Journal of Environmental Management 380 (2025) 125084

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Where could climate-smart rewilding be located in Europe?

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ABSTRACT

Climate-smart rewilding is a promising approach to ecological restoration that combines the benefits of dynamic and process-based restoration with carbon sequestration for climate change mitigation. However, little is known about suitable locations for climate-smart rewilding in Europe as there is a lack of continental scale, spatial assessments of where to rewild.

We present an approach to map the potential for climate-smart rewilding in Europe by considering three dimensions: (1) Ecological potential representing the best conditions for restoring key ecological processes, (2) Carbon potential describing the potential for carbon sequestration, and (3) Land potential reflecting the societal (opportunity) costs of dedicating land to rewilding. Using these three dimensions, we map the climate-smart rewilding potential across Europe and analyse synergies and trade-offs between them.

Our findings show that the potential for climate-smart rewilding is scattered across Europe with hotspots predominantly found in mountainous regions, such as the Alps and the Scottish Highlands. The Iberian Peninsula, parts of Scandinavia, the North of the UK, and the East of Europe, also show opportunities for climate-smart rewilding. The patterns highlight that high potential is not equally distributed across European countries, adding complexity to the actual implementation of measures to reach restoration targets. Furthermore, high potential areas are often characterised by a high potential for one dimension, with limited synergies between the ecological, carbon and land potential dimensions, emphasising the tension between competing land demands. The approach presented here offers valuable input for planning processes and the exploration of future scenarios.

1. Introduction

Three-quarters of the world's land has been substantially altered by humans through the conversion of land for anthropogenic use and associated management practices (IPBES, 2019). This has contributed to widespread ecosystem degradation with negative consequences for people and nature, e.g., loss in agricultural productivity due to soil erosion or decline of pollinators, dysfunctional ecosystems due to habitat disruption leading to species loss or increased carbon emissions due to deforestation (IPBES, 2018; Jiang et al., 2024; Prăvălie et al., 2024). To reverse degradation, there is an important need for ecosystem restoration, which can jointly address the biodiversity and climate crises by increasing carbon storage, reducing emissions, improving habitats for plants and animals, and leading to greater resilience of ecosystems to environmental change (IPBES, 2018; IPCC, 2023; Strassburg et al., 2019).

The growing awareness of the need for restoration has led to more political activity around the topic resulting in an increase in the number of restoration policies. The United Nations (UN) proclaimed 2021–2030 as the UN Decade on Ecosystem Restoration with the aim to 'prevent, halt and reverse the degradation of ecosystems worldwide' (United Nations, 2019). The European Union (EU) committed in the EU Biodiversity Strategy 2030 to launch an EU nature restoration plan, which was adopted as the Nature Restoration Regulation (NRR) (Regulation EU 2024/1991, 2024) in June 2024. Its overall objective is to restore 'at least 20 % of land areas and at least 20 % of sea areas by 2030, and all ecosystems in need of restoration by 2050'. Furthermore, the EU Climate Law (Regulation EU 2021/1119, 2021)states that nature restoration plays a vital role in achieving the target set for all member states to become climate neutral by 2050.

However, despite ambitious targets and increased understanding of the importance of ecosystem restoration, progress towards desired outcomes (e.g., halting biodiversity loss) has been slow and unsatisfactory (Cortina-Segarra et al., 2021; Massenberg et al., 2023; Segar et al., 2022). Several reasons have been identified for this. There is a need for strategic environmental assessments to minimise trade-offs resulting

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https://doi.org/10.1016/j.jenvman.2025.125084
Received 20 December 2024; Received in revised form 7 March 2025; Accepted 19 March 2025
Available online 28 March 2025

from competing demands on land and to find areas with the best possible restoration outcomes (Anderson-Teixeira, 2018; Cortina-Segarra et al., 2021; IPCC, 2023; Strassburg et al., 2020). Strassburg et al. (2020) further emphasised the importance of spatial allocation for restoration, as the outcomes of ecosystem restoration for biodiversity conservation and climate change can vary substantially depending on where the restoration takes place. Furthermore, the continued focus on static biodiversity conservation targets, which mainly focus on habitat and species protection without considering the underlying ecological processes has acted as another barrier to progress (Bennett et al., 2009). Flexible and dynamic restoration approaches considering global change conditions, rather than static targets, are needed to achieve current biodiversity goals (Arneth et al., 2020). Therefore, there is a need for restoration ecology to move away from restoring ecosystems to fixed reference systems and instead actively shape the future by considering the novelty of existing and resulting ecosystems (McNellie et al., 2020).

