Global evidence synthesis on land use change and zoonotic risks

Authors: Dr Adam Fell[1*], Dr Soushieta Jagadesh[2,3], Dr A. Bradley Duthie[1], Dr Luci Kirkpatrick[4] and Professor Nils Bunnefeld[1,2]

[1] Biological and Environmental Sciences, University of Stirling, Stirling FK9 4LA, Scotland, UK

[2] Alternet-Eklipse, Brussels, Belgium

[3] International Society for Infectious Diseases (ISID), Boston, MA 02116, USA

[4] School of Environmental and Natural Sciences, Bangor University, Bangor, North Wales, LL57 2DG

* Corresponding author – adamjohnfell1994@gmail.com

Abstract

The COVID-19 pandemic has spotlighted the growing threat of zoonotic diseases, often exacerbated by land-use changes (LUC) such as deforestation and habitat fragmentation. We conducted a systematic literature review (2000–2024) to assess how different types of LUC affect zoonotic disease transmission, summarizing key findings and trends in geographic focus on the vectors/hosts/reservoirs and pathogens studied, in addition to identifying research gaps. We also evaluated the potential of restoration interventions to mitigate disease risks. Our analysis shows that LUC such as deforestation and urbanisation often increase transmission risks, particularly for disease transmitted by mosquitos and rodents, while some restoration strategies (e.g. reforestation, wetland conservation) can reduce these risks. However, effects vary by disease group and region. The literature remains geographically biased, with most studies concentrated in wealthier regions despite higher disease burdens in low-income areas. We propose 50 high-priority locations, primarily in Western Africa and Southeast Asia, for future research. Findings are available through an open-access online atlas, which includes supporting case studies and policy briefs to inform One Health–oriented restoration planning.

Key words / Key phrases:

Zoonotic disease, Ecosystem restoration, Land-use change, Biodiversity, Public health, Landscape degradation

The emergence of SARS-CoV-2 and the subsequent COVID-19 pandemic has brought global attention to the serious global health threat posed by zoonotic diseases[1,2] — diseases transmitted from animals to humans. However, while COVID-19 captured worldwide attention, zoonotic spillover events have been occurring throughout history with significant implications for global health[3]. Emerging zoonotic diseases account for over 60% of infectious diseases globally[4], posing substantial implications to public health, economies and ecosystems[5]. While many have historically resulted in localised outbreaks, the risk of zoonotic pathogen spillover from wildlife is increasing as humans and wildlife share environments more frequently[6]. The drivers behind this include increased human encroachment into natural environments, deforestation, agricultural expansion, and urbanisation. As human activity reshapes natural landscapes, it increases human-wildlife interactions and creates ecological disruptions, such as nutritional stress and altered host immunity, which can elevate the risk of zoonotic spillover[7,8].

Unprecedented rates of anthropogenic land-use change (LUC) – which we define as the transformation of natural landscapes for urban, agricultural, or other human uses – have replaced natural environments with human-dominated landscapes through urbanisation, agricultural intensification, deforestation, and habitat fragmentation[9,10]. These changes disrupt ecosystems and alter human–wildlife interactions, creating conditions conducive to the emergence and transmission of zoonotic diseases[11]. By reducing natural habitats and home ranges, LUC forces many species into closer proximity to humans, increasing the human-wildlife interactions and the likelihood of disease spillover[12]. Land-use change, a major driver of emerging infectious diseases, has contributed to over 30% of new disease emergences since 1960, including Nipah virus in Malaysia and Ebola spillovers in West and Central Africa[8,13]. Human-induced habitat loss and environmental degradation reduce biodiversity, which can have profound effects on disease ecology[14,15]. Biodiversity loss has been linked to increased disease transmission, as it disrupts ecological processes that regulate disease dynamics, such as reductions in higher trophic-level predators, which help control populations of disease-carrying species like rodents[16]. The "dilution effect" theory suggests that biodiversity loss can increase disease risk because incompetent host species are often lost first, leaving behind abundant, highly competent reservoirs. This community shift favours efficient pathogen transmission, thereby amplifying outbreak potential[17,18].

In response to the challenges of accelerating land-use change, biodiversity loss, and increased zoonotic disease emergence, global initiatives like the United Nations Decade of Ecosystem Restoration (*https://www.decadeonrestoration.org/what-decade*), the European Green Deal (https://www.esdn.eu/fileadmin/ESDN_Reports/ESDN_Report_2_2020.pdf), and the UN's 2030 Sustainable Development Goals (*https://sdgs.un.org/*) emphasise the critical need to restore degraded landscapes, which we define as areas where ecological integrity, biodiversity, or ecosystem services have been diminished due to human activities such as deforestation, pollution, or land conversion. Restoration – the process of assisting recovery of degraded, damaged, or destroyed land – is increasingly recognised as a strategy to reduce zoonotic disease risks by promoting more resilient and functional ecosystems with higher biodiversity and improved ecological processes[19,20]. Global restoration initiatives, such as the New York Declaration on Forests, aim to restore 350 million hectares of degraded land to conserve biodiversity and address climate change, food security, and public health challenges, highlighting the scale and ambition of current restoration efforts (https://forestdeclaration.org/about/new-york-declaration-on-forests/). Such efforts can improve ecosystem services, including disease regulation, by supporting the maintenance of diverse species and promoting healthier human-nature interactions[21,22].

While restoration holds promise for mitigating zoonotic risks, it also presents challenges. Increased biodiversity during early recovery stages may temporarily heighten disease risks as ecosystems recover[23,24]. The assumption that reversing landscape degradation and increasing biodiversity will fully restore disease regulation to its original state is overly simplistic. Restoration often occurs where human interaction with the environment persists or increases, allowing continued exploitation of the landscape, which can heighten the risk of pathogen exposure and spillover. For instance, agroforestry integrating native trees into farmland can raise contact between wildlife, livestock, and humans[25], while urban green spaces may create habitats for hosts/reservoirs such as rodents or vectors like ticks, potentially facilitating the spread of diseases such as Bartonella or Lyme disease[26,27]. Moreover, restored ecosystems do not return to their original state, but can attain a level of complexity comparable to intact habitats, with successful outcomes heavily dependent on the ecological, spatial, and social contexts of implementation[28,29].

This study provides a comprehensive analysis of existing literature on how landscape changes influence zoonotic disease transmission risks. Drawing on global studies, policy briefs and case studies from 2000 to 2024, we summarise the key findings, identifying trends in geographical focus, vectors/host/reservoirs, pathogens, and the themes most explored. This study aims to systematically assess: (i) whether specific geographical regions, vectors/hosts/reservoirs, or pathogen groups are over- or under-represented in the literature, (ii) how various pathogen groups respond to different types of landscape changes, and (iii) the extent to which different themes and topics are covered, identifying gaps and offering insights into potential impacts on local populations through socioeconomic factors and human-wildlife interactions. A central contribution of this study is the identification of regions and research areas most in need of further investigation, alongside the development of an interactive evidence atlas. The atlas is a tool designed to make our findings accessible and actionable for researchers, policymakers and public health officials, enabling dynamic exploration of the global landscape of restoration and zoonotic disease transmission research. By bridging ecological, epidemiological, and socioeconomic perspectives, this study aligns with the One Health framework, emphasising the interconnectedness of human, animal, and environmental health in shaping zoonotic disease risks.

Results:

Literature Search:

We collected 49,753 studies from the Web of Science database and an additional 4,451 from citation and manual searching. After duplicate removal, 52,713 articles identified via keyword search proceeded to screening. Following a comprehensive review by multiple investigators, 173 peer-reviewed studies were included for data extraction alongside 30 policy briefs and 58 case studies from grey literature. Of the 173 peer-reviewed studies included, 39 focused specifically on restoration, while the remainder addressed various forms of LUC, reflecting a marked research imbalance that underscores the need for further investigation into restoration-related disease outcomes. This is detailed in the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) flowchart (*Supplementary Figure 1*).

The number of studies investigating the impact of restoration on zoonotic disease transmission risk has remained consistently low since 2000, with fewer than four studies published annually until 2023, when six studies were published (Figure 1a). In total, only 39 restoration-focused studies were conducted over the last 24 years, averaging 1.2 studies per year from 2000-2019 and increasing to 3.0 studies per year from 2020-2024. In contrast, research on landscape degradation and zoonotic disease transmission has been more robust, with an average of 3.95 studies per year from 2000-2019 that increased substantially to 11.0 studies per year from 2020-2024. This represents a 150% increase in restoration-focused research and a 178% increase in degradation-focused research when comparing pre-2020 and post-2020 periods.

Twenty percent of the selected studies were either conducted globally or across multiple UN Geoscheme Regions (United Nations Statistics Division. Standard country or area codes for statistical use. https://unstats.un.org/unsd/methodology/m49/). The remaining 138 studies were carried out in 93 different countries. However, the distribution of studies across these countries was uneven, with 74 studies (53.6% of the 138 studies conducted nationally/regionally) concentrated in just four countries: Brazil (28; 20.3%), the USA (26; 18.8%), Kenya (10; 7.2%), and Malaysia (10; 7.2%) (Figure 1b).

Figure 1.

<u>Study Themes, Vectors/Hosts/Reservoirs and Pathogens:</u>

Almost 75 percent of the research comprised field-based studies, while 36 studies focused on other themes such as experimental work, hypothesis/theoretical frameworks, reviews, and descriptive analyses. Field studies were the most common type of study across the majority of regions, excluding Northern Africa, Western Africa and Western Asia (Figure 2a).

Twelve common disease vectors/hosts/reservoirs were identified across the studies. Mosquitoes (46 studies; 35%), rodents (25 studies; 19%), and ticks (18 studies; 13.6%) were the most frequently studied, comprising 68% of the total. Ticks were the most studied in Northern America, while mosquitoes were the primary focus in almost half of the other regions (East Africa, Middle Africa, South-eastern Asia, South America & Oceania). Bats accounted for a significant portion of the studies conducted in Middle Africa (33%), Southern Asia (33%) and Oceania (33%) (Figure 2b).

