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REVIEW

Landscape Ecology Meets Disease Ecology in the Tropical America: Patterns, Trends, and Future Directions

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Abstract

Purpose of Review In this paper, we synthesize the status and trends of studies assessing the effects of landscape structure and changes on zoonotic and vector-borne disease risk in the Tropical America region (i.e., spanning from Mexico to southern South America). Understanding how landscape structure affects disease emergence is critical to designing prevention measures and maintaining healthy ecosystems for both animals and humans.

Recent Findings We found that there is a small number of articles being published each year regarding landscape structure and zoonotic and vector borne diseases in the Tropical Americas region, with a slight growing trend after 2013. We identified a large knowledge gap on the subject in most of the countries: in 15 of 27 countries, no article was found, and 72% of the current literature available is concentrated in only three countries (Brazil, Panama, and Colombia). Five diseases represent about 68% of the available knowledge, which compared to over 200 types of known zoonoses and vector-borne diseases, is an extremely low number. Most of the knowledge that exists for the region is about landscape composition, with few studies evaluating configuration parameters.

Summary In general, landscape changes presented a positive effect on zoonotic and disease risk in most of the studies found, with habitat loss, fragmentation and increases in the amount of edge habitats leading to an increased risk of the diseases investigated. The continued integration of landscape ecology into disease ecology studies can increase the knowledge about how land use change is affecting animals and human health and can allow the establishment of guidelines to create landscapes that have a low pathogenicity.

Keywords Landscape structure · Forest loss · Knowledge gaps · Fragmentation · Emerging infectious diseases · Human health · Tropical ecosystems

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Introduction

Zoonotic diseases, also known as infectious diseases transmitted from animals to humans [1], are a significant global concern [2]. These diseases result from the transmission of diverse microorganisms through direct contact, consumption of contaminated substances (i.e., food, water), or exposure to animals (vectors, hosts, and reservoirs) [3]. With zoonotic diseases accounting for 75% of known emerging pathogens [4], they have become a pressing issue with significant implications for public health. Moreover, the increasing trends in zoonotic diseases are influenced by various factors, including population growth, deforestation, land use and climate change, and globalization [5, 6]. Understanding and effectively addressing zoonotic diseases are paramount, as they not only cause millions of deaths each year [7] but also result in substantial economic damages. Therefore, comprehensive knowledge and robust control measures are vital to mitigate the risks associated with zoonotic disease emergence and transmission [2, 5, 6] making this topic of utmost societal importance.

Landscape ecology plays a crucial role in understanding the relationship between landscape characteristics and infectious disease dynamics in specific regions, communities, and species-specific contexts [8, 9]. Both composition and configuration aspects can determine host presence and abundance, transmission rates, disease prevalence, and consequently spatiotemporal patterns of diseases [10, 11]. Consequently, recent studies have shown how land use type, habitat fragmentation, and hydrological aspects affect disease dynamics and transmission [12, 13]. For instance, habitat fragmentation and human encroachment resulting from the loss of forested areas in Africa have been associated with increased opportunities for the transmission of the Ebola virus from animal reservoirs to humans [14, 15]. Similarly, in both the Amazon Basin and Southeast Asia, the loss of natural forest and their conversion to agricultural plantations have been linked to the exacerbated transmission of vector-borne diseases such as malaria and dengue fever [16, 17]. This happens because deforestation, land use change, and habitat simplification promote generalist and host species, increasing their abundance and the risk of zoonotic pathogen transmission [6, 18–21]. However, regional context and species-specific factors further shape this landscape-disease relationship [12, 22, 23]. Understanding these relationships through a landscape ecology lens contributes to more effective disease management strategies [24, 25] and allow better land use planning, to ensure the establishment of landscapes with a low pathogenicity [26].

The Tropical America, spanning from Mexico to southern South America [27], is recognized as the most diverse region in the world, and consequently, harbors a high diversity of pathogens [28]. It also faces the higher rates of land use change (i.e., loss of native vegetation) of the globe [29], which makes several parts of this region hotspots for future emerging infectious diseases [30, 31]. Understanding how landscape changes influence the diversity, trends, and patterns of zoonoses is of paramount importance due to their potential economic, environmental, and public health implications globally [5, 32]. However, our current knowledge about the mechanisms through which land-use change influences host and pathogen communities and the risk of cross-species transmissions is limited, especially in the Tropical America region [33]. These gaps in knowledge need to be identified and are critical as they hinder our ability to develop effective strategies for disease prevention and control [32, 33]. A focused investigation into the mechanisms underlying the impact of land-use change on zoonotic disease dynamics in the Tropical America is essential to fill these knowledge gaps and pave the way for informed decision-making and targeted interventions [9, 32, 33].

In this synthesis we aim to fill this research gap and assess the knowledge about vector-borne and zoonotic diseases and landscape structure in the Tropical America region. To achieve this, we create a conceptual model for the Tropical America region summarizing the main relationships and effects found in a landscape ecology perspective; Subsequently, we identify knowledge gaps to propose an agenda regarding landscape ecology and vector-borne and zoonotic disease for the next five years of research. Our results will enhance our understanding of disease dynamics in this region, contribute to improved public health outcomes [9, 19, 32, 33], and allow for better strategies to fill current knowledge gaps.

Literature Synthesis

To assess the general knowledge about zoonotic/vector-borne diseases and landscape structure in the Tropical America region, a syntehsis of the literature was carried out using five steps, based on Arksey and O'Malley [34] and Levac et al., [35]: (1) Identifying the goal of the synthesis: the main objective of this systematic map was to evaluate the existing knowledge on landscape dynamics and disease transmission in the Tropical America, by answering the question (i) what is the relationship between landscape structure and the emergence of vector-borne and zoonotic diseases in the Tropical America? (2) Identification of relevant articles: a scientific literature search was conducted using the *litsearchr* package [36], which creates a pool of possible keywords relevant to a field of study. First, we ran a search on 14 March 2023 on Scopus database using the "naïve keywords" (neotropic*

OR forest OR tropical* OR landscape) AND (zoonotic diseases OR zoonos* OR infectious diseas* OR diseas* OR vector* OR virus*), resulting in 1901 articles. Results were then imported into R, and by using the *litsearchr* package [36], important keywords were identified in a keyword co-occurrence network: (tropical disease OR tropical region OR neotropics OR forest) AND (infectious disease OR public health OR risk factor OR zoonotic disease OR borne disease OR neglected tropical OR zoonotic pathogen). A new search using these keywords was performed on 15 March 2023 on Scopus, and resulted in 54 articles. To ensure we were covering as many studies as possible, we used the results from both searches (1930 unique articles) and conducted a snowball procedure with the selected articles. The searches were conducted in English and with no restriction on year (as disease outbreaks can happen in isolated points in time, we did not restrict the years of search to capture the largest number of studies possible). We choose english instead of other languages, because the results can be replicated by any researcher of the world. Code with *litsearchr* search, papers downloaded using the naive search, and papers resulting from the *lisearchr* search are all available at (https://github.com/paulaprist/CurrentLandscape.git).

To decide on the inclusion of articles, we use a multi-step process: (i) five reviewers performed a preliminary scan of the titles and abstracts, in order to discard those that were not related to our objectives. As a result, from 1930 unique articles, 103 were included for full reading and were then further evaluated by two reviewers, who jointly decided on their inclusion or exclusion. From the 103, 55 more articles were selected for reading after the snowball procedure, regardless of whether they were an empirical, modeling or review study. (3) Article selection: an article was only included in the review if it was written in English and addressed some aspect of landscape ecology and zoonotic/vector-borne diseases. Our inclusion criterion for the landscape aspect was if quantitative or qualitative measurements of any landscape structure element were performed (i.e., both composition and/or configuration), which would allow a comparison to be made between the results found and the different elements of the landscape. For vector-borne and zoonotic diseases, we included articles that assessed the presence or abundance of vectors, hosts, or reservoirs, prevalence of infection in them, or human cases of associated diseases. (4) Data management: to extract and summarize the data we created a spreadsheet, including authors, year of publication, title, geographical location, disease evaluated, landscape feature evaluated, response found. (5) Analyzing, summarizing, and reporting the results: we conducted a qualitative analysis synthesizing the main patterns found in the literature.

Status and Trends of Research in the Tropical America Region

We carefully read 158 articles relating landscape variables and zoonotic/vector-borne diseases, and found that 74 met our criteria, entering the final analysis (Table 1). Most of the studies were empirical (64 studies), followed by modeling studies (eight), and meta analysis (two studies). The selected articles were classified into three main categories referring to the landscape variables investigated: landscape composition (i.e., land use and land cover composition and their relative proportion), landscape configuration (i.e., the spatial arrangement of the landscape units) and landscape structure (i.e., landscape composition and configuration together). Studies that accessed vegetation indexes such as NDVI were classified as landscape composition studies. Similarly, studies that evaluated disturbance (i.e., urbanization, agricultural areas, edge habitats) were also classified as landscape composition studies.

The earliest knowledge found in our synthesis for the Tropical America region regarding landscape structure and zoonotic/vector-borne diseases was from 2002, with a low number of studies being published per year, until it increased in 2016 (Fig. 1). Despite a boom in the number of articles in 2021, there is only a small growth in the number of articles published per year. Even considering that the total number almost doubled after 2013, we still see less than 10 studies being published every year (with the exception of 2021). This shows that this is still an under-explored topic in the scientific community of this region.

Likewise, 83% of the studies found are concentrated in five countries: 55% in Brazil ($n = 41$), 11% in Panama ($n = 8$), 6% in Colombia ($n = 5$), and 5% in Argentina and Peru ($n = 4$ each). Mexico presented three studies, while Paraguay two. All the other countries had only one study each. Two studies were performed in more than one country (Brazil and Argentina and in the entire Tropical America region). This shows that there is a large knowledge gap about landscape-zoonosis dynamics in 15 of the 27 countries that compose the Tropical America region (Fig. 2).

