Current Biology

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Expanding European protected areas through rewilding

Highlights

- Ca. 117 million hectares (ha) is suitable for rewilding, with 70% in cooler climates
- Passive rewilding opportunities are predominant in Scandinavia, Scotland, Iberia
- Active rewilding opportunities are widely distributed across Europe
- Rewilding provides an alternative land use to land abandonment in Europe

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In brief

Araújo and Alagador develop an approach to prioritize European landscapes for rewilding, identifying 117 million hectares (ha) as suitable. Passive rewilding is prominent in Scandinavia, Scotland, Iberia, the Baltics, Ireland, and southeastern Europe, while active rewilding is viable in Corsica, Sardinia, southern France, the Netherlands, Denmark, Sweden, and Norway.

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Expanding European protected areas through rewilding

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SUMMARY

Rewilding seeks to address biodiversity loss by restoring trophic interactions and fostering self-regulating ecosystems. Although gaining traction in Europe and North America, the extent to which rewilding can meet post-2020 protected-area targets remains uncertain. We formulated criteria to map suitable areas for rewilding by identifying large tracts of land with minimal human disturbances and the presence of key mammal species. We find that one-quarter of Europe, approximately 117 million hectares (ha), is compatible with our rewilding criteria. Of these, 70% are in cooler climates. Passive rewilding opportunities, focused on managing existing wilderness, are predominant in Scandinavia, Scotland, the Iberian Peninsula, and notably in the Baltic states, Ireland, and southeastern Europe. Active rewilding opportunities, marked by reintroduction of absent trophic guilds, are identified in Corsica, Sardinia, southern France, and parts of the Netherlands, Denmark, Sweden, and Norway. Our mapping supports European nations in leveraging land abandonment to expand areas for nature conservation, aligning with the European Biodiversity Strategy for 2030. Nevertheless, countries with limited potential for rewilding should consider alternative conservation strategies.

INTRODUCTION

The recent Global Assessment Report on Biodiversity and Ecosystem Services[1] underscores that nations, collectively, have not met the internationally agreed-upon biodiversity targets.[2] However, this challenge manifests differently across the globe. In many developing countries, the primary struggle is to prevent the further destruction of their remaining pristine natural ecosystems.[3] In contrast, several developed nations are identifying opportunities to rewild areas that were previously developed or disturbed,[4,5] capitalizing on abandoned agricultural or post-industrial lands.[6] Highlighting the urgency and scale of the challenge, the United Nations (UN) declared 2021–2030 the "UN Decade on Ecosystem Restoration", emphasizing the need to prevent, halt, and reverse ecosystem degradation to avert potential mass extinctions.[7] Complementing this, both the Bonn Challenge and the New York Declaration on Forests have set an ambitious goal to restore up to 350 million hectares (ha) worldwide by 2030.

In Europe, the moment is particularly auspicious for restoring areas for biodiversity conservation because decreasing cropland area[8] is prompting a debate of what land uses could emerge as an alternative to the abandonment of the less productive farmlands.[9,10] Additionally, on the political front, several initiatives are converging into the goal of maintaining and, whenever appropriate, increasing the natural capital of the European continent. First and foremost, the European Union has launched the European Biodiversity Strategy for 2030, which urges member states to increase the extent of their protected areas by up to 30% of European land and sea while setting aside at least 10% of the territory for strict conservation.[11] In 2009, European Parliament passed a "Resolution on Wilderness in Europe" calling for new wilderness areas to be conserved through legal conservation of existing wildlands, rewilding, and promotion of the value of wilderness. The European Commission also published a technical report providing the "Guidelines on Wilderness and Natura 2000"[12] and, more recently, developed a working document on "Criteria and Guidance for Protected Areas Designation" under the European Biodiversity Strategy for 2030[13] that explicitly recognizes the principles inherent to managing "species and habitats protected under the Nature Directives that benefit from wilderness management" should also be "applicable to areas with potential for rewilding". Internationally, there is also a strong focus on ecological restoration.

Amid a suite of conservation strategies, rewilding stands out as a promising approach for both conserving biodiversity and restoring ecosystems. The approach dovetails with initiatives promoting nature-urban coexistence in cities and sustainable practices in agriculture and forestry.[14] Rewilding offers an avenue to expand protected areas, even in regions with significant human history,[15] and can bolster climate adaptation policies for biodiversity.[16] The pressing question remains: to what extent can rewilding help meet the European Biodiversity Strategy for 2030 targets, and which countries stand to gain the most?

While the rewilding debate persists,[17,18] there is a shared drive to counteract biodiversity loss and, where feasible, prioritize natural processes over anthropogenic influences.[19] Depending on the regional context, some have argued that a degree of recoupling of human-animal relationships might be also warranted.[20] Much has been discussed about how to manage rewilding,[21] but the "where" question received comparatively less attention. That is, out of all the potentially suitable locations for rewilding, which ones should be prioritized? This question is important because there are significant numbers of rewilding initiatives, for example, involving land acquisition and/or management in places such as Bulgaria, Croatia, Germany, Italy, the Netherlands, Portugal, Romania, Spain, and Sweden.[22,23] In the absence of clear criteria for identifying and prioritizing rewilding areas, there is a risk that the limited resources available for conservation could be misallocated.[24]

We have developed transparent, repeatable, and simple criteria for mapping rewilding opportunities and guiding efforts for land acquisition and management. Given the range of possible definitions,[25] we categorize rewilding into two primary types. Active rewilding involves the reintroduction of missing native herbivore and carnivore species critical to the regeneration of top-down trophic interactions.[26] Passive rewilding focuses on management interventions that promote natural dynamics, including recolonization of missing large carnivores and herbivores.[6] The overarching goal for both approaches is to enable self-regulation of ecosystems by restoring or maintaining complex top-down trophic interactions. Essential to this self-regulation is the minimization of human disruptions,[19] the preservation of large natural areas,[27] and the presence of key carnivore, omnivore, and herbivore species for the management of natural processes.[28]

To identify rewilding opportunities throughout Europe, we executed a four-step protocol. The initial step involved the identification of minimal human footprint (hf) areas on a 1 km × 1 km grid.[29] Grid cells reflecting a hf value (on a scale from 0 to 50) of hf $\leq$ 5 were earmarked, and a sensitivity analysis was further conducted to assess the consistency of results to hf threshold choice variation (see supplemental information). This approach is rooted in the evidence that human activities are primary contributors of contemporary species extinctions.[30] The guiding principle is that conducting rewilding in areas less impacted by human activities would more easily lead to the reconstitution of complex trophic communities.[31]

Abiding by established conservation guidelines,[27] the second step consisted of grouping the low-impact areas into continuous clusters. Aggregating low-impact areas into clusters increases the chance that these areas will be able to maintain home ranges of critical species and facilitate mobility between them. Area clusters were categorized by size: areas greater than 10,000 ha and smaller than 50,000 ha were classified as meso-rewilding ecosystems; those exceeding 50,000 ha as macro-rewilding ecosystems; and areas over >100,000 ha as mega-rewilding ecosystems. The focus on such large areas is driven by the stated goal of replacing human management of plant biomass, either using domestic herbivores or managing natural herbivore populations by top-down natural regulation driven by large carnivores and omnivores.[32] Ensuring long-term (>100 years) survival of carnivore and omnivore populations with large home ranges has been estimated to demand vast territories exceeding 100,000 ha.[33] This threshold may be conservative in certain cases. For instance, home ranges of brown bears extending over 400,000 ha have been documented in Serbia.[34] Smaller regions will generally restrict the viability of populations of species with large area requirements and also limit persistence of metapopulations, which depend on natural colonization by subpopulations.[35] In other words, the smaller the rewilding sites, the greater the need for human management of natural processes.[27] A familiar example is the requirement for human intervention in controlling herbivore grazing when areas are too small and significant carnivore populations are absent[36] (Figure S1A).

The third step revolved around the choice of key species available for rewilding and the discrimination between areas qualifying for active and passive rewilding (Figure S1A). The process involved mapping the distribution of key species, including weighty (>4 kg) carnivores and omnivores, as well as select herbivores recognized for their impactful role in energy circulation within ecosystems either because of their substantial body mass (>20 kg) or because of their high local abundance across extensive areas,[37] such as small mammals like rabbits and hares[38] (Table S1; Figure S2). We note that we excluded species such as the red fox and wild boar owing to their ubiquitous presence across environments—including urban areas. Their inclusion would have complicated the identification of high-priority rewilding areas intended to be less influenced by human activities.

In our scheme, an area qualifies for passive rewilding if it includes the presence of at least one key herbivore in meso-rewilding ecosystems. In macro- and mega-rewilding ecosystems, the requirement would be for at least one key herbivore and carnivore species to co-occur. Likewise, an area would qualify for active rewilding if it did not meet the species occurrence criteria established for passive rewilding. Although these criteria are arbitrary, they effectively illustrate the general principles of our approach and can be adapted to meet the needs of more specific applications. To evaluate the impact of different numbers of key species thresholds on the results, we conducted a sensitivity analysis (see STAR methods). An integral part of rewilding is the establishment of an expected baseline regarding the pool of species that would be expected in the absence of anthropogenic pressures. To that end, we analyzed the estimated historical potential distribution of selected herbivore, carnivore, and omnivore species (herein referred to as "natural range")[39] prior to Pleistocene-Holocene extinctions and compared it with the current distribution.