In response to these needs, rewilding has been proposed as a new approach to ecosystem restoration (Soulé and Noss, 1998). Rewilding can play a central role in meeting global restoration efforts, e.g., halting biodiversity loss, reversing land degradation and mitigating climate change (Damholdt Bergin et al., 2024; Hart et al., 2023; Perino et al., 2019; Svenning, 2020), through its focus on restoring ecological processes to obtain a resilient and self-sustaining ecosystem in an open-ended and flexible manner (Carver et al., 2021; Hering et al., 2023; Perino et al., 2019). Within the rewilding literature, a wide variety of different concepts exist and continue to expand. These range from 'passive rewilding', i.e. natural succession following agricultural abandonment, to 'active rewilding' which emphasises the integration of societal needs and acceptance and allows some management, to 'trophic rewilding', which focuses on the reintroduction of missing keystone species (Carver et al., 2021; Perino et al., 2019; Svenning, 2020). All these approaches have a common focus on ecological aspects and addressing the biodiversity crisis. However, given the need to address the climate crisis as well (IPCC, 2023), it is essential to also explore the climate change mitigation benefits of rewilding. So far, studies looking at the synergies between ecological restoration and climate change mitigation are rare, even though, ecological restoration has been described as a promising natural climate solution (Griscom et al., 2017; IPBES, 2018; IPCC, 2023). Synergies could, for example, arise from rewilding degraded high-carbon ecosystems such as former peatlands, wetlands or forests (IPBES, 2018). Thus, here we adopt a 'climate-smart rewilding' approach that aims to explore the synergies that rewilding offers for biodiversity, climate change mitigation, and society. In doing so, we take a broad definition of rewilding that includes all rewilding approaches that also have a climate benefit.

So far, research on rewilding is often theory-led and misses practical or evidence-based approaches (Svenning et al., 2016). Studies prioritising how much and where to set aside land for rewilding are scarce and do not exist at the continental scale with the notable exception of Araújo and Alagador (2024) who recently mapped rewilding opportunities to expand protected areas in Europe based on human footprint, size of contiguous area, and presence of key animals. Furthermore, the interactions between ecology, society, economy and culture are often not considered, even though they are essential for a holistic rewilding approach (Massenberg et al., 2023). To our knowledge, studies investigating the potential for rewilding at a European scale accounting for the different demands on land are lacking. Existing studies have identified priority areas for ecosystem restoration globally (Strassburg et al., 2020), have put a focus on prioritising areas for rewilding within selected sites nationally (Damholdt Bergin et al., 2024), or over the extent of the Alps (Zoderer et al., 2024). Except for Strassburg et al. (2020) these studies focused on the ecological aspects of rewilding or restoration. However, interdisciplinary assessments are needed to minimise trade-offs resulting from competing demands on land and to bring rewilding to the forefront of political discussions.

In this study, we aim to address the barriers around the lack of continental-scale, integrated spatial assessments as well as the lack of a focus on flexible restoration approaches and the often-omitted climate aspect of rewilding by considering the biodiversity-climate-society nexus. Thus, we introduce an approach to map the potential for climate-smart rewilding in Europe. We first present an overview of the European climate-smart rewilding potential, subsequently we explore synergies and trade-offs across the ecological, climatic and socioeconomic domains and then analyse how the rewilding potential may differ according to different priorities. We frame the study around the research question '*Where could climate-smart rewilding be located in Europe?*'. We present our results as spatially-explicit, rewilding potential maps at a 1 km^2 resolution.

2. Methods

2.1. Conceptual framework of the rewilding potential

We developed a conceptual framework to study the potential for climate-smart rewilding at the European scale. We describe climate-smart rewilding potential through three dimensions: (1) Ecological potential, (2) Carbon potential, and (3) Land potential (Fig. 1). The ecological potential aims to facilitate best conditions for restoring ecological processes to enable self-sustaining ecosystems. Processes such as dispersal, stochastic disturbance and trophic complexity are taken into account as inspiration for the set of indicators as they have been identified as key processes in establishing functional and resilient ecosystems, which is a prerequisite for successful rewilding (Perino et al., 2019). The carbon potential is about enhancing carbon storage through rewilding for climate change mitigation. Restored ecosystems have a high potential for storing more carbon compared to the current land use at the site. They count as one of the most cost-effective land-based climate change mitigation actions (IPBES, 2018), especially when done for high-carbon ecosystems such as former peatlands, wetlands or forests. The land potential accounts for trade-offs between competing demands on land arising from the divergent interests of different stakeholders (Cortina-Segarra et al., 2021).

