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Perspective

Toward climate-smart rewilding: An integrated framework for biodiversity, climate change, and society

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SUMMARY

The Kunming-Montreal Global Biodiversity Framework calls for restoring at least 30% of degraded ecosystems by 2030, while the IPCC and IPBES emphasize restoration as central to addressing climate change and biodiversity loss. Rewilding, defined as the promotion of self-sustaining, complex ecosystems through minimal human intervention, has emerged as a prominent restoration strategy, yet its climate change mitigation potential is often underexplored. Here, we propose a climate-smart rewilding framework that explicitly integrates biodiversity recovery with climate mitigation, climate adaptation, and socio-economic considerations. Using Europe as a case study, we map potential synergies and trade-offs among carbon sequestration, ecosystem resilience to climate change, wildlife-based tourism opportunities, and the risk of livestock predator conflict. We argue that this integrative framework provides a practical basis for identifying and assessing restoration strategies that deliver multiple benefits across regional and continental scales.

INTRODUCTION

Ecosystem restoration has become central to contemporary climate policy agendas, which increasingly emphasize its potential to contribute to climate change mitigation and adaptation through enhanced carbon uptake and storage.[1–4] In parallel, commitments to large-scale restoration and biodiversity recovery are being made as part of the UN Decade on Ecosystem Restoration and major biodiversity policies, including the Kunming-Montreal Global Biodiversity Framework, which targets restoration of at least 30% of degraded ecosystems by 2030, and the EU Nature Restoration Regulation.[5,6] As these climate- and biodiversity-driven mandates are implemented, they can pull restoration planning in different directions because "climate" objectives span both mitigation and adaptation: approaches designed to maximize rapid, quantifiable mitigation benefits may sideline adaptation functions (resilience to drought, fire, and floods; connectivity for climate-driven range shifts; and the persistence of carbon under disturbance) and may not align well with biodiversity-oriented priorities, producing policy-driven trade-offs between carbon metrics, climate resilience, and biodiversity recovery.[7–9]

Achieving multiple restoration outcomes simultaneously requires navigating structural constraints and managing inevitable trade-offs.[10] Carbon-prioritizing interventions that focus on rapid, measurable biomass gains, often via monoculture forest plantations (Figure 1), can reduce habitat complexity and disturbance resilience and may even weaken the durability of stored carbon.[11–13] Conversely, biodiversity-prioritizing interventions can deliver clear conservation gains (e.g., meadow management for endemic species),[14] but their added climate mitigation benefits are often uncertain, slow, or modest relative to carbon-first approaches (Figure 1).[15–17] These contrasts highlight the need for approaches that optimize multiple objectives across carbon metrics, climate resilience, and biodiversity recovery rather than privileging a single objective (Figure 1). Here, we propose climate-smart rewilding as one such approach, harnessing ecological processes to strengthen resilience, support biodiversity, and deliver societal benefits while safeguarding and enhancing carbon sinks.[18–22]

Rewilding has gained traction as a process-led restoration approach that rebuilds complex, self-sustaining ecosystems by restoring key ecological processes and reducing long-term human control.[24] Its promise of delivering benefits for both biodiversity and society has drawn increasing attention from scientists, conservationists, policymakers, and the public.[24–29] Promoted as a solution for biodiversity loss and climate change,[30–32] its ability to deliver both objectives can depend on management emphasis and context (see Waylen et al.[33]). By restoring ecosystem functioning, rewilding can enhance carbon storage and climate resilience while supporting biodiversity.[34–39] It may also generate societal and economic co-benefits, including improved water and soil conditions, reduced long-term management costs, and rural livelihood opportunities through ecotourism and recreation, while strengthening biodiversity-dependent sectors such as agriculture and forestry.[30,31,40–46] Realizing these benefits, however, often requires alignment with broader land-use planning in contested landscapes.[47]

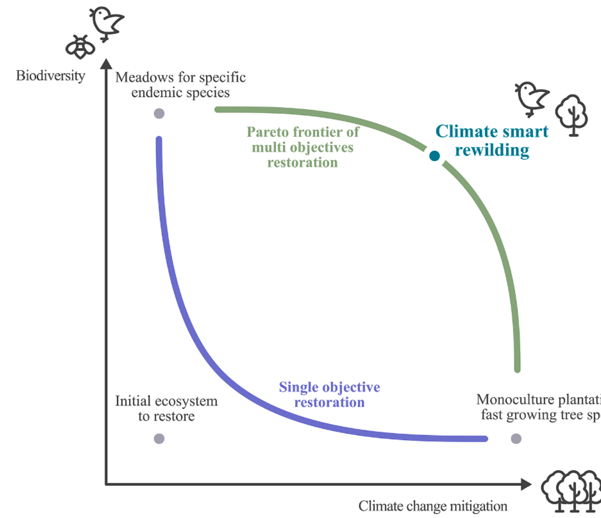

Figure 1. Conceptual representation of single-objective versus multi-objective ecosystem restoration outcomes
Potential outcomes of different ecosystem restoration pathways for biodiversity (*y* axis) and climate change mitigation potential (*x* axis), starting from a degraded ecosystem (bottom left). Single-objective restoration often results in solutions below the purple curve, reflecting trade-offs. Carbon-prioritizing interventions can deliver rapid, measurable carbon gains but often simplify ecosystems and reduce biodiversity. In contrast, biodiversity-prioritizing interventions maximize conservation outcomes but may yield weaker, slower, or uncertain mitigation benefits. The green curve depicts a multi-objective Pareto frontier (i.e., the set of best achievable trade-offs among multiple objectives).[23] Its concave shape reflects the existence of multi-objective restoration strategies, such as climate-smart rewilding, that can simultaneously achieve relatively high biodiversity and climate mitigation outcomes.