Mosquito-borne diseases were the most studied across the majority of regions, with exceptions in Europe and Northern America, where tick-borne and rodent-borne diseases were more prevalent, and Southern Asia, where zoonoses (bat- and rodent-borne) were the primary focus (Figure 2b). As shown in Figure 2c. viruses were the most studied pathogens overall with 31%, though this varied by region. Bacteria were the primary focus in Northern America, making up 66% of the studies, while protozoan diseases were most studied in Eastern Africa (53%), South America (52%), Central America (40%) and South-eastern Asia (40%) (Figure 2c). Detailed information on the specific diseases, pathogens, and vectors/hosts/reservoirs, for each of the 173 studies is provided in *Supplementary Table 8*.

Figure 2.

Hierarchical Cluster Analysis:

To compare how different types of landscape changes influence disease transmission across disease groups, we calculated a directional consensus standardised score from all relevant studies and visualised the results using a hierarchical cluster heatmap (Figure 3). The x-axis includes both land-use change drivers (e.g., deforestation, fragmentation, urbanisation), restoration interventions (e.g., reforestation, wetland restoration) and biodiversity–disease relationships such as “Biodiversity loss” (studies that reported declines in species richness/abundance) and “Dilution effect” (studies that explicitly tested whether higher biodiversity reduced transmission risk). For instance, mosquito-borne and bat-borne diseases clustered with fragmentation and deforestation, indicating a consistent association across studies. However, given the heterogeneity of study designs and contexts, these clusters should be interpreted with caution and seen as suggestive rather than definitive. Directional consensus standardised scores, representing the effect of landscape changes on disease transmission risk to humans, ranged from -3.5 (indicating an increase in risk) to 3.5 (indicating a decrease in risk). Most zoonoses, especially those transmitted by rodents and bats, showed negligible or increased transmission risk with landscape degradation. Rodent- and bat-borne diseases were affected by urbanisation (standardised score: -2.75 and -1.75, respectively), land use alterations (standardised score: -0.75 both), and deforestation (-0.75 and -2.75, respectively), while bat-borne diseases also experienced significant changes with habitat fragmentation (-2.75), and rodent-borne diseases with biodiversity loss, defined as a broader decline in species richness and ecosystem diversity (-0.75). A similar pattern was observed for vector-borne diseases, with the transmission risk to humans from mosquito-borne diseases being particularly influenced by deforestation (-3.5), fragmentation (-3.29), anthropization (-2.75), and urbanisation (-1.75). In contrast, tick-borne diseases exhibited a decrease in transmission risk with urbanisation (+2.26). The raw aggregated effect values can be found in *Supplementary Table 6*.

Restoration interventions showed mixed effects on disease transmission risk. Support for the dilution effect was strongest in tick-borne, mosquito-borne, and other vector-borne diseases (mean score: +2.26), with consistent evidence also for rodent-borne diseases (+3.26). Mosquito-borne disease risk improved through wetland restoration (+3.47) and broad conservation efforts aimed at maintaining or enhancing existing ecosystems and wildlife populations (+1.26), reflecting a consistent positive effect across a limited number of restoration studies. Conversely, reforestation, which restores tree cover in previously deforested areas, was associated with an increased risk of zoonoses and tick-borne diseases (–0.75), potentially due to altered breeding habitats. Similarly, species removal, referring to deliberate reduction or eradication of certain species, often invasive or disease-host species, was linked to heightened risk of rodent-borne diseases (–0.75), but a reduced transmission risk for tick-borne diseases (+2.26). Afforestation, the planting of trees in areas that were not previously forested, and restoration services, ecosystem management interventions aimed at rehabilitating degraded environments, had no significant mean effect on disease transmission risk.

Figure 3.

The reviewed studies showed varying degrees of attention to different themes. Only 18.5% of studies discussed socioeconomic factors. Similarly, evidence for human-wildlife interactions was explored in 34.7% of the publications. Beyond these thematic discussions, a sizeable number of studies (64.7%) included recommendations or proposed solutions, reflecting a strong emphasis on providing actionable insights to their conclusions. Additionally, limitations and challenges were acknowledged in 75.7% of the studies (*Supplementary Figure 2*).

Necessity for Further Research:

To identify priority areas for future research, we modelled the current geographical distribution of evidence using a hierarchical Bayesian spatial model and quantified the Need for Further Research (NFR) as the product of local uncertainty and population density (Figure 4). This approach highlights areas where new studies would yield the greatest informational value for understanding links between landscape change and disease emergence. We selected 50 locations that would benefit from further research on disease dynamics in areas undergoing landscape changes. Amongst the 50 locations, 84% of sites were equally distributed between Western and Middle Africa (21 locations) and South-Eastern Asia

(21 locations). We identified 12% (6 locations) in Central and South America and only one site each in Oceania and Northern America.

Figure 4.

Case Studies and Policy Reports:

Among the 58 landscape restoration case studies, 16 (28%) were conducted before 2000, 24 (41%) between 2000 and 2010, and 18 (31%) from 2011 onward. Most studies were concentrated in Middle Africa (29%), followed by Eastern Africa (14%) and Central America (10%). South America and South-Eastern Asia contributed 7% each, while Europe, North America, Western Africa, and Southern Asia had 5% each. Minimal representation was noted in Central Asia, Northern Africa, and Western Asia (2–3%), indicating a need for broader geographic coverage. Biodiversity conservation and natural resource management (38%), agroforestry (21%), and afforestation (9%) were prominent themes, with smaller efforts in wetland restoration (5%) and rewilding (3%). Unique approaches included controlled under-burning and water supply management. However, investigating of zoonotic risk and infectious diseases were absent as explicit objectives.

Among the 30 national and organisational policy briefs reviewed, 43% were published before 2020, and 57% afterward. Most were concentrated in Europe (33%) and global frameworks (30%), with limited representation from regions experiencing higher degradation and zoonotic risk. Recommendations emphasised community engagement (33%), governance for resilience (27%), gender equity (23%), capacity-building (27%), and integrating One Health approaches (13%). Targeted actions, such as regulating wildlife trade (7%) and promoting sustainable land use (27%), aim to address health and environmental challenges, with a focus on long-term funding, adaptive management, and cross-sectoral collaboration.

Online Evidence Atlas:

Our online evidence atlas (https://bradduthie.shinyapps.io/atlas/) provides an interactive visualisation of the geographic distribution of scientific literature, case reports, and policy briefs examining how restoration and landscape degradation influence disease transmission. The tool enables users to explore spatial and thematic patterns, identify research gaps, and access linked references through clickable map markers. By integrating scientific and grey literature, the atlas supports researchers in identifying under-studied regions and themes, while offering policymakers a means to visualise where evidence for restoration–health linkages is strongest or lacking. A schematic of the atlas layout is presented in Figure 5, illustrating its main components and interactive features.

Further details on the user interface, including instructions on navigating layers, filtering studies, and accessing regional summaries, are provided in the Supplementary Information (Figure 3).

Figure 5.

Discussion:

While research on landscape change and zoonotic spillover risk has increased since COVID-19, a key gap remains: studies investigating restoration impacts are limited. This imbalance—far more studies address degradation than restoration—underscores the need for empirical research explicitly linking landscape restoration to disease transmission risk, particularly as global restoration efforts accelerate without adequate disease monitoring frameworks in place. Our findings indicate a predominant focus on mosquitoes and mosquito-borne diseases, which were the most frequently studied globally. However, the attention given to specific pathogens, viruses, bacteria, and protozoans, varied across regions. Our findings highlight a clear geographic and economic bias in the global research landscape, which becomes even more evident when examining the disproportionate distribution of studies. We also observed that different types of land-use change, including restoration activities, trigger diverse responses depending on the disease studied, underscoring the need for more context-specific research. Recent work by Mahon et al. (2024) [30] complements our synthesis by providing a quantitative baseline and strengthening the contextualisation of biodiversity loss and land-use change as key drivers of zoonotic risk.

Almost half (43%) of all studies were concentrated in four countries - USA, Brazil, Kenya, and Malaysia - while 102 countries had none. Nearly 65% of studies occurred in four UN Geoscheme regions (Europe, Northern America, South America, and South-Eastern Asia), with a clear dominance of high-income countries, particularly the USA. According to the World Bank's 2024 classification, all but one study from Europe and Northern America were conducted in high-income countries. The exception was a study including four upper middle-income countries: Albania, Bosnia and Herzegovina, North Macedonia, and Ukraine. Overall, nearly 80% of all studies originated from high- or upper-middle-income countries, leaving less than 20% from lower-middle- or low-income regions. Geographic and socio-economic biases in research effort are well documented, with high-income countries overrepresented in ecological and health studies[31,32] Such imbalances risk overlooking key regions where restoration-driven disease dynamics may be most relevant, underscoring the need for a more globally inclusive research agenda. Grey literature searches reveal a major policy gap: restoration policies rarely address potential impacts on disease transmission, especially in lower-income regions with the highest disease burdens. Addressing these imbalances will require increased investment in research and policy development tailored to the specific challenges of these regions and closer integration of restoration, health, and community policies to ensure interventions are both socially and epidemiologically sustainable[33].

Despite these patterns, few studies address socioeconomic factors; those that do emphasise a strong link between lower GDP and higher disease risks. Lower-income countries tend to have higher disease burdens, such as those caused by mosquito-borne diseases like malaria and dengue, or protozoan infections like Chagas disease, yet these geographic areas are clearly underrepresented in the research[34,35]. Addressing this gap requires a One Health approach[36], integrating human, animal, and environmental health, because interventions in LMICs must consider complex social, ecological, and health factors driving disease risk, which may differ from patterns observed in more frequently studied high-income regions.

The distribution of the identified NFR locations underscores the urgent need for more focused research in lower-income regions, particularly in Western Africa, Middle Africa and South-eastern Asia, where landscape restoration may have the greatest potential to influence public health outcomes, positively or negatively, depending on intervention type, implementation context, and disease ecology. These regions face higher disease burdens but remain critically understudied. Expanding research efforts in these areas with large-scale, longitudinal studies[37,38] could provide invaluable insights into how landscape changes influence disease spillover, ultimately helping to inform more effective restoration strategies and public health policies.