Concluding our process, we used Marxan[40] to run a maximum coverage algorithm at the country level. The objective was to ascertain the feasibility of enabling European nations to reach the stipulated 30% and 10% protected-area coverage milestones through a rewilding-oriented strategy that achieved conservation of large ecosystems with low human pressure and balanced trophic communities.

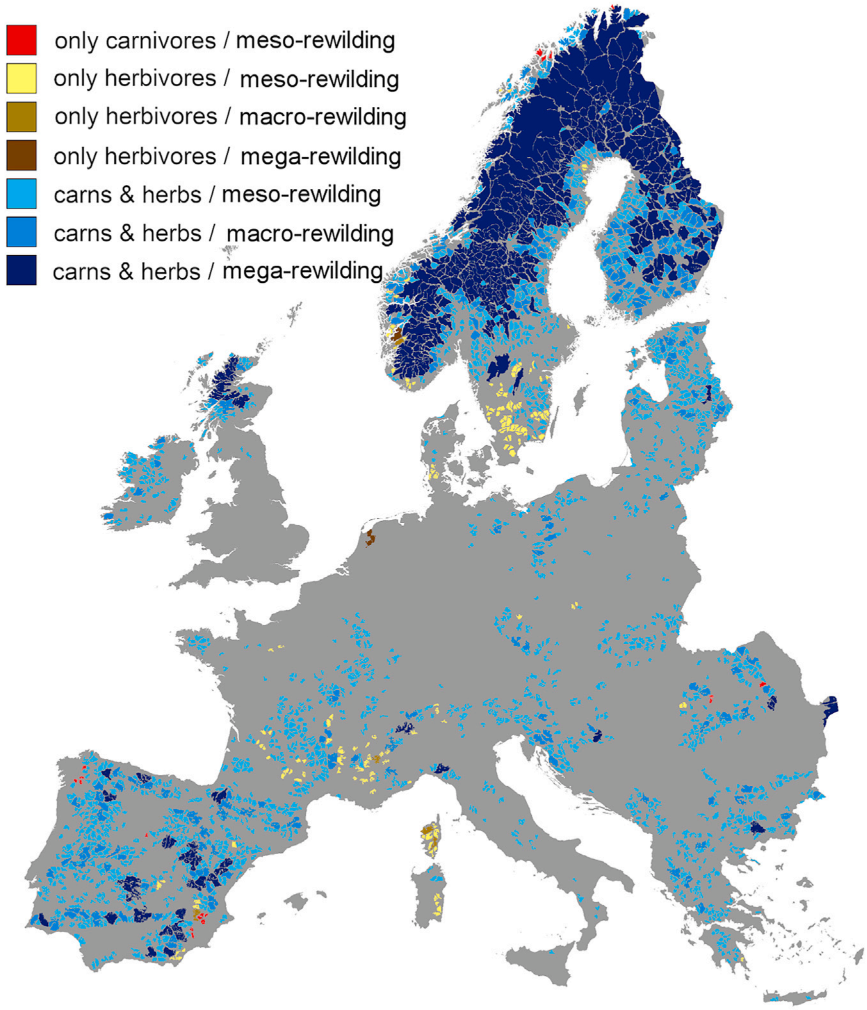

Figure 1. Mapping rewilding opportunities
Blue: areas primed for passive rewilding with both carnivore and herbivore species present. Yellow/brown/red: Areas requiring active rewilding via carnivore (yellow/brown) or herbivore (red) re-introductions. Gradients in blue and green show rewilding site sizes, transitioning from lighter (smaller) to darker (larger).
See also Figure S1.

RESULTS

Utilizing the described framework for mapping rewilding opportunities in Europe, we found that nearly 25% of the continent (roughly 117 million ha: 36.7%, 12.9%, and 50.4% for meso-, macro-, and mega-rewilding ecosystems, respectively) holds potential for rewilding (Figure 1). A great proportion of this area (76%) lies within Scandinavia, Scotland, and the Iberian Peninsula. These areas not only boast the most expansive rewilding potential but they also are where the mega-rewilding ecosystems consisting of extensive uninterrupted patches (>100,000 ha) with minimal human interference coincide with the occurrence of key herbivore and carnivore/omnivore populations. These attributes earmark these territories as ideal candidates for passive rewilding, which is generally more cost-effective and less divisive than its active counterpart. Areas such as the Baltic states, Ireland's west coast, and the mountainous regions of eastern and southeastern Europe also present prospects for passive rewilding, though in the macro- to meso-rewilding segments (Figure 1). For active rewilding, which requires the reintroduction of herbivore or carnivore/omnivore species, suitable locations include Corsica, Sardinia, southern France, the Netherlands, southern Denmark, southern Sweden, and southwestern Norway (Figure 1).

The criteria for distinguishing between regions needing active versus passive rewilding rely on the presence of at least one key herbivore or carnivore/omnivore. Yet, in reality, there is a gradient of trophic complexity, which varies with the numbers of trophic guilds and species per guild[41] that should ideally be factored into rewilding project designs. Some regions identified as viable for passive rewilding largely exceed our predefined threshold of one species per trophic category (carnivore and herbivore). Notable examples include large tracts in Scandinavia, Scotland, the Baltic states, and mountainous regions of the Iberian Peninsula, often featuring more than four species per trophic group (Figure S2). However, other regions distinctly lack in either carnivore/omnivore or herbivore species, with carnivores/omnivores more often being absent (Figure 2). For instance, extensive areas in western Iberia—such as the Côa Valley in northeastern Portugal—that are currently undergoing rewilding efforts[20] appear to have fewer carnivore species than their natural potential would suggest (Figure 2; also see Figures S4 and S5 for a sensitivity analysis contrasting passive and active rewilding categories based on species count variations).

By (exponentially) relating the area of active rewilding with the required number of occurring species, we observed that the European surface areas estimated to be suitable to active rewilding are more sensitive to variations in the minimum number of key herbivore species (area = 0.14 exp 0.78.nsp: p < 0.001; r2 = 0.97; where nsp refers to the number of species) than carnivore species (area = 0.11 exp 0.72.nsp; p < 0.001; r2 = 0.91) (Figure S5B). As the threshold of key herbivore and carnivore/omnivore species required for active rewilding rises (as reflected by the red and dark green bars in Figure S5B), there is a decline in the area identified as suitable for passive rewilding (denoted by blue bars). On the other hand, if stricter criteria for human impact are set in place (specifically, hf = 0), only Scandinavia emerges as a viable candidate for rewilding (as depicted in Figure S3). When human impact values fluctuate within the range of $0 < \mathrm{hf} \leq 5$, a proportional distribution of land cover classes within prospective

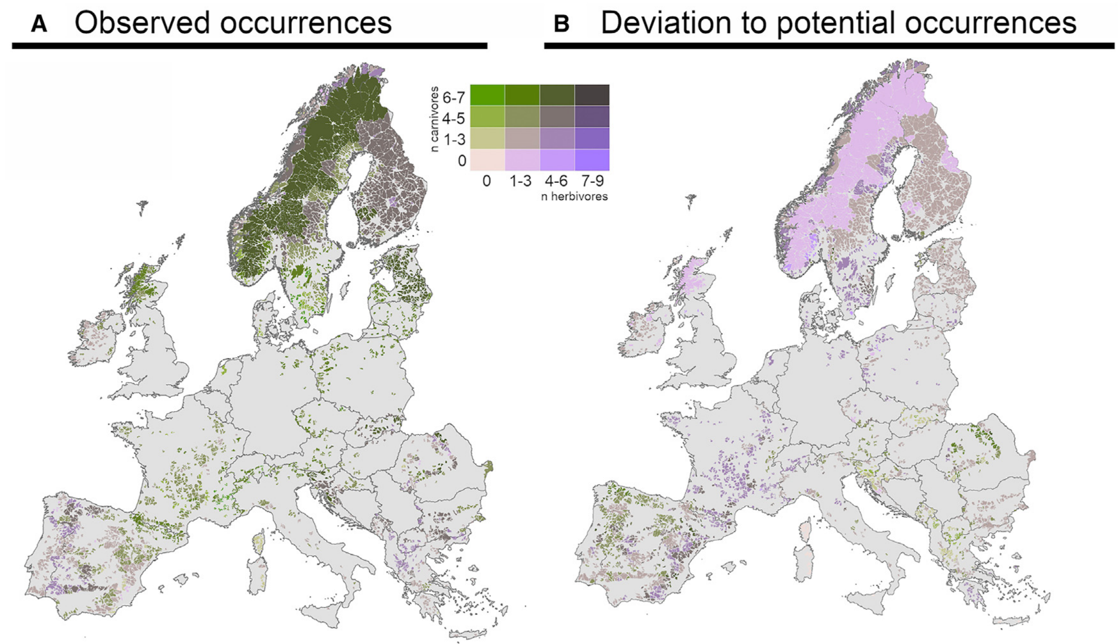

Figure 2. Species count within rewilding areas

(A) Observed counts of carnivore/omnivore and herbivore species.

(B) Number of absent species in each trophic group compared to historical distribution-based expected richness. See Figure S2 for a visualization of the observed and potential species richness of herbivores and carnivores in Europe.

rewilding locations appears (refer to Figure S4). Adjusting the parameter that accounts for human impact, Scotland and the Iberian Peninsula distinctly come forward as the next most favorable regions for rewilding after Scandinavia (as shown in Figure S3).

