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2 This Perspective discusses essential considerations for how ecosystem restoration may influence  
3 spillover of zoonotic pathogens, and how such considerations may be integrated into restoration  
4 design.

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**Perspective**

10

**Adaptive Ecosystem Restoration to Mitigate Zoonotic Risks**

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44 **Summary**

45 Infectious diseases pose a significant threat to global health security. Key wildlife species, potentially  
46 harboring numerous zoonotic pathogens, are increasingly forced to adapt to disturbances from land  
47 use change, human encroachment, and climate change. While evidence is rather convincing  
48 pertaining to the increased risks of zoonotic diseases with degradation and disturbances, the  
49 scientific literature on the mitigating effects of ecosystem restoration on zoonotic spillover is  
50 scattered, inconclusive and challenged by lack in a conceptual framework and practical guidance. In  
51 the light of rising restoration needs and activities, we outline six critical considerations when  
52 examining impacts of zoonotic diseases from ecosystem restoration: 1. Assessment of zoonotic  
53 disease targets; 2. Time lag between restoration and recovery; 3. Integration of trophic rewilding; 4.  
54 Robust study designs; 5. Controlling for confounding and modifying drivers; 6. Stakeholder  
55 engagement and co-creation with communities. Failure to account for these considerations makes  
56 the scientific contribution of restorations less valuable and may even jeopardize global efforts to  
57 reverse the global biodiversity decline.

58

59 **Keywords**

60 Biodiversity recovery, ecological restoration, nature-based solutions, reservoirs, rewilding, rodents,  
61 spillover, stakeholder engagement, vector-borne diseases, zoonoses

62

## 63 **Background**

64 The epidemic potential of infectious diseases, particularly zoonoses with a wildlife reservoir, is a  
65 rising concern for global health security<sup>1-4</sup> and mammals, along with birds, constitute the majority of  
66 species that serve as reservoirs for zoonotic pathogens<sup>5,6</sup>. Among mammalian wildlife, rodents, bats,  
67 and primates are identified as the primary hosts for most zoonotic viruses<sup>5</sup>. Rodents, in particular,  
68 represent the most species-rich taxon and the largest number of reservoir species<sup>7,8</sup>.

69 Pathogen richness is generally positively correlated with species richness and composition. However,  
70 high biodiversity has been shown to reduce overall infection rates in wildlife populations, primarily  
71 due to the higher prevalence of non-reservoir species in species-rich communities<sup>9-11</sup>. The  
72 phenomenon, known as the "dilution effect"<sup>19</sup>, occurs when non-reservoir species disrupt pathogen  
73 amplification through various mechanisms, including: a reduction in encounters where competitively  
74 superior non-reservoirs prevent pathogen transmission among competent reservoirs<sup>12-15</sup>; regulation  
75 of susceptible hosts by maintaining low abundance of reservoirs<sup>12</sup>; or, increased mortality of infected  
76 hosts due to predation<sup>16,17</sup>. The protective effects of biodiversity against transmission of zoonotic  
77 pathogens are increasingly threatened, in part due to anthropogenic influences, such as, climate  
78 change, habitat loss, urbanization, pollution, deforestation and forest fragmentation<sup>2,18,19</sup>. Critical  
79 natural habitats, such as old-growth forest, have been clearcut or converted into managed forests,  
80 grasslands have been turned into cropland, and natural wetlands have been turned into aquaculture  
81 or been drained. These changes disproportionately affect specialist, non-competent reservoir species  
82 that are vital for mitigation of pathogen transmission risk, while generalist species, which are more  
83 likely to serve as reservoirs, thrive in degraded ecosystems<sup>20,21</sup>. While there is consensus that  
84 biodiversity loss tends to increase disease risk<sup>18,21-25</sup>, the reverse remains less clear and ambiguous.

85 There are general suggestions regarding how to address the link between ecosystem restoration and  
86 disease risk<sup>26-28</sup>, but until now, many more studies document a relationship between disturbances

87 and degradation and zoonotic diseases, compared to the reversed effects of restoration<sup>26</sup>. This gap in  
88 the scientific literature needs to be systematically addressed and carefully studied.

89 This is particularly important considering the growing investment in ecosystem restoration along with  
90 legal enforcement such as the European restoration law<sup>29</sup>, which provides the opportunity to reach  
91 multi-functional ecosystem targets, including low pathogen transmission and disease risk, a term  
92 that has been phrased as “landscape immunity”<sup>30</sup>.

93 Although ecosystem restoration is increasingly recognized as a critical strategy to counteract  
94 biodiversity loss and its associated disease risks<sup>26,31-33</sup>, the process of transforming degraded and  
95 ecosystems laden with zoonotic hazard into biodiversity-rich and healthy ones, requires practical  
96 guidance that hitherto is largely missing.