Socioeconomic disparities also influence human-wildlife interactions, a key factor in the transmission zoonotic disease and vector-borne disease with zoonotic cycles[39]. Rural communities engaged in agriculture or resource extraction face elevated vulnerability to these diseases during periods of landscape transformation for livelihood support[40,41]. The process of converting natural landscapes into agricultural or extraction areas inadvertently increases exposure to disease through more frequent contact with vectors and wildlife hosts/reservoirs, whether through land degradation or certain types of restoration interventions[42]. Additionally, reliance on bushmeat and illegal wildlife trade in low-income regions further increases transmission risks[43]. Despite the significant role of human–wildlife interactions in zoonotic disease risk, only one-third of the studies explicitly acknowledged these factors, partly reflecting that nearly half focused on vector-borne transmission where wildlife host interactions are less directly addressed. Communities in these regions face a dual burden: the environmental impacts of landscape changes and the economic costs of disease management, with limited access to healthcare and other resources[44]. These constraints exacerbate the risk of zoonotic and vector-borne diseases by limiting capacity for disease prevention, surveillance, and response, particularly in low-income regions where economic disparities affect long-term public health infrastructure and community development[45,46].

Research understandably concentrates on high-burden disease hosts and vectors, such as mosquitoes, rodents, and ticks. Mosquito-borne diseases including malaria, dengue fever, and lymphatic filariasis, remain a significant burden globally, with an estimated 212 million malaria cases annually[47]. In contrast, Europe and Northern America see a higher prevalence of tick-borne diseases like Lyme disease[48], while rodent-borne zoonoses linked to rapid urbanisation are the primary focus in regions like Central and Southern Asia[49]. However, this focus can inadvertently overshadow less-studied diseases and contexts, particularly in regions or ecosystems undergoing active landscape restoration underscoring the need for more geographically balanced and context-specific research. While there is extensive research in Europe and Northern America on mosquito vectors and climate change impacts, relatively few studies have examined how land-use change, or restoration may influence mosquito-borne disease transmission in these regions[50]. As rising temperatures enable vector range expansion to higher latitudes, filling this knowledge gap is important to anticipate emerging risks.

Our cluster analysis shows varied effects of landscape changes on zoonotic diseases. Rodent- and bat-borne diseases often increase with landscape degradation, while tick-borne diseases tend to decline with urbanisation and landscape alteration. Restoration efforts generally reduce transmission risks for vector-borne diseases, but exceptions exist—such as increased mosquito-borne disease risk during afforestation[51]. Evidence for a dilution effect was strongest for vector-borne zoonoses (ticks, mosquitoes), with more variable results for directly transmitted zoonoses[52]. Similarly, there was a decrease in transmission risk for rodent-borne zoonoses with restoration efforts, but an increase in bat-borne disease transmission[53].

The review of policy and case studies highlights the need for inclusive governance frameworks that engage local communities, indigenous groups, and stakeholders to align restoration with environmental and socio-economic goals[54,55]. Strengthening community capacity, especially for women and marginalised groups, is crucial for sustainable land management because it enhances local ownership, improves long-term project viability, and ensures restoration efforts are adapted to local contexts[56]. Communities with greater capacity are better equipped to maintain restored landscapes beyond initial implementation phases and can develop contextually appropriate solutions that address both ecological and social needs[57]. Integrating One Health solutions addresses biodiversity loss, land degradation, and emerging diseases by bridging environmental, human, and animal health[36]. The One Health Joint Plan of Action (2022–2026), developed by the Quadripartite Alliance (WHO, FAO, WOAH, and UNEP), provides a framework for coordinated responses to health threats at the human-animal-environment interface[55]. Landscape restoration should prioritise ecological resilience by combining scientific knowledge, local expertise, and socio-economic considerations such as community livelihoods, land tenure systems, and public health infrastructure. Engaging stakeholders - local communities, public health officials, conservation agencies, and policymakers - is essential to ensure context-specific, sustainable implementation[56].

This study has some limitations[58]. Relying solely on Web of Science may have excluded studies from other databases or non-English sources. Although grey literature was included, studies addressing ecological and health outcomes separately may have been missed if not integrated in a single source. We also excluded non-zoonotic animal diseases, which could offer insights into ecological mechanisms like dilution or amplification. The included literature is geographically and socioeconomically biased, with a focus on high-income countries, limiting applicability to low-income regions where zoonotic risks and landscape dynamics differ. Additionally, the synthesis spans diverse definitions of “restoration” and “degradation,” and heterogeneity in study design requires cautious interpretation. Still, by classifying landscape change into subtypes, we enhance interpretability and uncover disease-specific patterns. These findings highlight the need for more region-specific, interdisciplinary research to inform One Health approaches to landscape management and zoonotic disease mitigation. The spatial scale of included studies varied widely, from local site-level assessments to national-scale analyses, which may influence disease outcomes in scale-dependent ways. Future work should account for this heterogeneity to better interpret LUC disease relationships.

As the UN’s Decade for Restoration drives large-scale environmental restoration efforts, it is crucial to understand how these initiatives impact disease spillover risks. While our review found a growing number of studies examining the effects of land-use change on zoonotic risk, research specifically evaluating restoration efforts remains limited, with only 39 studies identified over a 24-year period. This highlights a critical evidence gap that needs to be addressed to ensure that restoration projects do not inadvertently increase health risks. The RESTOREID project is an important initiative in this context, as it aims to examine the intricate links between restoration efforts and infectious disease dynamics. The development of an online interactive evidence atlas as part of this study offers a valuable tool for stakeholders to explore and interpret the current knowledge base, facilitating more informed, One Health-oriented restoration planning and future research targeting both ecological and public health outcomes.

Methods:

We employed a multistep approach to review and model the evidence on the relationship between landscape alterations and infectious disease emergence. This project builds on the Eklipse Biodiversity and Pandemics evidence project[38], funded by the European Commission Directorate-General for Environment (DG Env), further advancing the understanding of the links between biodiversity, land use, and zoonotic disease risk. For this study, we systematically mapped the evidence based on a recent report[59] through the following steps: conducting a systematic literature search, screening and reviewing articles, extracting data, synthesising and mapping the results, and modelling geographical areas in need of further research[60].

Systematic literature search:

To address the limited evidence on landscape restoration and zoonotic disease transmission, we included studies on both landscape degradation and restoration, allowing for a comprehensive assessment of how different types of land-use change influence disease emergence. A comprehensive literature search was conducted using the Web of Science search engine in April 2024. The search was performed using the specific keywords listed in *Supplementary Table 2*. These keywords were derived from the previous work done in the Eklipse Biodiversity and Pandemics report[38], a knowledge synthesis initiative commissioned by several European Commission Directorates and international partners to identify interdisciplinary research and action priorities for a strategic research agenda addressing the links between biodiversity, ecosystem change, and pandemic risk. This ensured alignment with established research in the field. Keywords were refined iteratively to capture a broad spectrum of relevant literature while maintaining specificity to the study objectives. To supplement the search, forward and backward citation chasing was conducted using the CitationChaser Shiny app (*https://estech.shinyapps.io/citationchaser/*) to capture any additional relevant literature. Although the search was limited to a single engine, the extensive results from both the initial and supplementary searches provided thorough coverage due to the relatively small number of articles meeting the inclusion criteria. Additionally, we reviewed grey literature related to current and planned restoration projects. However, we opted not to include grey literature from national government policies or organisational reports in this synthesis, as we found very few that specifically addressed zoonotic diseases.

Screening and review of articles:

We implemented a single stage abstract screening process with two reviewers. The online software Rayyan.ai (*https://www.rayyan.ai/*) facilitated the screening and review of the obtained publications[61]. Each publication was classified as "Include," "Exclude," or "Maybe" based on the title, abstract, and predefined inclusion criteria. For "Maybe" entries, both reviewers jointly screened the full text to reach a consensus. Any studies that discussed the impact of landscape restoration, degradation or land use changes on zoonotic disease transmission risks were included. Types of studies included: reviews, descriptive studies, theoretical studies, experimental studies, policy frameworks, perspectives & opinion pieces. Studies were classified as field studies when real-world evidence was collected through environmental sampling or field surveys, and as theoretical/modelling studies when based solely on passive data sources or hypothesised relationships without active data collection. Any studies that focussed on diseases with no transmission potential to humans and any pharmaceutical and clinical trials were excluded.

Data extraction:

Data were extracted from the articles using a predefined template (*Supplementary Table 3*). Along with the article metadata, the additional information extracted included geographical location of the study, study scale, thematic focus, transmission type, pathogen group, and species involved were recorded. In this study we defined zoonotic diseases as those transmitted directly from animals (wildlife, livestock, or companion animals) to humans (e.g., hantaviruses, Ebola Virus Disease). Vector-borne diseases were defined as those transmitted by arthropods such as mosquitoes, ticks, or fleas, and may include zoonotic (e.g., Lyme disease) or non-zoonotic diseases (e.g., dengue, some malaria species). Diseases with dual zoonotic–anthroponotic cycles (e.g., dengue, yellow fever, Zika) and all malaria species, including

Plasmodium knowlesi, are classified as vector-borne to ensure consistency. Review papers covering multiple diseases with heterogeneous pathogen or transmission pathways were coded as a single entry under the category most representative of their primary thematic focus such as multiple zoonoses or wildlife diseases, to avoid misclassification and over-inflation of disease counts. For transparency, we also explicitly indicate in *Supplementary Table 7* which diseases were classified as zoonotic, vector-borne or other according to these definitions. The key data included the type of restoration, direct/indirect impacts of landscape restoration and degradation on disease and human-wildlife interactions and extracted evidence on disease outbreaks and socioeconomic considerations. The category "biodiversity loss" included studies reporting reduced biodiversity (quantitatively via richness, abundance, or diversity indices, or qualitatively via species/habitat loss) linked to disease outcomes. "Dilution effect" was used only for studies that explicitly examined epidemiological consequences of biodiversity change and referred to the mechanism as a dilution effect. Validation criteria assessed bias, imprecision, inconsistency, reporting bias, and the quality of evidence, along with reviewer confidence[62]. In addition to peer-reviewed studies, we also reviewed grey literature, including national government policies, case studies, and policy reports. We applied a systematic search strategy using predefined keywords related to landscape restoration (e.g., ecosystem restoration, reforestation, land rehabilitation) and zoonotic diseases (e.g., disease spillover, emerging infectious diseases, One Health) to identify relevant studies and projects in Google Scholar and restoration project databases such as the Global Restoration Projects database, FAO's Forest and Landscape Restoration Mechanism, and the UN Decade on Ecosystem Restoration platform. For these documents, we extracted key results, lessons learned from the case studies, and policy recommendations.