At the same time, climate change introduces an additional layer of uncertainty by modifying the environmental conditions that govern rewilding trajectories.[48] When undertaking rewilding initiatives, it is crucial to take into account a world characterized by shifting species ranges, community reshuffling, the disruption of existing biotic interactions and the formation of new ones, changing ecosystem dynamics, and an increasing frequency and intensity of stochastic disturbances.[49–52] Such transformations may result in shifts in species richness, community composition, functional traits, and biome distribution over time.[53,54] As species experience changes in fitness due to climate shifts, leading to declines in some areas and increases in others, their ability to track suitable conditions depends on the presence of natural corridors, highlighting the importance of improved connectivity and secure dispersal routes.[55] Climate change can also disrupt trophic processes, particularly when interacting species respond differently to changing climatic conditions.[56,57] Additionally, climate change is expected to modify natural disturbance regimes, leading to intensified droughts, wildfires, floods, and biotic disturbances.[58,59]

Despite rising policy pressure to jointly deliver biodiversity, climate, and societal benefits, rewilding is rarely assessed using a framework that clearly connects climate mitigation and adaptation goals to the design, feasibility, and outcomes of rewilding projects. Existing assessments seldom consider how shifting climatic conditions shape rewilding feasibility and trajectories or how rewilding can contribute to mitigation, strengthen ecosystem resilience, and produce societal opportunities and constraints. This absence of a decision-relevant framework constrains the ability of planners to anticipate where objectives align, where they diverge, and what trade-offs are likely to emerge across real-world landscapes (Figure 1). Here, we develop a framework for climate-smart rewilding that integrates biodiversity recovery with climate mitigation and adaptation objectives while explicitly incorporating socio-economic benefits and risks (Figure 2). To demonstrate the framework, we apply it to spatially explicit examples across Europe, illustrating how it can guide prioritization and highlight areas of potential synergy as well as contexts where carbon, biodiversity, and social goals do not overlap. Finally, we discuss the strengths, limitations, and practical implications of implementing the approach in policy and planning.

CONCEPTUAL FRAMEWORK FOR REWILDING IN THE CONTEXT OF CLIMATE CHANGE AND SOCIETY

The climate-smart rewilding framework builds on and generalizes the framework proposed by Perino et al.,[24] which highlights three key ecological processes as being the main targets of rewilding: dispersal and connectivity, trophic complexity, and stochastic disturbances (Figure 2). Interventions on each of these processes target a key dimension of biodiversity (Table 1), community composition for trophic complexity, ecosystem structure for dispersal and connectivity, and ecosystem function for stochastic disturbance (Figure 2).[60,61] By placing biodiversity at its core, the framework emphasizes that rewilding outcomes for climate change mitigation, adaptation, and human well-being are mediated through biodiversity responses. Its main innovation is the systematic integration of climate change and socio-economic factors, treating them both as drivers shaping rewilding decisions and as outcomes influenced by rewilding interventions (Table 1). Consistent with the IPBES Conceptual Framework, climate-smart rewilding views climate change as both a motivating force and a resulting consequence mediated through changes in ecosystem functioning. This integrated perspective highlights the capacity of rewilding to jointly advance biodiversity conservation, climate change mitigation and adaptation, and human well-being and underscores the necessity of incorporating socio-economic considerations into rewilding planning, implementation, and management through the coordinated integration of climate change, biodiversity, and human well-being (Figure 2).

Translating this integrative framework into practice necessitates the design and implementation of targeted interventions that operationalize its three foundational ecological processes while explicitly accounting for their synergistic contributions to climate change mitigation and adaptation, biodiversity enhancement, and socio-economic outcomes (Table 1). For instance, reducing intensive land use can enhance habitat heterogeneity and trophic interactions, supporting the recovery and expansion of wildlife populations (Table 1, rewilding actions).[64] Moreover, restoring natural vegetation on abandoned farmland enhances habitat connectivity and structural heterogeneity, facilitating species dispersal, access to microclimatic refugia, and adaptive range shifts under changing climatic conditions (Table 1, rewilding actions).[97] In this context, the reintroduction or facilitation of the natural expansion of native grazers and browsers constitutes

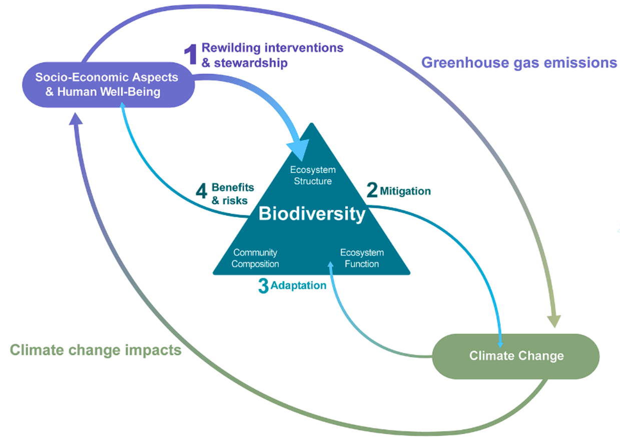

Figure 2. Integrated framework for climate-smart rewilding across biodiversity, climate change, and socio-economic outcomes
The framework positions rewilding interventions and stewardship (1) as its primary "drivers" for restoring biodiversity and ecological dynamics. These actions strengthen ecosystem structure through greater dispersal and connectivity, improve community composition via increased trophic complexity, and enhance ecosystem function by allowing more natural stochastic disturbances. Together, these changes promote biodiversity recovery and resilience, supporting climate change mitigation (2) and adaptation (3) while evaluating socio-economic benefits and risks (4) to guide sustainable, large-scale climate-smart rewilding.

a further critical intervention (Table 1, rewilding actions). These feeding guilds fulfill key ecological functions by enhancing biodiversity, regulating vegetation structure to reduce wildfire risk, reducing methane emissions through decreased dependence on domestic ruminants, and promoting carbon sequestration via spatially heterogeneous grazing regimes (Table 1, climate change mitigation and climate change adaptation).[31,65,75,98] Finally, facilitating the expansion of wildlife populations can create opportunities for sustainable ecotourism that benefit local communities and visitors, provided measures are implemented to minimize the risk of human-wildlife conflict (Table 1, socio-economic benefits and socio-economic risks).[40]

Developing effective rewilding strategies requires balancing trade-offs and prioritizing interventions that enhance climate resilience while supporting biodiversity. For the climate-smart rewilding framework to be effectively implemented and garner sustained support from local communities, stakeholders, conservation practitioners, and policymakers, it must explicitly account for the socio-economic implications of rewilding for human well-being. These implications can be systematically evaluated by considering the benefits, risks, and opportunity costs associated with biodiversity restoration and the resulting increase in human-nature interactions (Table 1, socio-economic benefits and socio-economic risks). A comprehensive rewilding approach should foster ecological integrity,[62] mitigate the impacts of climate change on both ecosystems and society, and integrate socio-economic dimensions to maximize long-term outcomes.