97 In this perspective, we aim to advance the evaluation of mitigating impacts of ecosystem restoration  
98 on zoonotic diseases through outlining key considerations when planning, studying and reporting on  
99 restoration and zoonotic diseases (see Fig. 1 for the adaptive design and Table 1 for examples). We  
100 highlight the need to consider both the direct intended and unintended effects of the restoration by  
101 selecting and monitoring zoonotic disease indicators and targets from a range of plausible reservoirs  
102 and hosts affected. We point out existing temporal latencies in such systems to adapt to the  
103 disturbance, as well as the effect of the restoration as a transient disturbance in itself. In addition, we  
104 argue for robust study designs and consideration of confounding and modifying factors such as  
105 multiple context specific anthropogenic factors that co-occur and modify restoration efforts and their  
106 implications for infectious diseases. For example, climate change further exacerbates the biodiversity  
107 crisis by amplifying species loss<sup>34</sup>, and causing range shifts of both reservoirs and vectors<sup>35</sup>, with likely  
108 knock-on effects on disease risk<sup>36-40</sup>. Moreover, we emphasize the importance of engagement with  
109 stakeholders and local communities for gaining local acceptance of restoration measures, for  
110 monitoring and maintaining recovery of biodiversity, disease risk mitigation, and for the identification  
111 of success factors.

## 112 **Potential and Challenges of Ecosystem Restoration: Key Considerations**

113 In light of rising restoration needs and activities, we outline six critical considerations when  
114 examining impacts of zoonotic diseases from ecosystem restoration.

### 115 **1. Assessment and inclusion of relevant zoonotic targets**

116 While selected research projects on ecosystem restoration with infectious disease endpoints have  
117 been implemented<sup>32</sup>, many of the major international flagship ecosystem restoration programs and  
118 initiatives (e.g., the UN Great Wall Initiative, G20 Global Land Initiative, European Green Deal)<sup>41-44</sup>,  
119 lack explicit infectious disease endpoints. Improving ecosystem services is an intrinsic aim of  
120 ecosystem restoration<sup>45</sup> and disease regulation is one such service<sup>46</sup>. Restoration activities including  
121 flagship ones tend to have targets for biodiversity, climate change mitigation and human well-being,  
122 but to our knowledge, zoonotic disease risk mitigation as an explicit target is generally missing from  
123 these projects. This is an obvious critical gap and to address this we suggest conducting a context  
124 specific One Health<sup>47</sup> assessment of the restoration, considering the local context (<sup>48</sup>; Table 1). A One  
125 Health assessment entails a multidisciplinary and collaborative process with six distinct steps: a)  
126 define the scope and objectives by identifying specific health issues; b) engage local communities  
127 and experts across relevant sectors to design and review restoration plans; c) conduct cross-sectorial  
128 data collection, monitoring, and surveillance; d) perform ecological and epidemiological risk  
129 assessment using models and statistical tools; e) develop integrated intervention strategies for  
130 disease control and ecosystem restoration; and f) evaluate and adapt the effectiveness of  
131 restorations and interventions (Fig. 1)<sup>47,48</sup>.

132 Such a One Health assessment would help to develop zoonotic disease targets for comprehensive  
133 monitoring of dilution impacts and allow better understanding of any potential negative unintended  
134 consequences including health risks to humans, animals and the environment. This is currently a  
135 clear gap in ecosystem restoration practice and consequently multiple opportunities for better

136 understanding of zoonotic disease prevention are currently not realized, transferred and upscaled. At  
137 the European level, the importance and opportunity of disease risk mitigation via ecosystem  
138 restoration has been recognized by the European Environment Agency<sup>49</sup> but given global restoration  
139 efforts, we argue that disease risk mitigation should be recognized as an integral part of restoration  
140 planning.

141 Depending on the context, disease risk targets do not necessarily imply immediate monitoring of  
142 potential human disease but rather monitoring of zoonotic hazard, proxies of hazard (e.g., presence  
143 and abundance of vectors and/or reservoirs), and monitoring of target species and species  
144 communities that can either amplify or dilute pathogen transmission and disease risk (Fig. 1).

## 145 **2. Time lag between restoration and recovery**

146 Initially, restoration activities such as stream re-meandering, shrubland burning, or reforestations,  
147 which aim to increase biodiversity in the long term often involve ecosystem disturbances<sup>50-52</sup>. Many  
148 of these projects rely on heavy machinery (e.g. for boulder placement), or prescribed burning. These  
149 hitherto understudied restoration-associated disturbances can create temporary habitats dominated  
150 by generalist species, including reservoirs and vectors<sup>53</sup>. Upon recovery from the restoration-induced  
151 disturbance until succession towards the secondary climax habitat (similar to the pre-degradation  
152 primary habitat), the abundance and proportion of reservoirs and vectors is likely to decrease (Fig.  
153 2). When considering restoration in the context of zoonotic targets, it is important to account for the  
154 transient nature of initial disturbances, as the eventual impacts on pathogen transmission and  
155 disease risk may differ significantly from those observed during early, non-equilibrium phases of the  
156 restored system.