A total of 16 zoonotic diseases/vector related-diseases have been studied in the Tropical America region 87 times (considering that one single article sometimes have analyzed more than one disease), but again, with a trend of many studies looking at a low number of diseases. Five diseases represent 68% of the total current knowledge—malaria (25% $n = 22$), Chagas disease and Leishmaniasis (13%, $n = 11$ each), yellow fever (9%, $n = 8$), and hantavirus (8%, $n = 7$). Spotted fevers, Arboviruses (diseases specifically transmitted by Culicidae and *Aedes aegypti*), and mosquito-borne diseases (studies evaluating mosquitoes communities) accounted for 13.9% of the studies found

Table 1 Papers selected through our systematic literature synthesis relating landscape structure and zoonotic and vectorborne diseases in the Tropical Americas

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
1	Abad-Franch F, Palomeque FS, Aguilar HMV, Miles MA (2005) Field ecology of sylvatic *Rhodnius* populations (Heteroptera, Triatominae): risk factors for palm tree infestation in western Ecuador. Tropical Medicine & International Health, 10: 1258–1266	Ecuador	Empirical	Chagas disease	Composition	Anthropic versus conserved environment	Positive	Vector infestation was higher in anthropic landscapes
2	Abella-Medrano CA, Ibáñez-Bernal S, MacGregor-Fors I, Santiago-Alarcon D (2015) Spatiotemporal variation of mosquito diversity (Diptera: Culicidae) at places with different land-use types within a neotropical montane cloud forest matrix. Parasites & vectors, 8, 487	Mexico	Empirical	Mosquito-borne diseases	Composition	Different land-use types (shade coffee plantation, cattle field, urban forest, peri-urban forest, well-preserved forest)	None	Mosquito assemblage was homogeneous (i.e., highly similar richness) across the studied landscape
3	Abreu FVS de, de Andreazzi CS, Neves MSAS, Meneguete PS, Ribeiro MS, Dias CMG, et al. (2022) Ecological and environmental factors affecting transmission of sylvatic yellow fever in the 2017–2019 outbreak in the Atlantic Forest, Brazil. Parasit Vectors. 15:23	Brazil	Modelling	Yellow fever	Composition	Habitat type (forest, rural fragment, urban fragment), Fragment size, NDVI	Positive (for forest and both fragment types) No effect Positive	NDVI increase vectors abundance
4	Achilles GR., Kautzmann RP, Chagas HDF, Pereira-Silva JW, Almeida JF, Fonseca FR, da Silva MNF, Pessoa FAC, Nava AFD, Ríos-Velásquez CM (2021) Presence of trypanosomatids, with emphasis on Leishmania, in Rodentia and Didelphimorphia mammals of a rural settlement in the central Amazon region. Memorias do Instituto Oswaldo Cruz, 116, e200427	Brazil	Empirical	Leishmaniasis	Composition	Habitat degradation (continuous forest, forest with planting, planting, and peridomiciliar)	Positive	Leishmaniasis had higher infectious rates on peridomiciliar, followed by continuous forest

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
5	Adorno BR, Santos LAC, Silva AC de L, Souza MMO de, Neto C de M e S (2022) O desmatamento, o uso do solo do Cerrado e a incidência de leishmaniose visceral, malária e febre amarela no Estado de Goiás. Revista Brasileira de Geografia Física.15:2853–86	Brazil	Empirical	Leishmaniasis, malaria and yellow fever	Composition	Deforestation, urbanization and mining	Positive	The number of malaria and leishmaniosis cases increased with native vegetation loss and with and increase in urban areas. For malaria, mining activities was also important to increase risk
6	Andreazzi CS, Martinez-Vaquero LA, Winck GR, Cardoso TS, Teixeira BR, Xavier SCC, et al. (2023) Vegetation cover and biodiversity reduce parasite infection in wild hosts across ecological levels and scales. Ecography	Brazil	Modelling	Chagas disease	Structure	Vegetation cover change, NDVI, Amount of native vegetation edges	Positive for native vegetation loss	*T. Cruzi* prevalence increased with vegetation loss at 10 km scale
7	Barrientos-Roldán MJ, Abella-Medrano CA, Ibáñez-Bernal S, Sandoval-Ruiz CA (2022) Landscape Anthropization Affects Mosquito Diversity in a Deciduous Forest in Southeastern Mexico, *Journal of Medical Entomology*, 59(1), 248–256	Mexico	Empirical	Mosquito-borne diseases (main genera: *Culex* and *Anopheles* spp.)	Composition	Deciduous forest and anthropized zone	Positive	Higher abundances of mosquito-borne diseases are found in anthropic areas (with the exception of the cold season)
8	Bennett KL, McMillan WO, Enríquez, V. et al. (2021) The role of heterogenous environmental conditions in shaping the spatiotemporal distribution of competing *Aedes* mosquitoes in Panama: implications for the landscape of arboviral disease transmission. *Biol Invasions* **23**, 1933–1948	Panama	Empirical	Arboviruses	Composition	NDVI Human population density	Negative Positive	*Ae. aegypti* and *Ae. Albopictus* presence is negatively affected by NDVI and positively by human population density

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
9	Buzanovsky LP, Sanchez-Vazquez MJ, Maia-Elkhoury ANS, Werneck GL. (2020) Major environmental and socioeconomic determinants of cutaneous leishmaniasis in Brazil—a systematic literature review. Rev Soc Bras Med Trop. 53	Brazil	Meta analysis	Cutaneous Leishmaniasis	Composition	Amount of forest areas Agro-pastoral activities	Positive	Cutaneous Leishmaniasis risk is increased in rural areas with agro-pastoral activities and next to forest areas
10	Chaves LF, Cohen JM, Pascual M, Wilson ML (2008) Social exclusion modifies climate and deforestation impacts on a vector-borne disease. PLoS neglected tropical diseases, 2(1), e176	Costa Rica	Empirical	Cutaneous Leishmaniasis	Composition	Forest proximity	Positive	Living close to the forest edge decreases the risk provided other factors are taken into account
11	Chaves LSM (2016) Kertes-zia Theobald (Diptera: Culicidae) mosquitoes and bromeliads: A landscape ecology approach regarding two species in the Atlantic rainforest. Acta Tropica	Brazil	Empirical	Malaria	Composition	Dense tropical rainforest, restinga, and rural areas	Positive	*Anopheles cruzii* was more common in dense tropical forest, while *Anopheles bellator* abundance in restinga areas
12	Chaves LSM, Conn JE, López RVM et al. (2018) Abundance of impacted forest patches less than 5 km2 is a key driver of the incidence of malaria in Amazonian Brazil. Sci Rep. 8:7077. https://doi.org/10.1038/s41598-018-25344-5	Brazil	Modelling	Malaria	Composition	Deforestation Fragmentation	Positive	Number of malaria cases increased with deforestation and fragmentation
13	Chaves LSM, Bergo ES, Conn JE, Laporta GZ, Prist PR, et al. (2021) Anthropogenic landscape decreases mosquito biodiversity and drives malaria vector proliferation in the Amazon rainforest. PLOS ONE 16(1): e0245087	Brazil	Empirical	Malaria	Structure	Forest cover percentage Forest edge density Distance house-water drainage	Negative Positive Negative	*Ny. darlingi* abundance was negatively affected by % of forest cover and positively affected by increases in the amount of edge habitats. Distance from water decrease *Ny. darlingi* abundance

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
14	Cortez V, Canal E, Dupont-Turkowsky JC, Quevedo T, Albujar C, et al. (2018) Identification of *Leptospira* and *Bartonella* among rodents collected across a habitat disturbance gradient along the Inter-Oceanic Highway in the southern Amazon Basin of Peru. PLOS ONE 13(10): e0205068	Peru	Empirical	Leptospirosis and bartonellosis	Composition	Disturbed, edges and nondisturbed areas	Positive	Bartonella prevalence in rodents was higher in disturbed sites when compared to edges and undisturbed ones
15	de Ávila MM, Brilhante AF, de Souza CF et al. (2018) Ecology, feeding and natural infection by *Leishmania* spp. of phlebotomine sand flies in an area of high incidence of American tegumentary leishmaniasis in the municipality of Rio Branco, Acre, Brazil. *Parasites Vectors* **11**, 64	Brazil	Empirical	Leishmaniasis	Composition	Forest and peridomestic environments in rural area, and urban forest	Positive	Sand flies abundance increased in forest and peridomestic environments in rural areas, when compared to urban environments
16	Dellicour S, Rose R, Faria NR, Vieira LFP, Bourhy H, Gilbert M, Lemey P, Pybus OG (2017) Using Viral Gene Sequences to Compare and Explain the Heterogeneous Spatial Dynamics of Virus Epidemics, *Molecular Biology and Evolution*, 34, 10, 2563–2571, https://doi.org/10.1093/molbev/msx176	Argentina, Brazil	Empirical	Rabies	Composition	Different land use types—barren vegetation, croplands, forests, grasslands, savannas, shrublands, urban areas, wetlands	No effect	No significative relation between land use type and rabies spread
17	Dias TC, Stabach JA, Huang Q, Labruna MB, Leimgruber P, et al. (2020) Habitat selection in natural and human-modified landscapes by capybaras *(Hydrochoerus hydrochaeris)*, an important host for *Amblyomma sculptum* ticks. PLOS ONE 15(8): e0229277. https://doi.org/10.1371/journal.pone.0229277	Brazil	Empirical	Brazilian spotted fever	Composition	Distance to water Distance to grasses/shrubs Distance to forest interior NDVI	Positive Positive Negative (natural landscapes) Positive (anthropized landscapes) Positive	Capybaras avoid forests in natural landscapes (prefer grasses and bushes), but prefer these habitats in modified landscapes (distance to forest interior is the most important variable in predicting habitat preference in antrhopic landscapes). Water was consistently selected in both landscapes. NDVI positively affected habitat selection during daytime in both landscapes, but it was a weaker variable when compared to others

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
18	Ferro e Silva AM, Sobral-Souza T, Vancine MH, Muylaert RL, de Abreu AP, et al. (2018) Spatial prediction of risk areas for vector transmission of *Trypanosoma cruzi* in the State of Paraná, southern Brazil. PLOS Neglected Tropical Diseases 12(10): e0006907	Brazil	Modelling	Chagas disease	Structure	Vegetation cover (%) Structural connectivity (in log (ha)/100)	Positive Positive	High vegetation cover (mainly sazonal and mixed-ombrophilous forests) and structural connectivity were more favorable to Triatomine occurence
19	Fletcher IK, Grillet ME, Moreno JE, Drakeley C, Hernández-Villena J, Jones KE, Lowe R (2022) Synergies between environmental degradation and climate variation on malaria re-emergence in southern Venezuela: a spatiotemporal modelling study. The Lancet. Planetary health, 6(9), e739–e748. https://doi.org/10.1016/S2542-5196(22)00192-9	Venezuela	Empirical	Malaria	Composition	Forest loss	Positive	Malaria risk to humans was associated with forest loss and mining areas
20	Fletcher IK, Gibb R, Lowe R, Jones KE (2023) Differing taxonomic responses of mosquito vectors to anthropogenic land-use change in Latin America and the Caribbean. PLoS Negl Trop Dis 17(7): e0011450. https://doi.org/10.1371/journal.pntd.0011450	Neotropical region	Meta analysis	Dengue and Malaria	Composition	Forest loss	Positive	*Aedes aegypt* abundance increases in urban areas, malaria vectors presented a strong positive response to recent deforestation
21	Gottdenker NL, Calzada JE, Saldaña A, Carroll CR (2011) Association of anthropogenic land use change and increased abundance of the Chagas disease vector Rhodnius pallescens in a rural landscape of Panama. *The American journal of tropical medicine and hygiene*, *84*(1), p.70	Panama	Empirical	Chagas disease	Composition	Habitat degradation—Different land use types representing degradation (late secondary forest, early secondary forest, mid-secondary forest, pasture, and peridomiciliary areas)	Positive	Vector abundance was higher in degraded habitats