Naturally, focusing on the rewilding of areas already legally protected could entail lower financial costs and conflicts compared to rewilding unprotected, economically productive, areas. However, to attain the conservation and restoration targets of the European Biodiversity Strategy for 2030, designating new areas with rewilding potential as protected might be essential. When we superimpose areas already safeguarded at the national or European Union level (such as those within the Natura 2000 network) with territories having rewilding potential, it emerges that between 19.59% and 24.63% of European protected lands are suitable for passive rewilding projects (Table S2). Of these, only 0.27%–0.31% would demand active rewilding with the precise proportion depending on the species number criteria used to typify the rewilding approach (Table S2). However, a significant portion of the protected areas in central Europe, alongside regions in England, Wales, and Italy, exceed the hf threshold (hf > 5), which we use as boundary to delimit rewilding potential (Figure 3). This observation aligns with *a priori* expectations, because these regions encompass some of Europe's most intensively developed and populated areas. In contrast, a vast expanse of currently unprotected land, spanning regions such as Scandinavia, Scotland, the Iberian Peninsula, and the Baltic states, not to mention mountainous terrains in France, the Balkans, and Eastern Europe, display substantial potential for rewilding (Figure 3).

Overall, nearly three-quarters of potential rewilding areas exist outside currently protected areas, underscoring the opportunities for European countries to meet the post-2020 targets.[11,42] It is worth noting that a few nations, including Bulgaria, Germany, Greece, Luxembourg, Slovakia, and Slovenia, have already realized the 30% conservation target. However, most countries still have to earmark additional territories for conservation (Figure 4). Leveraging these rewilding opportunities, 11 nations, namely Estonia, Finland, France, Latvia, Montenegro, Norway, Poland, Portugal, Spain, Switzerland, and the United Kingdom, could potentially meet the 30% conservation target. Conversely, 17 other countries will need to focus on regions that currently bear heavier human disturbance (Figure 4).

The European Union has also laid down the target to conserve at least 10% of the territory within strictly nature-focused protected areas (e.g., categories I and II of IUCN). Only Norway meets the target, closely followed by Sweden and Finland (Figure 4). Countries such as Croatia, Estonia, Ireland, Latvia, Macedonia, Montenegro, Portugal, and Spain show considerable potential to attain the 10% strict conservation-area target, especially when the rewilding concept is harnessed to its fullest.

The use of conservation prioritization algorithms emerges as an effective approach to achieving protected area targets. In our study, we adopted specific criteria, including aspirations to fulfill the 10% strict protection and 30% overall land protection benchmarks for every European country. We emphasized preserving expansive land tracts, minimizing human interference, and accentuating regions with stable trophic relationships. Following these guidelines, we identified territories that could bolster the currently protected regions, consistent with national and European legal frameworks. For each country, the solution providing the largest number of occurring species in both trophic

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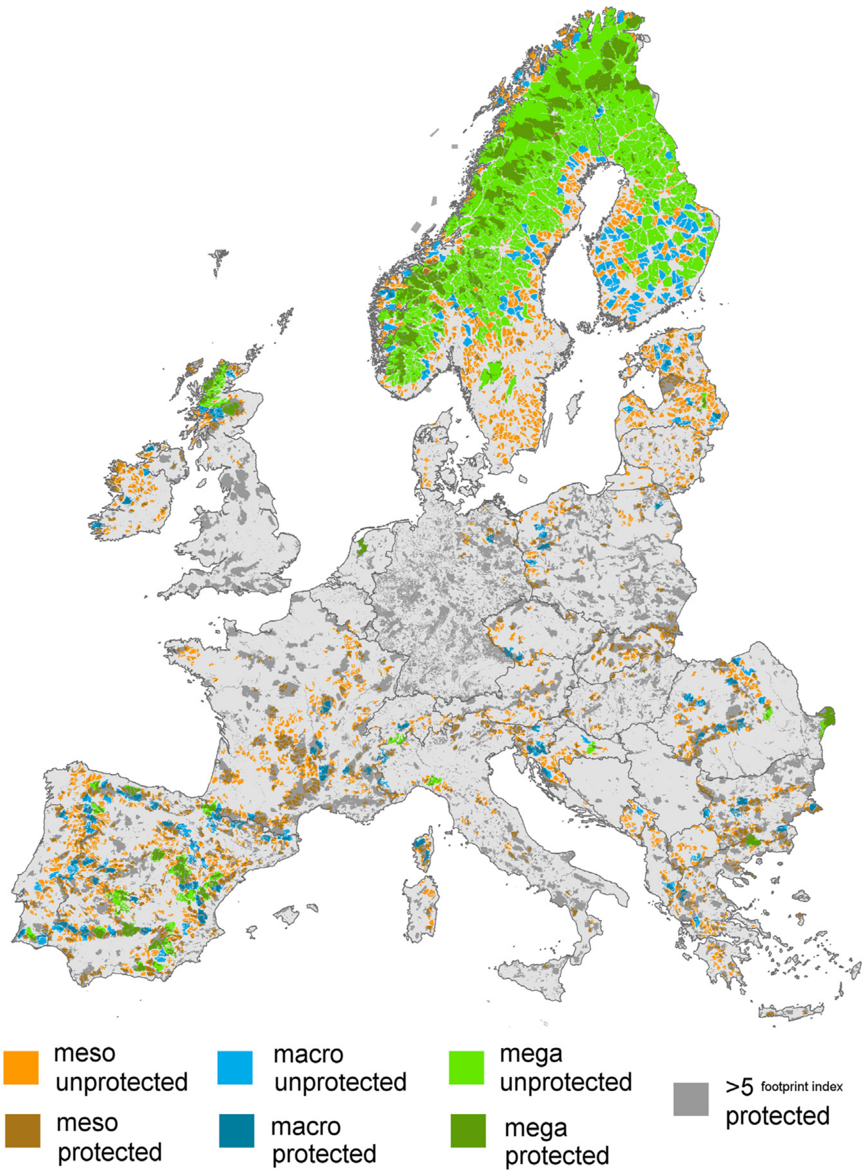

Figure 3. Rewilding potential versus protected areas in Europe
Grey: protected areas with low rewilding potential due to high human footprint.
Green: mega-rewilding ecosystems (dark green, protected; light green, unprotected).
Blue: macro-rewilding ecosystems (dark blue, protected; light blue, unprotected).
Orange: meso-rewilding ecosystems (dark orange, protected; light orange, unprotected).

classes was kept. Our analysis sorted countries into three categories. First, countries such as Norway, Sweden, and Finland, marked in yellow in Figure 5, are either on track or have already met their conservation targets, as showcased by their strict preservation of close to 10% of their rewilding areas. Second, some countries, also yellow-shaded in the map—including the aforementioned Scandinavian countries, Scotland, France, and others in southwestern and southeastern Europe—are positioned to achieve the 30% conservation mark if they conserve the designated rewilding areas. Conversely, nations depicted in white—mainly central European countries, England, Wales, and Italy, concerning the 10% goal; and Ireland, Belgium, the Netherlands, Denmark, Lithuania, southern and southeastern European countries, with regard to the 30% objective—will not reach their conservation aims by relying solely on proposed rewilding criteria. These observations underscore the need for a broader array of conservation strategies in these regions, possibly involving smaller protected areas with greater human interference.

Analyzing the intersection between areas of rewilding potential and the European climatic zones allows understanding of the biophysical context within which they occur. As shown in Figure 6, a significant fraction—almost 70%—of rewilding prospects in Europe are situated in colder climatic zones. This paints an uneven representation, implying that specific European biomes, especially the colder ones, are disproportionately suitable to rewilding interventions. Delving deeper, specific climate zones such as polar climates (ET), cold climates with chilly summers (Dfc and Dsc), and temperate climates that experience cold summers without a dry season (Cfc), exhibit greater opportunities for rewilding. These zones, despite their spatial extent, show a greater propensity for rewilding than what their area might suggest ($p < 0.001$; Table S4). This trend extends to temperate zones with warm, dry summers (Csb). Conversely, numerous other climate zones have fewer rewilding possibilities than their area would statistically dictate ($p < 0.001$). A plausible explanation for this observation lies in the intersection of climate and human activity. Typically, as regions exhibit milder climates—characterized by higher temperatures and increased water availability—they become more conducive for human inhabitation and activities. Such areas inherently become more attractive for agriculture, settlements, and other human-led endeavors, reducing their viability for rewilding initiatives.[43]

DISCUSSION

Rewilding is a powerful approach among various possible strategies aimed at preserving Earth's biological diversity.[7] In Europe, nearly a quarter of its land, equivalent to about 117 million ha, holds potential for rewilding, and roughly half of this area could harbor mega-rewilding sites with more than 100,000 ha. Large portions of this land are nestled within cold, remote expanses of Scandinavia and the Scottish Highlands. The tendency for wild spaces to be situated in regions that are colder and more