157 In the same fashion, temporal mismatch between structural and biotic recovery is a common  
158 challenge in restoration efforts, which also may yield misleading conclusions of the long-term effects  
159 on zoonotic diseases if not accounted for. Structural restoration (e.g., re-establishing physical  
160 features of ecosystems) often occurs faster than the recovery of species communities. For example,

161 stream restoration via re-meandering or boulder placement can reestablish physical structures  
162 within months, whereas the recovery of biotic communities may take decades<sup>51</sup>. Rewetting of  
163 drained agricultural fields and forests increases the amount of water in the landscape, viz., structural  
164 restoration, but this is no guarantee that the species originally associated with the undrained  
165 habitats return. The non-response of species to ecosystem restoration might further be challenged  
166 by impoverished species pools at the landscape or regional scale, with species being locally or  
167 regionally already extinct, a process referred to as the ghost of land use past<sup>54</sup>. During this lag,  
168 generalist species that act as reservoirs or vectors may dominate, increasing disease risk until the  
169 community fully recovers (Fig. 2).

### 170 **3. Integration of trophic rewilding into comprehensive and system-oriented restoration**

171 Ecosystem recovery tends to be protracted at best, particularly using traditional ecosystem  
172 restoration measures, which leaves critical niches for essential ecosystem functions unoccupied for  
173 extended periods of time. To mitigate this issue, trophic rewilding, a restoration concept focused on  
174 reintroducing keystone and other ecologically significant species, may provide a more immediate  
175 approach to restore ecosystem function. Rewilding by inducing trophic cascades thereby not only  
176 restores ecosystem structures but also biodiversity and trophic interactions<sup>55,56</sup>. Prominent examples  
177 include the reintroduction of European Bison (*Bison bonasus*)<sup>55</sup>, Eurasian beaver (*Castor fiber*)<sup>57</sup>, and  
178 rhinoceros (*Rhinoceros* spp.)<sup>58</sup>. Additionally, the term rewilding is increasingly used in the context of  
179 “making nature wilder” without automatically restoring degraded ecosystems by reintroducing  
180 predator species that have either been regionally extinct or are at low population size, e.g., lynx (*Lynx*  
181 spp.)<sup>59,60</sup>, tigers (*Panthera tigris*)<sup>61</sup>, lions (*Panthera leo*)<sup>62</sup>, mesocarnivores<sup>63,64</sup>, raptors<sup>65-67</sup>, and  
182 owls<sup>68,69</sup>. Hence, their reintroduction can also contribute to zoonotic disease mitigation by increasing  
183 mortality of reservoirs and/or sanitizing the environment from pathogen-loaded carcasses<sup>16,17,70</sup> (Fig.  
184 3). Trophic rewilding of apex predators potentially causes human-wildlife conflicts<sup>71</sup>, which need to  
185 be solved in collaboration with concerned stakeholders prior to and throughout any such rewilding

186 takes place. In addition, if habitat degradation either directly or indirectly has caused the loss of apex  
187 predators, their reintroduction may only be meaningful if the necessary structures and features are  
188 restored or compensated for<sup>71</sup>.

189 In their natural habitats, many raptors and owls rely on nests or holes in old trees for reproduction.  
190 Such habitat features may only become available after full recovery from degradation and the  
191 initialization of ecosystem restoration, resulting in long time lags between restoration and  
192 colonization of more specialized predators. Many raptors and owls accept artificial nesting platforms  
193 and nest boxes<sup>72,73</sup>. To set these up already during the restoration and recovery phase might  
194 contribute to reducing zoonotic hazard due to predation on reservoirs<sup>74,75</sup>, especially rodents, during  
195 the phase of temporal mismatch between structural and biotic recovery; a phase likely dominated by  
196 generalists that are overrepresented by reservoirs (Fig. 3). Such trophic rewilding via indirect  
197 rewilding (e.g., nest boxes) avoids potential animal welfare challenges since raptors and owls would  
198 not be translocated but only be attracted by the built structures if the surrounding landscape  
199 provides sufficient food resources.

200 The potential health benefits of trophic rewilding as an ecosystem restoration measure are not  
201 limited to iconic or large vertebrates. For instance, reforestation of winter-flowering forests can  
202 support nectar-feeding bats and reduce spillover risk in degraded systems<sup>33,76</sup> (Table 1). However, just  
203 as artificial roosts for predators must be assessed with broader ecological and health implications in  
204 mind, so too must artificial roosts for bats. Evaluating such structures solely from a conservation  
205 standpoint<sup>77</sup> may overlook potential One Health trade-offs—particularly in regions experiencing high  
206 disease risk from bat-borne pathogens such as *Henipavirus hendraense* also known as Hendra virus.