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
22	Gottdenker NL, Chaves LF, Calzada JE, Saldaña A, Carroll CR (2012) Host life history strategy, species diversity, and habitat influence Trypanosoma cruzi vector infection in Changing landscapes. PLoS Negl Trop Dis. 6(11):e1884. https://doi.org/10.1371/journal.pntd.0001884. Epub 2012 Nov 15. PMID: 23166846; PMCID: PMC3499412	Panama	Empirical	Chagas disease	Composition	Habitat degradation	Positive	T. cruzi rate was higher in mid secondary forest remnants and peridomiciliary sites when compared to contiguous forests
23	Hamlet A, Gaythorpe KAM, Garske T, Ferguson NM (2021) Seasonal and inter-annual drivers of yellow fever transmission in South America. PLOS Neglected Tropical Diseases 15(1): e0008974. https://doi.org/10.1371/journal.pntd.0008974	Brazil	Empirical	Yellow fever	Composition	Agricultural output Agricultural seasonality	Positive Positive	Yellow fever in humans and NHP is positively affected by agricultural sazonality (rice harvesting and peanut planting) and agricultural output (number of bean, corn and soya farms)
24	Hancke D, Suárez OV (2016) Infection levels of the cestode Hymenolepis diminuta in rat populations from Buenos Aires, Argentina. *Journal of Helminthology*. 90(2):199–205. https://doi.org/10.1017/S0022149X15000164	Argentina	Empirical	Hymenolepiasis diminuta	Composition	Shantytowns, parklands, industrial–residential areas and scrap metal yards	Positive	Higher abundance levels of parasites in shantytowns due to higher abundance of hosts
25	Hancke D, Suárez OV (2017) Helminth Diversity in Synanthropic Rodents from an Urban Ecosystem. Ecohealth. 14(3):603–613. https://doi.org/10.1007/s10393-017-1239-8	Argentina	Empirical	Helminth richness and diversity among invasive rodent species	Composition	Residential neighborhoods, Shantytowns and Parklands	Positive	Higher helminth richness and diversity in *R. norvegicus* from parklands and shantytowns
26	Hancke D, Suárez OV (2020) Co-occurrence of and risk factors for Cryptosporidium and Giardia in brown rats from Buenos Aires, Argentina. Zoonoses Public Health. 67(8):903–912. https://doi.org/10.1111/zph.12777	Argentina	Empirical	Cryptosporidium spp. and Giardia lamblia	Composition	Parks, Shantytowns and scrap metal yards	Positive	Prevalence is higher in parks than in shanty towns and scrap metal yards

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
27	Hahn MB, Gangnon RE, Barcellos C, Asner GP, Patz JA (2014) Influence of Deforestation, Logging, and Fire on Malaria in the Brazilian Amazon. PLoS ONE 9(1): e85725. https://doi.org/10.1371/journal.pone.0085725	Brazil	Empirical	Malaria	Composition	Number of paved and unpaved roads and fires; deforestation	Positive	Malaria risk to humans was increased with higher paved and unpaved roadways and fires; deforestation did not affect malaria risk
28	Hernández-Valencia JC, Rincón DS, Marín A, Naranjo-Díaz N, Correa MM (2020) Effect of land cover and landscape fragmentation on anopheline mosquito abundance and diversity in an important Colombian malaria endemic region. PLOS ONE 15(10): e0240207. https://doi.org/10.1371/journal.pone.0240207	Colombia	Empirical	Malaria	Structure	land use types and Habitat fragmentation	Positive	Diversity of Anopheles species were lower in landscapes with a higher fragmentation. Species abundance was higher in anthorpic environments
29	Herrera HM, Rademaker V, Abreu UG, D'Andrea PS, Jansen AM (2007) Variables that modulate the spatial distribution of Trypanosoma cruzi and Trypanosoma evansi in the Brazilian Pantanal. Acta Trop. 102(1):55–62. https://doi.org/10.1016/j.actatropica.2007.03.001	Brazil	Empirical	Chagas disease	Composition	Preserved and cattle ranching area	Positive	*T. cruzi* infection in rodents was significantly higher in preserved than in cattle ranching areas
30	Ilacqua RC, Medeiros-Sousa AR, Ramos DG, Obara MT, Ceretti-Junior W, Mucci LF, et al. (2021) Reemergence of Yellow Fever in Brazil: The Role of Distinct Landscape Fragmentation Thresholds. J Environ Public Health.1–7	Brazil	Empirical	Yellow fever	Structure	Proportion of remaining forest cover (%) Density of forest edge (m/ha)	Positive Positive	Habitat fragmentation is associated with an increase of 85% in Yellow fever virus events in both humans and NHP. Intermediate levels of forest cover (30–70%) combined with higher levels of forest edge densities contribute to the YFV dispersion and the exponential growth of YF cases

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
31	Kane J, Smith RL (2020) Bertiella sp. (Meyner, 1895) infection of Alouatta caraya (Humboldt, 1812) in urban and natural environments in Ñeembucú, southwest Paraguay. Am J Primatol. 82(9):e23166. https://doi.org/10.1002/ajp.23166	Paraguay	Empirical	Bertiella infection	Composition	Urbanization degree (with green areas)	Positive	Bertiella prevalence in monkeys increase with urbanization
32	Kowalewski MM, Salzer JS, Deutsch JC, Raño M, Kuhlenschmidt MS, Gillespie TR (2011) Black and gold howler monkeys (Alouatta caraya) as sentinels of ecosystem health: patterns of zoonotic protozoa infection relative to degree of human-primate contact. Am J Primatol. 73:75–83	Argentina	Empirical	Cryptosporidium and Giardia spp.	Composition	Sites with different degrees of human use	No effect	Prevalence not significatively related with degree of human use
33	Laporta GZ, Ramos DG, Ribeiro MC, Sallum MAM (2011) Habitat suitability of Anopheles vector species and association with human malaria in the Atlantic Forest in south-eastern Brazil. *Memorias do Instituto Oswaldo Cruz*, *106*, 239–245	Brazil	Modelling	Malaria	Composition	Forest cover (%)	Positive for *An. Cruzii*, Negative for *An. Marajoara*	*An. cruzii* was correlated with the forested slopes of the Serra do Mar, *An. bellator* with the forested coastal plain and *An. marajoara* with the deforested areas. Both *An. marajoara* and *An. cruzii* were positively associated with malaria cases
34	Laporta GZ, Ilacqua RC, Bergo ES. et al. (2021) Malaria transmission in landscapes with varying deforestation levels and timelines in the Amazon: a longitudinal spatiotemporal study. *Sci Rep* **11**, 6477. https://doi.org/10.1038/s41598-021-85890-3	Brazil	Empirical	Malaria	Composition	Remaining amount of forest cover (accumulated deforestation)	Positive	The maximum frequency of pathogenic sites occurred at the intermediate forest cover level (50% of accumulated deforestation). The incidence density of infected anophelines in sites where the original forest cover decreased by more than 50% in the first 25 years was at least twice as high as the incidence density calculated for the other sites studied
35	Loaiza JR, Dutari LC, Rovira JR, Sanjur OI, Laporta GZ, Pecor J, et al. (2017) Disturbance and mosquito diversity in the lowland tropical rainforest of central Panama. Sci Rep. 7:7248	Panama	Empirical	Malaria	Composition	Different levels of disturbance (colonizing, mixed and climax forest habitats)	Positive	Species diversity peaked in old-growth forests. Colonist mosquito species were more likely to be involved in pathogen transmission than climax species. Vector species occurrence decreased notably in undisturbed forest settings

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
36	Loaiza JR, Rovira JR, Sanjur OI, Zepeda JA, Pecor JE, Foley DH, Dutari L, Radtke M, Pongsiri MJ, Molinar OS, Laporta GZ (2019), Forest disturbance and vector transmitted diseases in the lowland tropical rainforest of central Panama. Trop Med Int Health, 24: 849–861. https://doi.org/10.1111/tmi.13244	Panama	Empirical	Diseases that has mosquitoes, sandflies, and biting-midges as vectors	Composition	Three different sites representing a gradient of forest disturbance	Positive for mosquitoes, Negative for Culicoides and Phlebotominae	Pristine forests increased risk of diseases transmitted by Culicoides and Phlebotominae. Disturbed habitats increase risck of infections transmitted by mosquitoes (*Culex Mel. pedroi, Culex declarator, Culex coronator, Aedes serratus, Coquillettidia venezuelensis, Coquillettidia nigricans* and *Psorophora cingulata*)
37	MacDonald AJ, Mordecai EA (2019) Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing. Proc Natl Acad Sci U S A.116(44):22,212–22,218. https://doi.org/10.1073/pnas.1905315116	Brazil	Empirical	Malaria	Composition	Deforestation at municipality level	Positive	Deforestation has a strong positive effect on malaria incidence
38	Moreno M, Guzmán-Rodríguez L, Valderrama-Ardila C, Alexander N, Ocampo CB (2020) Land use in relation to composition and abundance of phlebotomines (Diptera: Psychodidae) in five foci of domiciliary transmission of cutaneous leishmaniasis in the Andean region of Colombia. Acta Trop. 2203:105,315. https://doi.org/10.1016/j.actatropica.2019.105315	Colombia	Empirical	Leishmaniasis	Composition	Land use types	Positive for agricultural areas	Abundance vectors was positively affected by sugarcane and coffee plantations

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
39	Muylaert R, Sabino-Santos G, Prist P, Oshima J, Niebuhr B, Sobral-Souza T, et al. (2019) Spatiotemporal Dynamics of Hantavirus Cardiopulmonary Syndrome Transmission Risk in Brazil. Viruses 11:1008	Brazil	Empirical	Hantavirus	Composition	Water Initial or medium growth forest Wetland Old growth forest Cerrado Soil Soy Pasture Citrus Coffee Maize Sugarcane Other cultured crops Tree plantation (Eucalyptus) Buildings (rural and urban) Others (such as mining areas) Landscape heterogeneity (Shannon diversity index)	No effect No effect No effect No effect No effect No effect No effect No effect No effect No effect Positive Positive No effect Positive No effect No effect Positive	Landscape diversity, sugarcane, maize, and tree plantations positively influenced the proportion of hantavirus rodent hosts
40	Muylaert RL, Bovendorp RS, Sabino-Santos G, Prist PR, Melo GL, Priante C de F, et al. (2019) Hantavirus host assemblages and human disease in the Atlantic Forest. PLoS Negl Trop Dis. 13:e0007655	Brazil	Empirical	Hantavirus	Composition	Native forest Forestry Sugarcane Maize Pasture	Positive No effect Positive Positive No effect	Amounts of native forest, maize and sugarcane, combined with temperature, were the most important factors influencing the increase of disease risk. Population at risk (rural workers) and rodent host diversity also had a positive effect on disease risk
41	Oliveira, T.M.P., Laporta, G.Z., Bergo, E.S. et al. (2021) Vector role and human biting activity of Anophelinae mosquitoes in different landscapes in the Brazilian Amazon. *Parasites Vectors* 14, 236. https://doi.org/10.1186/s13071-021-04725-2	Brazil	Empirical	Malaria	Structure	Amount of forest cover Edge density Distance of the house from the drainage network	Positive Positive Negative	The number of malaria cases and the number of *Plasmodium*-infected Anophelinae were more prevalent in sites with higher edge density and intermediate forest cover (30–70%). The distance of the drainage network to a dwelling was inversely correlated to malaria risk
42	Olson SH, Gangnon R, Elguero E, Durieux L, Guégan JF, Foley JA, et al. (2010) Links between climate, malaria, and wetlands in the Amazon Basin. Emerg Infect Dis. 15:659–62	Brazil	Empirical	Malaria	Composition	Deforestation	Positive	Malaria incidence was positively affected by deforestation