APPLYING THE FRAMEWORK: THREE EXAMPLES

To illustrate how the climate-smart rewilding framework can be applied, we conducted three spatially explicit analyses

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Table 1. Key interventions and outcomes in the climate-smart rewilding framework

	Community composition (trophic complexity)	Ecosystem structure (dispersal and connectivity)	Ecosystem function (stochastic disturbances)
Rewilding actions	• creation of no hunting or fishing zones[62] • the reduction of wildlife-livestock conflicts through the adaptation of the husbandry system[62] • facilitating the recovery and expansion of wildlife populations through reduced livestock grazing and the reintroduction of native species with key functional roles[24,63,a] • reduce carrion and deadwood removal and supplemental feeding activities[62]	• removing dams, roads, fences, and any other man-made obstacles[62] • manage human access to recorded and predicted migration routes for plants and animals, including birds and insects, to create landscapes that are more permeable to movement[62,64] • repurpose abandoned landscapes for habitat connectivity[64,a]	• reduce human activities that appropriate net primary productivity, for instance, by reducing forest harvest, livestock grazing intensity, or agricultural inputs[62,a] • occasionally reduce the suppression of wildfires ignited within rewilded areas[65] • restore natural hydrological regimes and land-water interactions[42]
Climate change mitigation	• replacing domestic ruminants with large wild non-ruminant herbivorous species can decrease methane (CH4) emissions[31] • more natural grazing by wildlife reduces fire frequency and overall carbon emissions[35] • trampling by grazers/browsers can increase soil carbon storage/reduce C soil emissions[66] • seed dispersal of large-seeded trees by large birds and scatter hoarders can enhance C sequestration per unit tree[67]	• increasing long-distance seed dispersal allows the expansion of forests, grasslands, and other vegetation forms, enhancing the potential for carbon uptake and storage in these ecosystems, i.e., by allowing plant species to track climate change[67] • more connected diversity of habitats increases vegetation complexity and carbon stocks[68] • increasing net primary productivity in connected abandoned landscapes[69]	• a more natural rate of stochastic disturbances (and increasing active management that prevents fire propagation from outside the rewilded area) can decrease the amount of carbon and other GHGs that are released into the atmosphere[70] • restoring flooding regimes can shift the role of riparian zones from a carbon source to a carbon sink[71] • the expansion of wetlands can significantly enhance long-term carbon sequestration and storage[72]
Climate change adaptation	• the presence of key ecosystem engineers (e.g., beavers) increases heterogeneity and complexity inside an ecosystem, increasing its resilience to climate change[73] • increasing vegetative habitat diversity due to natural grazing can increase potential refuges for different species under increasing temperatures[74] • reintroducing a mix of grazers and browsers can limit forest expansion and create diverse habitat mosaics (e.g., grass and shrublands) that are more resistant to extreme climatic events (e.g., limiting fire spread)[75]	• connecting different ecosystems can increase access to potentially more areas with thermal refugia, vegetation cover, and access to water resources in different seasons, reducing the impact of extreme climate events (e.g., heat waves)[76] • increasing well-connected migration routes and stepping stones can allow animals to reduce their exposure to climate fluctuations and rapid phenological timing changes while also being important for plant dispersal (and hence vegetation) mediated via the large herbivores[77] • increasing dispersal can improve gene flow from one habitat patch to another, improving the functional adaptability of populations to rapid climatic changes[78]	• permitting the occurrence of disturbances, such as natural wildfires in rewilded areas, can foster a mosaic of vegetative stages that enhance biodiversity and subsequently improve the resilience of ecosystems facing temperature fluctuations associated with climate change[79] • restoring natural river flow can help migrating aquatic species to reach areas where climate fluctuations are more stable[80] • increasing adaptability and resilience through more diversity and heterogeneity by reducing management in forests and other vegetation[81]

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Table 1. ***Continued***

	Community composition (trophic complexity)	Ecosystem structure (dispersal and connectivity)	Ecosystem function (stochastic disturbances)
Socio-economic benefits	• increasing opportunities for enjoyment of biodiversity and wildness contributing to psychological and physical health[82] • fostering social cohesion and enhancing a sense of identity and pride related to wildlife among local communities that preserve cultural heritage[43] • enabling sustainable ecotourism that benefits both local inhabitants and visitors[40] • deadwood can increase biodiversity and recreational choices for forest visitors[83]	• more connectivity between urban and natural areas, can increase access to wilderness and provide several advantages to people (e.g., recreation, bike and walking routes with natural surroundings)[84] • wider access to water sources among different communities along the restored rivers[85] • increased connectivity among natural habitats can enhance ecosystem services such as crop pollination and conservation biological control of pests[86]	• increasing regulation of water quality and quantity for urban or rural areas[86] • disaster risk reduction of floods[87] • restoring river ecosystems helps to provide quality environments and puts urban people in closer contact with nature, while in rural areas, it may also provide sustenance[88]
Socio-economic risks	• damages to crops and livestock[89] • disease spreading from interacting with wild animals[89] • economic burdens of wildlife comeback (e.g., reintroduction costs, increasing food prices, wildlife-vehicle collisions)[89]	• increased risks of human-wildlife conflicts due to more natural areas in proximity to human settlements[89] • reduction in land available for agriculture, forestry, or urban development[90] • increased risk of frequent (due to climate change) extreme events (mega-fires, floods, etc.) reaching human settlements[91]	• increased exposure to natural wildfires (from rewilded areas)[92] • increased flooding (due to decreasing flood management) in adjacent rural or urban areas[93] • elevated risk of ecosystem disturbances such as pest outbreaks and post-disturbance vegetation changes that may temporarily reduce recreational value and site attractiveness[94]

Rewilding management actions, their effects on climate change adaptation and mitigation, and biodiversity's benefits and risks to people are listed. Each column corresponds to a rewilding component—trophic complexity, connectivity, and stochastic disturbances[24]—and its links to essential biodiversity variables (EBVs): community composition, ecosystem structure, and ecosystem function.[60,95,96] Examples are illustrative, not exhaustive; actions are assigned to the component they primarily influence, although many affect multiple components. GHG, greenhouse gas.
[a]Actions are discussed in the framework's application to climate mitigation, adaptation, and socio-economic trade-offs (see the supplemental information for table development).