Data synthesis and visualisation:

The data were synthesised into multiple evidence maps, categorising studies according to the UN Geoscheme Regions (*https://unstats.un.org/unsd/methodology/m49/#ftn13*). Regional classifications follow the United Nations Geoscheme; thus, "Middle Africa" is used to denote the region more commonly referred to as "Central Africa". These maps detailed the number of studies and different research themes, vector species, transmission types, and pathogen groups. To capture variation within broad categories, we classified landscape changes into subtypes (e.g., fragmentation, reforestation, wetland restoration) and assessed their directional effects on disease transmission risk across different zoonotic groups. Visualisations were created using the *ggplot2* package in R Statistical Software (v4.4.1; R Core Team, 2024). To illustrate the impact of various landscape changes on disease transmission, a hierarchical cluster heatmap was generated using the *ComplexHeatmap* package[63]. This approach allowed us to summarise patterns across different disease groups and landscape change types. Each study that reported a statistically significant relationship was scored as -1 if the landscape change was associated with an increase in disease transmission risk, +1 if associated with a decrease in risk, and 0 if no statistically significant effect was found. Only studies presenting empirical evidence with defined methods and statistical analyses were included in the scoring of landscape change effects. Theoretical or conceptual articles without original data were excluded from the quantitative synthesis and heatmap analysis to ensure that only well-supported empirical findings contributed to effect scoring. These values were aggregated by disease type and landscape change category, and a mean score was calculated for each combination, then standardised. The resulting standardised scores reflect the relative direction and consistency of effect across studies, rather than formal statistical effect sizes. For example, a score of -3.5 indicates strong and consistent evidence across multiple studies for increased transmission risk, while +3.5 reflects consistent evidence of decreased risk. The heatmap was then clustered hierarchically to highlight similarities and differences in how various disease types respond to different landscape changes, both degradation and restoration. In this review, "risk of transmission" refers specifically to the potential for zoonotic pathogens to spill over into human populations due to landscape changes. While some studies assessed pathogen prevalence in animal hosts, only those discussing implications for human health, directly or indirectly, were included in the final analysis.

Need for further research:

We extracted 271 geographical locations from 90 of the included studies and reports and georeferenced location latitude and longitude coordinates in decimal degrees. We generated pseudo-absence points stratified by human population density to avoid bias from uninhabited areas and ensure background sampling reflected the spatial distribution of human presence. We then extracted data from eight environmental and demographic covariates selected based on their relevance to landscape change and zoonotic disease emergence: mean temperature and total precipitation (climate variables influencing vector and host distributions), elevation (as a proxy for habitat variability), global human modification index (capturing anthropogenic pressure), mammal richness index (as a proxy for host biodiversity), forest cover loss (proxy for deforestation indicating habitat degradation), accessibility to the nearest city (reflecting human mobility and contact potential), and human population density (as a driver of landscape pressure and disease risk). These are described in further detail *in Supplementary Table 4*. We projected the covariate data in the World Geodetic System version 84 (GISGeography, https://gisgeography.com) and resampled them by using a pixel resolution of 5 minutes of arc (0.08333 degrees), equating to ≈10 × 10 km resolution. We then modelled the distribution of current evidence using a binomial logistic regression in a hierarchical Bayesian framework. The binary outcome variable was the presence (1) or absence (0) from 1000 generated pseudo-absence points of georeferenced evidence (study location) within each pixel. We used a binomial logistic regression model in a hierarchical Bayesian framework with an intrinsic conditional autoregressive model[64] to model the distribution of current evidence. To account for spatial autocorrelation between neighbouring pixels, which could otherwise bias the model, we included an intrinsic conditional autoregressive (iCAR) component. This spatial model structure improves accuracy by borrowing strength from nearby pixels with similar values. We calculated the uncertainty using the standard deviation of each pixel. We then identified 50 locations that would benefit from further research to maximise information gained from landscape alteration and disease emergence. We quantified the necessity for further research (NFR), a previously described measure[65], as the product of the uncertainty of the geographical distribution of current evidence and human population density. Population density was included as a covariate in the Bayesian model to capture its role as a driver of disease emergence, and as a weighting factor in the NFR index to prioritise areas with higher potential human exposure. These two uses serve distinct purposes, epidemiological modelling and research prioritisation. We identified and placed a hypothetical research study on the pixel with the highest NFR value, then gradually reduced NFR around this first hypothetical study by a 50-km radius, applying spatial discounting within a 50 km radius around each selected point to avoid overlap. We used the same procedure to add consecutive research by using the pixels with the highest NFR until we identified 50 locations that could benefit from additional research. This approach selects discrete pixel locations iteratively and applies a 50 km spatial discounting radius, producing point-based rather than continuous outputs. The mapped priorities therefore represent specific modelled locations, not broader spatial regions. The number 50 was chosen to balance global representation with visual interpretability.

Development of Online Evidence Atlas:

To complement our systematic map, we developed an online evidence atlas hosted on the *Shinyapps* platform[66]. This atlas serves as a dynamic repository for the literature identified in our review, aimed at facilitating future searches of studies related to the effects of restoration and landscape degradation on zoonotic disease transmission, like the interactive visualising tool *EviAtlas*[66]. The online platform will allow users to access summarised data from our review, including geographic distributions, vector and pathogen types, and thematic focuses, with options for downloading data for further analysis. By making this information openly accessible, we aim to foster interdisciplinary collaboration, support data sharing, and assist in bridging research gaps. The evidence atlas offers a centralised source for researchers, governments, and policymakers to explore real-time data and better understand current trends in LUC research, identifying where additional focus may be needed based on spatial or thematic gaps.

The atlas was developed using R, with a combination of CSS (Cascading Style Sheets) for the user interface (UI) design and utilises the *shiny* package to convert R code into HTML, creating an interactive online platform accessible from all major web browsers[67]. Once completed, the app was deployed on Shiny's servers at *https://www.shinyapps.io*, ensuring global accessibility and ease of use. To visually present the spatial distribution of studies, we used the R package *leaflet*, which allows for an interactive map display of scientific literature locations, country case reports, policy briefs, and the 50 identified "Need for Research" locations. These points of interest are overlaid on a map, providing a comprehensive view of where research has been conducted and where gaps remain. Users can interact with the map to view detailed metadata about each study, including vector, disease, and theme information, categorised by UN Geoscheme regions for consistency with the review. Additionally, the platform hosts data summaries from the review, including proportional breakdowns of studied vectors, disease types, and research themes. By structuring these summaries by geographic region, the atlas enables users to quickly identify patterns and assess gaps in research across different regions. We are exploring options for open contributions to the Online Evidence Atlas, enabling future inclusion of peer-reviewed and practitioner-submitted case studies with appropriate quality controls and metadata standards.

Data availability:

The data that supports the findings in this study can be found in *Supplementary tables 6* and *8*.

Code availability:

The code used for the analysis in this study can be found at https://github.com/adamjohnfell/RestoreID_Project.

Acknowledgements:

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Author Contributions:

All authors contributed to the conceptualisation of the research. AF and SJ collected the data and conducted the analysis. AF and SJ lead the writing for the draft manuscript. All authors contributed critically to the revisions of the manuscript and gave final approval for publication.

Competing Interests Statement:

The authors declare no competing interests.

Figure legends/captions and brief titles (for main text figures):

Temporal & geographic distributions of published studies

Figure 1. (A) Annual count of published studies from 2000 to 2024 investigating the impacts of landscape degradation or restoration on zoonotic disease transmission risks. (B) The geographic distribution of 138 studies focusing on the effects of landscape degradation and restoration on zoonotic disease transmission risks during the same period. Colours represent the percentage of studies published in each country.

Geographic distributions of study themes, vectors/hosts/reservoirs and pathogens

Figure 2. Fifteen UN Geoscheme Regions (represented by different colours; see https://unstats.un.org/unsd/methodology/m49/ for regional definitions), with corresponding pie charts illustrating the proportions of various 2a) research themes, 2b) vectors/hosts/reservoirs species and 2c) pathogen groups represented in a total of 138 studies. Some regions do not have corresponding pie charts as these studies lacked that information. Mosquito, tick and bat silhouettes obtained from PhyloPic (https://www.phylopic.org/).

Effects of land-use change and biodiversity–disease relationships

Figure 3. Heatmap showing the size and direction of reported effects of land-use change and biodiversity–disease relationships on disease transmission risk across different disease groups (Vector borne diseases in blue, Zoonoses in brown, General in purple, Neglected diseases in green, Wildlife diseases in pink & Tuberculosis in orange). Each cell represents the mean directionality derived from studies reporting statistically significant results: blue with downward arrow indicates a reported positive association (e.g., decreased disease risk), red with upward arrow indicates a negative association (e.g., increased risk), and white indicates a reported no significant effect with a bidirectional marker.

Priority sites with necessity for further research

Figure 4. Fifteen UN Geoscheme Regions (represented by different colours; see https://unstats.un.org/unsd/methodology/m49/ for regional definitions) with the locations of 50 priority sites with necessity for further research (NFR) on landscape alterations and disease emergence.

Online Evidence atlas

Figure 5. Overview of the Online Evidence Atlas (https://bradduthie.shinyapps.io/atlas/) interface displaying the interactive map and filtering panels.