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
43	de Oliveira Padilha, M.A., de Oliveira Melo, J., Romano, G. et al. (2019) Comparison of malaria incidence rates and socio-economic-environmental factors between the states of Acre and Rondônia: a spatio-temporal modelling study. *Malar J* 18, 306. https://doi.org/10.1186/s12936-019-2938-0	Brazil	Empirical	Malaria	Composition	Annual accumulated deforestation (km^2)	Positive for time-series dynamic and in Acre, Negative in Rondônia	In Acre, malaria incidence increased as deforestation increased. In Rondônia, malaria incidence decreased while as deforestation increased. Time-series dynamic regression showed a positive association between malaria incidence and accumulated deforestation
44	Padmanabha H, Hidalgo M, Valbuena G, Castaneda E, Galeano A, Puerta H, Cantillo C, Mantilla G (2009) Geographic variation in risk factors for SFG rickettsial and leptospiral exposure in Colombia. Vector Borne Zoonotic Dis. 9(5):483–90. https://doi.org/10.1089/vbz.2008.0092	Colombia	Empirical	Spotted fever group, rickettsial and leptospiral infections	Composition	Forest cover Human settlement	Positive Positive	Forest cover > 10% is strongly associated with leptospirosis exposition. Isolated homes at rural areas are associated with rickettsia exposition
45	Penados Penados D, Pineda J, Catalan M, Avila M, Stevens L, Agreda E, Monroy C (2020). Infestation dynamics of Triatoma dimidiata in highly deforested tropical dry forest regions of Guatemala. Memorias do Instituto Oswaldo Cruz, 115, e200203. https://doi.org/10.1590/0074-02760200203 al	Guatemala	Empirical	Chagas disease	Composition	Land use types (houses, monocultures and pastures, woodland and shrubland, and bare soil))	None	No effect found between land use type and vector abundance

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
46	Pereira Dos Santos T, Roiz D, Santos de Abreu FV, Luz SLB, Santalucia M, Jiolle D, Santos Neves MSA, Simard F, Lourenço-de-Oliveira R, Paupy C (2018) Potential of Aedes albopictus as a bridge vector for enzootic pathogens at the urban-forest interface in Brazil. Emerg Microbes Infect. 28;7(1):191. https://doi.org/10.1038/s41426-018-0194-y	Brazil	Empirical	Vectors of epidemic arboviruses	Configuration	Distance from forest edge	Negative	Eggs and adults mainly collected in forest edges. *Ae. albopictus* colonization in forests decreased with edge distance (200–300 m inside the forest)
47	Prist PR, Uriarte M, Tambosi LR, Prado A, Pardini R, D´ Andrea PS, Metzger JP (2016) Landscape, environmental and social predictors of Hantavirus risk in São Paulo, Brazil. *PloS one*, *11*(10), e0163459	Brazil	Empirical	Hantavirus	Structure	Proportion of native habitat cover Number of forest fragments Proportion of sugarcane	No effect No effect Positive	Hantavirus risk increased with proportion of land cultivated for sugarcane, Human Development Index and population at risk
48	Prist PR, Uriarte M, Fernandes K, Metzger JP (2017) Climate change and sugarcane expansion increase Hantavirus infection risk. PLoS neglected tropical diseases. 11(7):e0005705	Brazil	Modelling	Hantavirus	Composition	% of forest cover Density of native vegetation fragments Proportion of sugarcane	No effect No effect Positive	Sugarcane expansion will increased the risk of Hantavirus infection in the state of São Paulo by 2050
49	Prist PR, Prado A, Tambosi LR, Umetsu F, de Arruda Bueno A, Pardini R, Metzger JP. (2021) Moving to healthier landscapes: Forest restoration decreases the abundance of Hantavirus reservoir rodents in tropical forests. Science of the Total Environment. 752:141,967	Brazil	Empirical	Hantavirus pulmonary syndrome	Structure	Three habitat types: Agricultural areas, forest fragments and continuos forests. In each habitat the following variables were measured: Percentage of native forest cover (200, 500 and 800 m radii) Forest edge density (200, 500 and 800 m radii) Percentage of native forest cover at landscape level Type of crops (“corn” or “others”)	Fragments—Positive for *O. nigripes* Continuous forests—Negative for *O. nigripes* Positive for *O. nigripes*, Negative for *N. lasiurus* (800 m-scale) No effect Positive for *O. nigripes* No effect	*N. lasiurus* abundance is negatively affected by % of forest cover. *O. nigripes* abundance explained by habitat type and regional forest cover, and their interaction (% forest cover decreased *O. nigripes* abundance in fragments and continuous forests, but increased abundance in agricultural areas)

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
50	Prist PR, Tambosi LR, Mucci LF, Pinter A, Pereira de Souza R, de Lara Muylaert R, Roger Rhodes J, Henrique Comin C, da Fontoura Costa L, Lang D'Agostini T, Telles de Deus J. (2022) Roads and forest edges facilitate yellow fever virus dispersion. Journal of Applied Ecology. 59(1):4–17	Brazil	Empirical	Yellow fever	Structure	Water Agriculture Urban Native forest Natural non-forest Forestry areas (exotic spp. plantations) Forest edges Core areas Roads	Positive Positive No effect Positive No effect Positive Positive Negative Positive	Yellow fever risk increase in roads next to forests and in forest edges, specially when in interface with water, agricultures, and tree plantations
51	Rondón S, León C, Link A, González C (2019) Prevalence of Plasmodium parasites in non-human primates and mosquitoes in areas with different degrees of fragmentation in Colombia. Malar J. 18:276	Colombia	Empirical	Malaria	Configuration	Sites with different degrees of habitat fragmentation Distance to the nearest town	Positive No effect	Fragmentation and distance to the nearest town were not significative for *Plasmodium* prevalence in NHP, but forest fragmentation had a positive effect in the minimum infection rate in *Anopheles* mosquitoes
52	Roque AL, Xavier SC, Gerhardt M, Silva MF, Lima VS, D'Andrea PS, Jansen AM (2013) Trypanosoma cruzi among wild and domestic mammals in different areas of the Abaetetuba municipality (Pará State, Brazil), an endemic Chagas disease transmission area. Vet Parasitol. 31;193(1–3):71–7. https://doi.org/10.1016/j.vetpar.2012.11.028	Brazil	Empirical	Chagas disease	Composition	Degradation level	Positive (peak in intermediate levels)	The potential of hosts to infect vectors differed significantly according to the degree of land use (prevalences of 5% in the area with high human occupation, 41% in the preserved area, and 64% in the area with sparse human habitation)
53	Santos AS, Almeida AN (2018) The impact of deforestation on malaria infections in the Brazilian Amazon. *Ecological economics*, *154*,.247–256	Brazil	Empirical	Malaria	Composition	Deforestation	Positive	Deforestation increases the number of malaria cases

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
54	Santos WS, Gurgel-Gonçalves R, Garcez LM, Abad-Franch F. (2021) Deforestation effects on Attalea palms and their resident Rhodnius, vectors of Chagas disease, in eastern Amazonia. PLoS One. 16(5):e0252071. https://doi.org/10.1371/journal.pone.0252071	Brazil	Empirical	Chagas disease	Composition	Habitat degradation (old and young forests and pasture)	Positive	Vector infestation in palms was more frequently in disturbed landscapes, especially in pasture and then followed by young forests
55	Scinachi CA, Takeda GACG, Mucci LF, Pinter A (2017) Association of the occurrence of Brazilian spotted fever and Atlantic rain forest fragmentation in the São Paulo metropolitan region, Brazil. Acta Trop. 166:225–233. https://doi.org/10.1016/j.actatropica.2016.11.025	Brazil	Empirical	Brazilian Spotted Fever	Structure	Forest area (2 and 10 km) Edge perimeter Functional connection Forest fragmentation	Negative Positive Negative Positive	Infection risk of spotted fever is correlated with deforestation and lack of connectivity between fragments
56	Solórzano-García B, White JM, Shedden A (2023) Parasitism in heterogeneous landscapes: Association between conserved habitats and gastrointestinal parasites in populations of wild mammals. Acta Trop. 237:106,751. https://doi.org/10.1016/j.actatropica.2022.106751	Mexico	Modelling	General parasitism, Nematodes, Cestodes, Spirometra, Strongyloides, Trichostronglydae, Kiluluma sp., Trypanoxyuris	Structure	Mature secondary forest (%) Edge density (m/ha) Road density (m/ha) Conserved habitat (%) Grassland (%) River density (m/ha) Nearest town (km)	No effect Negative for howler monkeys, spider monkeys, and tapirs Negative for howler monkeys, Positive for large felids Positive only to overall parasite richness Positive for spider monkeys Negative for large felids Positive for large felids	Overall parasite richness increased with proportion of conserved habitat, but hosts infection show idiossincratic responses to landscape metrics
57	Streicker DG, Allgeier JE (2016) Foraging choices of vampire bats in diverse landscapes: potential implications for land-use change and disease transmission. J Appl Ecol, 53: 1280–1288. https://doi.org/10.1111/1365-2664.12690	Peru	Empirical	Rabies	Composition	Livestock availability	Negative	In Amazon, livestock availability decreased incidence of feeding on humans and wildlife, decreasing rabies risk to humans