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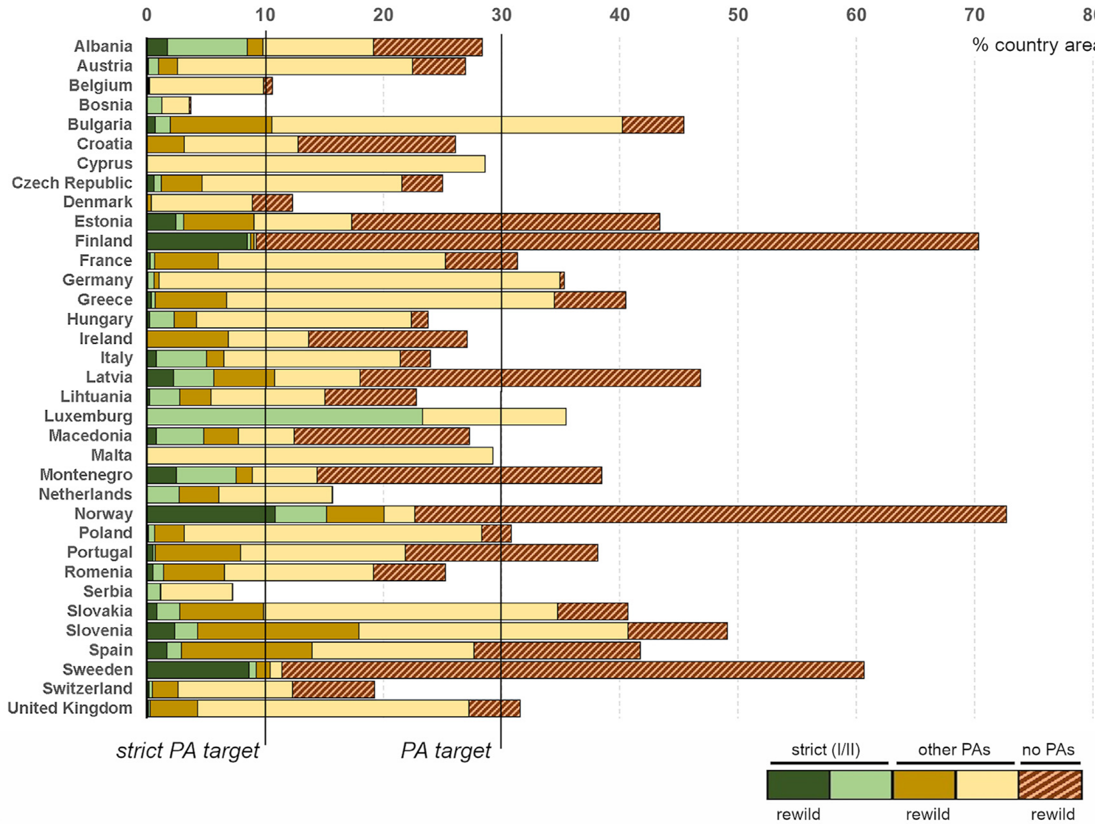

Figure 4. Rewilding potential in European protected areas

Dark/light green: area of strict conservation (IUCN categories I and II) with/without rewilding potential. Dark/light brown: other protected areas (including Natura 2000 sites) with/without rewilding potential. Striped orange: potential rewilding ecosystems not legally protected.
Vertical lines indicate 10% strict and 30% overall protection targets.

secluded—and often less biodiverse—is a pattern that is not exclusive to Europe.[44] This phenomenon results from the competition between humans and wildlife for space in the more productive, warmer, and wetter lands.[43] However, Europe presents exceptions, most notably the Iberian Peninsula, which despite its diverse temperate and arid climates remains one of the continent's biodiverse hubs.[45] The scattering of rewilding opportunities throughout Europe underscores a chance for national governments to enlarge their protected areas, especially in regions where human activities are sparse. This could lead to diminished opportunity costs and pave the way toward achieving European and global conservation and restoration benchmarks.

Yet, the possibility of rewilding vast territories with minimal human interference is not uniformly accessible across countries. Nations such as Belgium, Denmark, and the Netherlands, among others, face limitations in rewilding large, low-human-impact tracts (Figures 3, 4, and 5). These countries may, however, be well suited for alternative rewilding approaches that require more intensive management across smaller areas. To meet European conservation objectives,[11] these countries might consider land reclamation, transforming productive landscapes into conservation areas.[46] Others could focus on creating networks of micro-reserves[47,48] that protect smaller, relatively undisturbed habitats such as forests, scrublands, and wetlands scattered across suburban and rural settings. Additionally, traditional systems,[49] including multi-use systems,[50] historically intertwined with biodiversity-rich landscapes, such as the oak parklands in the Iberian Peninsula,[51,52] or the extensive agricultural[53,54] and forestry systems[55] in various parts of Europe, if managed sustainably, could provide valuable conservation opportunities. However, implementing such strategies in landscapes dominated by intensive farming[56] and forestry[57] presents significant challenges.

The proposed methodology outlines a flexible series of steps for identifying areas with rewilding potential. It is crucial to emphasize that the approach is adaptable rather than implying the adherence to rigid rules and thresholds. This flexibility acknowledges the significant uncertainties that exist, particularly regarding decisions on whether to actively introduce key species—in which case detailed plans for reintroduction must be developed—or to rely on their natural colonization. Natural colonization is generally preferred where feasible because it incites less controversy with local communities. However, the determination of whether active introductions are required to accelerate the restoration of natural processes involves complex considerations. For example, it requires understanding of ecosystems' alternative stable states and the critical roles different trophic guilds play in these dynamics. Furthermore, accurately assessing the likelihood of natural colonization demands advanced modeling techniques. These models should ideally integrate detailed information on the contiguity or proximity of potential

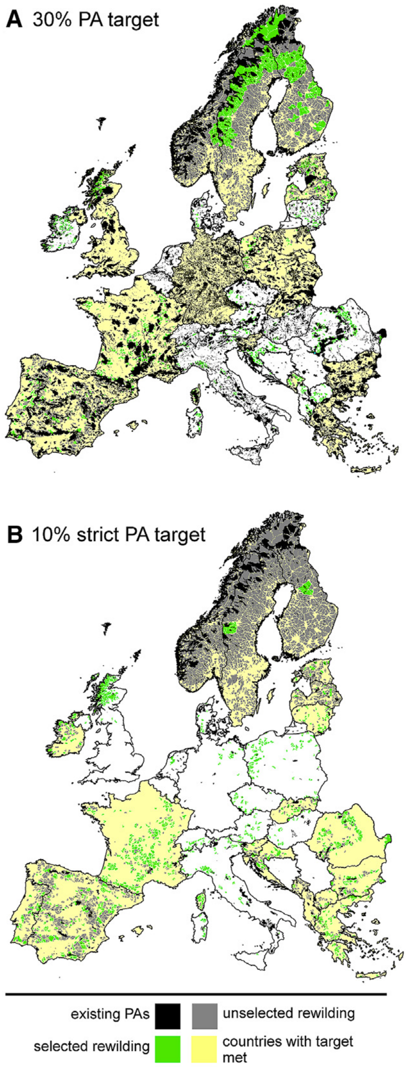

Figure 5. Country-level optimization for EU 2030 biodiversity targets
The yellow-shaded areas indicate countries meeting area targets, either through existing protected areas (PAs) (in black), or by complementing protected areas with rewilding sites (in green). Unselected rewilding sites (in grey) are candidate areas for rewilding that were not prioritized with our algorithm. White-shaded areas represent countries where proposed rewilding fails to meet targets. Notice that in (A) all protected areas are marked in black and considered for the 30% target, whereas in (B) only protected areas classified as IUCN categories I and II are considered for the 10% target and marked in black. See also Figure S8.

source populations, the habitat requirements for dispersal of the target species, and insights into their dispersal capabilities.[58] Our approach provides a framework that can be adapted as new information becomes available, ensuring rewilding efforts are both effective and reflective of the latest ecological insights.

Although the scientific mapping of rewilding opportunities is an instrumental first step toward guiding land acquisition and management decisions, the real challenge lies in its execution. Europe, with its intricate tapestry of historical, political, and socio-economic narratives, will inevitably face conflict when attempting to designate new protected areas unless they demonstrably benefit local communities.[59] These challenges are not merely environmental but are deeply rooted in societal perceptions and values. Any conservation endeavor, whether it is a passive or active rewilding of remote areas, or a more hands-on restoration of formerly productive terrains, is likely to stir debates unless the local community sees tangible benefits. Engaging with stakeholders, harnessing participatory planning methods, fostering dialogue, and proposing compensatory measures can pave the way toward sustainable, socially accepted solutions.[60,61]

In essence, we believe that scientists should transition from being prescriptive to acting as "honest brokers," presenting various scenarios, shedding light on potential trade-offs, and evaluating the implications of choosing one set of alternatives over others.[62] By emphasizing rewilding, the framework presented in this research provides a foundation to bolster accountability in the pursuit of meeting the ambitious targets set forth by the European Biodiversity Strategy for 2030.[11]

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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  - Protected areas
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  - Meeting the 2030 protected area targets at country level
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- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2024.07.045.