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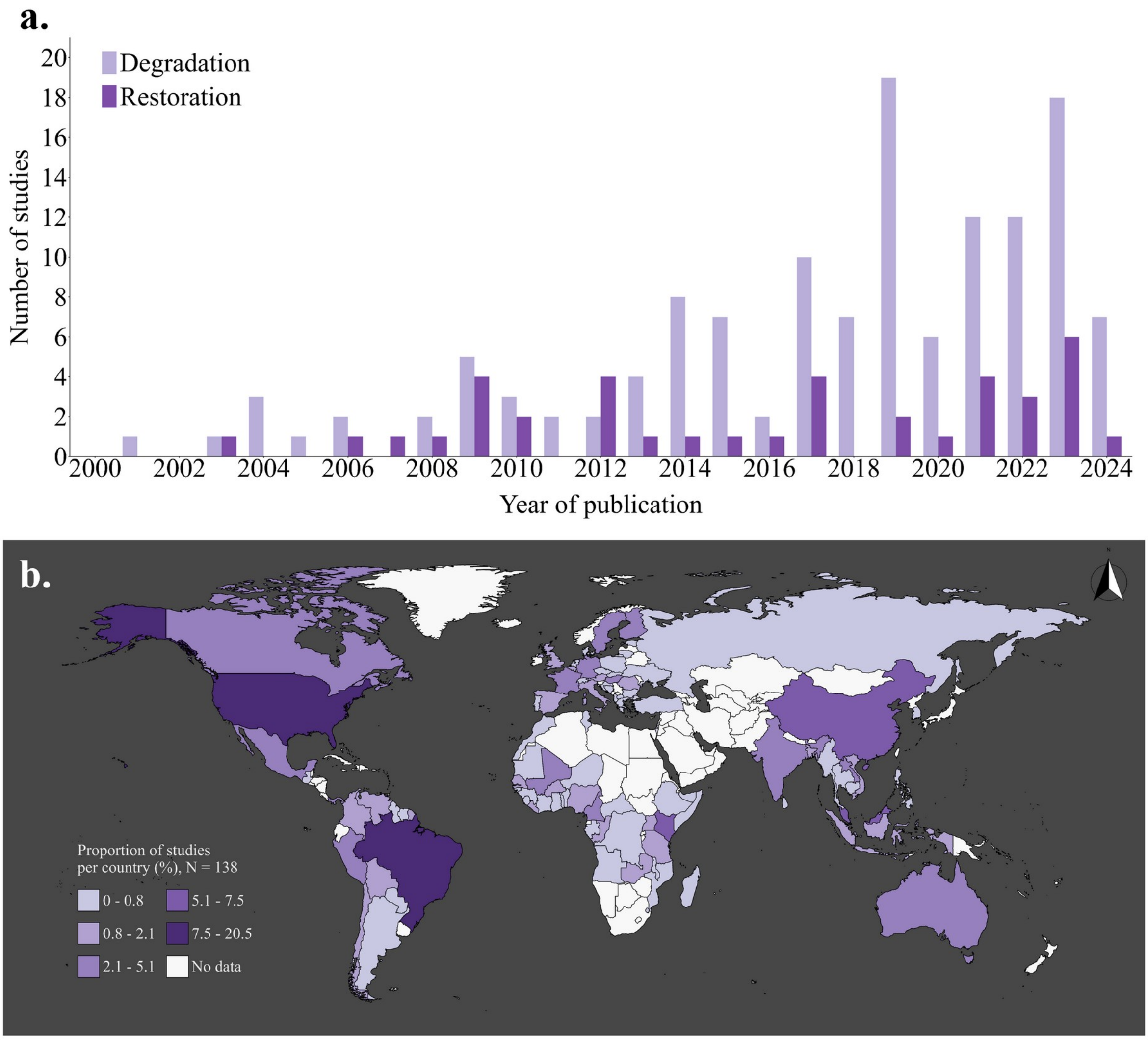

Figure 1. (A) Annual count of published studies from 2000 to 2024 investigating the impacts of landscape degradation or restoration on zoonotic disease transmission risks. (B) The geographic distribution of 138 studies focusing on the effects of landscape degradation and restoration on zoonotic disease transmission risks during the same period. Colours represent the percentage of studies published in each country.

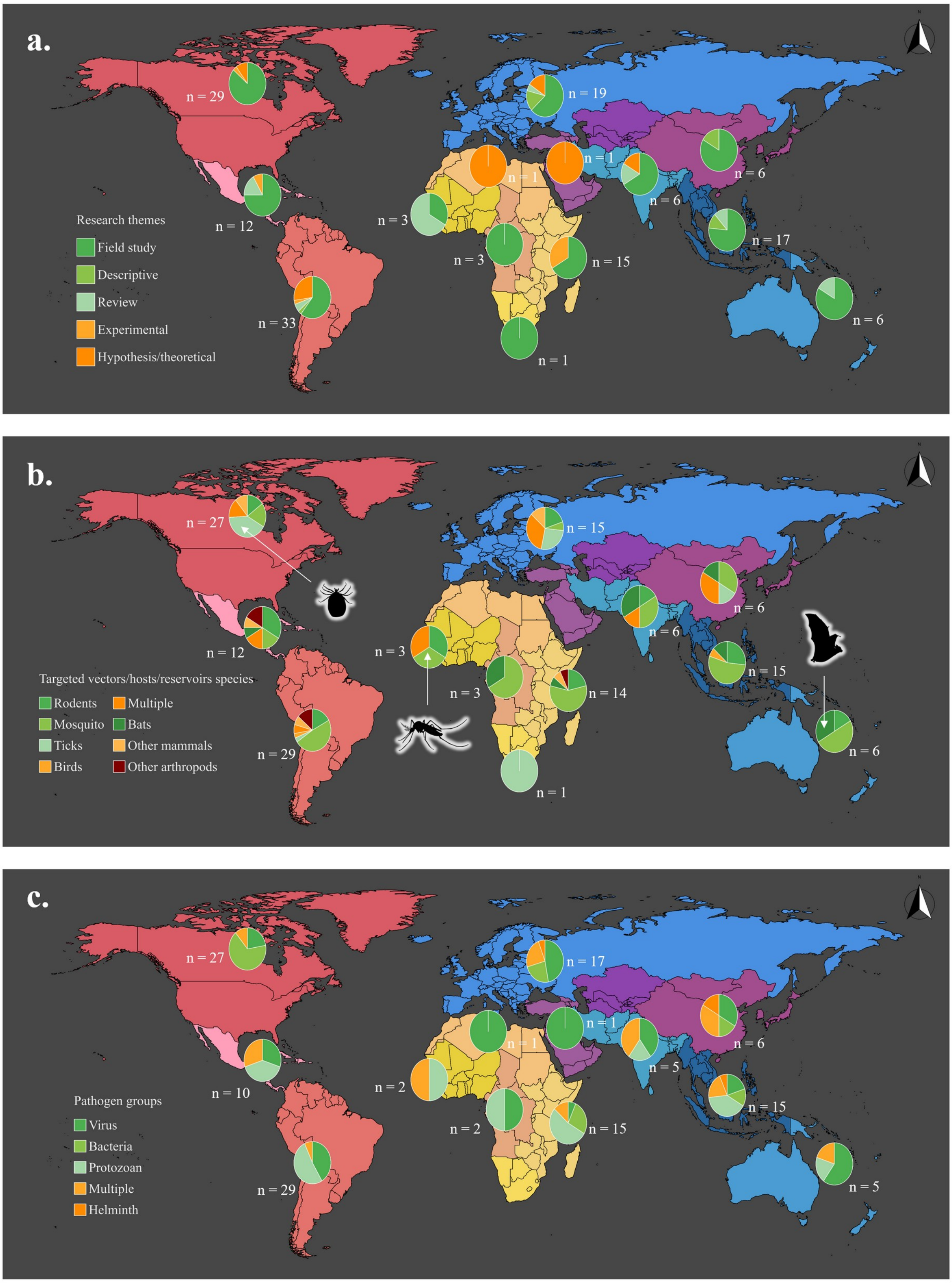

Figure 2. Fifteen UN Geoscheme Regions (represented by different colours; see https://unstats.un.org/unsd/methodology/m49/ for regional definitions), with corresponding pie charts illustrating the proportions of various 2a) research themes, 2b) vectors/hosts/reservoirs species and 2c)

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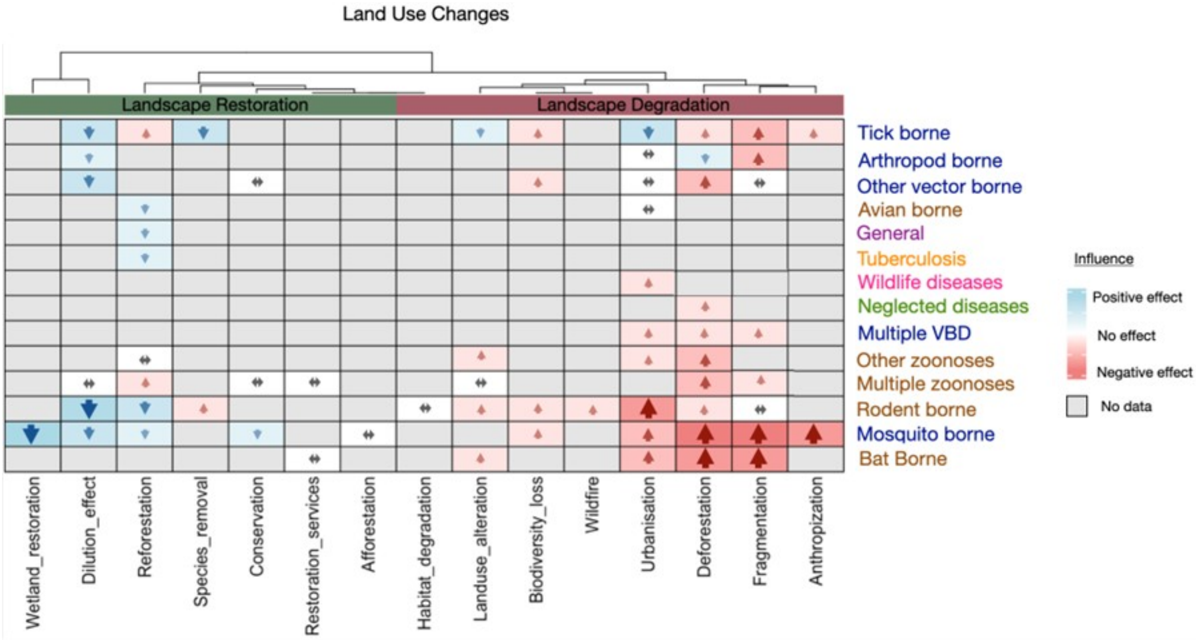