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
58	Suzán G, Giermakowski JT, Marcé E, Suzán-Azpiri H, Armién B, Yates T (2006). Modeling hantavirus reservoir species dominance in high seroprevalence areas on the Azuero Peninsula of Panama. Am J Trop Med Hyg. 74(6):1103–10.	Panama	Empirical	Hantavirus pulmonary syndrome	Structure	Number of patches Mean patch size Median patch size Patch size coefficient of variance Patch size SD Total edge Edge density Mean patch edge Mean shape index Area weighted mean shape index Mean perimeter–area ratio Mean patch fractal dimension Area weighted mean patch size fract. dimen Slope	*Z. brevicauda*: Negative (1000 m scale), *L. adspersus*: Positive (500 and 1000 m) *Z. brevicauda*: Positive (1000 m scale), *L. adspersus*: Positive (500 m) and Negative (1000 m) *Z. brevicauda*: Positive (1000 m scale), *L. adspersus*: Positive (500 m) and Negative (1000 m) *Z. brevicauda*: Negative (1000 m scale), *L. adspersus*: Positive (500 m) *Z. brevicauda*: Negative (1000 m scale), *L. adspersus*: Positive (500 m) *Z. brevicauda*: Negative (1000 m scale), *L. adspersus*: Positive (500 m) *Z. brevicauda*: Negative (1000 m scale), *L. adspersus*: Positive (500 m) *Z. brevicauda*: Positive (1000 m scale), *L. adspersus*: Positive (500 m) and Negative (1000 m) *Z. brevicauda*: Positive (1000 m scale), *L. adspersus*: Positive (500 m) and Negative (1000 m) *Z. brevicauda*: Positive (1000 m scale), *L. adspersus*: Positive (500 m) and Negative (1000 m) *Z. brevicauda*: Negative (1000 m scale), *L. adspersus*: Positive (500 m) *Z. brevicauda*: Negative (1000 m scale), *L. adspersus*: Positive (500 m) *Z. brevicauda*: Negative (1000 m scale), *L. adspersus*: Positive (500 m) *Z. brevicauda*: Negative, *L. adspersus*: Positive	Higher abundances of *Z. brevicauda* found in flat areas, where humans also dominate. Slope was the only variable related to abundance of the two more dominant rodents (negativelly to *Z. brevicauda* and positivelly to *L. adspersus*)

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
59	Thies SF, Bronzoni RVM, Michalsky ÉM, Santos ESD, Silva DJFD, Dias ES, Damazo AS (2018) Aspects on the ecology of phlebotomine sand flies and natural infection by Leishmania hertigi in the Southeastern Amazon Basin of Brazil. Acta Trop. 177:37–43. https://doi.org/10.1016/j.actatropica.2017.09.023	Brazil	Empirical	Leishmaniasis	Composition	Level of urbanization (with forest areas)	Positive	Higher sand flies diversity and frequency in permanent forest preservation areas
60	Tirera S, de Thoisy B, Donato D, Bouchier C, Lacoste V, Franc A, et al. (2021) The Influence of Habitat on Viral Diversity in Neotropical Rodent Hosts. Viruses 13:1690	French Guiana	Empirical	Rodent borne viral diseases	Composition	Disturbed and pristine forests, savannahs, and peri-urban habitats	Positive (from peri-urban, disturbed, and pristine habitats)	Viral diversities were greater in pristine habitats compared with disturbed ones, and lowest in peri-urban areas
61	Travi BL, Adler GH, Lozano M, Cadena H, Montoya-Lerma J (2002) Impact of habitat degradation on phlebotominae (Diptera: Psychodidae) of tropical dry forests in Northern Colombia. *Journal of Medical Entomology*, *39*(3),.451–456	Colombia	Empirical	Leishmaniasis	Composition	Habitat degradation	Negative	Habitat degradation negatively affected sand fly communities, decreasing vector abundance
62	Valero NNH, Prist P, Uriarte M (2021) Environmental and socioeconomic risk factors for visceral and cutaneous leishmaniasis in São Paulo, Brazil. Science of The Total Environment. 797:148,960	Brazil	Empirical	Leishmaniasis	Composition	Native vegetation cover	Positive	Higher probability of leishmaniosis occurrence in municipalities with high native forest cover
63	Valle D, Clark J (2013) Conservation Efforts May Increase Malaria Burden in the Brazilian Amazon. PLOS ONE 8(3): e57519. https://doi.org/10.1371/journal.pone.0057519	Brazil	Empirical	Malaria	Composition	Forest cover	Positive	Malaria incidence was related to greater forest cover

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
64	Vaz VC, D'Andrea PS, Jansen AM (2007) Effects of habitat fragmentation on wild mammal infection by Trypanosoma cruzi. Parasitology. 134(Pt 12):1785–93. https://doi.org/10.1017/S003118200700323X	Brazil	Empirical	Chagas disease	Configuration	small (< 10 ha), medium (10–40 ha), and large (> 40 ha) fragments, continuous forest	Negative (from fragmented to continuous forest)	Seroprevalence was higher in the fragmented habitat than in the continuous forest
65	Vieira CJSP., Andrade CD, Kubiszeski JR, Silva DJF, Barreto ES, Massey AL, Canale GR, São Bernardo CS, Levi T, Peres CA, Bronzoni RVM (2019) Detection of Ilheus virus in mosquitoes from southeast Amazon, Brazil. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, 113(7), 424–427. https://doi.org/10.1093/trstmh/trz031	Brazil	Empirical	Arboviruses (culicidae)	Composition	Different land use types—urban, forest fragments and agricultural areas	Positive for forest areas	Mosquito diversity and abundance was higher in forest areas. Urban areas were dominated by Culex species
66	Vieira CJDSP, Steiner São Bernardo C, Ferreira da Silva DJ, Rigotti Kubiszeski J, Serpa Barreto E, de Oliveira Monteiro HA, … & Vieira de Morais Bronzoni, R (2022) Land-use effects on mosquito biodiversity and potential arbovirus emergence in the Southern Amazon, Brazil. Transboundary and Emerging Diseases, 69(4), 1770–1781	Brazil	Empirical	Arboviruses (culicidae)	Configuration	Forest edge density, forest size and shape	Positive	Arbovirus vectors' richness and abundance were associated with small size of forest remnants with more irregular shape and higher edge density
67	Vittor AY, Gilman RH, Tielsch J, Glass G, Shields T.I.M., Lozano WS, Pinedo-Cancino V, Patz JA, (2006) The effect of deforestation on the human-biting rate of Anopheles darlingi, the primary vector of falciparum malaria in the Peruvian Amazon. *American Journal of Tropical Medicine and Hygiene*, *74*(1), 3–11	Peru	Empirical	Malaria	Composition	Forest cover in a 1km2 radius	Negative	Deforestation (areas with < 20% of forest cover) increase *A. darlingi* biting rate in 278 times when compared to non-deforested areas (areas with > 70% of forest cover)

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
68	Vittor AY, Pan W, Gilman RH, Tielsch J, Glass G, Shields T, Sánchez-Lozano W, Pinedo VV, Salas-Cobos E, Flores S, Patz JA (2009) Linking deforestation to malaria in the Amazon: characterization of the breeding habitat of the principal malaria vector, Anopheles darlingi. Am J Trop Med Hyg. 81(1):5–12	Peru	Empirical	Malaria	Composition	Forest cover in a 1km2 radius	Negative	*Anopheles darlingi* larvae were most frequently found in sites with < 20% forest cover
69	Vittor AY, Armien B, Gonzalez P, Carrera JP, Dominguez C, et al. (2016) Epidemiology of Emergent Madariaga Encephalitis in a Region with Endemic Venezuelan Equine Encephalitis: Initial Host Studies and Human Cross-Sectional Study in Darien, Panama. PLOS Neglected Tropical Diseases 10(4): e0004554. https://doi.org/10.1371/journal.pntd.0004554	Panama	Empirical	Vector-borne alphaviruses (Madariaga virus-MADV and Venezuelan equine encephalitis-VEEV)	Composition	Habitat type (pasture, farms, shrubs, forests) Proximity to human dwellings Activities (cattle ranching, farming, fishing)	Positive No effect Positive	MADV—positivelly associated with pasture (cattle and horses) and farms (rice, cassava and watermelon). Inverselly correlated with the presence of shrubs within 10 m from residence. VEEV—positivelly associated with farms (rice, sugarcane, watermelon and yam), forests (hunting and logging activities), activities in rivers and pastures (cattle). The prefered habitat of vector rodents coincided with areas associated with human infection risk (*Zygodontomys brevicauda*—sugarcane, *Transandinomys bolivaris*—forest)
70	Wayant NM, Maldonado D, Rojas de Arias A, Cousiño B, Goodin DG (2010) Correlation between normalized difference vegetation index and malaria in a subtropical rain forest undergoing rapid anthropogenic alteration. Geospat Health. 4(2):179–90. https://doi.org/10.4081/gh.2010.199	Paraguay	Empirical	Malaria	Composition	NDVI	Negative	Number of malaria cases increased in modified areas (from forest to non-forest)

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
71	Wilk-da-Silva R, Mucci LF, Ceretti-Junior W, Duarte AMRC, Marrelli MT, Medeiros-Sousa AR (2020) Influence of landscape composition and configuration on the richness and abundance of potential sylvatic yellow fever vectors in a remnant of Atlantic Forest in the city of São Paulo, Brazil. Acta Trop. 204:105,385. https://doi.org/10.1016/j.actatropica.2020.105385	Brazil	Empirical	Yellow fever	Structure	Forest area with intermediate and high degrees of conservation (FA) Consolidated urban area (CUA) Anthropic area associated with forest area (AAF) Lake areas Edge between FA and CUA Edge between FA and AAF	Negative for YF vectors No effect No effect No effect No effect Positive for YF vectors	Landscapes with higher amounts of forest edge areas had increased richness and abundance of YF vector species
72	Wilk-da-Silva R, Medeiros-Sousa AR, Laporta GZ, Mucci LF, Prist PR, Marrelli MT. (2022) The influence of landscape structure on the dispersal pattern of yellow fever virus in the state of São Paulo. Acta Trop.228:106,333. https://doi.org/10.1016/j.actatropica.2022.106333	Brazil	Empirical	Yellow fever	Structure	Forest Formation and its interface with: Water Human-impacted area (no-vegetation) Urban area Non-forest formation (native bushy or herbaceous vegetation) Forestry (Eucalyptus or Pinus spp.) plantations	Negative Negative No effect Negative Positive Positive	Yellow fever virus was influenced by forest edges in interface with agricultural areas
73	Winck GR, Raimundo RLG, Fernandes-Ferreira H, Bueno MG, D'Andrea PS, Rocha FL, Cruz GLT, Vilar EM, Brandão M, Cordeiro JLP, Andreazzi CS (2022) Socioecological vulnerability and the risk of zoonotic disease emergence in Brazil. Sci Adv. 8(26): eabo5774. https://doi.org/10.1126/sciadv.abo5774	Brazil	Modelling	Chagas disease, yellow fever, spotted fever, skin and visceral leishmaniasis, hantavirus, leptospirosis, malaria, and rabies	Composition	Proportion of natural vegetation cover City remoteness	Negative Positive	The mean zoonotic diseases was negatively affected by vegetation cover and positively affected by city remoteness

Table 1 (continued)

ID	Reference	Country of study	Type of study	Disease (s) measured	Landscape classification	Landscape metrics measured	Effect on disease risk	Outcome
74	Yamada K, Valderrama A, Gottdenker N, Cerezo L, Minakawa N, Saldaña A, Calzada JE, Chaves LF (2016) Macroecological patterns of American Cutaneous Leishmaniasis transmission across the health areas of Panamá (1980–2012). Parasite Epidemiol Control. 18;1(2):42–55. https://doi.org/10.1016/j.parepi.2016.03.003	Panama	Empirical	Leishmaniasis	Composition	Proposrtion of forest cover	Both positive and negative	Leishmaniasis reaches a maximum value at intermediate levels of forest cover and then decreases as forest cover increases

(with four studies each), while rabies and leptospirosis 6.8%. Cryptosporidium, Giardia spp., Bertiella infection, and helminths form 9% ($n = 5$). Apparently, this bias is related to the countries where the studies were conducted; for instance, all of the top five most studied diseases are common infections in Brazil, the country with the largest number of studies.