Each dimension (ecological, carbon and land potential) is represented in the mapping by a set of spatially explicit indicators (detailed reasoning see section 2.2 - 2.4). The set of indicators was chosen to best represent each of the three potentials and to cover as much of Europe as possible at a high spatial resolution of at least 1 km^2. Maps of each indicator can be found in the Appendices (Figure S 1). Additionally, Table S 1 gives a detailed overview of the datasets, including resolution, extent, year, etc. We first mapped the three potentials individually by combining the normalised indicators in an additive approach (Fig. 1). Subsequently, we combined the three potentials, also in an additive approach, to obtain the overall climate-smart rewilding potential at a European scale at a 1 km^2 spatial resolution (section 2.5). The potential maps per dimension and the combined rewilding potential map were used to run a set of spatial analyses to study the distribution, synergies and trade-offs within the different dimensions (section 2.6). For the mapping, we considered all terrestrial areas, with the exception of urban areas as these usually have a very high resistance to land-use change. The extent of terrestrial land and the exclusion of urban areas was taken of an updated version (2020) of the Historic Land Dynamics Assessment+ (HILDA+) database (Winkler et al., 2020).

2.2. Ecological potential indicators

The indicators for the ecological potential dimension focus on ecological integrity and functioning by representing various abiotic and biotic components of ecosystems. We chose landscape connectivity, geodiversity and water disturbance potential to be most relevant for the ecological potential, which are reasoned and explained in the following sections.