Table 2. Indicators, rewilding interventions, and outcomes used in the spatial analyses

Category	Example 1: Climate change mitigation	Example 2: Climate change adaptation	Example 3: Social benefits	Example 4: Social risks
Current biodiversity component (triangle in Figure 2; orange on the maps in Figure 3)	ecosystem function: proportion of NPP remaining in the ecosystem after human appropriation[99]	ecosystem structure: effective mesh size[100–102]	community composition: current distribution of large mammals[95]	community composition: current distribution of wolves and bears[95]
Potential rewilding action (arrow 1 in Figure 2; Table 1; purple on the maps in Figure 3)	areas with probable agricultural abandonment[103]	areas with probable agricultural abandonment[103]	potential expansion of large mammals[95]	potential expansion of wolves and bears[95]
Rewilding outcomes (arrows 2, 3, or 4 in Figure 2)	carbon sequestration based on potential additional carbon stock[104]	important connectivity areas based on climate velocity[105]	wildlife tourism: people willing to travel to see large mammals[106]	low wildlife conflict: areas with low livestock density[107]

Current biodiversity components, potential rewilding actions, and outcome proxies were employed to operationalize the climate-smart rewilding framework across four spatially explicit applications: climate change mitigation, climate change adaptation, social benefits, and social risks. Biodiversity components (function, structure, composition) were evaluated using defined thresholds to delineate areas with favorable ecological states and high rewilding potential. These areas were subsequently overlaid with continuous indicators of climate mitigation and adaptation potential, together with socio-economic benefits and risks, to elucidate potential synergies and trade-offs

integrating ecological, climatic, and socio-economic dimensions. The basic idea of each analysis is to identify where there are opportunities for rewilding interventions to improve biodiversity (Figure 2, arrow 1; Table 1, rewilding actions) and to assess their outcomes in one of the three components of the framework: climate mitigation (Figure 2, arrow 2; Table 1, climate change mitigation and climate change adaptation), climate adaptation (Figure 2, arrow 3; Table 1, climate change mitigation and climate change adaptation), or socio-economic benefits and risks (Figure 2, arrow 4; Table 1, socio-economic benefits and socio-economic risks). Each example focuses on a specific rewilding intervention, a particular biodiversity dimension affected by that intervention, and its outcome for one of the three components of the framework (Table 2; Figure 3). For each analysis, we first quantified and mapped the rewilding outcome, representing the spatial distribution of the targeted benefit or risk (grayscale maps in Figure 3; Table 2). We then delineated potential rewilding areas across Europe, identifying locations where the focal intervention (e.g., farmland abandonment or species range expansion) is most probable (purple areas in Figure 3; Table 2). Finally, we incorporated the biodiversity component by overlaying regions with high values of the relevant ecological attribute (e.g., ecosystem function, structure, or community composition) to indicate areas of existing ecological significance (orange areas in Figure 3; Table 2). These spatial analyses are not formal optimization exercises and sometimes rely on coarse proxies for the metrics used to represent the three components; however, they are intended to be illustrative of the framework's potential to reveal synergies and trade-offs among biodiversity, climate, and socio-economic objectives (Figure 4). Detailed descriptions of the data sources, assumptions, and analytical methods underpinning these spatial prioritizations are provided in the supplemental information.

Example 1: Climate change mitigation on abandoned farmlands

The European Union (EU) has set ambitious goals for restoring degraded ecosystems and enhancing their carbon storage capacity; achieving these goals will require practical, evidence-based strategies to ensure their effective implementation.[108] Rewilding abandoned farmlands could be one highly feasible and cost-effective approach.[44,64] Farmland abandonment is a widespread phenomenon in many European regions[109] as a result of the migration of rural residents to urban areas in search of better opportunities, inadequate infrastructure, the remoteness of regional centers, difficulties in land management, low soil fertility combined with insufficient funds for improvement, and the reduced labor demands resulting from advancements in agricultural technologies.[110,111] Future projections estimate that approximately 200,000 km^2 of EU farmland are at high risk of abandonment over the coming years.[112]

To assess the potential for climate change mitigation through rewilding, we first evaluated the rewilding outcome in terms of potential carbon storage capacity, using spatially explicit estimates of carbon storage (Table 2).[104] We then delineated potential rewilding areas by projecting farmland abandonment for 2000–2040 based on probabilistic scenarios (Table 2).[103] Finally, we characterized the biodiversity component—ecosystem function—through land-use intensity (or a proxy for natural

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disturbance), calculated as the proportion of net primary productivity (NPP) remaining after human appropriation (HANPP), with $1 - \text{HANPP/NPP}$ serving as an inverse index.[99] Only areas exceeding the high-natural disturbance threshold were retained (Table 2). We also intersected areas with unrealized carbon storage and projected abandonment, indicating the capacity to sequester an additional ~3.4 Pg C under rewilding scenarios (see supplemental information).

The integration of farmland abandonment projections with areas of high natural disturbance revealed several regions with strong potential for carbon storage (Figure 3A). Notable hotspots included mountainous areas of the Apennines and Sicily in Italy, the southern and central Alps, ranges in southeast France, the northern Iberian Peninsula, Poland, Slovakia, Bulgaria, and Romania, as well as parts of western Britain and Ireland (Figure 3A). These areas combine relatively low current land-use intensity with high ecological integrity, creating favorable conditions for natural vegetation recovery and long-term carbon accumulation. Rewilding in such landscapes could substantially enhance carbon sequestration on land, complement existing mitigation strategies, and contribute meaningfully to European climate targets.

Despite this potential for climate change mitigation, the risks must be carefully considered (Table 1, socio-economic benefits and socio-economic risks). For example, expanding biomass on abandoned agricultural land may heighten wildfire likelihood, particularly in Mediterranean regions.[113,114] Disturbed sites are also vulnerable to invasive species dominance, producing simplified, species-poor landscapes that further increase fire risk.[115] To address this challenge while safeguarding carbon benefits, it is crucial to implement integrated management strategies (Table 1, rewilding actions). These may include prescribed low-intensity fires to reduce fuel loads, reintroduction of wild-living large grazers and browsers to promote heterogeneous herbivory, protection of migration routes to sustain genetic exchange, and controlled domestic grazing to stabilize disturbance regimes (Table 1, rewilding actions).[30,65] By combining such measures with passive rewilding, it becomes possible to maximize carbon benefits while minimizing ecological risks (Table 1, climate change mitigation, climate change adaptation, socio-economic benefits, and socio-economic risks). Identifying priority areas for spontaneous tree regeneration and the reintroduction of wild-living large herbivores is thus particularly important. Taken together, this spatial analysis provides a supply-side perspective, emphasizing land availability and its capacity to deliver effective carbon storage across Europe under climate-smart rewilding strategies.