207 Control of vectors in addition to reservoirs can be an efficient disease risk mitigation tool. Bats are  
208 important reservoirs but also contribute to ecosystem health by arthropod pest control<sup>78</sup>. Many  
209 birds, especially within the order of Passeriformes (e.g., swallows, warblers) and Apodiformes (e.g.,  
210 swifts, hummingbirds), as well as reptiles and spiders are important predators of adult mosquitoes

211 even if they are not specialized on mosquitoes<sup>79,80</sup>. In addition, many fish and amphibian species  
212 predate on mosquito eggs and larvae<sup>79,81</sup> and might hence reduce vector emergence (Fig. 3).  
213 Likewise, reptiles and spiders are predators of ticks and might reduce vector abundance<sup>79,82</sup>.  
214 Structural restoration that provides habitats and structures for predators, for example stone mounds  
215 for reptiles and spiders as well as nest boxes, nesting platforms, and perches for raptors and owls,  
216 can be an efficient tool towards disease risk mitigation in the early post-restoration phase, when  
217 vectors and reservoirs likely thrive. Indeed, mosquitoes<sup>83</sup> and many rodent species<sup>84,85</sup> are early  
218 colonizers after disturbances (Fig. 3). Already the mere presence of predators – or even a simulation  
219 of their presence – can create a landscape of fear<sup>86</sup> that might change the colonization strategy of  
220 vectors and reservoirs including avoidance of predator-dense habitats<sup>82,87</sup>. It should be kept in mind  
221 though that trophic rewilding with non-keystone species is a poor substitute for proper ecosystem  
222 restoration towards post-restoration ecosystem functioning (Fig. 3e).

223 Finally, trophic rewilding implies the relocation of wildlife from either captivity or the wild, including  
224 their associated microbiota and pathogens. To avoid any spillover to other wildlife or infections of  
225 conspecifics due to introduced pathogens, it is therefore crucial to check the pre-release health  
226 status of the animals prior to any release into the wild<sup>88</sup>.

#### 227 **4. Monitoring and evaluation using robust study designs**

228 A major challenge for prospective evaluation of restoration effects is the implementation of a  
229 rigorous long-term study design including baseline monitoring of restoration contrasts and controls.  
230 Such designs are needed to reduce bias, enable robust statistical evaluation and to reliably guide  
231 ecosystem restoration measures towards reduced disease risk. Restoration processes have both a  
232 geographical (depicted by the restored area and species distribution) and temporal (from restoration  
233 disturbance to reaching equilibrium of the restored system) component. Study and evaluation  
234 designs therefore need to account for spatio-temporal aspects<sup>40</sup>. Furthermore, it is advisable to  
235 design studies with temporal and spatial controls to distinguish changes occurring in restored areas

236 from those in non-restored controls, which may also be influenced by natural succession or other  
237 environmental pressures (Fig. 1). Evaluation of restoration success requires solid restoration design  
238 that adjusts or at least accounts for bias as well as assessment and consideration of confounding  
239 effects (for example environmental pollution). Here, a randomization of restoration and control areas  
240 would be preferable but is often impractical. Instead, before-after (BA; also referred to as interrupted  
241 timeseries or difference-in-difference temporal design), quasi experimental designs or control-impact  
242 (CI) approaches have demonstrated to be more feasible and provide often sufficient adjustment for  
243 bias<sup>50,51</sup>. Preferably, control-impact studies should include sites that are at different successional  
244 stages after restoration (for example<sup>89</sup>). In addition, natural experiments such as forest fires –  
245 especially if combined with control sites – offer the opportunity to determine whether prescribed  
246 burning, often used as a restoration tool, may also mitigate zoonotic hazard<sup>53</sup>. Outcome metrics of  
247 such evaluation would have to capture both intended and unintended impacts on zoonotic disease  
248 relevant indicators.

249 So far, evaluation of restoration is largely lacking rigorous designs, for example, historic and  
250 monitoring data necessary to define baseline conditions of pre-degradation structures and species  
251 communities. This lack of data became evident for example when defining reference conditions as  
252 needed in the context of the European Water Framework Directive. For many quality factors of this  
253 directive, modelling approaches and expert knowledge had to be used for defining these reference  
254 conditions in the absence of baseline data, which partly resulted in high uncertainty in reference  
255 values<sup>90</sup>. Such a lack of background data makes it difficult to establish SMART targets in ecosystem  
256 restoration, i.e., targets that are Specific, Measurable, Achievable, Relevant, and Time-based. To  
257 accomplish SMART restoration requires significant considerations and adaptations in the planning  
258 and funding of restoration measures. Planning needs to include a phase – preferably multiple years  
259 to account for between-year differences – for sampling baseline data. Funders have an important  
260 role here as funding need not only to cover the actual restoration measure, but also the collection of  
261 baseline and follow-up data to evaluate its wider impacts.

262 Monitoring can benefit from novel technology and approaches to data collection and processing,  
263 including community-based participatory research, and computer vision applied to relevant image,  
264 video and acoustic data <sup>91</sup>.

265 Robust study designs and indicators for monitoring of SMART targets allow the calculation of effect  
266 sizes to quantify the impact of the ecosystem restoration that are comparable across systems and  
267 taxa<sup>51</sup>. Using models for transfer, upscale and forward prediction or findings from the evaluation can  
268 help to study impacts from modifying spatial contextual and time-varying factors. For example,  
269 scenario projections of the zoonotic indicators under climate change scenarios can provide insights if  
270 the future impact is sensitive to anticipated potential changes in climate.