Small, isolated patches in otherwise highly intensively managed

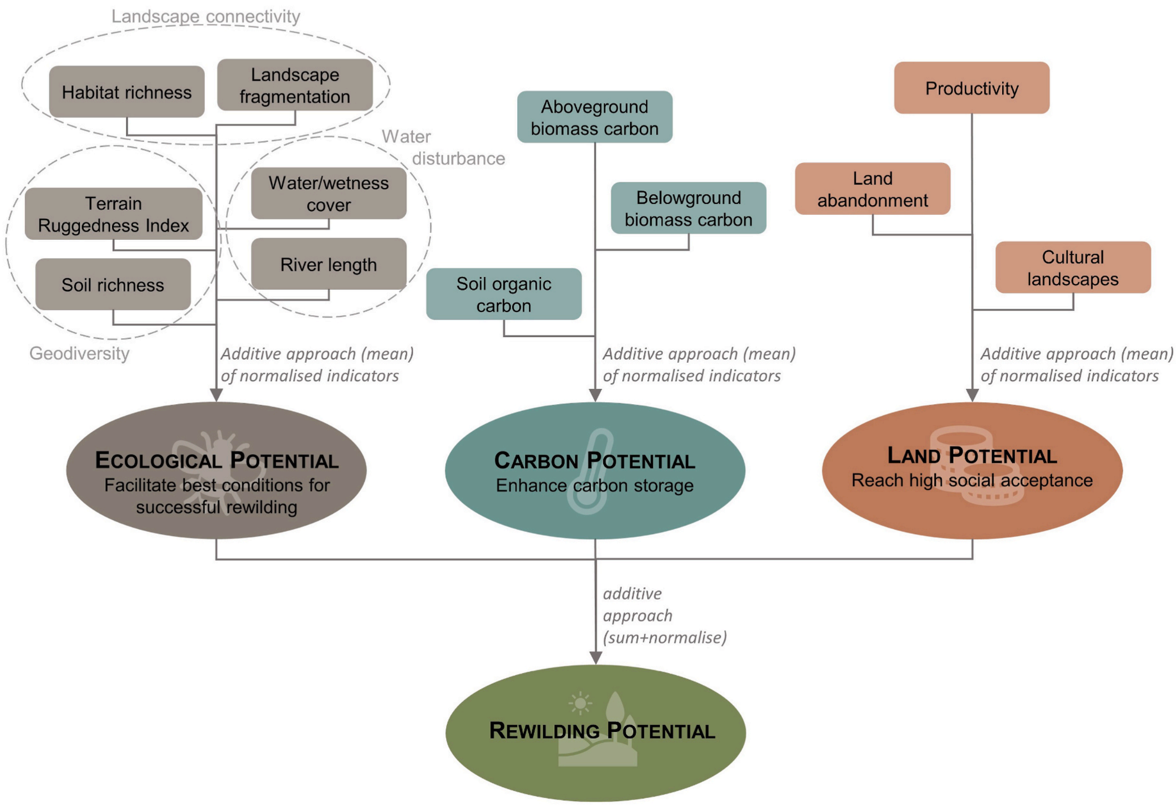

Fig. 1. Overview of indicators (small rectangles) used to calculate the rewilding potential for the three dimensions ecological, carbon and land potential (ellipses). The sum of the three dimensions is the overall rewilding potential for Europe (green ellipse), analysed at 1 km^2 resolution. For details on each indicator and the datasets used see Methods and Appendices (Figure S 1, Table S1).

landscapes are not suitable for restoring ecological processes (Corlett, 2016). In particular, the restoration of trophic complexity as one of the main ecological processes relevant for rewilding as defined by Perino et al. (2019) needs larger areas to support self-sustaining populations. Linnartz and Meissner (2014) defined a minimum area of 450 ha on nutrient rich soils and up to 4500 ha or more on poor soil as being needed for self-sustaining populations of large herbivores in Europe. In addition, to allow species dispersal into the newly rewilded area, a variety of habitats and ecological niches need to be present in the surrounding (Rudnick et al., 2012). To consider the importance of neighbourhood we extended the analysis from 1 km^2 to an area of 5 km^2 (2500 ha) for the indicators *habitat richness*, *soil richness*, *water and wetness cover* and *river length*. This was implemented using the ArcGIS tool "Focal Statistics" for a 5 × 5 km rectangle.

Landscape connectivity, defined 'as the extent to which a landscape facilitates the movements of organisms and their genes', is critical for species dispersal and metapopulation function (Rudnick et al., 2012). Thus, high landscape connectivity is essential for successful rewilding, leading to resilient ecosystems with connectivity within and between ecosystems (Perino et al., 2019).

We used *landscape fragmentation* as the first indicator within the landscape connectivity category. Fragmented landscapes limit the dispersal of species between habitats (Rudnick et al., 2012). At the same time, linear fragmentation elements (e.g., major transport routes) can act as dispersal pathways for invasive species (Vicente et al., 2010), negatively affecting the success of rewilding projects. This could have negative impacts on the success of rewilding projects. We used landscape fragmentation data from the European Environment Agency (2021) based on the effective mesh density. Effective mesh density is a measure of 'the degree to which the possibilities for movement of wildlife in the landscape are interrupted by barriers' (European Environment Agency; Swiss Federal Office for the Environment, 2011). The dataset considers roads from class 1 (motorways) to class 4 (connecting roads), railways and built-up areas as barriers. European Environment Agency; Swiss Federal Office for the Environment (2011) used an effective mesh density threshold of 100, stating that any pixel with equal or higher values is characterised by very high fragmentation. This was adopted for our analysis by reclassifying all values above that threshold to 100. High fragmentation is considered equal to low ecological potential for rewilding, which was implemented by inverting the fragmentation values (Eqn 2).

In addition to low fragmentation due to artificial barriers, (semi-) natural habitats need to be present in the surrounding area for improved landscape connectivity. Having different natural habitats in the surrounding allows seed and species dispersal into a newly rewilded area, enabling the establishment of functional ecosystems with little or no need for human intervention (Perino et al., 2019; Carver et al., 2021). Hence, we used *habitat richness* of (semi-) natural habitats as a second indicator within the landscape connectivity category. We calculated the sum of different habitats in the neighbourhood of a 5 × 5 km square around each target pixel. We used the EUNIS level 2 habitat classification of the Ecosystem Types of Europe map from (European Environment Agency, 2019) with a resolution of 100 m. We excluded all habitats falling into EUNIS class 'I' (Arable land and market gardens) and class 'J' (constructed, industrial and other artificial habitats). We assumed these habitats are largely degraded and so, do not contribute to improved seed and species input. The target pixel itself was excluded from the calculation. This approach allowed us to focus on the dispersal potential offered by the neighbourhood, rather than on whether the target pixel is already diverse or not. High habitat richness in the surrounding area leads to an improved rewilding potential.