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AUTHOR CONTRIBUTIONS

M.B.A, and D.A. conceptualized the study. D.A. performed analyses. M.B.A. wrote the original draft. D.A. provided edits on the manuscript and drafted the methods. M.B.A. acquired funding for the study. All authors reviewed and approved the final version of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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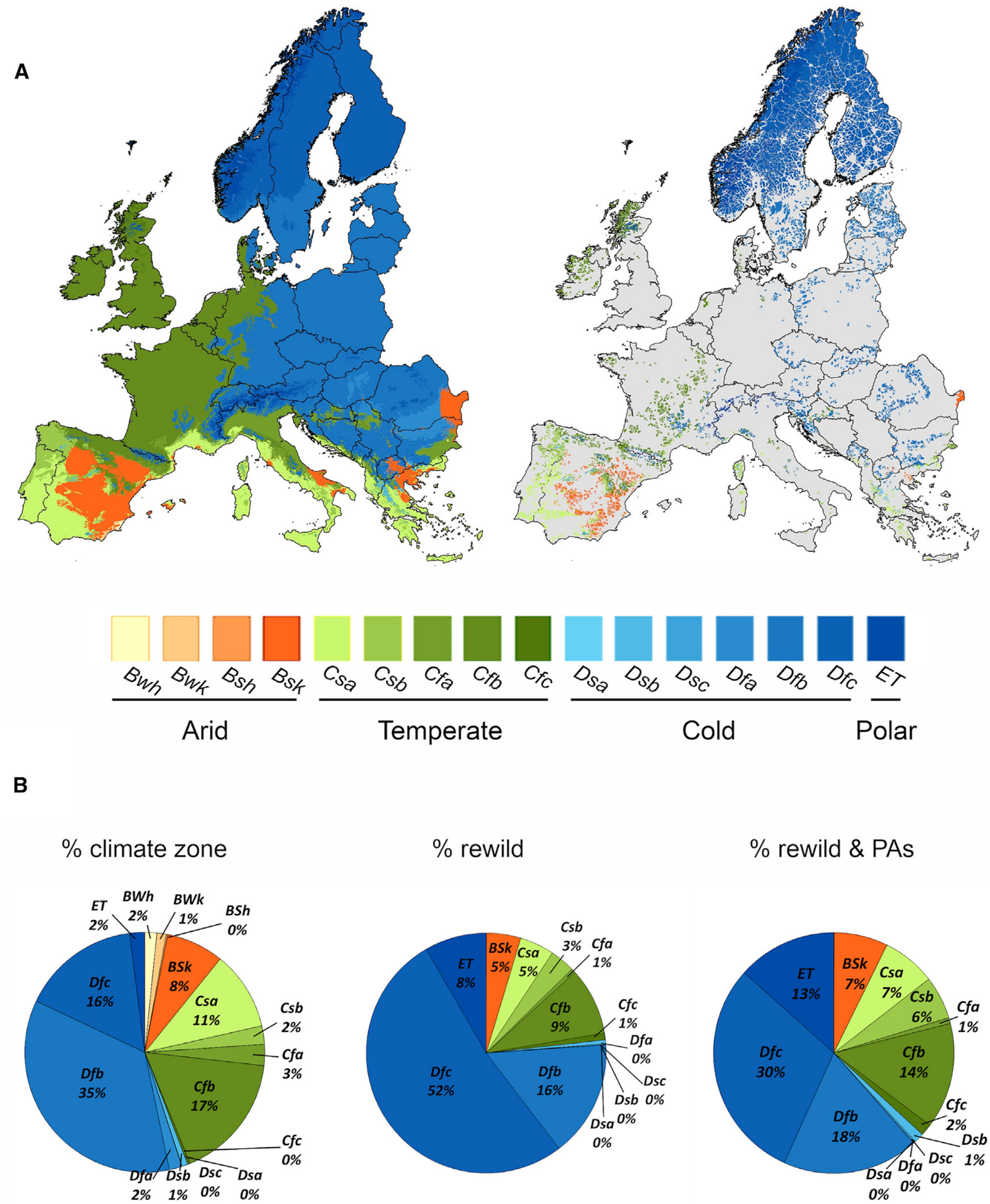

Figure 6. Correlation of European climate zones and rewilding potential

(A) Overview of European climate zones (left) and their relevance to potential rewilding (right).

(B) Comparative representation of each climate zone in Europe, protected areas, potential rewilding ecosystems, and those already protected.

Key: Bwh, hot desert; Bwk, cold desert; Bsh, hot steppe; Bsk, cold steppe; Csa, hot dry summer; Csb, warm dry summer; Cfa, hot wet all year; Cfb, warm wet all year; Cfc, cold wet all year; Dsa, hot dry summer, cold winter; Dsb, warm dry summer, cold winter; Dsc, cold dry summer, cold winter; Dfa, hot wet all year, cold winter; Dfb, warm wet all year, cold winter; Dfc, cold wet all year, cold winter; ET, polar frost.

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REFERENCES

1. IPBES (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services (summary for policy makers).

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://doi.org/10.5281/zenodo.3553579.

2. Visconti, P., Butchart, S.H.M., Brooks, T.M., Langhammer, P.F., Marnewick, D., Vergara, S., Yanosky, A., and Watson, J. (2019). Protected area targets post-2020. Science *364*, 239–241.
3. Bradshaw, C.J.A., Sodhi, N.S., and Brook, B.W. (2009). Tropical turmoil: a biodiversity tragedy in progress. Front. Ecol. Environ. *7*, 79–87. https://doi.org/10.1890/070193.
4. Josh Donlan, C., Berger, J., Bock, C.E., Bock, J.H., Burney, D.A., Estes, J.A., Foreman, D., Martin, P.S., Roemer, G.W., Smith, F.A., et al. (2006). Pleistocene Rewilding: An Optimistic Agenda for Twenty-First Century Conservation. Am. Nat. *168*, 660–681. https://doi.org/10.1086/508027.
5. Carey, J. (2016). Core Concept: Rewilding. Proc. Natl. Acad. Sci. USA *113*, 806–808. https://doi.org/10.1073/pnas.1522151112.
6. H.M. Pereira, and L.M. Navarro, eds. (2015). Rewilding European Landscapes (Springer Open).
7. UNEP (2021). Becoming #GenerationRestoration: Ecosystem restoration for people, nature and climate (United Nations Environment Programme).
8. Araújo, M.B., Nogués-Bravo, D., Reginster, I., Rounsevell, M.D.A., and Whittaker, R.J. (2008). Exposure of European biodiversity to changes in human-induced pressures. Environ. Sci. Pol. *11*, 38–45.
9. Ceaușu, S., Hofmann, M., Navarro, L.M., Carver, S., Verburg, P.H., and Pereira, H.M. (2015). Mapping opportunities and challenges for rewilding in Europe. Conserv. Biol. *29*, 1017–1027. https://doi.org/10.1111/cobi.12533.
10. Merckx, T., and Pereira, H.M. (2015). Reshaping agri-environmental subsidies: From marginal farming to large-scale rewilding. Basic Appl. Ecol. *16*, 95–103.
11. European Commission (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. EU Biodiversity Strategy for 2030 (European Commission).
12. European Comission (2013). Guidelines on Wilderness in Natura 2000 - Management of Terrestrial Wilderness and Wild Areas within Natura 2000 Network (European Commission Publications Office). https://ec.europa.eu/environment/nature/natura2000/wilderness/pdf/WildernessGuidelines.pdf.
13. European Comission (2022). Criteria and guidance for protected areas designations (European Commission).
14. Svenning, J.-C. (2020). Rewilding should be central to global restoration efforts. One Earth *3*, 657–660. https://doi.org/10.1016/j.oneear.2020.11.014.
15. Yang, R., Cao, Y., Hou, S., Peng, Q., Wang, X., Wang, F., Tseng, T.-H., Yu, L., Carver, S., Convery, I., et al. (2020). Cost-effective priorities for the expansion of global terrestrial protected areas: Setting post-2020 global and national targets. Sci. Adv. *6*, eabc3436. https://doi.org/10.1126/sciadv.abc3436.
16. Carroll, C., and Noss, R.F. (2021). Rewilding in the face of climate change. Conserv. Biol. *35*, 155–167. https://doi.org/10.1111/cobi.13531.
17. Nogués-Bravo, D., Simberloff, D., Rahbek, C., and Sanders, N.J. (2016). Rewilding is the new Pandora's box in conservation. Curr. Biol. *26*, R87–R91.
18. Rubenstein, D.R., and Rubenstein, D.I. (2016). From Pleistocene to trophic rewilding: A wolf in sheep's clothing. Proc. Natl. Acad. Sci. USA *113*, E1. https://doi.org/10.1073/pnas.1521757113.
19. Sinclair, A.R.E., Soulé, M.E., Virtanen, R., and Wardle, D.A. (2011). Trophic Downgrading of Planet Earth. Science *333*, 301–306.
20. DeSilvey, C., and Bartolini, N. (2019). Where horses run free? Autonomy, temporality and rewilding in the Côa Valley, Portugal. Trans. Inst. Br. Geogr. *44*, 94–109. https://doi.org/10.1111/tran.12251.
21. Perino, A., Pereira, H.M., Navarro, L.M., Fernández, N., Bullock, J.M., Ceaușu, S., Cortés-Avizanda, A., van Klink, R., Kuemmerle, T., Lomba, A., et al. (2019). Rewilding complex ecosystems. Science *364*, eaav5570.
22. Jepson, P., Schepers, F., and Helmer, W. (2018). Governing with nature: a European perspective on putting rewilding principles into practice. Philos. Trans. R. Soc. Lond. B Biol. Sci. *373*, 20170434. https://doi.org/10.1098/rstb.2017.0434.
23. Palau, J. (2020). Rewilding Iberia: Explorando el potencial de la renaturalización en España (Lynx).
24. Pressey, R.L., Humphries, C.J., Margules, C.R., Vane-Wright, R.I., and Williams, P.H. (1993). Beyond opportunism: key principles for systematic reserve selection. Trends Ecol. Evol. *8*, 124–128.
25. N. Pettorelli, S.M. Durant, and J.T. du Toit, eds. (2019). Rewilding (Cambridge University Press).
26. Svenning, J.-C., Pedersen, P.B.M., Donlan, C.J., Ejrnæs, R., Faurby, S., Galetti, M., Hansen, D.M., Sandel, B., Sandom, C.J., Terborgh, J.W., and Vera, F.W.M. (2016). Science for a wilder Anthropocene: Synthesis and future directions for trophic rewilding research. Proc. Natl. Acad. Sci. USA *113*, 898–906. https://doi.org/10.1073/pnas.1502556112.
27. Van Wieren, S.E. (1988). Effects of large herbivores upon the animal community. In Grazing and Conservation Management, M.F. Wallis DeVries, S.E. Van Wieren, and J.P. Bakker, eds. (Springer Netherlands), pp. 185–214.
28. Estes, J.A., Terborgh, J., Brashares, J.S., Power, M.E., Berger, J., Bond, W.J., Carpenter, S.R., Essington, T.E., Holt, R.D., Jackson, J.B.C., et al. (2009). Resolution of Wilderness in Europe (European Parliament). https://www.europarl.europa.eu/doceo/document/TA-6-2009-0034_EN.html?redirect.
29. Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R., Possingham, H.P., Laurance, W.F., Wood, P., Fekete, B.M., et al. (2018). Last of the Wild Project, Version 3 (LWP-3): 2009 Human Footprint, 2018 Release (NASA Socioeconomic Data and Applications Center (SEDAC)).
30. Di Marco, M., Venter, O., Possingham, H.P., and Watson, J.E.M. (2018). Changes in human footprint drive changes in species extinction risk. Nat. Commun. *9*, 4621. https://doi.org/10.1038/s41467-018-07049-5.
31. Mestre, F., Rozenfeld, A., and Araújo, M.B. (2022). Human disturbances affect the topology of food webs. Ecol. Lett. *25*, 2476–2488. https://doi.org/10.1111/ele.14107.
32. Svenning, J.-C., Munk, M., and Schweiger, A. (2019). Trophic rewilding: ecological restoration of top-down trophic interactions to promote self-regulating biodiverse ecosystems. In Rewilding, N. Petorelli, S.M. Durant, and J.T. du Toit, eds. (Cambridge University Press), pp. 73–89.
33. Belovsky, G.E. (1987). Extinction models and mammalian persistence. In Viable Populations for Conservation, M.E. Soulé, ed. (Cambridge University Press), pp. 35–57.
34. Ćirović, D., de Gabriel Hernando, M., Paunović, M., and Karamanlidis, A.A. (2015). Home range, movements, and activity patterns of a brown bear in Serbia. Ursus *26*, 79–85.
35. Hanski, I. (1998). Metapopulation dynamics. Nature *396*, 41–49.
36. Cornelissen, P., Bokdam, J., Sykora, K., and Berendse, F. (2014). Effects of large herbivores on wood pasture dynamics in a European wetland system. Basic Appl. Ecol. *15*, 396–406. https://doi.org/10.1016/j.baae.2014.06.006.
37. Mills, L.S., Soul, xe, E.,M., and Doak, D.F. (1993). The Keystone-Species Concept in Ecology and Conservation. Bioscience *43*, 219–224. https://doi.org/10.2307/1312122.
38. Delibes-Mateos, M., Redpath, S.M., Angulo, E., Ferreras, P., and Villafuerte, R. (2007). Rabbits as a keystone species in southern Europe. Biol. Conserv. *137*, 149–156. https://doi.org/10.1016/j.biocon.2007.01.024.
39. Faurby, S., Davis, M., Pedersen, R.Ø., Schowanek, S.D., Antonelli, A., and Svenning, J.-C. (2018). PHYLACINE 1.2: The Phylogenetic Atlas of Mammal Macroecology. Ecology *99*, 2626. https://doi.org/10.1002/ecy.2443.
40. Ball, I.R., Possingham, H.R., and Watts, M. (2009). Marxan and relatives: Software for spatial conservation prioritisation. In Spatial conservation prioritisation: Quantitative methods and computational tools, A. Moilanen,