## 271 **5. Confounding and modifying factors in ecosystem recovery**

272 Restoration efforts are complicated by several confounding and modifying factors, including climate-  
273 induced regime shifts (modifying), and environmental pollution (confounding)<sup>2</sup>. While the  
274 confounding factors will be addressed and adjusted for by an appropriate design, the modifying  
275 factors and co-drivers may make it impossible to take the restored system back to its historical  
276 pristine situation. For example, climate change may introduce new conditions that alter species and  
277 pathogen dynamics which need to be accounted for on top of the baseline conditions. Specific  
278 habitat types planned to be achieved by restoration measures might be unrealistic due to climate-  
279 induced regime shifts of species, with knock-on effects on the presence and abundance of reservoirs,  
280 non-reservoirs, vectors, and pathogens (Fig. 2). These shifts caused by system modification could also  
281 result in non-reservoir species becoming reservoirs and pathogens switching reservoirs (Fig. 2). For  
282 example, restoring old-growth taiga forest that is clear-cut takes >200 years until original structures  
283 and species communities are recovering<sup>92</sup>. Considering the ongoing and expected further warming at  
284 northern latitudes<sup>93</sup>, taiga forests, especially at the southern biome range, will likely turn into  
285 temporal broadleaved forest during such a long period. In broadleaved compared to coniferous  
286 forests, trees producing large seeds dominate, which for example will shift the community structure

287 of rodents, ungulates, and their associated vectors and pathogens (Fig. 2). Likewise, and within a  
288 similar timeframe, in temperate broadleaved forest in North America, climate change will increase  
289 the severity and frequency of forest fires, which will exacerbate additional forest dieback due to pest  
290 outbreaks (bark beetles). These forests will, driven by climate change, likely turn into temperate  
291 grasslands and savanna<sup>94</sup> with associated shifts in species communities and associated zoonotic  
292 hazard.

293 Given that climate change can alter the trajectory of restoration by shifting species ranges and  
294 transforming habitat types, there is a need for ecosystem restoration projects that have a timeframe  
295 beyond decades to already consider projected modifying and climate-driven regime shifts in the  
296 planning phase, for example by choosing tree species for afforestation that cope with both current  
297 and future climatic conditions.

298 Another aspect of contextual drivers are compounds introduced into the environment that can either  
299 kill keystone species, alter species behavior<sup>95</sup>, or impair an organism's health status, all of which with  
300 devastating cascading effects on ecosystem health including disease risk. Such confounding factors  
301 might vary among restoration sites of varying spatial extent or among seasons and years, and  
302 therefore bias – if not accounted for – the restoration-target relationship. The diclofenac-induced  
303 mass mortality of vultures on the Indian subcontinent is one such striking example. Diclofenac is an  
304 anti-inflammatory drug that has been of veterinary use for treatment of cattle on the subcontinent.  
305 It is highly toxic to vultures and other raptors and has resulted in a more than 95 % decline in vulture  
306 population size until 2003<sup>96</sup>. The almost entire loss of these important scavengers and their  
307 ecological sanitary services has resulted in an increase in the numbers of feral dogs, carcasses of wild  
308 and domestic ungulates, and rats, and consequently an increase in rabies, and water-borne diseases,  
309 which according to an estimate by Markandya, A. et al. (2008) has added an annual burden of 2.4  
310 billion US dollars 1993-2006 to the Indian health care system<sup>70</sup>. Scavengers like vultures can  
311 potentially be reintroduced. However, any such restoration program using trophic rewilding will fail

312 until the environmental threat (like diclofenac and other pharmaceuticals) has been eliminated.  
313 Likewise, ecosystem restoration projects on contaminated land or aquatic systems without necessary  
314 remediation risk 1) confounding any restoration-hazard relationship, 2) the reemergence of polluting  
315 compounds and 3) jeopardizing ecosystem health<sup>97</sup>. Other confounding effects including light and  
316 noise pollution need to be accounted for in ecosystem restoration. For example, while large efforts  
317 are made to provide nesting and roosting habitats for insectivorous bats in urban areas and managed  
318 forest areas, bats might still not recolonize such areas due to light pollution (sensu<sup>98</sup>).

## 319 **6. Stakeholder engagement and co-creation with communities**

320 Ecosystem restoration efforts – regardless of whether mitigating infectious diseases is an explicit goal  
321 – must involve local communities and the integration of local and traditional knowledge. Local  
322 communities possess an intimate understanding of their environment, including the behaviors of  
323 local wildlife, seasonal dynamics, and historical changes in the landscape<sup>99,100</sup>. This knowledge is  
324 invaluable for identifying ecologically and epidemiologically critical habitats, species interactions, and  
325 potential disease reservoirs and vectors that may not be immediately apparent to outside  
326 researchers<sup>28,100</sup>. For instance, indigenous knowledge about native plant species and their uses, for  
327 example, can aid in identifying natural repellents for pathogen transmitting vectors, thus contributing  
328 to their control<sup>101</sup>.