With respect to landscape parameters, most of the knowledge focuses on understanding how landscape composition affects the transmission risk of these diseases (50.67%, $n = 56$), with 19% ($n = 14$) of studies assessing both composition and configuration; and ~ 5.5% ($n = 4$) focusing only on the configuration of native vegetation areas.

Most of the studies found a significant relationship between landscape aspects and disease risk, with more conserved habitats (higher forest amounts, NDVI and connectivity) showing higher pathogen and host diversity [37–39], but with lower prevalence and infection intensities [37, 39]. Consequently, these habitats also present a low spillover risk, which corroborates with the dilution effect hypothesis [40]. For yellow fever virus, it was also found that more conserved areas can barrier the movement of the virus, decreasing transmission risks for this disease [41]. Habitat loss was appointed as an important driver of the Brazilian spotted fever [42], leishmaniasis, malaria [43, 44], and Chagas disease [45]. Likewise, disturbed/impacted areas presented lower pathogen and host diversity, but with hosts exhibiting higher abundances and pathogen prevalences and infection intensities [37, 39] and a higher spillover risk. However, some studies also found an opposite effect—large amounts of forest areas, and the closer an individual is to the forest or dense vegetation areas, higher are the risk of contracting leishmaniasis and malaria [46, 47]. However, none of these studies had a landscape ecology design, where some of the potential cofounding factors are controlled. In addition, none of them (but see [48]) assessed non linear responses (i.e., for example, leishmaniasis reaches a maximum value at intermediate levels of forest cover and then decreases as forest cover increases [48]) and potential forest cover thresholds, where sharp increases in transmission risk can occur when habitat loss reaches a certain value. But in summary, with the existing knowledge to date, *landscape composition has a positive association with most of the diseases studied*, with habitat loss and degradation (i.e., urbanization, anthropogenic land use types) presenting the greatest risk to human health.

Landscape Configuration Features also Presented a Positive Effect on the Transmission Risk of Zoonotic/Vector-Borne Diseases, with Habitat Fragmentation and Increases in the Amount of Forest Edges Being the Most Important Drivers Habitat fragmentation has lead to an increase in the infection rate of *Anopheles* mosquitoes [49], and consequently boosted malaria transmission risk, especially if these

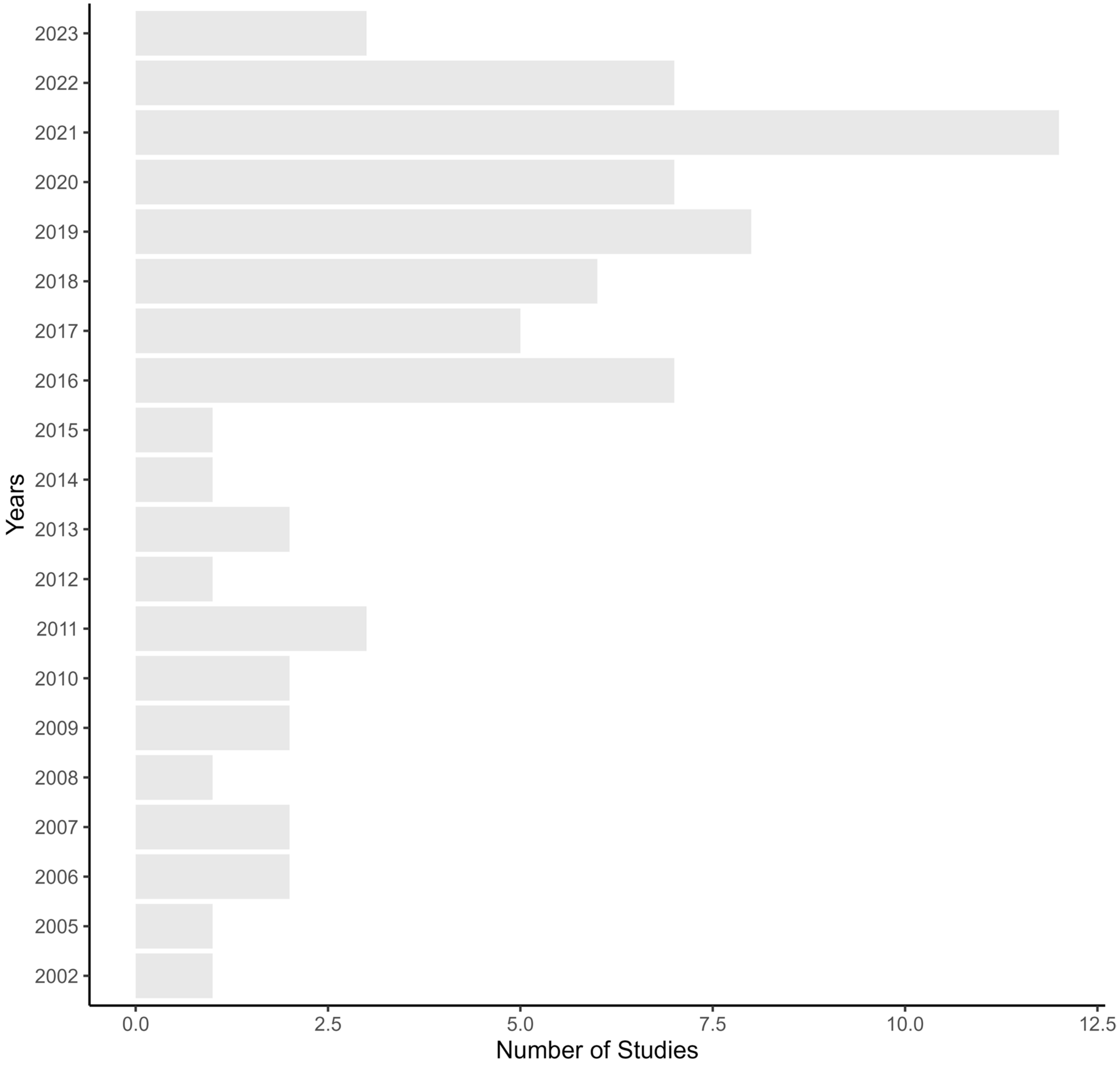

Fig. 1 Number of articles published per year in the Tropical America region about landscape structure and zoonotic/vector borne diseases

forest patches are immersed in an agro-pastoral matrix [50, 51]. For yellow fever virus, a similar response was observed, with highly fragmented habitats composed by large amounts of forest edges in interface with agricultural areas, and forest roads increasing the movement and potentially transmission risks [41, 52, 53]. For other diseases, like the Brazilian spotted fever, not only habitat loss and fragmentation are important but also isolation between these remnants [42], while for hantavirus and leishmaniasis, an important landscape feature that seems to determine transmission risk is the amount of sugarcane, coffee and maize present [54–57]. Despite these indications, no studies have tested effects of habitat configuration controlling the amount of forest cover in the landscape, which could potentially affect the results obtained.

From 74 studies evaluated, four found no significant relationships between landscape changes and disease risk [58, 59]. In all of them, the effects of land use types and degradation on arboviruses, Chagas disease, Cryptosporidium, *Giardia* spp., and rabies risk were tested. However, these studies did not test or control for important landscape

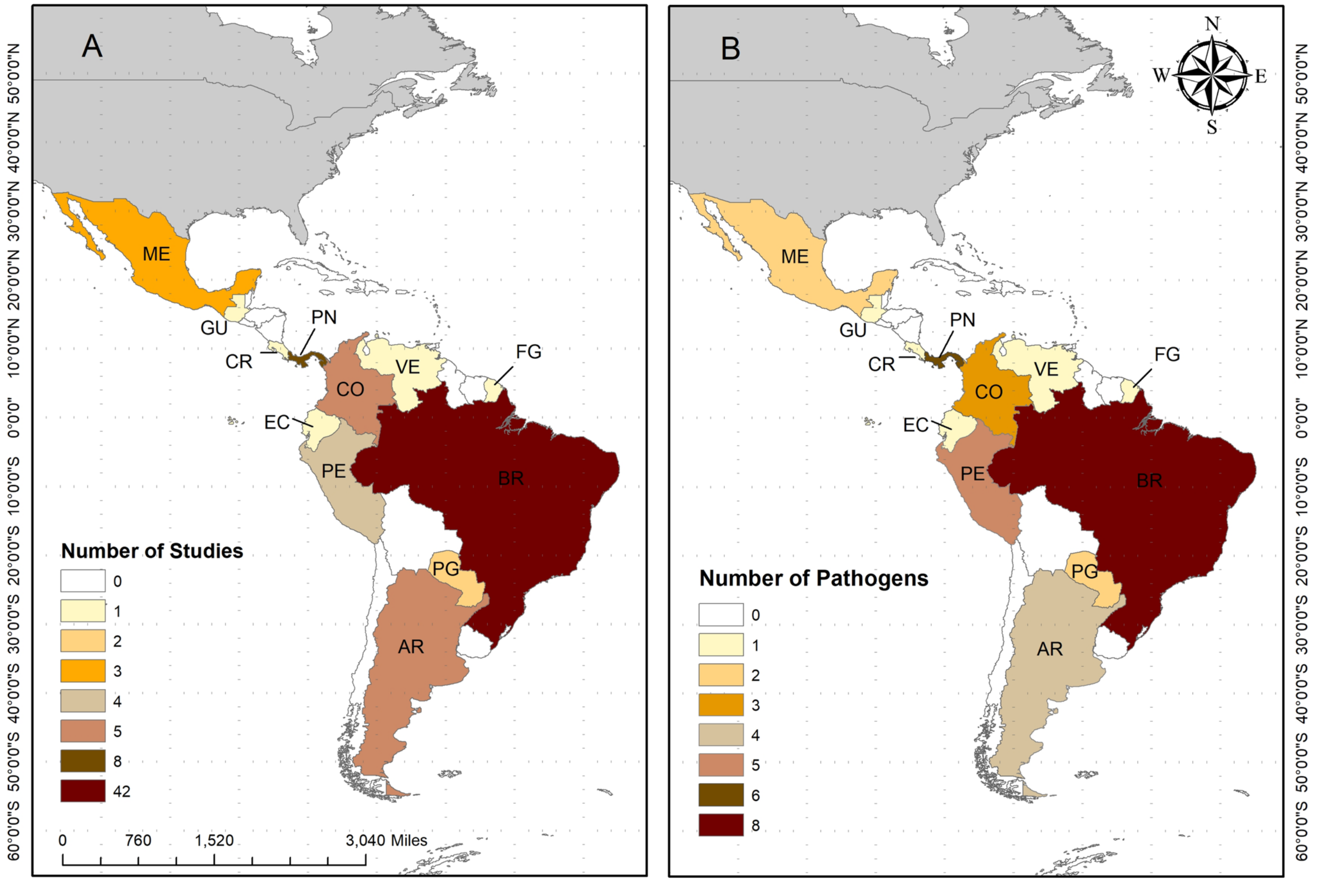

Fig. 2 Nmber of papers evaluating landscape effects on zoonotic/vector-borne diseases per country in Tropical America (**A**). Number of pathogens studied in these papers per country (**B**). AR, Argentina; BR, Brazil; CO, Colombia; CR, Costa Rica; EC, Ecuador; FG, French Guiana; GU, Guatemala; ME, Mexico; PE, Peru; PG, Paraguay; PN, Panama; VE, Venezuela