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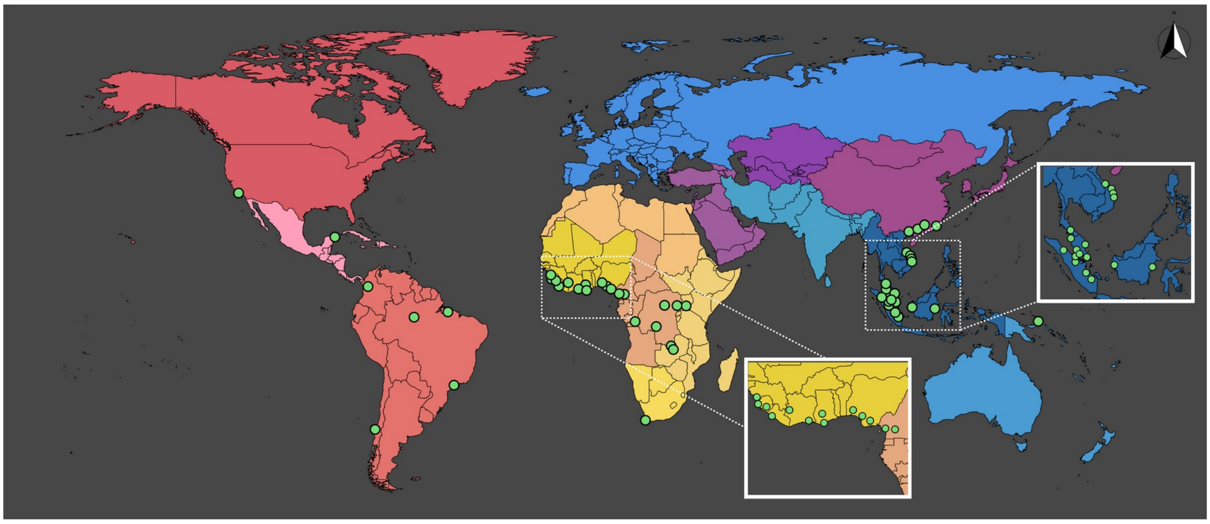

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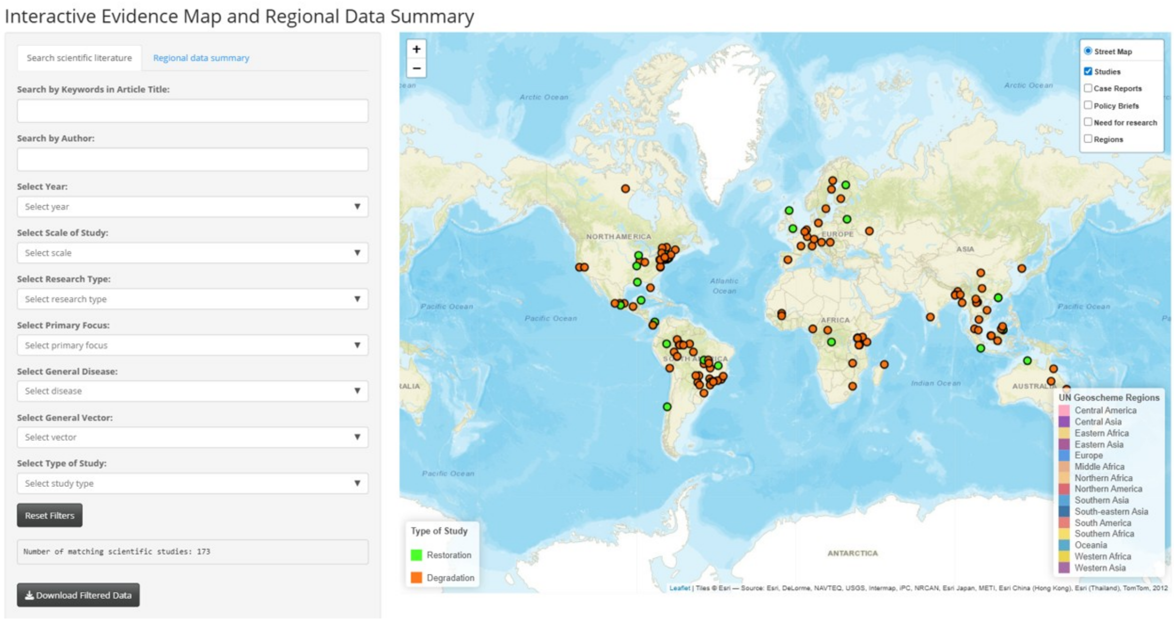


Figure 5. Overview of the Online Evidence Atlas (https://bradduthie.shinyapps.io/atlas/) interface displaying the interactive map and filtering panels.

Supplementary Material:

Supplementary table 1. Components of the research question using the *PerSPEcTiF* framework.

Perspective	**Setting**	**Phenomenon of interest**	**Environment**	**Timing**	**Findings**
Journal articles, national policies and organisational reports relevant to restoration of degraded ecosystems	Global	Impact of landscape degradation on zoonotic spillovers, disease outbreaks in animal and human populations, cross-species pathogen transmission, and pandemics. Restoration of degraded ecosystems reducing or increasing the disease risk. Dynamics of ecosystem restoration at the human/ wildlife/ livestock/ pathogen interface. Consequences on local populations following ecosystem restoration.	Terrestrial, freshwater & marine ecosystems	From, and including, 2000 to early 2024	Current state of evidence and knowledge gaps. Comparison of existing protocols and policies. Consequences of restoring ecosystems on the mechanisms of disease dynamics- local and international perspective.

Inclusion criteria:

The inclusion criteria ensured that the studies captured a comprehensive range of research focused on biodiversity, land-use changes including deforestation, intensive agriculture, and urbanisation, restoration efforts, human health impacts, and infectious disease transmission risks.

- Peer-reviewed literature published between 2000-2024
- English language
- Focus on land-use changes and infectious disease emergence or transmission.
- Focus on landscape restoration and infectious disease emergence or transmission.
- Focus on the influence of socioeconomic factors landscape alterations and infectious diseases and vice versa.

Supplementary table 2. Electronic database search keyword.

Term	**Keywords**
Biodiversity	biodivers*, biodivers* loss*, communiti* composit*, divers* affect*, divers* decreas*, ecolog* factor*, ecolog* variabl*, increas* speci*, speci* divers*.
Land-use	communit* restor*, habitat* restor*, ecosystem* restor*, ecolog* restor*, landscape* ecology*, ecosystem* service*, habitat* fragment*, habitat* alterat*, human-wildlife* interact*, ecosystem* health*, communit* structure*, deforestation*, afforestation*, edge effect*, forest* cover*, forest* fragment*, forest* patch*.
Health	affect* human*, dilut* effect*, direct* transmit*, emerg* outbreak*, human* diseas*, human* exposur*, human* health*, human* popul*, infect* preval*, preval* increas*, public* health*, spillover* risk*, epidemic*, pandemic*.
Zoonotic disease	affect* diseas*, decreas* diseas*, increas* diseas*, diseas* emerg*, diseas* preval*, diseas* suppress*, infecti* diseas*, vector-born* diseas*, zoonot* diseas*, zoonot* releas*, diseas* spillover*, diseas* ecology*, diseas* transmiss*, host-pathog* inter*, diseas* outbreak*, diseas* reservoir*, diseas*, zoonos*, pathogen* trans*, infection*.

Supplementary table 3. Data extraction form.

Section	Attribute	Explanation
Pre-filled metadata	Article type	Web of Science/Citation chasing
	Article source	Review/Original article/Book chapter/Comment
	Publication details	Title, authors, publication year, DOI
	Language of publication	The language the article is written in
Data extraction	Geographical location	Location or study area of research
	Location coordinates	Yes/No – if yes, lat and long were extracted
	Scale of the study	Global/Continental/Multi-regional/National/Regional/Local
	Theme	Dilution effect/Disease dynamics at the human/wildlife/livestock/ pathogen interface at degraded landscapes/Impact of landscape degradation on spillover risk/Impact of restoration degradation on spillover risk/Social, economic and public health impact on restoration of degraded landscapes/Existing policies on landscape restoration and disease emergence
	Infectious disease	Disease which is the main focus of the article
	Disease transmission type	Zoonoses/Vector-borne/Generalist
	Pathogen group	Virus/bacteria/protozoan/fungi/parasite/prion
	Vector/reservoir/host	Species which is the main focus of the article
	Method to assess risk	Historical data/Environmental sampling/Modelling/Population screening/Other
	Ecosystem	Terrestrial/Freshwater/Marine/Salt marsh
	Recommendations	Yes/No
	Research type	Hypothesis or theoretical/ Experimental/ Field study/ Descriptive/Review/Recommendation/Opinion or perspective
	Knowledge areas	Model/theory/Framework or protocol/Lessons learnt/Knowledge gaps/Tools/Other

	Type of restoration	Afforestation/Reforestation/Species removal/Species introduction/Wetland restoration/Other
	Impact of landscape restoration on disease	Direct/Indirect/NA
	Impact of landscape degradation on disease	Direct/Indirect/NA
	Impact on human-wildlife interactions	Direct/Indirect/NA
	Evidence for Landscape restoration on disease outbreaks	"Extracted word by word from the article"
	Evidence for Landscape degradation on disease outbreaks	"Extracted word by word from the article"
	Evidence for effects on human-wildlife interactions	"Extracted word by word from the article"
	Are Socioeconomic factors considered?	"Extracted word by word from the article"
	Limitations & challenges	"Extracted word by word from the article"
	Knowledge gaps/future research	"Extracted word by word from the article"
	Recommendations & proposed solutions	"Extracted word by word from the article"
Validation	Risk of bias*	High/Medium/Low
	Imprecision**	High/Medium/Low
	Inconsistency***	High/Medium/Low
	Reporting bias****	High/Medium/Low
	Quality of evidence*****	High/Medium/Low
	Reviewer confidence	High/Medium/Low

Validation troubleshooting:

*Risk of bias - Bias occurs when the results of a study do not represent the truth because of inherent limitations in design or conduct of a study.

**Imprecision - For EXPERIMENTAL STUDIES ONLY. The GRADE approach to rating imprecision focuses on the 95% confidence interval around the best estimate of the absolute effect.

*** Inconsistency - For REVIEWS ONLY. Certainty in a body of evidence is highest when there are several studies that show consistent effects.

**** Reporting bias - Reporting bias occurs when the dissemination of research findings is influenced by the nature and direction of the results.

*****Quality of evidence - Final assessment of quality.

Supplementary table 4. Eight climatic, environmental and demographic covariates used to generate the "Necessity for Further Research" locations.