329 Yet, not all degraded ecosystems are suitable for restoration. Engagement of local communities,  
330 along with that of other stakeholders including representatives of historical archives, veterinary  
331 science, and public health, is needed to identify sites and areas that should be exempt from  
332 ecosystem restoration due to resurrecting disease risk. For example, in vast areas of Europe, anthrax  
333 outbreaks among livestock were common in the 18<sup>th</sup> century and until the mid-20<sup>th</sup> century, leading  
334 to affected carcasses being buried in soil to avoid spread of spores<sup>102</sup>. Such burial grounds include  
335 drained pastureland that is potentially subject to ecosystem restoration. In Sweden, regional county

336 administrations responsible for ecosystem restorations are now requested to investigate the  
337 presence of any such burial sites when planning wetland restoration<sup>103</sup>.

338 Several successful ecosystem restoration projects have actively involved local communities,  
339 showcasing the critical role these communities play in ecological recovery via co-creation. Reyes-  
340 García et al. (2019) highlighted the importance of including indigenous people and local communities  
341 in the planning and execution of restoration activities to ensure both immediate and long-term  
342 benefits<sup>104</sup>. In Mexico, community-based restoration projects have shown that when local  
343 communities actively participate from the design phase through implementation, the projects yield  
344 better conservation outcomes and sustainable resource management<sup>105</sup>. Restoration actions that  
345 incorporate local customs, beliefs, and practices are more likely to gain acceptance and cooperation  
346 from the community<sup>106</sup>.

347 Local communities are often directly dependent on their natural resources for subsistence and  
348 economic activities. Involving them in restoration efforts ensures that these efforts do not  
349 inadvertently disrupt their livelihoods but rather support them sustainably<sup>48</sup>. Effective community  
350 participation played a crucial role in the successful control of diseases such as Ebola, rinderpest, and  
351 neglected tropical diseases<sup>100</sup>. Therefore, stakeholder involvement and engagement can facilitate  
352 rapid response and adaptive management, allowing for timely interventions to prevent the spread of  
353 pathogens<sup>28,107</sup>. In this context, systemic resilience and community engagement, a transdisciplinary  
354 and grassroots process coined “Lateral Public Health” expands beyond sectorial and disciplinary  
355 boundaries<sup>108</sup>. Lateral public health aims at developing community capacity for risk reduction  
356 through social capital by connecting parties unequal in power and access (e.g., government with  
357 community members). This process is not aimed explicitly at reducing disease risk but rather at  
358 building social capital through restoration projects<sup>108</sup>.

359 Involving local communities in restoration projects can also strengthen local governance and policy  
360 frameworks<sup>109</sup>. Furthermore, empowered communities are more likely to engage in practices that

361 reduce disease risks, such as creating buffer zones, restoring wetlands, or maintaining natural  
362 habitats that support predators of pathogen-transmitting vectors<sup>32</sup>. Collectively, these examples  
363 illustrate that the success of restoration projects often centers on the meaningful and sustained  
364 engagement of local communities.

365

## 366 **Outlook**

367 While ecosystem restoration presents a promising strategy for mitigating zoonotic disease risk, it  
368 must be carefully evaluated by appropriate zoonotic risk indicators and tailored methodologies that  
369 can also address various confounding and modifying factors of contextual relevance. Thus, the  
370 evidence for ecosystem restoration and pathogen transmission and disease mitigation must adhere  
371 to high standards to maximize its value and facilitate the transfer and scaling of impacts. Currently,  
372 more direct evidence of One Health approaches is needed that link restoration efforts to pathogen  
373 transmission and disease risk reduction. Our six considerations above pave the way towards  
374 restoration-induced landscape immunity where adaptive ecosystem restoration offers a proactive  
375 strategy to reduce zoonotic pathogen transmission and disease risks by re-establishing ecological  
376 integrity, enhancing biodiversity, increasing ecosystem resilience, and regulating pathogen dynamics.  
377 By incorporating the six considerations that address the outlined crucial knowledge gaps into the  
378 suggested adaptive design, we propose a roadmap (Fig. 1) that incorporates

- 379 1) Definition of SMART restoration targets
- 380 2) Monitoring of the targets based on a robust restoration design
- 381 3) Evaluation of restoration goals and pathogen occurrence and transmission and disease risk  
382 or its proxies
- 383 4) Adaptation of the restoration approach if goals risk to fall short and specifically if zoonotic  
384 hazard and disease risk amplify

385 Given the alarming decline of biodiversity worldwide, ecosystem restoration, including trophic  
386 rewilding initiatives must be urgently and effectively implemented. Our roadmap is critical to guiding  
387 timely action, preventing unintended consequences and accelerating ecosystem recovery.