K.A. Wilson, and H.P. Possingham, eds. (Oxford University Press), pp. 185–195.

41. González-del-Pliego, P., Mendoza, M., Santana, J., Ribeiro, J., Reino, L., and Araújo, M.B. (2023). Vacant niches help predict invasion risk by birds. J. Biogeogr. *50*, 1827–1837. https://doi.org/10.1111/jbi.14693.
42. CBD (2020). Update of the zero draft of the post-2020 global biodiversity framework.
43. Araújo, M.B., and Rahbek, C. (2007). Conserving biodiversity in a world of conflicts. J. Biogeogr. *34*, 199–200. https://doi.org/10.1111/j.1365-2699.2006.01687.x.
44. Pimm, S.L., Jenkins, C.N., and Li, B.V. (2018). How to protect half of Earth to ensure it protects sufficient biodiversity. Sci. Adv. *4*, eaat2616. https://doi.org/10.1126/sciadv.aat2616.
45. Araújo, M.B., Lobo, J.M., and Moreno, J.C. (2007). The effectiveness of Iberian protected areas in conserving terrestrial biodiversity. Conserv. Biol. *21*, 1423–1432.
46. Plieninger, T., and Gaertner, M. (2011). Harnessing degraded lands for biodiversity conservation. J. Nat. Conserv. *19*, 18–23. https://doi.org/10.1016/j.jnc.2010.04.001.
47. Laguna, E., Deltoro, V.I., Pèrez-Botella, J., Pèrez-Rovira, P., Serra, L., Olivares, A., and Fabregat, C. (2004). The role of small reserves in plant conservation in a region of high diversity in eastern Spain. Biol. Conserv. *119*, 421–426. https://doi.org/10.1016/j.biocon.2004.01.001.
48. Miller, J.R., and Hobbs, R.J. (2002). Conservation where people live and work. Conserv. Biol. *16*, 330–337.
49. Bignal, E.M., and McCracken, D.I. (2000). The nature conservation value of European traditional farming systems. Environ. Rev. *8*, 149–171.
50. Elleason, M., Guan, Z., Deng, Y., Jiang, A., Goodale, E., and Mammides, C. (2021). Strictly protected areas are not necessarily more effective than areas in which multiple human uses are permitted. Ambio *50*, 1058–1073. https://doi.org/10.1007/s13280-020-01426-5.
51. Ferraz-de-Oliveira, M.I., Azeda, C., and Pinto-Correia, T. (2016). Management of Montados and Dehesas for High Nature Value: an interdisciplinary pathway. Agrofor. Syst. *90*, 1–6. https://doi.org/10.1007/s10457-016-9900-8.
52. Bugalho, M.N., Caldeira, M.C., Pereira, J.S., Aronson, J., and Pausas, J.G. (2011). Mediterranean cork oak savannas require human use to sustain biodiversity and ecosystem services. Front. Ecol. Environ. *9*, 278–286. https://doi.org/10.1890/100084.
53. Sanz-Pérez, A., Sardà-Palomera, F., Bota, G., Sollmann, R., Pou, N., and Giralt, D. (2021). The potential of fallow management to promote steppe bird conservation within the next EU Common Agricultural Policy reform. J. Appl. Ecol. *58*, 1545–1556. https://doi.org/10.1111/1365-2664.13902.
54. Sutcliffe, L.M.E., Batáry, P., Kormann, U., Báldi, A., Dicks, L.V., Herzon, I., Kleijn, D., Tryjanowski, P., Apostolova, I., Arlettaz, R., et al. (2015). Harnessing the biodiversity value of Central and Eastern European farmland. Divers. Distrib. *21*, 722–730. https://doi.org/10.1111/ddi.12288.
55. Jonsson, B.G., Svensson, J., Mikusiński, G., Manton, M., and Angelstam, P. (2019). European Union's Last Intact Forest Landscapes are at A Value Chain Crossroad between Multiple Use and Intensified Wood Production. Forests *10*, 564. https://doi.org/10.3390/f10070564.
56. Pe'er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Muller, R., Bontzorlos, V., Clough, D., Bezák, P., Bonn, A., et al. (2019). A greener path for the EU Common Agricultural Policy. Science *365*, 449–451.
57. Lindenmayer, D.B., Franklin, J.F., and Fischer, J. (2006). General management principles and a checklist of strategies to guide forest biodiversity conservation. Biol. Conserv. *131*, 433–445. https://doi.org/10.1016/j.biocon.2006.02.019.
58. Fordham, D.A., Akcakaya, H.R., Brook, B.W., Rodriguez, A., Alves, P.C., Civantos, E., Trivino, M., Watts, M.J., and Araujo, M.B. (2013). Adapted conservation measures are required to save the Iberian lynx in a changing climate. Nat. Clim. Change *3*, 899–903. https://doi.org/10.1038/NCLIMATE1954.
59. Segar, J., Pereira, H.M., Filgueiras, R., Karamanlidis, A.A., Saavedra, D., and Fernández, N. (2022). Expert-based assessment of rewilding indicates progress at site-level, yet challenges for upscaling. Ecography *n/a*. Ecography *2022*, e05836. https://doi.org/10.1111/ecog.05836.
60. Lees, C.M., Rutschmann, A., Santure, A.W., and Beggs, J.R. (2021). Science-based, stakeholder-inclusive and participatory conservation planning helps reverse the decline of threatened species. Biol. Conserv. *260*, 109194. https://doi.org/10.1016/j.biocon.2021.109194.
61. Biggs, D., Abel, N., Knight, A.T., Leitch, A., Langston, A., and Ban, N.C. (2011). The implementation crisis in conservation planning: could "mental models" help? Conserv. Lett. *4*, 169–183. https://doi.org/10.1111/j.1755-263X.2011.00170.x.
62. Pielke, J.,R.A. (2007). The honest broker: making sense of science in policy and politics (Cambridge University Press).
63. Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., and Wood, E.F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci. Data *5*, 180214. https://doi.org/10.1038/sdata.2018.214.
64. Williams, P.H., Humphries, C., Araújo, M.B., Lampinen, R., Hagemeijer, W., Gasc, J.-P., and Mitchell-Jones, T. (2000). Endemism and important areas for representing European biodiversity: a preliminary exploration of atlas data for plants and terrestrial vertebrates. Belg. J. Entomol. *2*, 21–46.
65. Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R., Possingham, H.P., Laurance, W.F., Wood, P., Fekete, B.M., et al. (2016). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. Nat. Commun. *7*, 12558. https://doi.org/10.1038/ncomms12558.
66. Tucker, M.A., Böhning-Gaese, K., Fagan, W.F., Fryxell, J.M., Van Moorter, B., Alberts, S.C., Ali, A.H., Allen, A.M., Attias, N., Avgar, T., et al. (2018). Moving in the Anthropocene: Global reductions in terrestrial mammalian movements. Science *359*, 466–469.
67. Araújo, M.B. (2004). Matching species with reserves - uncertainties from using data at different resolutions. Biol. Conserv. *118*, 533–538.
68. Hill, M.F. (1973). Diversity and evenness: A unifying notation and its consequences. Ecology *54*, 427–432.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Other		
Human footprint index	Venter et al.[29]	https://sedac.ciesin.columbia.edu/data/set/wildareas-v3-2009-human-footprint
Protected areas in Europe	N/A	https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA
Current ranges of European mammals (PHYLACINE)	Faurby et al.[39] (Note: data used is from 2020 update)	https://github.com/MegaPast2Future/PHYLACINE_1.2/tree/master/Data/Ranges
Potential natural ranges of European mammal (PHYLACINE)	Faurby et al.[39] (Note: data used is from 2020 update)	https://github.com/MegaPast2Future/PHYLACINE_1.2/tree/master/Data/Ranges
Political boundaries of Europe	N/A	https://www.eea.europa.eu/en/datahub/datahubitem-view/94438969-2dd5-4ba3-b708-e4d29a8b7699
Koppen climate zones	Beck et al.[63]	https://www.nature.com/articles/sdata2018214
Deposited data		
Map of European rewilding patches (by area)	This paper	https://doi.org/10.5281/zenodo.11455582
Map of optimized rewilding policies in each European country to reach the 30 × 30 target for protected areas	This paper	https://doi.org/10.5281/zenodo.11455582
Map of optimized rewilding policies in each European country to reach the 10% target for strict protected areas	This paper	https://doi.org/10.5281/zenodo.11455582
Software and algorithms		
Arc GIS Pro	N/A	https://www.esri.com/en-us/my-esri-login
Marxan 2.43	Ball et al.[40]	https://marxansolutions.org/software/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Miguel Araújo (maraujo@mncn.csic.es).