As the second category within the ecological potential, we used water disturbance potential. Natural disturbances have the potential to increase ecosystem complexity and are therefore a key component of natural ecosystems (Bengtsson et al., 2003; Franklin et al., 2000). We considered the potential of natural disturbances of flooding, similar to Damholdt Bergin et al. (2024), by the presence of streams, lakes and permanent and temporary wetland and temporary water. For streams we calculated the *river length* in kilometre. For standing water, we used *permanent/temporary water and wetland cover* in percent. For both water indicators the analysis was done for the 2500 ha square to include the surrounding area resulting in water and wetland cover in percent per 2500 ha. The data for rivers and lakes were derived from the hydroSHEDS dataset (Lehner and Grill, 2013; Messager et al., 2016). Rivers considered in the dataset have a catchment area of at least 10 km^2 or an average river flow of at least 0.1 m^3/s, or both (Lehner and Grill, 2013). Lakes were considered when having a surface area of at least 10 ha (Messager et al., 2016). The water and wetness status from Copernicus (EEA, 2020) shows the occurrence of water and wet surfaces over the period from 2012 to 2018 and was chosen to include areas being characterised by water, as wetlands or floodplains, which are not already covered by the other two indicators. Both indicators contribute with an increase in the values (longer or higher coverage) equating to an increase in the ecological potential. We are aware, that fire or pest outbreaks, for example, also play a role in disturbance regimes in Europe (Perino et al., 2019; Franklin et al., 2000). However, these impacts might be limited to a more regional scale, e.g. Mediterranean region as hotspot for fire outbreaks versus low fire risk in the North of Europe. Additionally, datasets representing fire, pests and diseases, for example, are limited at the European scale, partly because they are also strongly stochastic processes with large year to year variability. For those reasons we did not include any other disturbance at this stage.

Geodiversity as the third category is defined as the variety of rocks, sediments, soils, landforms and geological processes making up the non-living components of the Earth (Alahuhta et al., 2022). It plays an important role in ecosystem maintenance and functionality by offering niche space, refugia and opportunities for isolation and divergent adaptation and therefore boosts biodiversity and species coexistence (Stein et al., 2014; Brunbjerg et al., 2017). We covered geodiversity by using *soil richness* and *terrain roughness*. Soil richness was calculated based on the soil types from the European Soil Database (European Soil Data Centre; Panagos et al., 2022; Panagos et al., 2012), by considering a 5 × 5 km square of the neighbourhood. Local topographic heterogeneity was represented by the Terrain Roughness Index (TRI) (Riley et al., 1999), which takes the difference in elevation between the target cell/centre cell and the eight cells surrounding it. For the calculation we used the ASTER global digital elevation model from NASA (NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team, 2019). Again, higher values of soil richness and terrain roughness resulted in higher values for the ecological potential.

2.3. Carbon potential indicators

The carbon potential dimension aims to represent unrealised carbon storage in present-day landscapes by highlighting areas that have a high potential to store more carbon when being restored compared to the current situation. The unrealised carbon storage is based on the difference between the current and the potential land carbon storage in woody biomass above- and belowground and soil organic matter. We used data from Walker et al. (2022a) on *potential carbon storage* in aboveground woody biomass (AGB), belowground woody biomass (BGB), and soil organic carbon (SOC). They calculated present-day carbon based on several environmental variables (climate, land-use, topography, etc.) for AGB and SOC and root:shoot ratios per ecoregion for BGB. Their potential shows the maximum accumulation of carbon that could be realised assuming current biogeophysical conditions and the absence of human disturbance. We are aware that this indicator could change substantially under future climate change conditions. However, determining potential carbon stock under climate change conditions is a difficult task that requires extensive modelling work and is beyond the scope of this study which focuses on today's conditions. With this approach our focus is primarily on identifying areas with considerable potential for improvement in carbon storage instead of present-day carbon-rich land (e.g., peatlands). Identifying current carbon-rich land would be more important when defining areas to protect to avoid further degradation.

2.4. Land potential indicators

Abandoned land has the lowest conflict potential with food and timber production and so is often proposed as easily-available land for rewilding (e.g., Brown et al. (2024), Carver (2019), Ceaușu et al. (2015)). Pointereau et al. (2008) defined land abandonment as 'the cessation of agricultural activities on a given surface of land, which is not used for another activity (such as urbanisation or afforestation)'. To estimate land abandonment, we used an updated version of the Historic Land Dynamics Assessment+ (HILDA+) database (Winkler et al., 2020). HILDA+ includes annual land use changes from 1960 to 2020 worldwide at a resolution of 1 km^2 highlighting changes in six land use/cover (LUC) categories: urban, cropland, pasture/rangeland, forest, unmanaged grass/shrubland, sparse/no vegetation (Winkler et al., 2020). We classified grid cells that permanently changed from agricultural use (cropland or pasture/rangeland) to unmanaged grass/shrubland as abandoned land, similar to the approach used in Lee et al. (2023). This transition could take place in any year between 1960 and 2020 as long as the cell is still abandoned in 2020.

