, particularly the permission paperwork needed from farmers. Also, the Ministry of Agriculture and Livestock has used an international regulation of free-range wild boar monitoring to justify farmer hunting and sampling [87].

10. The wild boar problem demands a One Health approach

As native and exotic free-living wild boars have been reportedly reservoirs for several zoonotic viruses, bacteria and parasites, with concomitant environmental impact on native areas, a One Health approach should be always proposed as a holistic and effective response. Over time, increase of human habitation in suburban areas, land use for agricultural purposes, hunting activities and wild boar meat consumption have also increased wild boar exposure to domestic animals and humans [58]. In addition, wild boar abundance as game species with high reproduction rates worldwide has contributed to a large and widespread non-conventional meat supply, recently warning the European Union about spillover risk of transmissible diseases to domestic pigs. Such direct and indirect risk of foodborne pathogens may compromise food security and safety, as wild boar may harbor and transmit zoonotic agents by food to humans, requiring specific game meat inspection [94].

Wild boars may be a distinct example of a One Health impact, caused and maintained in the past decades by illegal anthropic actions in several countries, particularly as exotic species in Brazil [95] and USA [96]. Human greed and commercial activities guided by hunting culminated on wild boar release, intentional scape and spreading in all six Brazilian biomes, including national and state preservation units, agricultural lands, and livestock pastures, with similar wide spreading in the USA, invading 35/50 (70%) states [97,98]. Surprisingly, wild boars have been reportedly indicated as a One Health concern worldwide only (and recently) for circulating zoonotic protozoa and viruses in Portugal [99] and dissemination of antimicrobial resistant *E. coli* in Northern Italy, suggesting wild boar role as antibiotic resistance spreader, requesting inclusion in surveillance programs [100].

11. Population monitoring, disease surveillance and future research

Population monitoring has been another important wild boar issue. Ideally, digital cartography of vegetation coverage to map habitat suitability for wild boars should be made, in association with the georeferenced and presence records, to predict and analyze population dynamics, as proposed for Bulgaria, and reported by Poland, Germany, Switzerland, Italy, Portugal and Spain in Europe [101], and in the USA [70]. Although wild pigs have invaded all biomes and almost all Brazilian regions, with high densities in the tropical forests of the Atlantic Forest, few studies have mapped [102].

Effective wild boar management and population monitoring have relied on accurate estimative of population density and spreading [103], with wild boar presence in Brazil confirmed since the 1980's [9]. Despite few studies of individual numbers and behavior in Brazil, higher female and piglet population in different conservation units have revealed ideal nursery habitats for wild boars, particularly due to hunting prohibition in such areas [17]. In addition, wild boars have switched their activity from 24-h to daylight period, after implementation of nocturnal hunting with dogs as population control method [104]. Trapping cameras have also revealed more activity during the wet season, probable due to the presence of *Araucaria angustifolia* tree seeds in Atlantic Forest areas [104]. Wild boar population density worldwide has ranged from less than 1 to 43 individuals/km^2, depending on environment conditions, resources availability and human proximity [105]. As previously suggested for terrestrial environments, population density may be classified as low with 1 individual/km^2, moderate with 6 individual/km^2 and high density with equal or higher than 11 individuals/km^2 [3], with South America and Brazil presenting moderate to high wild boar population density [3].

Disease surveillance should be also continuously performed, as wild boars have affected human health by a series of zoonotic diseases, particularly rabies and Brazilian spotted fever, while providing blood meals for potential overpopulation of ticks and hematophagous bats [29,30] Wild boars have also threatened wildlife and livestock health, posting sanitary challenges for commercial farms and native species, with the Brazilian Ministry of Agriculture and Livestock considering mandatory the surveillance of classical swine fever, African swine fever, porcine reproductive and respiratory syndrome, and Aujeszky disease, in compliance with the World Organization for Animal Health [51].

Future studies should be conducted to clarify and pinpoint the wild boar role as amplifiers of *Rickettsia* spp. and rabies virus reservoirs in Brazil. In addition, swine disease distribution may overlap free-range wild boar occurrence, threating native tayassuidae species and commercial swine farms. Wild boars may also carry important pathogens for native and livestock herbivores and wild and domestic carnivores. Finally, distribution in all Brazilian regions and biomes, including bordering areas with several South American countries, may post wild boars as sentinels for One Health concern diseases, such as equine encephalitis virus [38].

12. Final considerations

In such a scenario, the study herein has provided strong evidence for better understanding the wild boar impact on human, animal, plant, and environmental health in Brazil. Moreover, initial governmental actions based on first-ever legalized hunting in Brazil were disastrous and directly threatened native species and caused animal cruelty issues for both hunting dogs and wild boars. In May 2023 the Brazilian government launched the "Second National Wild Boar Plan", aiming to review the current assessment, impact and side-effects of control and prevention measures. Thus, as presented herein, wild boar issues demand a One Health approach not only for assessing the impact, but also on planning, evaluation, and monitoring of control and prevention procedures.

Funding

This work is part of a One Health Grant sponsored by the Araucária Foundation of Paraná State (Protocol # SUS2020111000007).

Declaration of Competing Interest

None declared.

Data availability

Data will be made available on request.

Acknowledgments

Authors kindly thank the Brazilian Ministry of Environment, Ministry of Agriculture and Livestock and Ministry of Health for the assessment of information regarding wild boar impact on their responsibilities.

Appendix A. Supplementary data

Wild boar occurrence in Brazil according to Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), 2019. Supplementary data to this article can be found online at https://doi.org/10.1016/j.onehlt.2023.100577.

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