Example 2: Climate change adaptation for ecosystem resilience

Rewilding is expected to enhance the adaptive capacity of ecosystems to climate change by increasing connectivity, linking fragmented habitats, facilitating species movement, and promoting genetic exchange.[24,26,38,48] Connectivity is vital for maintaining stable populations and enabling ecosystems to adjust to shifting environmental conditions, as rising temperatures disrupt species' behaviors, physiology, migration, and life cycle events,[116–120] with some species relocating and others modifying their phenological schedules to cope with changes.[121–123] Those unable to adapt face increasing risks of extinction, contributing to biodiversity loss.[124] Beyond supporting biodiversity, rewilding also plays a crucial role in enhancing society's resilience and mitigating the impacts of extreme weather events, such as floods, droughts, and wildfires.[87,125,126] For example, restored ecosystems, such as wetlands that absorb and store stormwater or forests and grasslands that improve soil structure, infiltration, and water retention, can reduce exposure to climate hazards while supporting agricultural productivity and food security during droughts (Table 1, rewilding actions, socio-economic benefits, and socio-economic risks).[42,127] In this sense, rewilded ecosystems can both adapt to changing conditions and continue providing essential services to humans and wildlife alike.[42,125,127]

To identify where connectivity could most effectively facilitate climate change adaptation, we first delineated priority connectivity areas based on climate velocity, quantifying the rate and direction at which species must shift their distributions to maintain climatic suitability under projected warming (Table 2).[105] Climate velocity was computed by dividing the temporal temperature gradient, derived from the difference between baseline and end-of-century temperature projections over an 80-year interval, by the spatial temperature gradient, estimated using the Horn[128] slope algorithm, thereby yielding a measure of temperature displacement ($^{\circ}$C km^{-1} year^{-1}). We subsequently estimated potential rewilding by spatially projecting the probability of farmland abandonment, representing areas that could serve as corridors for species movement (Table 1, rewilding actions), using datasets and assumptions consistent with those applied in example 1 (Table 2).[103] Lastly, we characterized the biodiversity component of ecosystem structure through effective mesh size (Table 2),[100] a quantitative indicator of barrier-free habitat availability, calculated with a moving-window procedure that explicitly treated water bodies, permanent ice, and anthropogenic infrastructure as structural barriers to species movement (see supplemental information).

The spatial analysis revealed that regions with high connectivity and high climate velocity were particularly concentrated in northeastern Europe, including Poland, the Baltic States, Finland, parts of Sweden, and also westward in Ireland (Figure 3B). Species in these rapidly changing climate areas will need to shift ranges rapidly to maintain access to suitable habitats,[129] underscoring the critical importance of restoring large-scale migration corridors. By contrast, many mountainous regions in southern Europe, including northern Portugal, Spain, the Alps, the Apennines, and the Balkans, exhibited low climate velocity (Figure 3B). These regions are therefore less urgent for corridor development but remain important conservation priorities. Transforming abandoned land into dynamic mosaic landscapes with forests, grasslands, and shrublands could help maintain ecological connectivity and facilitate species movements toward more climatically stable regions.

Despite these opportunities, enhancing connectivity, while offering substantial ecological benefits, can also create conflicts with competing land-use priorities.[44,90] Where agricultural or development interests are strong, efforts to establish migration corridors must be carefully balanced with conservation goals and local community needs.[90,130–134] In human-dominated landscapes, maintaining smaller embedded corridors may be more feasible,[76,135] whereas in regions facing potential habitat fragmentation, such as parts of eastern Europe, establishing large protected areas linked by extensive corridors may be more effective.[136,137] Developing and expanding such corridors can facilitate rapid species migration toward more climatically suitable northern and mountainous areas, thereby strengthening ecological resilience (Table 1, climate change mitigation and climate change adaptation). Careful attention to trade-offs and competing land uses will be essential to ensure that rewilding delivers both ecological and societal benefits in the face of accelerating climate instability (Table 1, climate change mitigation, climate change adaptation, socio-economic benefits, and socio-economic risks).

Example 3: Social benefits and trade-offs related to the wildlife comeback

Rewilding can offer society both significant opportunities and complex challenges (Table 1, socio-economic benefits and socio-economic risks). Restoring degraded landscapes into healthy ecosystems can improve air and water quality, enhance food security, regulate disease, and strengthen resilience to natural hazards.[138,139] It can also create new economic opportunities through ecotourism, sustainable land use, and reduced reliance on environmentally harmful subsidies while reviving social and economic resilience in rural areas.[45,140–142] Rewilding may further provide psychological and health benefits, particularly in urban settings, and surveys show that many Europeans prefer landscapes with wilder features, such as complex forests and natural floodplains.[143–145] At the same time, rewilding can displace existing land uses, elevate wildfire risks, and intensify human-wildlife conflicts, generating opposition in regions where nature is perceived as threatening.[113,146–148] These contrasting dynamics highlight the need for careful planning and management to ensure that rewilding delivers both ecological and societal benefits (Table 1, climate change mitigation, climate change adaptation, socio-economic benefits, and socio-economic risks).

To evaluate trade-offs between social benefits and risks, we first quantified rewilding outcomes by mapping two contrasting societal dimensions: potential wildlife tourism and risk of conflict with livestock production (Table 1, socio-economic benefits and socio-economic risks; Table 2). For tourism, potential visitor demand was estimated by integrating human population density[149] with willingness-to-travel functions relating distance to visitation probability,[106] combined with areas of current and projected large mammal presence (Table 2). To assess conflict risk, we identified areas where projected range expansions of brown bear (*Ursus arctos*) and gray wolf (*Canis lupus lupus*) may overlap with livestock production, using spatial densities of cattle, sheep, and goats across Europe,[107] along with reindeer distributions in Scandinavia.[150] We then delineated potential rewilding areas by projecting the likely range expansion of large mammals, prioritizing high-probability colonization zones when current and future ranges overlapped (Table 2).[95] Finally, we defined the biodiversity component as the community composition of large mammals, using current distribution data for eight focal species[95] (see supplemental information).