388

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392

### 393 **Author contributions**

394 F.E., J.C.S, and J.R. conceptualized the study. All authors contributed to write the original draft.

395

### 396 **Declaration of interests**

397 The authors declare no competing interests.

398

### 399 **Data availability**

400 All the data used in this study are included in this Perspective.

401

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669 **Tables**

670 **Table 1. Examples of how ecosystem restoration can mitigate zoonotic disease risk originating in wildlife.** For each example, the initial objective of  
 671 restoration is given, along with specific challenges associated with this example. The method used to measure restoration outcomes is also given, including  
 672 whether a before-after control-impact (BACI) approach was used. The key considerations numbered relate to the considerations discussed in the main text  
 673 (1. Monitoring of zoonotic disease targets; 2. Time lag between restoration and recovery; 3. Integration of trophic rewilding; 4. Robust study designs; 5.  
 674 Controlling for confounding and modifying drivers; 6. Stakeholder engagement and co-creation with communities).

Initial objective of restoration	Challenge	Restoration measure and outcome including approach (BACI)	Key considerations	References
Reduction in prevalence of <i>Schistosoma</i>	Schistosomiasis is prevalent due to eutrophic waterbodies rich in aquatic macrophytes	Reduction of nutrient input and bioremediation (reduction in submerged macrophyte biomass) reduce snail habitat and abundance and reduce disease burden. BACI.	1-2, 4-6	48
Forest restoration towards ecotourism opportunities	Degraded forests in Malaysia have high abundance of malarial mosquito vectors	Forest restoration with native tree species reduces vector abundance while	1-2, 4	110

		plantation with non-native oil palms ( <i>Elaeis guineensis</i> ) and eucalyptus ( <i>Eucalyptus pellita</i> ) increases the abundance. CI.		
Experimental removal of invasive shrub Amur honeysuckle ( <i>Lonicera maackii</i> ) to reduce number of infected ticks	High tick-borne disease risk in areas with dense cover of Amur honeysuckle	Removal of Amur honeysuckle decreases deer activity and numbers of infected ticks. BACI.	1-2, 4	111
Reducing risk of Hendra virus spillover by landscape management	Food shortage in winter-flowering forests drives <i>Pteropus</i> bats into agricultural areas and risks Hendra virus spillover	Planting of nectar trees away from agricultural areas decreases spillover risk and restoration of winter-flowering forests is a likely long-term strategy to reduce spillover risk. BACI.	1-4, 6	28,33,76

### **Box 1. Definition of terms used in this article**

**Confounder** A third variable causing bias in the statistical evaluation of a cause-and-effect relationship regarding the effect of restoration on zoonotic targets.

**Disease risk** The likelihood of infection depending on hazard, exposure and vulnerability<sup>112</sup>.

**Driver** Natural or human-induced factors that directly or indirectly cause a change<sup>46</sup>.

**Ecosystem restoration** The process of halting and reversing degradation, resulting in improved ecosystem services and recovered biodiversity. Ecosystem restoration encompasses a wide continuum of practices, depending on local conditions and societal choice<sup>45</sup>.

**Effect** The change in indicators of zoonotic targets associated with restoration.

**Evaluation** The process of quantitative and qualitative understanding of the spatio-temporally sensitive effects of restoration-induced change on zoonotic targets.

**Exposure** The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas<sup>113</sup>.

**Hazard** Process or phenomenon of organic origin or conveyed by biological vectors, including exposure to pathogenic micro-organisms, toxins and bioactive substances that may cause loss of life, injury, illness or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage<sup>113</sup>. Here mainly used as zoonotic hazard, i.e., presence, abundance, and prevalence of vector-borne and zoonotic pathogens.

**Indicator** Observed value representative of a phenomenon of study. In general, indicators quantify information by aggregating different and multiple data<sup>114</sup>.

**Modifier** A third variable modifying the cause-and-effect relationship regarding the effect of restoration on zoonotic targets.

**One Health** Integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems. It recognizes the health of humans, domestic and wild

animals, plants, and the wider environment (including eco-systems) are closely linked and interdependent<sup>47</sup>.

**Projection** The process of using models to evaluate long-term change in the targets in relation to co-drivers and modifying situations using scenario-based approaches including for example, climate change scenarios

**Reservoir** Agent in which a pathogen multiplies and evolves

**Trophic rewilding** An ecological restoration strategy that uses species introductions to restore top-down trophic interactions and associated trophic cascades to promote self-regulating biodiverse ecosystems<sup>55</sup>.

**Vulnerability** The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards<sup>113</sup>.

**Zoonotic target** Intended disease outcome (pathogen occurrence, pathogen transmission and/or disease risk) that can be monitored and evaluated by indicators.