Covariate	Source
Climate covariates	
Mean temperature	https://www.worldclim.org
Precipitation	https://www.worldclim.org
Environmental covariates	
Altitude	https://www.worldclim.org
Global human modification of terrestrial systems	Global Human Modification of Terrestrial Systems. Palisades, New York: NASA Socioeconomic Data and Applications Centre (SEDAC). https://doi.org/10.7927/edbc-3z60.
Mammal richness index	https://www.iucnredlist.org/resources/other-spatial-downloads#SR_2023
Forest cover loss proxy for deforestation	Hansen, M. C., et al. High-Resolution Global Maps of 21st-Century Forest Cover Change. Science 342 (2013): 850-53. https://glad.earthengine.app/view/global-forest-change.
Demographic covariates	
Accessibility to the nearest city	Nelson, A., et al. A suite of global accessibility indicators. Sci Data 6, 266 (2019). https://doi.org/10.1038/s41597-019-0265-5
Population density	Centre for International Earth Science Information Network - CIESIN - Columbia University. 2018. Gridded Population of the

	World, Version 4 (GPWv4): Population Density, Revision 11. Palisades, New York: NASA Socioeconomic Data and Applications Centre (SEDAC). https://doi.org/10.7927/H49C6VHW

Supplementary table 5. The "Necessity for Further Research" (NFR) map, a product of the uncertainty, population density, and deforestation. We predicted locations in the study area such as to minimise the mean NFR across all the pixels in the map. The coordinates of the highest NFR i value was located on the NFR map and the NFR was reduced by a sequence of 75%, 50% , and 25% in a 50-km radius in concentric circles around the site.

Number	Latitude	Longitude	City/Town	Country	Region
1	3.875	11.54167	Yaoundé	Cameroon	Middle Africa
2	4.041667	9.791667	Douala	Cameroon	Middle Africa
3	-2.958333	104.7083	Palembang City	Indonesia	South-eastern Asia
4	6.708333	-1.625	Kumasi	Ghana	Western Africa
5	-1.625	103.625	Jambi	Indonesia	South-eastern Asia
6	1.541667	103.7917	Johor	Malaysia	South-eastern Asia
7	5.458333	-4.041667	Abidjan	Côte d'Ivoire	Western Africa
8	-36.875	-73.20833	San Pedro de la Paz	Chile	South America
9	0.375	32.54167	Kampala	Uganda	Eastern Africa
10	-34.125	18.70833	Cape Town	South Africa	Southern Africa
11	0.5416667	101.4583	Pekanbaru City	Indonesia	South-eastern Asia
12	-0.04166667	109.375	Pontianak	Indonesia	South-eastern Asia
13	0.4583333	29.45833	Beni	Democratic Republic of the Congo	Middle Africa
14	6.291667	-10.70833	Paynesville	Liberia	Western Africa
15	-3.041667	-59.95833	Manus	Brazil	South America
16	3.041667	101.7083	Seri Kembangan	Malaysia	South-eastern Asia
17	4.125	103.4583	Cherating	Malaysia	South-eastern Asia
18	22.79167	108.2917	Nanning	China	Eastern Asia
19	0.5416667	25.20833	Kisangani	Democratic Republic of the Congo	Middle Africa
20	34.375	-119.625	Montecito	USA	North America
21	16.45833	107.5417	Hue	Vietnam	South-eastern Asia
22	15.45833	108.7917	Bình Thuận	Vietnam	South-eastern Asia

23	-11.70833	27.45833	Lubumbashi	Democratic Republic of the Congo	Middle Africa
24	8.458333	-13.20833	Freetown	Sierra Leone	Western Africa
25	-4.375	15.20833	Kinshasa	Democratic Republic of the Congo	Middle Africa
26	6.208333	-75.625	Medellin	Colombia	South America
27	5.041667	-1.291667	Elmina	Ghana	Western Africa
28	23.54167	111.2917	Wuzho	China	Eastern Asia
29	1.708333	101.4583	Dumai	Indonesia	South-eastern Asia
30	-23.54167	-46.375	Suzano	Brazil	South America
31	-12.79167	28.20833	Kitwe	Zambia	Eastern Africa
32	-4.291667	152.2917	Kokopo	Papua New Guinea	Oceania
33	24.79167	113.625	Shaoguan	China	Eastern Asia
34	2.208333	102.2917	Malacca	Malaysia	South-eastern Asia
35	-5.875	22.375	Kananga	Democratic Republic of the Congo	Middle Africa
36	-0.4583333	117.125	Samarinda City	Indonesia	South-eastern Asia
37	21.125	-86.875	Cancun	Mexico	Central America
38	5.375	100.5417	Kulim	Malaysia	South-eastern Asia
39	7.958333	-11.70833	Bo	Sierra Leone	Western Africa
40	24.45833	117.625	Longhai City	China	Eastern Asia
41	14.54167	109.125	Binh Dinh	Vietnam	South-eastern Asia
42	6.291667	5.625	Benin City	Nigeria	Western Africa
43	7.041667	100.4583	Songkhla	Thailand	South-eastern Asia
44	2.958333	99.04167	Pematang Siantar City	Indonesia	South-eastern Asia
45	-1.458333	-48.45833	Belem	Brazil	South America
46	7.375	-7.541667	Man	Côte d'Ivoire	Western Africa
47	13.70833	109.2917	Quy Nhon	Vietnam	South-eastern Asia
48	5.458333	7.041667	Ihiagwa	Nigeria	Western Africa
49	7.375	3.958333	Ibadan	Nigeria	Western Africa
50	9.708333	-13.45833	Coyah	Guinea	Western Africa

Supplementary table 6. The aggregated effect values for the effects of land use change on disease transmission risk across different disease groups for our hierarchical cluster heatmap (Fig. 3). Values represent the cumulative number of studies reporting significant effects, where positive values indicate more studies found a positive association (e.g., decreased disease risk) and negative values indicate more studies found a negative association (e.g., increased risk). The total

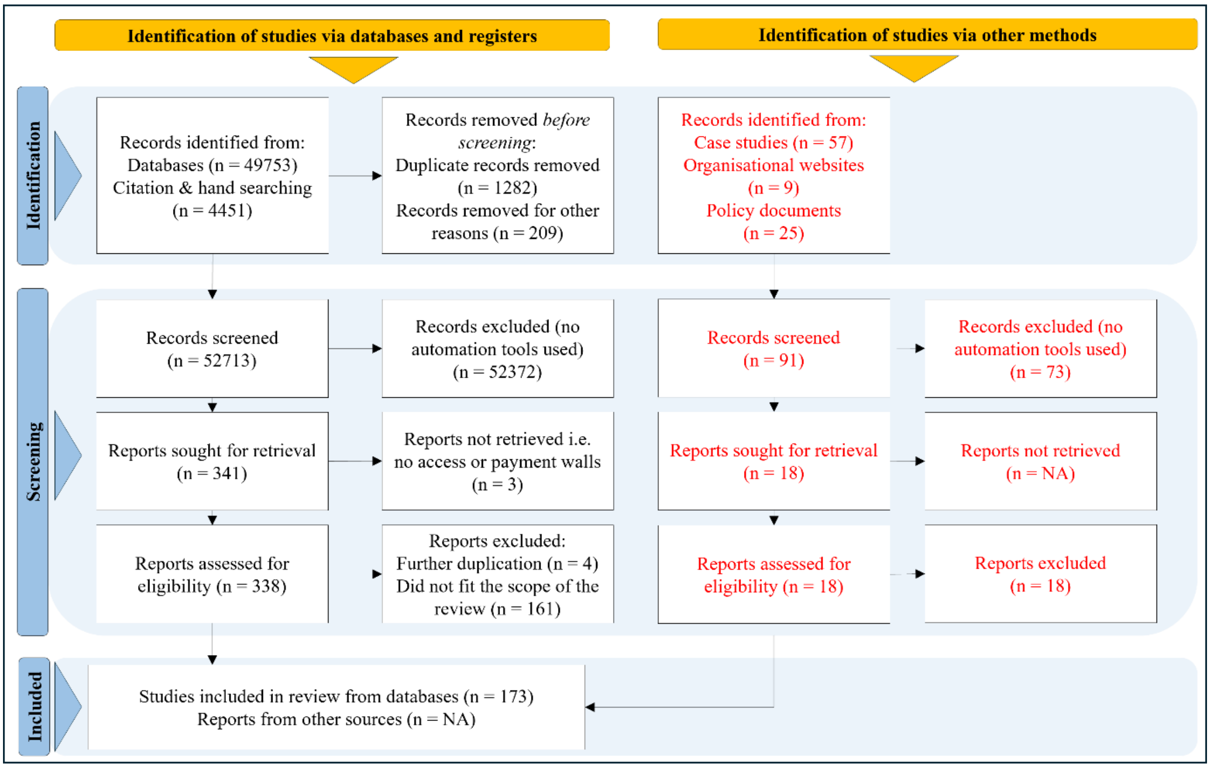
Disease transmission	**Afforestation**	**Anthropization**	**Biodiversity loss**	**Conservation**	**Deforestation**	**Dilution effect**	**Fragmentation**	**Habitat degradation**	**Landuse alteration**	**Reforestation**	**Restoration services**	**Species removal**	**Urbanisation**	**Wetland restoration**	**Wildfire**	*Total number of studies*
Arthropod-borne	NA	NA	NA	NA	1	1	-2	NA	NA	NA	NA	NA	0	NA	NA	7
Avian-borne	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA	0	NA	NA	2
Bat-borne	NA	NA	NA	NA	-3	NA	-3	NA	-1	NA	0	NA	-2	NA	NA	12
General	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA	NA	NA	NA	1
Mosquito-borne	0	-3	-1	1	-17	2	-5	NA	NA	1	NA	NA	-2	4	NA	54
Multiple VBD	NA	NA	NA	NA	-1	NA	-1	NA	NA	NA	NA	NA	-1	NA	NA	3
Multiple Zoonoses	NA	NA	NA	0	-2	0	-1	NA	0	-1	0	NA	NA	NA	NA	9
Neglected diseases	NA	NA	NA	NA	-1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1
Other vector-borne	NA	NA	-1	0	-2	2	0	NA	NA	NA	NA	NA	0	NA	NA	8
Other zoonoses	NA	NA	NA	NA	-2	NA	NA	NA	-1	0	NA	NA	-1	NA	NA	7
Rodent-borne	NA	NA	-1	NA	-1	3	0	0	-1	2	NA	-1	-3	NA	-1	28
Tick-borne	NA	-1	-1	NA	-1	2	-2	NA	1	-1	NA	2	2	NA	NA	36
Tuberculosis	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA	NA	NA	NA	1
Wildlife diseases	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-1	NA	NA	1
Total number of studies	3	4	4	3	41	15	36	1	8	16	2	3	27	4	1	

at the bottom reflects the number of studies evaluating the dilution effect, not the arithmetic sum of scores. Opposing results within a study can cancel each other numerically, so the column sum does not represent the study count