Our results suggest that regions most likely to attract ecotourism driven by wildlife comeback are concentrated in central Europe, including southern Germany, Switzerland, and Austria, as well as parts of southern Europe such as northern Iberia (notably the Pyrenees), southern France, and northern Italy (Figure 3C). These areas combine recovering populations of large mammals with dense human populations, which together increase accessibility and tourism potential. Conversely, areas with high potential for livestock-predator conflict include northern Spain, Italy, Romania, and parts of the Balkans, especially the Greek peninsula (Figure 3D). These regions host expanding populations of brown bears and wolves while maintaining high densities of free-ranging or semi-extensive livestock, creating conditions for frequent depredation events.[151] Some mitigation measures are already being implemented in high-conflict areas, such as nighttime fencing or the use of livestock-guarding dogs in the Iberian Peninsula, which can substantially reduce predation pressure; however, these approaches are not universally effective and may require adaptation to local ecological and social contexts.[152,153]

Rewilding is often framed as an inspiring solution, yet its consequences for local economies can make it socially and politically complex.[40] While the trends we found highlight the potential for ecotourism to generate significant economic benefits for these regions, it is important to recognize that the success of this industry heavily depends on the aesthetic appeal of the landscapes, underscoring the need to preserve and enhance natural beauty alongside conservation efforts.[154] Overall, rewilding initiatives have the potential to promote economic growth at various levels: from local landowners benefiting directly from rewilding on their lands to regional economies with emerging ecotourism-related companies and nationally through increased tourism (Table 1, socio-economic benefits and socio-economic risks).[40,45] By attracting visitors to restored landscapes and culturally rich areas, these efforts can potentially generate revenue and incentivize conservation. However, there is also a risk that economic gains may be prioritized at the expense of ecological integrity.[142] This focus can lead to the commodification of nature, potentially clashing with traditional public access rights and alienating local ecotourists who value simplicity and challenge in their experiences.[141] Furthermore, the increased presence of wildlife and potential for natural disturbances in rewilded areas present additional risks to human activities and infrastructure.[155] Successfully balancing the ecological benefits of rewilding with the need to protect human interests and ensure public safety requires careful planning and management,[154] alongside a commitment to equitable and sustainable practices that avoid over-reliance on ecotourism and prioritize genuine ecological benefits alongside community well-being.[156]

INTEGRATING CLIMATIC, ECOLOGICAL, AND SOCIAL CO-BENEFITS THROUGH CLIMATE-SMART REWILDING

Achieving climate-smart rewilding requires navigating a constrained solution space in which carbon, biodiversity, and socio-economic objectives only partially overlap. Although these trade-offs are increasingly recognized, they remain difficult to operationalize because interventions optimized for one objective can limit flexibility under others.[157] Restoration strategies aligned with near-term climate mitigation often emphasize rapid biomass accumulation, whereas biodiversity-oriented approaches favor ecosystem heterogeneity and long-term

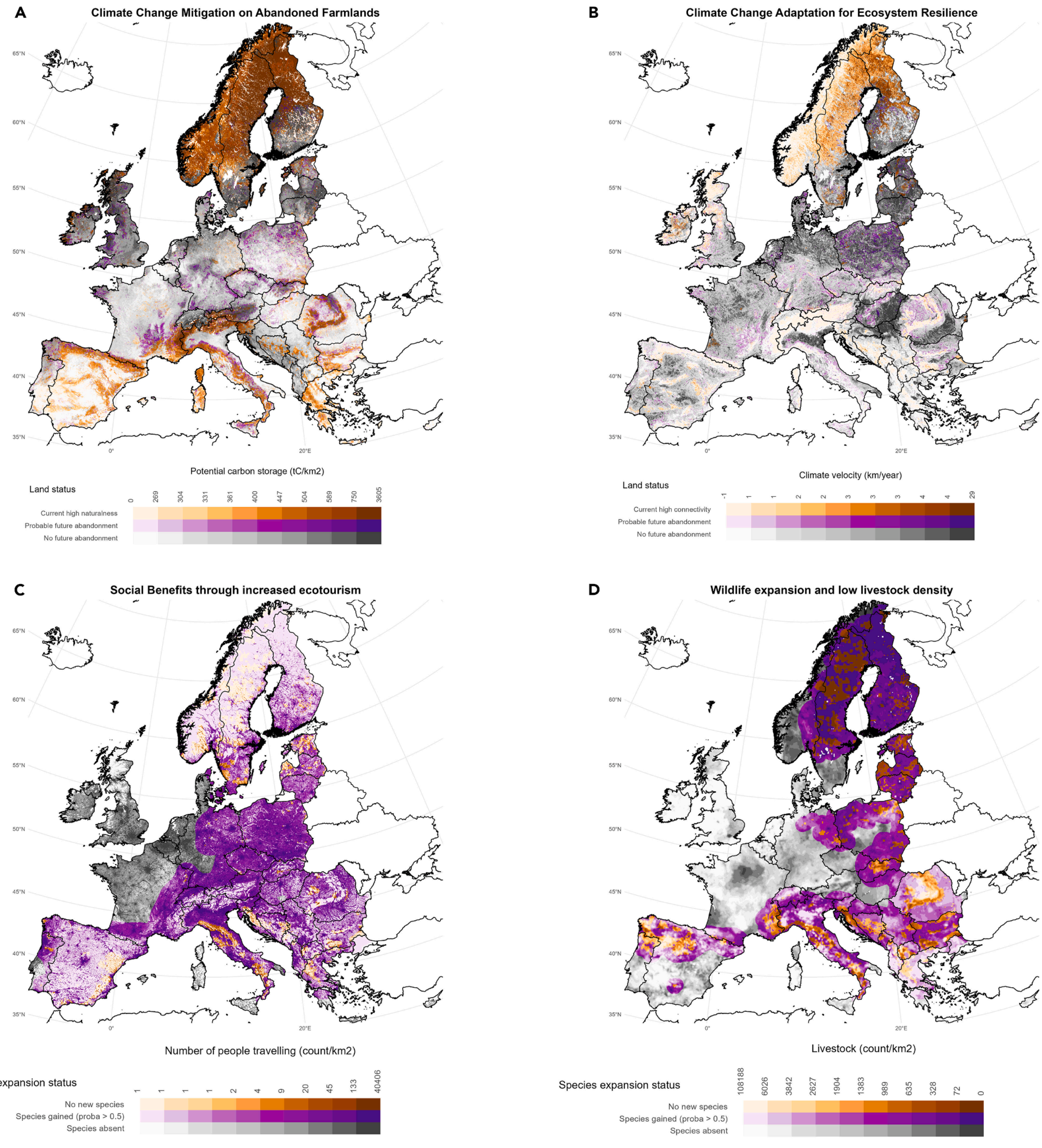

Figure 3. Spatial distribution of modeled rewilding outcomes integrating ecological, climatic, and socio-economic dimensions across Europe