factors, such as percent remaining cover between sampled points, which may affect the observed outcomes. Nevertheless, this pattern shows that in 95% of the knowledge found, landscape features affect the transmission risk of diseases in the Tropical America.

Based on the knowledge compiled, we built a conceptual model summarizing the most common relationships between landscape change and disease risk (Fig. 3). Natural and preserved landscapes (box 1) can harbor a high diversity of hosts, vectors and consequently, of pathogens. However, in these areas the abundance of vectors and reservoirs is low, and consequently pathogen prevalence (box 2). These factors, coupled with low human-wildlife contact rates, lead to a decrease in spillover risk (grey arrows, box 3). When human actions alter this natural environment through habitat loss (box 4), two possible pathways can alter the distribution of species and hence the risk of diseases in semi-natural and anthropogenic landscapes—land use changes from natural to urban (box 5), and from natural to agricultural environments (box 6).

Urbanization leads to a complete alteration of the fauna communities through the loss of sylvatic species (i.e., species that require natural habitats to survive; boxes 7 and 8), and the consequent increase in the abundance of synanthropic species (box 9). The propensity of these species to live exclusively or occasionally within or near human habitations (synanthropy) has long been recognized to increase the transmission risk of important zoonoses that threaten public health [60]. Therefore, in urban environments we normally see an increase in the transmission risk (red arrow) of zoonoses and vector-borne diseases linked to these species (i.e., dengue, zika virus, leptospirosis). However, at the same time, other diseases will have a reduced risk in highly urbanized areas (black arrow), because main hosts and vectors will not find suitable habitat for their survival in these locations (e.g., hantavirus, malaria, Chagas disease, leishmaniasis).

When the native vegetation loss gives space to agricultural areas (box 6), such as crops and pasture, for example, spillover risk will be dependent not only on the amount of area lost but also on the spatial arrangement of the remaining habitat areas (boxes 10 and 11). If vegetation loss leads to

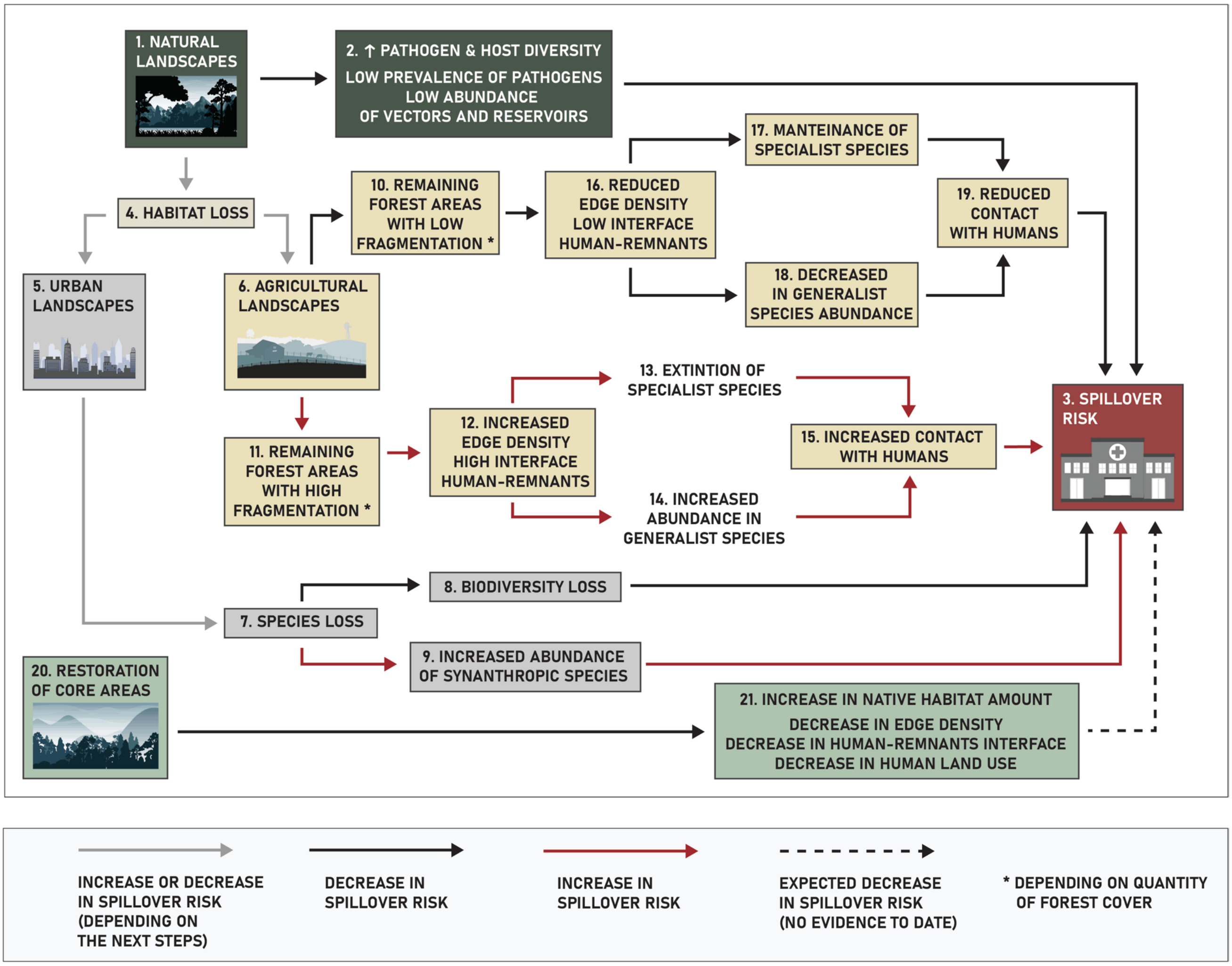

Fig. 3 Conceptual model showing the main relationships between landscape changes and zoonotic spillover risk based on the reviewed data for the Tropical America. Processes that can increase or decrease spillover risk are shown as gray arrows; processes that decrease spillover risk are shown as black processes that increase spillover risk are shown as red arrows. Images designed by freepik.com

landscapes with a high fragmentation state (box 11), spillover risk can be enhanced. This may happen because specialist species normally are extinct in these landscapes, giving space to generalist species, which normally act as reservoir and hosts for zoonotic diseases. These species not only adapat but also thrive in fragmented landscapes, increasing their abundances and consequently the infection prevalence of the pathgens they carry. In addition, highly fragmented habitats normally have increased forest edges, which boost contact between humans-wildlife, increasing spillover risk (red arrow). This is a favorable context to the circulation of yellow fever virus, for example, as small fragments surrounded by agro-pastoral activities may support viable populations of non-human primates and vector species (*Alouatta* and *Haemagogus* spp., respectively), making people who use the vicinity of the fragments especially vulnerable [50, 61]. However, these effects may be dependent on the amount of habitat remaining, a factor not yet tested for zoonotic diseases (see the "Future of the Disease Ecology in the Tropical America" section for more details).

If the remaining vegetation is present in a low fragmented state, with reduced amounts of edge density, spillover risk can potentially decrease. This happens because in less fragmented landscapes the abundance of specialist species are maintained, with a consequent reduction in the densities of generalist species (i.e., zoonotic disease hosts and reservoirs, [19]), which may contribute to the reduction of contact between generalist-reservoir species and humans [12] reducing spillover risk.

Based on these findings, we also expect that when forest restoration is promoted (box 20), it results in an increase of native habitat amount, which decreases the amount of edge density, and the interface between humans and wildlife (box 21), consequently decreasing transmission risk (dashed grey arrow). However, there is no evidence to date to support this hypothesis.

Future of the Disease Ecology in the Tropical America

Based on the body of empirical evidence found through the literature synthesis, we discuss some points that have been little or not at all explored, and that are important to be studied in the coming years to increase the knowledge about processes and mechanisms relevant to the effects of landscape structure on the emergence of zoonoses in the Tropical America. These gaps vary from investigating the nexus between simple landscape metrics and prevalence of infection in hosts, to more complex investigation of mechanisms associated with infectious disease emergence in socio-ecological systems.

There are gaps in Regional and Disease Knowledge that Should be Considered in Future Research Our results showed that a low number of diseases comprise most of the knowledge that exists today. Likewise, most of the countries that compose the Tropical America region have no studies on this topic. Given the great biodiversity of this region, coupled with the great diversity of pathogens and the high deforestation rates and land use change, it is essential that these knowledge gaps are filled. Not only studies on how landscape structure affects the risk of these diseases, but also how host and vector populations are affected by these changes, as well as the viral communities they carry, are essential to form a knowledge base and prevent human action from increasing not only the incidence of these diseases but also of pandemic potential viruses.

Most Studies are Restricted to Assessing the Effects of Land use Type, but do not Analyze the Effects of Landscape Dynamics: Effects of Time lag on Responses of Vectors, Hosts, and Reservoirs Many studies have demonstrated the impact of native vegetation loss on zoonotic diseases outbreaks [6, 20]. In contrast, the effects of landscape dynamics, which refer to the changes that occur in the landscape structure over time, are rarely evaluated (see [62]). These changes can include alterations in the size, shape, and connectivity of habitat patches, as well as the fragmentation or expansion of different land use types [63]. However, to gain a more comprehensive understanding of which factors are leading to an increased risk of these diseases, it is essential to analyze the effects of landscape structure dynamics on vector, host, and reservoir populations. In addition, it is important to consider that there is a time required for these species to adjust to the new landscape conditions. These time lag responses refer to the delay between changes in the landscape and the subsequent effects on disease dynamics [64]. Understanding the relationship between landscape dynamics and the time lag responses of vectors, hosts, and reservoirs is crucial for predicting and managing disease outbreaks. Therefore, we emphasize the importance of conducting long-term studies with different landscape dynamic aspects to gain a deeper understanding of this topic. These studies are essential for implementing appropriate land management strategies that consider the potential health impacts of landscape modifications.