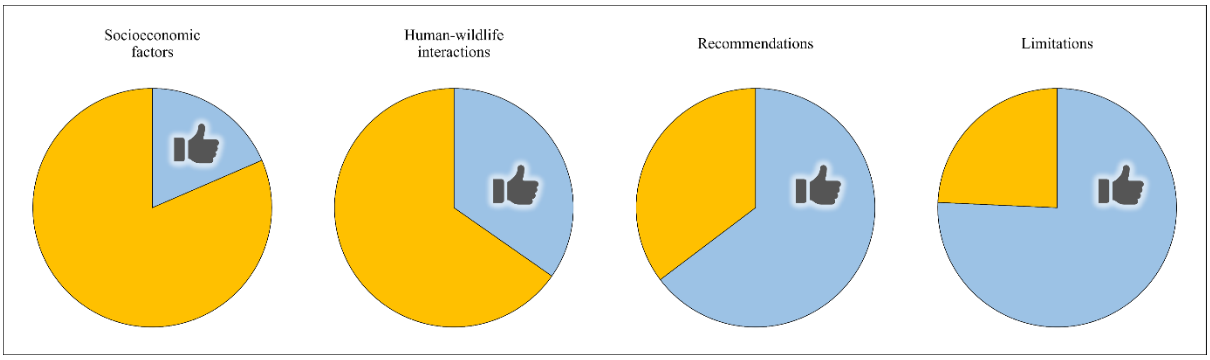
Supplementary table 7. Definition of disease categories used in the review.

Category	Definition	Examples
Zoonotic (direct transmission)	Diseases transmitted from animals (wildlife, livestock, companion animals) to humans without an arthropod vector.	Puumula hantavirus, Leptospirosis, Rabies, Brucellosis
Vector-borne (zoonotic)	Diseases transmitted from animals to humans via arthropod vectors.	West Nile virus, Lyme disease, Chagas disease, *Plasmodium knowlesi* malaria, Cutaneous leishmaniasis
Vector-borne (non-zoonotic)	Diseases transmitted by arthropod vectors that can circulate exclusively in human–vector–human cycles (no animal reservoir required for maintenance although sylvatic cycles may or may not be present).	Dengue, Yellow fever, Zika, *Plasmodium falciparum* malaria, *P. vivax* malaria, *P. ovale* malaria, *P. malariae* malaria
General	Diseases primarily acquired from environmental sources.	Waterborne disease – cholera and soil borne disease like tetanus and soil helminths
Neglected diseases	Neglected tropical diseases (NTDs) are a diverse group of conditions caused by a variety of pathogens (including viruses, bacteria, parasites, fungi and toxins) and associated with devastating health, social and economic consequences in impoverished communities in tropical areas. Although dengue, chikungunya, and leishmaniasis are classified as NTDs, we categorized them as vector-borne diseases, giving priority to transmission mode. Diseases were classified as NTDs only when the term was used as an umbrella category rather than for specific pathogens.	Buruli ulcer
Wildlife diseases	Studies primarily focused on wildlife and diseases circulating in wild animal populations, with or without documented human spillover.	Avian malaria, chytridiomycosis
Multiple zoonoses/VBD	Studies that reported aggregated outcomes for more than one zoonotic disease or VBD without providing disease-specific estimates	Studies reporting combined risk patterns for several zoonoses
Other zoonoses	Includes zoonotic diseases that did not fall into any of the named categories (e.g., bat-borne, rodent-borne, mosquito-borne) due to limited data or heterogeneous transmission modes.	Brucellosis, Q fever
Other VBD	Includes VBD that did not fall into any of the named categories (e.g., arthropod-borne,	Tsutsugamushi disease

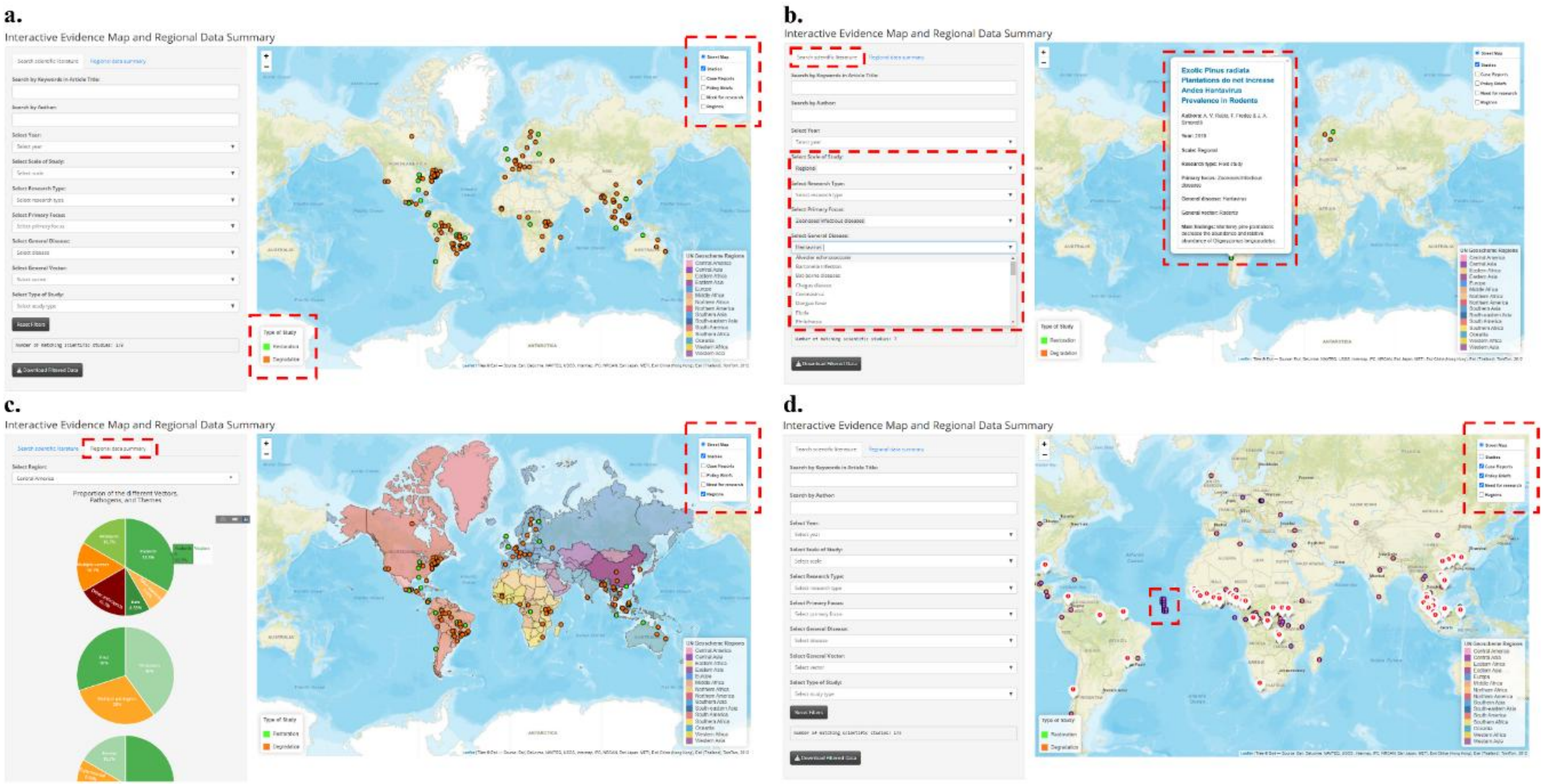
Category	Definition	Examples
	mosquito-borne, tick-borne) due to limited data or heterogeneous transmission modes.	
Tuberculosis	A directly transmitted bacterial disease caused by Mycobacterium tuberculosis, primarily affecting the lungs and spread via airborne droplets between humans. It was classified as a separate category given its unique transmission pathway, public health relevance, and the fact that it is not vector-borne or wildlife-associated.	Mycobacterium tuberculosis, Pulmonary TB



Supplementary figure 1. Prisma flowchart detailing the articles screened and included for data extraction. Adapted from Page et al, 2021.



Supplementary figure 2. Pie charts illustrating the proportion of studies discussing various topics within their publications. Each pie chart displays the percentage of studies that included specific content, with blue indicating the presence of the content and yellow indicating its absence. The topics covered are as follows: socioeconomic factors, human-wildlife interactions, recommendations or proposed solutions, and limitations and challenges (n=173).



Supplementary figure 3. Our online evidence map (https://bradduthie.shinyapps.io/atlas/) has a User Interface (UI) centred around an interactive map that displays the geographic locations of scientific literature, case reports, and policy briefs related to the effects of restoration and landscape degradation on disease transmission. Users toggle these layers on and off using the panel in the top-right corner (Supplementary figure 3a). Each marker on the map is clickable and opens a popup summary specific to the type of literature selected. For scientific literature, the summary includes the title, authors, year of publication, scale, research type, primary focus, general disease, general vector, and a brief overview of the findings (Supplementary figure 3b). For grey literature, summaries provide the title, year, results, and lessons learned. Titles in each summary are hyperlinked to their source, allowing for easy access to full documents. Additionally, users can toggle the display of "Need for Research" locations and UN Geoscheme regional boundaries to visualise global research gaps.

The panel to the left-hand side allows users to filter through the scientific literature using the first tab labelled "Search scientific literature". The user can use keywords to search for matches within the literature title or even search by author if known. The other options relate to the information in the summary popups, and all have pre-defined selection options from the drop-down menus (Supplementary figure 3b). After each selection, the studies are filtered displaying the ones with successful matches. Those studies that were global scale are present on the app but are not initially visible; this is because there is no generic location to add these to the map. Therefore, global studies are only visible once the scale selection of "Global" is selected. They are then visible in the Atlantic Ocean, with the global policy briefs too (Supplementary figure 3d). The filtered studies can be downloaded using the download button below these selection filters.

The second tab on the left-hand side panel, labelled "Regional data summary", has a drop-down menu for the UN Geoscheme regions (Supplementary figure 3c). Once a region is selected, summary pie charts are displayed. These pie charts represent the summary of scientific literature from each of these regions for Vectors/Hosts/Reservoirs, Pathogens and Themes of the studies, and are the ones present in this review (Fig. 2a; 2b; 2c).