(A–D) (A) Climate change mitigation potential expressed as carbon storage on land with a high probability of agricultural abandonment. (B) Climate change adaptation potential combining effective mesh size and climate velocity to identify areas supporting ecosystem resilience. (C) Social benefits from increased ecotourism potential, integrating probabilities of large mammal range expansion with visitor density. (D) Social risks from human-wildlife conflict, combining predicted wolf and bear expansion with livestock density. Color scales distinguish current versus potential future conditions: purple indicates areas with projected change (e.g., abandonment or species expansion), orange shows existing natural disturbance or connectivity, and white-to-black gradients represent low rewilding potential or absence of target species.

self-regulation, complicating spatial prioritization and policy implementation.[8] Our spatial analyses illustrate this constraint: as shown in examples 1 and 3, areas with high potential for carbon storage or biodiversity benefits are geographically limited and rarely coincide (Figure 3). These patterns highlight the risks of assuming automatic co-delivery of climate and biodiversity outcomes and underscore the need to move beyond single-metric optimization toward a single, coherent, spatially explicit

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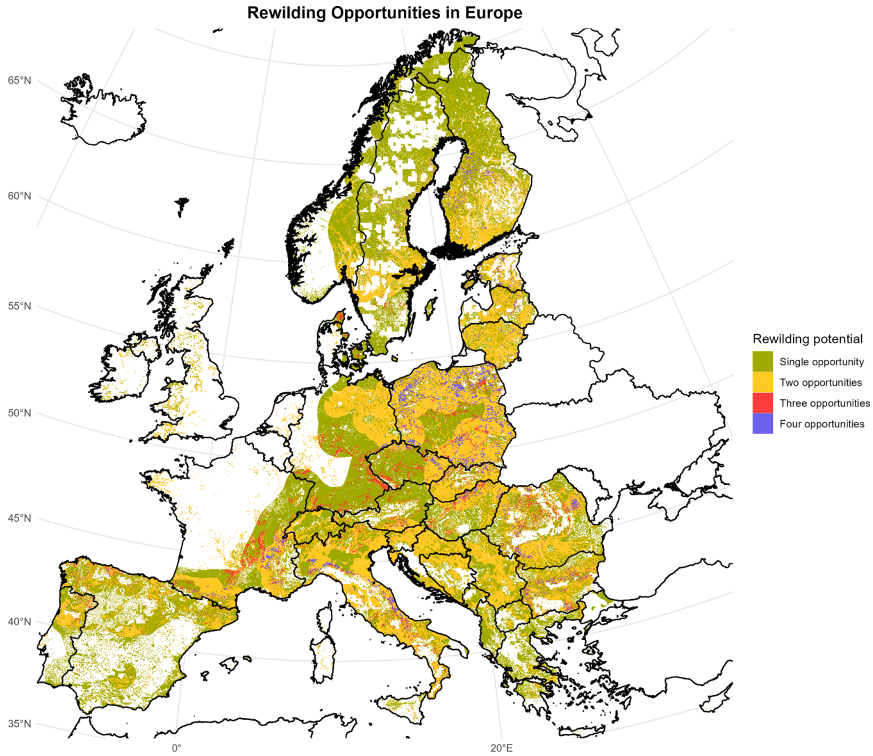

Figure 4. Areas of synergistic rewilding potential across Europe, highlighting regions where multiple benefits overlap (excluding the lowest 20% of values)
Color scheme indicates the following: green, a single benefit is present; orange, two benefits overlap; red, three benefits overlap; and purple, 4-fold overlap, representing the highest potential for delivering comprehensive ecological and socio-economic benefits.

prioritization framework that identifies where synergies are feasible and where trade-offs are unavoidable.

We identify regions in Europe where multiple positive outcomes of rewilding are most likely to co-occur. We mapped the spatial overlap of the four key opportunity layers (shown in purple in Figure 3), excluding areas in the lowest 20% of values. Building on the opportunities mapped in the previous examples (Figure 3), we identified areas where strong single rewilding opportunities occur (see supplemental information for further details) and, subsequently, regions where these advantages—carbon sequestration, increased biodiversity, and socio-economic gains—converge (Figure 4). Together, these maps illustrate how opportunities accumulate under different scenarios and provide a spatially explicit foundation to support regional conservation and rewilding planning. Our spatial analysis identified distinct regions where multiple rewilding co-benefits converge, particularly for climate change mitigation and adaptation, as well as opportunities for ecotourism (Figure 4). These convergence areas are most prominent in central and eastern Europe, including eastern Germany, Poland, the eastern Czech Republic, Slovakia, western Hungary, and parts of Romania and Bulgaria. Additional hotspots occur in the French Alps, the northern Iberian Peninsula, northern Denmark, southern Sweden, and southern Finland, indicating further potential for achieving multiple rewilding benefits. Areas where all assessed benefits—climate mitigation, climate adaptation, social well-being, and reduced conflict risk—coincide are more spatially constrained and are concentrated mainly in eastern Europe, with smaller clusters in southern Europe, notably in the Apennines and southern France (Figure 4).

By mapping the spatial convergence of climate mitigation, biodiversity recovery, ecosystem resilience, and socio-economic opportunities, we provide a practical tool for prioritizing regions where rewilding efforts are most likely to deliver synergistic outcomes. The concentration of high-opportunity areas in eastern and southern Europe highlights the importance of considering regional context, as these landscapes often retain greater ecological potential and lower levels of conflict than more intensively managed northwestern regions. However, the limited extent of areas where all benefits align underscores the need for careful planning and adaptive management to avoid unintended consequences, such as biodiversity loss from inappropriate afforestation or social pushback from increased human-wildlife interactions. This integrative approach provides a spatially explicit foundation for prioritizing rewilding interventions where they are most likely to deliver optimized combined benefits.