Materials availability

Material generated in this study includes 1 × 1 km resolution maps showing the distribution of areas with rewilding potential, categorized by size, degree of protection, and management type (active versus passive rewilding). Additionally, we developed optimized country-level rewilding scenarios to meet the 30% and 10% protected areas targets.

Data and code availability

- This paper analyzes existing, publicly available data. These accession numbers for the datasets are listed in the key resources table.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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EXPERIMENTAL MODEL AND SUBJECT DETAILS

The species

Our analysis focuses on mammal species that substantially impact ecosystem functioning and are crucial for guiding rewilding strategies. Data on the current and historic ranges (approximately 130,000 years ago) of these selected species were obtained from the PHYLACINE 1.2.1 dataset.[39]

An index of anthropic impact

We chose to use the Human Footprint Index (version 2018) to evaluate the impact of anthropogenic structures on a spatial basis at a 1 km^2 resolution. While several similar indices are available, the Human Footprint Index has proven valuable in multiple recent continental- to global-scale studies, with its footprint values finely tuned to real-world contexts.

Protected areas

The ranges of protected areas of Europe were obtained from the Protected Planet website (https://www.protectedplanet.net/en). This is the most comprehensive dataset on the distribution of protected areas at the global scale.

METHOD DETAILS

Mapping rewilding opportunities

We employed a straightforward three-step process to highlight rewilding opportunities. Firstly, we identified areas on a map (grid cells) where human activities had a minimal impact, falling below a specified threshold (as detailed below). Secondly, we singled out extensive, contiguous parcels of land meeting this low human-impact criterion and categorized them into small, medium, and large size classes, as described below. Thirdly, we assessed whether these aggregated land tracts were inhabited by key herbivores and carnivores, vital for managing plant biomass and controlling herbivore populations, respectively. The regions under consideration encompass all of Europe, except for Byelorussia, Moldavia, Russia, Ukraine, and Turkey, which were excluded owing to deficiencies in species distributions data.[64] Iceland was also omitted due to its remote location and the limited diversity of large mammal species.

We assessed human impact using the 2018 version of the Human Footprint Index (hf), a metric applied to a 1 km × 1 km grid cell system worldwide. This index aggregates the cumulative impacts of human activities into eight categories of pressure up to the year 2009.[29] On a global scale, we considered hf < 4 out of 50 classes of impact to be a reasonable threshold for identifying intact lands.[65] Beyond this threshold, mammal movements are expected to be hindered.[66] In Europe, grid cells with hf values of 4 and 5 predominantly correspond to pasture lands and are categorized as areas of moderate pressure.[65] However, in light of the current trend of land abandonment, especially in parts of Southern Europe, we still deemed these areas suitable for rewilding efforts[9,21] (see Figure S3 for tests assessing rewilding area coverage using hf thresholds ranging from hf = 0 to hf = 5). We focused on identifying potential rewilding areas over large continuous land tracts, which helped mitigate the influence of centripetal impacts from neighboring regions with hf scores greater than 5.

Assuming a negative relationship between the extent of human management and the size of wilderness areas, as illustrated in Figure S1, we established three size-classes for rewilding efforts, each demanding varying levels of human intervention: meso-rewilding ecosystems (≥10,000 ha, <50,000 ha); macro-rewilding ecosystems (≥50,000 ha, < 100,000 ha); mega-rewilding ecosystems (≥100,000 ha). To conduct the spatial analysis, we utilized ArcGIS 10.3.0. The original Human Footprint (hf) raster files were transformed into shapefiles, and the area coverage for each tract of contiguous land was estimated using the "Calculate Geometry" function.

Finally, as rewilding seeks to maintain or restore trophic controls and mechanisms in ecosystem processes, we assessed whether a minimum number of key trophic agents were present in the territory or if they were entirely absent, indicating the need for reintroduction. To obtain the baseline distribution of large (>4 kg) carnivores, omnivores, and key herbivores that play a significant role in energy flow management within ecosystems due to their large body mass (>20 kg) or high abundance (as seen with rabbits and hares; e.g., 35, 36), we used the European distribution atlas for mammals (Table S1; Figure S2). From the initial list of large mammals, we excluded the Red fox (*Vulpes vulpes*) and the Wild boar (*Sus scrofa*) due to their widespread distribution and generalist character. Additionally, we omitted introduced game species which, according to the PHYLACINE 1.2.1 dataset,[39] are not originally from Europe, namely the Sika deer (*Cervus nippon*), White-tailed deer (*Odoicoleus virginiatus*), and the Argali (*Ovis ammon*).

In our baseline analysis, we considered an area as not requiring reintroductions (i.e., falling under passive rewilding) if it had at least one selected carnivore or omnivore species and one herbivore species. For meso-scale patches (i.e., >10,000 ha and <50,000 ha), the presence of at least one herbivore species alone was sufficient (Figure S1). An overview of the observed richness of these selected selected species across Europe is provided in Figure S2.

The specific number of key herbivore and carnivore species required to categorize an area as either passive or active rewilding is arbitrary and plays a crucial role in determining the area of each category. Our sensitivity analysis, represented in Figures S4, S5 and S6, shed light on this variability. We tested how passive and active rewilding areas changed with the species number criteria fitting an exponential model to the results (using the function glm in CRAN-R).

As the criteria for essential herbivore and carnivore species fluctuated, we observed significant changes in the designated rewilding zones. Specifically, as the species count threshold for passive rewilding increased, the potential land area fitting this description contracted. Conversely, when the bar was raised for active rewilding, indicating a higher species requirement, areas designated for active reintroduction expanded. This underlines a critical trade-off: setting higher species thresholds makes passive rewilding more exclusive, thereby increasing the demands for active intervention. Thus, the criteria chosen for species presence directly impacts the scale and nature of rewilding strategies, necessitating careful consideration at the implementation phase by conservationists and stakeholders.

Furthermore, we utilized the PHYLACINE 1.2.1 database to characterize the potential historical distribution of the selected species, forming the baseline of our assessment. This helped us determine whether the reintroduction of an absent species would be justified. Species that were not expected to have historically occurred were excluded from the candidate list of species for reintroduction. Both current distribution maps for extant species and potential historical distributions were resampled to the UTM 50 km × 50 km cell system used for European species distributions atlases.[64] For a discussion of potential pitfalls of using the PHYLACE database see section on potential caveats below.

Mapping protected areas

To examine the overlap between areas with rewilding potential and existing protected areas, we retrieved the boundaries of protected areas from the Protected Planet website (https://www.protectedplanet.net), accessed in February 2021. This database comprises georeferenced information on protected areas designated at the national level, as well as those falling under European frameworks (e.g., Natura 2000 network) and international conventions and agreements (e.g., Ramsar Convention, UNESCO's Man and the Biosphere Programme). We discarded protected areas with point data only, as accurately mapping of boundaries for these areas is not feasible. Within the Protected Planet database, there are several instances of partially overlapping protected areas. To handle this, we assigned the overlapping fraction to the highest management category among the overlapping protected areas. Protected areas falling within the upper levels of IUCN's World Database on Protected Area (WDPA) hierarchy, specifically categories Ia, Ib and II, were considered as targeted for strict biodiversity protection, thus referred as strict protected areas.