Studies Evaluating Forest Gain are Completely Missing There is a substantial body of research that focuses on the relationship between deforestation and the emergence of zoonotic diseases. However, the impact of forest gain or other nature-based solutions on zoonotic disease risks in the Tropical America has not been empirically investigated. Only two studies, employing modeling and review approaches respectively, have examined this topic in this region (see [41, 61])—while a hypothetical restoration scenario presented positive effects in reducing the abundance of hantavirus reservoir rodents [61], a recent conceptual framework has shown that the effects of forest restoration on zoonotic diseases may depend on the existing landscape's context [26]. Understanding the potential effects of forest gain on zoonotic disease risk is crucial for the development of effective strategies for disease prevention and control, as well as for promoting ecosystem health, including nature-based solutions.

Few Studies have Focused on Green Areas within Urban Contexts Urban landscapes, with their intricate interplay of green spaces and gray infrastructure can serve as complex ecosystems that influence the presence and transmission of zoonotic and vector-bone diseases. For instance, the configuration and distribution of vegetation within urban areas can directly impact the abundance and diversity of species potentially acting as reservoirs or amplification hosts for zoonotic and vector-borne. Understanding these relationships is crucial for effective disease prevention and control strategies in urban settings. Yet, current research on urban landscapes and zoonotic and vector-borne diseases primarily focuses on other aspects, such as social determinants of health or the impact of natural outdoor environments on human health [65]. Consequently, the specific influence of urban design and landscape structure on zoonotic disease dynamics remains largely unexplored. Moreover, the findings from these studies could inform evidence-based urban planning and design strategies aimed at reducing zoonotic disease risks. Implementing nature-based solutions, such as strategically incorporating green spaces and green roofs [66] could help mitigate the transmission of zoonotic diseases. Additionally, optimizing building designs and spatial layouts to minimize potential disease hotspots and enhance public health measures could contribute to healthier urban environments.

Most Studies are Neglecting Landscape Configuration Aspects Based on our findings, there has been limited research assessing the impact of landscape configuration on the transmission risk of zoonotic and vector-borne diseases. The majority of the existing studies focus on evaluating the effects of landscape composition, particularly forest loss or the extent of remaining forest cover on zoonotic diseases, while disregarding the crucial aspects, such as arrangement of both habitat [67] and matrix [68]. Studies have demonstrated that these factors have a significant impact on landscape permeability and species interactions [69], and they may be more important than remaining coverage [70] particularly in disease transmission. However, the effects of habitat configuration are landscape context-dependent and species-specific, making predictions and generalizations difficult [71]. In relation to the landscape context, the size, shape, and proximity of habitat patches can interact with species traits to shape their responses to fragmentation [71]. We emphasize the significance of studies on zoonotic diseases, go beyond the conventional metrics of landscape composition, and offer a more nuanced understanding of the role of habitat configuration.

The Synergistic Relationship Between Climate Change and Landscape Structure and its Effect on Disease Transmission Risk has been Little Evaluated in Tropical America Regions Climate is a key factor limiting the distribution and establishment rate of vector populations [72], human-wildlife contact [73], and other risk factors that can modify zoonotic risk [74]. Temperature and precipitation play a key role in limiting the distribution of vectors and hosts, with temperature increases due to climate change creating favorable conditions for the expansion of the distribution range of these two groups of species [75, 76]. Increases in temperature can also lead to an acceleration of the extrinsic incubation period (i.e., time interval between infection and the vector's transmission capacity) [77] increasing the rate of replication of the pathogen in the vector, which becomes infectious more quickly, favoring prevalence and intensity of infection [77, 78]. These conditions are exacerbated by land use changes, and natural environment fragmentation—deforestation can heat a local area by as much as 4.5 ℃, and can even raise temperatures in undisturbed forests up to 6 km away [79]. These climate changes, even on a small scale, can favor the spread and transmission of diseases, making deforested and fragmented areas more at risk due to microclimatic conditions that favor the infectivity of the vectors present—one study in Asia, for example, found that the conversion from lowland rainforest to plantations increases suitability for *Aedes albopictus* development by 10.8% [80], while another one in Costa Rica found that the effects of the El Niño Southern Oscillation on the incidence of Leishmaniasis is exacerbated in places with greater deforestation [81]. These relationships between landscape, climate, and diseases are still little explored, especially in the Tropical America region, and are essential to better comprise the mechanisms behind spillover risk.

Landscape Effects are Scale-Dependent and it is Essential to Understand this in Order to Propose Appropriate Management Strategies Both landscape composition and configuration parameters have the potential to impact the dynamics of vector-borne and zoonotic diseases. However, these effects can be scale-dependent. A study in Southeast Asia, for example, found distinct effects from different spatial scales analyzed for zoonotic malaria occurrence [82]. Transmission dynamics of zoonotic malaria occurs among humans who live in settlements in deforested sites where the malarial parasite, *Plasmodium knowlesi*, is harbored by macaques (Macaca) and transmitted by anopheline vectors. Forest cover loss in the previous year influenced *P. knowlesi* occurrence only at small scales (within 0.5 km of households, or 0.78-km^2), while fragmentation had higher levels of influence at larger scales (5 km, or 78-km^2) [82]. Another study found that temperature and human population density at 1 km scale were important drivers of Hendra virus spillover, while forest cover and pasture were only predictors if considered in a 100-km radius scale [83]. Understanding these dynamics and their scales of effect are essential to propose adequate management and mitigation strategies.

There is a Large gap in Knowledge Between Trade-Offs and Synergies of Different Zoonotic/Vector-Borne Diseases, Which Should be Assessed Before Proposing Landscape Management Strategies It is reasonable to assume that each vector-borne and zoonotic disease has its own signature of scale, composition, and configuration in the human-modified landscape. Therefore, a landscape that can decrease the abundance of hosts and/or vectors of one pathogen may also lead to increases in the abundance of hosts of another pathogen. One study tried to understand these trade offs and synergies for three different diseases (malaria, leishmaniasis, and Chagas disease) in the Brazilian Amazon, using the number of human cases as response variable. They identify that there are trade-offs between the spatial and temporal aggregation of these diseases, with few municipalities being considered critical for more than one disease at the same time [84]. At the same time synergies between landscape features that can affect both malaria and cutaneous leishmaniasis were found—municipalities at risk should be considered those with more than 50% of forest cover and that are experiencing deforestation. For Chagas disease, the at-risk landscapes have continuous forests immersed in a matrix of non-pasture (i.e., crops of Açai trees) [84]. Understanding these trade-offs are of extreme importance to define the most cost-effective landscape management strategies. By knowing that a landscape management can decrease one zoonosis risk, while increasing another one, actions and control strategies that aim to change human risk behavior can be prioritized.

Human Behavior and Socioeconomic Aspects are Important Drivers in Determining Disease Risk and can also be Determined by Landscape Parameters The risk of zoonotic disease transmission is dependent on interacting ecological and human behavioral and socioeconomic factors [85, 86]. Humans are especially vulnerable for zoonotic pathogens when slaughtering, butchering, or consuming raw meat from wild animals [87], for example. In addition, human behaviors or costums that can lead to human-wildlife interactions can also lead to an increased risk of disease spillover, and these behaviors will change according to the landscape features close to these populations. Hunting is normally increased in fragmented landscapes, putting more people at risk for zoonotic spillover if compared with intact forest areas. Similarly, human cases of Marburg virus in Kenya were associated with visits to caves that house infected bats [88], while drinking untreated water can result in exposure to diverse pathogens, such as *Leptospira leptospirosa* spp. [89]. Despite its extreme importance, human risk behaviors are rarely taken into account in landscape epidemiology studies. Similarly, socioeconomic factors, which are also directly linked to zoonotic emergence [90] are understudied in a landscape ecology perspective. The lack of access to nutritious food, for example, is associated with an increased risk for multiple health conditions [91], while housing conditions can also be important factors to prevent or favor contact between humans, animal hosts, and zoonotic pathogens [92]. Identifying populations at risk [56], risky behaviors and customs and socioeconomic factors that lead to increased exposure of people to pathogens, and understanding how landscape features affect these drivers may be a key element in mitigating the risk of zoonotic disease transmission. Even if we manage landscapes by keeping host and vector density controlled, as well as the chance of contact between humans and these animals, risky human behavior can lead to the spread of pathogens and increased risk of transmission even in low pathogenicity landscapes. For instance, effective long-term community projects around natural areas have proven to reduce illegal resource extraction activities inside protected areas in Uganda through social change [93]. This type project likely decreases the contact between people and wildlife and as a consequence, reduces disease risk. At the same time, higher landscape accessibility (measured as combining terrain ruggedness, elevation, friction, slope, aspect, and tree cover) lead to more illegal resource extraction in the park, an important threat to biodiversity conservation. This example shows how health and biodiversity conservation is connected in fragmented landscapes and supports the idea that the environment needs to be managed under a One Health perspective, thinking about the interconnectedness between people's health, animal health, and environmental health [94]. Therefore, it is essential to better understand interconnectedness and behaviors and socioeconomic factors that lead to increased disease transmission risk in order to prevent spillovers from occurring in Tropical America landscapes.

Conclusions

Our synthesis has shown that the scientific production linking landscape change to zoonoses in the Tropical America still has been incipient and mainly focuses on malaria, yellow fever, Hantavirus, and Chagas disease. There is an urgent need for research connecting landscape ecology and disease ecology, so stakeholders can make science-informed decisions for land use management, and public health plans can be developed considering landscape pathogenicity. Despite significant knowledge gaps, our results point out that landscape structure affects dynamic processes of disease emergence, leading to consequences for ecosystem services and public health. Research on complex topics largely relies on capacity building and investment in research and development in the Tropical America and more broadly in the Global South. We plead for the enforcement of support in research on these topics in the Tropical America, which can be guided through interdisciplinary approaches such as One Health and Nature Based solutions.

Author Contribution Raquel L. Carvalho, Renata Muylaert, and Paula R. Prist conceived and designed the research. Matheus C. S. Mancini, Julia Barreto, Ricardo Arrais, Raquel L. Carvalho, Renata Muylaert, and Paula R. Prist performed the literature review. Matheus C. S. Mancini, Julia Barreto, Raquel L. Carvalho, Renata Muylaert, and Paula R. Prist wrote the manuscript. All authors approved the manuscript.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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