CONCLUSIONS, CAVEATS, AND FUTURE OUTLOOK

This study introduces a novel framework aimed at guiding rewilding initiatives that effectively address the challenges posed by global climate change and enhance biodiversity and societal outcomes. The climate-smart rewilding framework builds upon earlier methodologies by integrating aspects of climate change mitigation and adaptation alongside socio-economic considerations into the planning and execution of rewilding efforts.[24,27,32] By recognizing the close link between biodiversity and climate, our approach provides a comprehensive, policy-relevant framework. Its core focus is to enable species and ecosystems to adapt to rapid climate change while underscoring the crucial role of ecosystems in carbon sequestration. The framework promotes the development of self-sustaining ecosystems as a foundation for effective rewilding while integrating rewilding into climate mitigation efforts and assessing socio-economic impacts to guide policymakers and conservationists.[158]

Previous spatial studies have identified global and European priorities for biodiversity conservation and restoration[159–161] and explored opportunities for rewilding and ecological connectivity within Europe.[64,103] Building on this foundation, our study advances the restoration field by integrating land abandonment, protected area connectivity, and trophic reintroduction potential into a single European-scale framework explicitly designed to inform rewilding strategies under climate resilience objectives.

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By harnessing nature's capacity for both mitigation and adaptation, the framework creates pathways for ecosystem restoration and societal benefits. Successful implementation, however, requires careful planning, strong community engagement, and adaptive management to minimize risks. Although climate change often diverts attention and resources toward immediate mitigation and disaster response,[36] it also generates new opportunities. For instance, declining profitability or productivity of agricultural lands is leading to widespread abandonment, opening space for conservation and ecosystem restoration.[64,162,163]

Our framework and its spatial analysis shine a light on potential trade-offs within the key ecological components of rewilding (Figure 2; Table 1), particularly in the context of climate change mitigation and adaptation. For example, enhancing habitat connectivity through large-scale restoration can support species movement and woody plant regeneration (Table 1, rewilding actions) but may elevate wildfire risks in areas where large wildlife is scarce, potentially compromising carbon sequestration efforts (Table 1, socio-economic benefits and socio-economic risks). Likewise, re-establishing natural disturbance regimes might improve ecosystem integrity while posing challenges to business profitability and local livelihoods (Table 1, climate change mitigation, climate change adaptation, socio-economic benefits, and socio-economic risks). These patterns emphasize the need for context-specific strategies that explicitly assess trade-offs. A standardized one-size-fits-all approach is insufficient, as effective rewilding interventions depend on local ecological conditions, climate dynamics, socio-economic contexts, and clearly defined objectives such as carbon storage, biodiversity recovery, or climate resilience.

While the framework offers many promising opportunities, it is important to recognize its limitations, especially in its spatial exploration, which may oversimplify complex interactions and trade-offs among biodiversity, climate change, and socio-economic factors. This simplification can result in varying assessments of economic benefits, risks, and opportunity costs, including potential conflicts between human populations and wildlife. For example, the socio-economic maps (Figures 3C and 3D), which are based on a limited set of eight large mammal species, are inherently conservative estimates and may underestimate the potential for species dispersal and colonization over time. In particular, the framework may not fully capture how future changes in climate and society could reshape recolonization and persistence, including the expansion of new species, some of which are politically or socially sensitive (e.g., wolves), into areas currently deemed unsuitable.[164] Its performance is also context dependent, so implementation will often require adjustments to match the relevant spatial scale and local ecological and socio-economic conditions. Therefore, establishing clear success criteria and measurable indicators for climate-smart rewilding is crucial for its effective application.[62,61,157,165,166]

Looking ahead, future research should aim to explore a diverse range of intervention strategies beyond those presented in Table 1 and refine local selection criteria to optimize rewilding outcomes.[62] This exploration could include methods to boost trophic complexity, detailed analyses of connectivity to evaluate corridor designs, and assessments and modeling of disturbance regimes to balance ecosystem resilience with socio-economic aims. It could also include more direct assessments of societal benefits and disbenefits of different rewilding strategies while considering distribution and justice effects.[167] Improving the application of the climate-smart rewilding framework will require integrating it with emerging ecosystem accounting standards under the UN System of Environmental-Economic Accounting (SEEA), leveraging widely accepted and standardized ecosystem datasets now adopted in the EU and internationally (e.g., national ecosystem reporting, ESA Earth observation, TNFD, Nature Positive Initiative, and GBF), which could in turn accelerate uptake and support the integrated landscape management approaches discussed in this study.[168,169] To ensure the broader applicability of these strategies, adapting indicators to regional contexts, integrating Indigenous and other traditional knowledge systems, and tackling diverse governance challenges will be vital.[170] Comprehensive case studies across varied biomes will further validate the framework's effectiveness.[171] In conclusion, successfully implementing climate-smart rewilding strategies requires the incorporation of adaptive management frameworks, robust monitoring and evaluation methods, and investments in capacity-building and knowledge-sharing initiatives. This framework provides valuable guidance for policy and restoration efforts, aligning with the Convention on Biological Diversity (CBD) and EU biodiversity restoration targets.[5,172] By contributing to these important goals, our approach can mobilize additional resources and drive meaningful progress in addressing the intertwined challenges of climate change and biodiversity loss.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources can be directed to the lead contact, Gavin Stark (gavinstark89@gmail.com).

Materials availability

This study did not generate new, unique materials.

Data and code availability

The materials required to reproduce the results and figures in the main text, including code, scripts, and data, are available on Zenodo: https://zenodo.org/records/20266679 (DOI: 10.5281/zenodo.20265711).

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AUTHOR CONTRIBUTIONS

Conceptualization, G.S., M.W., N.F., A.H., and H.M.P.; formal analysis, G.S. and M.W.; investigation, G.S. and M.W.; methodology, G.S., M.W., N.F., and H.M.P.; project administration, H.M.P. and A.H.; supervision, N.F. and H.M.P.; visualization, G.S. and M.W.; writing – original draft, G.S.; writing – review & editing, all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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