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678 **Figure legends**

679

680 **Figure 1. The envisioned One Health based adaptive process for assessment of ecosystem**

681 **restoration.** The process is founded in stakeholder engagement and co-creation. SMART (specific,  
682 measurable, achievable, relevant, and time-based) targets are developed for environment (diversity,  
683 climate, land use), animals (species community structure, pathogen and disease prevalence, vectors  
684 and reservoir abundance), and humans (pathogen prevalence, cases of disease, exposuree). Based  
685 on a robust restoration design that applies a replicated before-after-control-impact (BACI) approach,  
686 the indicators of the targets as well as identified confounders (factors that potentially can bias the  
687 restoration outcome, such as environmental contaminants and light pollution) and modifiers (factors  
688 that modify the cause-and-effect relationship of the restoration and the targets, such as long-term  
689 changes in climatic and hydrological regime) are monitored. Targets are then evaluated by  
690 quantifying the impact of restoration on target indicators with uncertainty, significance, and  
691 interactions. The assessment process will be adjusted according to evaluation results.

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694 **Figure 2. Zoonotic hazard as a function of habitat degradation and ecosystem restoration.** Zoonotic

695 hazard, illustrated by red circles in the left panel, represents the presence, abundance, and  
696 prevalence of vector-borne and zoonotic pathogens. Degradation of primary habitat, exemplified by  
697 taiga forest (left panel), increases zoonotic hazard (**a-d**, right panel) since degradation favours  
698 generalists that are overrepresented among reservoirs. **a** Ecosystem restoration can reduce zoonotic  
699 hazard once the ecosystem has recovered from degradation and restoration towards a climax  
700 community in the recovered habitat with regained ecosystem functions. **a** Zoonotic hazard will only  
701 decline if restored habitat is fully recovered and repopulated by non-reservoir species that can dilute

702 the hazard. **b-c** Ecosystem recovery is a tedious process that can take decades or even centuries and  
703 various system modifications – if occurring non-synergistically – risk to keep zoonotic hazard at high  
704 levels despite restoration efforts. **b** Impoverishment of regional species pools contributes to the loss  
705 of specialist, hazard-diluting species and hence causes the non-decline of zoonotic hazard post-  
706 restoration. **b** Habitat structures are restored (e.g., reforested trees), but important biotic  
707 components, interactions, and ecosystem functions are missing compared to the primary habitat. **c**  
708 In an increasingly polluted environment, contaminants (illustrated by the metals and organic  
709 compound in the left panel) may immunocompromise organisms and increase their susceptibility to  
710 pathogen infection and hence induce a non-decline of zoonotic hazard despite full ecosystem  
711 recovery from degradation and restoration. **d** Climate-driven regime shifts (illustrated by the  
712 thermometer) during habitat recovery can result in a community structure typical for a different  
713 biome (here temperate broadleaved forest) with knock-on effects on presence and abundance of  
714 reservoirs, non-reservoirs, vectors, and pathogens as well as zoonotic hazard. This shift could also  
715 imply non-reservoir species becoming reservoirs and pathogens switching reservoirs. **d** (right panel)  
716 However, climate change modifying ecosystem structure and functioning could also decrease  
717 zoonotic hazard towards lower levels compared to pre-degradation. This could for example be the  
718 case in an increasingly warmer and drier climate where vector-borne or zoonotic pathogens rely on  
719 moist and cloudy conditions for their persistence. We are currently experiencing system  
720 modifications by multiple factors (here **b-d** in left panel) that might act synergistically to amplify  
721 zoonotic hazard beyond scenarios where these factors occur individually (**b-c** right panel).

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724 **Figure 3. Response of zoonotic hazard to nature restoration via rewilding.** Zoonotic hazard  
725 outcomes are illustrated for active (**a-b**) and combined active and passive (**c-f**) rewilding. **a** In a  
726 heavily managed and drained boreal forest landscape habitat generalists dominate with high

727 pathogen prevalence in reservoirs and vectors and hence high zoonotic hazard (presence,  
728 abundance, and prevalence of vector-borne and zoonotic pathogens; illustrated by red circles). **b** The  
729 reintroduction of beavers as keystone species induces a cascade of ecosystem responses. **b** The dam-  
730 building activity of beavers rewets the forest landscape and increases habitat heterogeneity, which in  
731 turn boosts biodiversity and the presence of specialist species that reduce zoonotic hazard. **c** In a  
732 landscape with straightened water courses and impoverished riparian zones, habitat generalists that  
733 are overrepresented among reservoirs dominate with high pathogen prevalence in reservoirs and  
734 vectors (see also **a**). **d** The use of heavy machinery can restore previous habitat structure (here  
735 meandering and presence of boulders) but with a resulting similar or even increased zoonotic  
736 hazard, with the latter due to provision of vector habitat (cf. **c**). **d** High zoonotic hazard in the post-  
737 restoration phase results from the temporal mismatch between structural and biological recovery  
738 where generalists and their pathogens dominate. **e** This temporal mismatch can be bridged by active  
739 and passive rewilding. Here, raptors and owls can be attracted to the restored area by providing  
740 perching poles, nesting platforms, and nest boxes. **e** Predators of vectors (here illustrated by  
741 amphibians) can be reintroduced and contribute together with raptors and owls to reduce zoonotic  
742 hazard. **f** Eventually the restored habitat (see **e**) recovers also biologically without the need for  
743 artificial structures with resulting increased biodiversity including habitat specialists that further  
744 dilute zoonotic hazard.

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