To match potential rewilding areas with protected area boundaries, we utilized the "Intersect" function in ArcGIS 10.3.0. We assessed rewilding opportunities within protected areas, taking into account all intersected areas,[67] as well as considering only protected rewilding patches exceeding 10,000 ha in size. Following the variation of species number criteria to establish active or passive rewilding sites (see above mapping rewilding opportunities) we assessed the area of each rewilding strategy within protected areas (Table S2). After evaluating the criteria for the variation in species numbers to determine active or passive rewilding sites (as detailed in the section mapping Rewilding Opportunities), we analyzed the extent of each rewilding strategy within protected zones (refer to Table S2).

Climate zones

We employed the Köppen-Geiger climate classification system to align the boundaries of rewilding and protected-rewilding sites with the the distribution of climate zones in Europe. The climate zone data at a 1 km × 1 km resolution was sourced from Beck et al..[63] The area covered by each climate zone within the study region determined the expected coverage of potential rewilding areas as well as those within protected areas. To estimate the expected extent of these patches within each climate zone, assuming a spatially uniform distribution, we utilized a hypergeometric distribution. The formula for calculating the expected extent (E(X)) of a class of patches in a specific climate zone is as follows:

$$E(X) = \frac{c.x}{A} \quad \text{(Equation 1)}$$

Where:

E(X) is the expected extent of the patches in the climate zone.

c represents the area of the climate zone.

x denotes the total area of rewilding or protected-rewilding patches.

A is the total area of the study region.

To assess the significance of observed extents of rewilding and protected-rewilding areas in each climate zone, we utilized the *phyper* function in CRAN-R to obtain *p*-values. We considered extent-values significant if they had *p*-values less than < 0.001 for the lower or the higher distribution tails, as indicated in Table S3. To calculate the intersected areas between climate zones, potential rewilding areas, and protected areas, we employed the "Intersect" function in ArcGIS 10.3.0, followed by the "Calculate Geometry" function.

Meeting the 2030 protected area targets at country level

The European Biodiversity Strategy 2030[11] sets forth ambitious conservation targets for protected areas. These targets involve covering a minimum of 30% of European land with protected areas, which should include enhanced connectivity, and ensure that at least 10% of European land is strictly protected. Achieving these targets poses several challenges in different countries, as illustrated in Figure 5, and will necessitate the utilization of multiple criteria and active stakeholder involvement. In this context, we employed an optimization approach to explore how mapping rewilding opportunities could facilitate the attainment of area-based conservation targets.

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Our analysis consisted of two distinct but interrelated components: one focused on the 30% conservation target and the other on the 10% strict conservation target. In the first analysis, we considered protected areas from all categories as fixed and we implemented a maximum coverage algorithm, independently, for each country with the aim of maximizing α-diversity and a balanced representation of species in the two trophic groups. This approach involved selection of unprotected rewilding patches within each country until the 30% area target was met. In some cases, certain countries had insufficient coverage of rewilding sites to reach the 30% target, and as a result, all the available unprotected rewilding sites were selected to maximize coverage (Table S4).

In the second analysis, we exclusively considered protected areas falling under categories Ia, Ib and II of the WDPA (strict protected areas) as fixed. The remaining unprotected rewilding sites were treated as candidate sites for selection until the 10% target was achieved. Like the previous analysis, countries with insufficient coverage of rewilding sites to meet the 10% target had all available areas designated as selected.

The analyses were conducted with Marxan software, version 4.0.6.[40] For each country and protected area target, we generated 100 solutions using the default calibration parameters of the simulated annealing procedure in Marxan. Among the 100 generated solutions, we retained the solution with the minimum value for the objective function (Equation 4) (i.e., with the largest and more balanced number of species among the two trophic groups). In the process of discriminating between rewilding sites, we used the richness of herbivore and carnivore species as criteria. When sites had the same number of species, or to break ties, we assigned higher scores to those sites with a more even distribution of species between the two trophic classes (carnivores/omnivore and herbivores). Evenness was quantified using the Shannon-Wiener entropy index[68] weighted by the total species richness (Figure S7). The formula for calculating the value index (Vi) of patch i is as follows:

$$v_i = -\left(nsp_i^{\,T}\right) \times \left[\frac{nsp_i^{\,C}}{nsp_i^{\,T}}.log\frac{nsp_i^{\,C}}{nsp_i^{\,T}} + \frac{nsp_i^{\,H}}{nsp_i^{\,T}}.log\frac{nsp_i^{\,H}}{nsp_i^{\,T}}\right] \qquad \text{(Equation 2)}$$

Where.

v_i represents the value of patch i. $nsp_i^{\,T}$, $nsp_i^{\,C}$ and $nsp_i^{\,H}$ denotes the total species richness, carnivore/omnivore species richness and herbivore species richness in patch i, respectively. In order to operate in Marxan, the value index was transformed to a cost index (which we chose to range from 0 to 10, Figure S7), to penalize selection of rewilding sites with a limited number of species:

$$c_i = \frac{100}{v_i} \qquad \text{(Equation 3)}$$

In cases where at least one of the trophic classes had no species, the entropy component in Equation 2 was undefined. To address this, we estimated the cost of such cases based on the following assumptions.

(1) The cost for rewilding patches with zero carnivore species and two to eight herbivore species (*C0H2, C0H3, …,C0H8*) was set to 1.5 times the cost of patches with an equivalent number of species (n = 2 to 8) and the most unbalanced representation of the two trophic groups (e.g.,. cost(*C0H2*) = 1.5 x cost(*C1H1*); cost(*C0H3*) = 1.5 x [cost(*C1H2*) = cost(*C2H1*)]; … cost(*C0H8*) = 1.5 x cost(*C1H7*)). The same approach was applied to patches lacking herbivores (i.e., *C2H0, C3H0*);
(2) The cost for rewilding patches characterized by one herbivore and zero carnivore species (i.e., *C0H1*) was determined by fitting a logarithmic regression to the costs of (*C0H2, C0H3, …,C0H8*) (Figure S7);
(3) The cost for rewilding patches characterized by one carnivore and zero herbivore species followed the equation cost(*C1H0*)/cost(*C2H0*) = cost(*C0H1*)/cost(*C0H2*);

The cost of *C0H0* patches was obtained using the same fitting function of b), with a positive infinitesimal approximation to zero (i.e., 0^+) (Figure S8).

The modified Marxan problem used was:

$$\min \sum_i c_i.x_i \qquad \text{(Equation 4)}$$

s.t

$$\sum_i a_i.x_i \leq A \qquad \text{(Equation 5)}$$

where xi is a binary variable setting the selection ($xi = 1$) or not ($xi = 0$) of the rewilding patch i; ai is the area of patch i, and; A defines, for each country, the maximum area to be selected following the 30% protected area and the 10% strict protected area targets. For the rewilding patches, i, which overlap existing protected areas $xi = 1$, such to anchor those patches in final solutions.

The objective function (Equation 4) minimizes the total cost and therefore it equates to maximizes solution value (which informs about the number of species among trophic groups). The constrain (Equation 5) imposes a maximum area in each country for the selection of patches.

Potential caveats

Our study, while providing key insights into the rewilding potential in Europe, is based on a number of assumptions which will necessitate fine-tuning as on-ground implementation strategies evolve.

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Species Selection: At the core of our analysis are species that play a pivotal role in maintaining trophic balance on a large scale. However, the scope of our study was macro-focused. Depending on the depth and focus of future studies, this species list could be expanded to capture a more diverse set of functional groups. These groups might offer nuanced insights into how ecosystems function across different spatial scales, facilitating a richer, more diverse landscape ready for rewilding.

Data Source and Resolution: Our choice of the European Atlas of Mammals as the primary data source was driven by the need for consistency between past and present species records. This decision, while pragmatic, does come with its set of challenges. The coarser spatial resolution means there is a potential for overestimating rewilding potential in certain grid cells. Alternative datasets, from citizen science efforts or the IUCN Red List, do exist. However, leaning on them could project a misplaced sense of accuracy, particularly when historical records inherently come with uncertainties.

Study Aim: Our central goal was to carve out a foundational framework that identifies avenues for protected area expansion through the lens of trophic rewilding. Factors like climate shifts and changing land-use patterns, while critical, were beyond this study's purview. As the global landscape evolves, future studies could incorporate these variables to reassess and recalibrate rewilding potentials.

Transient Connectivity: A significant aspect we did not delve deep into is the potential connectivity between areas with moderate human impact (i.e., grid cells where hf > 5). In real-world scenarios, many such zones could offer intermittent movement corridors for species, allowing them to colonize adjacent areas without the need for human intervention.

Socioeconomic Considerations: A broader perspective reveals that our top-down strategy does not delve deep into several socioeconomic drivers at the local level. These drivers can considerably influence the outcomes of rewilding initiatives. Conflicts between humans and wildlife are a complex issue across Europe. Addressing this challenge underscores the vital role of well-crafted policies and community-driven educational initiatives to foster proactive stakeholder engagement in the rewilding journey.

QUANTIFICATION AND STATISTICAL ANALYSIS

Statistical analyses were performed in R (version 4.2.2). The details have been explained in the results and method details.