Land may have different suitabilities for food, fodder, and timber production depending on environmental factors (e.g., soil quality, climatic conditions, …). Therefore, taking land out of production comes with the potential for different societal and economic conflicts depending on the suitabilities and the current land use (IPCC, 2023; Pilgrim et al., 2010). To depict such conflicts between ecosystem restoration and agricultural production and forestry, we considered highly *productive land* to be less suitable for rewilding. The index used from Tóth et al. (2013) shows the soil biomass productivity, calculated as a function of soil, climate and topographical conditions and land use (grassland, cropland and forest). The dataset covers the EU26+UK excluding Switzerland. Therefore, the land potential for Switzerland was only calculated from the other two considered indicators, which introduces a small bias, but doesn't have a substantial impact on our results (see sensitivity analysis Appendix A: Figure S 2, Table S 3). The higher the productivity, the lower the rewilding potential, hence we inverted the index from Tóth et al. (2013) (Eqn 2). In addition, we considered cultural aspects connected to landscapes by using an existing *cultural landscape* index from Tieskens et al. (2023). They calculated a cultural landscape index based on the three indicators landscape structure, management intensity and landscape value and meaning. The index has continuous values between 0 and 1, calculated separately for agricultural and forest cultural landscapes, to account for differences in terms of land management and structure (Tieskens et al., 2023). We assumed cultural landscapes to be less suitable for rewilding because of the high importance that cultural values play in human-nature relationships (Eqn 2).

2.5. Calculation of the rewilding potential

For the calculation of the rewilding potential, all indicators were normalised between 0 and 1 using a min-max normalisation *(x') (*Eqn 1*):*

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{1}$$

For the indicators 'landscape fragmentation', 'productivity' and 'cultural landscapes', the values were inverted (x_{inv}) (Eqn 2):

$$x'_{inv} = (x' - \max(x')) \times (-1) + \min(x') \tag{2}$$

The potential per dimension *(DIM)* was obtained by calculating the mean of the indicators on a pixel-per-pixel basis (Eqn 3). In this way, we avoided artificial reduction of the potential per dimension for cells where some indicators had no values. The dimension of the ecological potential *(DIM_{EP})* is represented by a maximum of 6 indicators (n = 6), the carbon potential *(DIM_{CP})* and the land potential *(DIM_{LA})* by a maximum of 3 indicators (n = 3).

$$DIM = \frac{1}{n}\sum_{i=1}^{n} x_i' \tag{3}$$

Finally, the three dimensions were summed to derive the rewilding potential *(RP)* (Eqn 4). For ease of comparison between the three dimensions as well as to the overall rewilding potential, the results were again normalised (cf. Eqn 1).

$$RP = DIM_{EP} + DIM_{CP} + DIM_{LP} \tag{4}$$

2.6. Spatial analysis

The mapping of the rewilding potential and all the analysis steps were done using the model builder within ArcGIS Pro 3.1.0. The analysis was done for all EU countries plus the United Kingdom and Switzerland, but excluding Croatia (EU26 + 2) because not all EU datasets include Croatia. Furthermore, we excluded urban and ocean (classification according to HILDA+ -dataset). All datasets were harmonised to the coordinate system ETRS89 (EPSG-Code: 3035) at a spatial resolution of 1 km^2. The main outcome of the approach was a map of rewilding potential at the European scale, represented by a dimensionless index ranging from 0 to 1.

To identify spatial patterns and explore the main drivers as well as synergies and trade-offs between the three dimensions, we ran a set of spatial analyses on the potential rewilding maps. We identified hotspots for each potential map based on the 20 % of the total area with the highest values (hereafter termed 'hotspots'). This threshold was inspired by the Nature Restoration Regulation (Regulation EU 2024/1991, 2024) target that requires at least 20 % of land areas to be restored by 2030.

The first analyses on the rewilding potential were done based on the overall rewilding potential hotspots. Here, we calculated and mapped which of the three dimensions were the main driver for the overall rewilding potential hotspots. Additionally, to also show if the main driver would align with high or low values of one of the other dimensions we conducted a pairwise analysis of the rewilding potential of the three dimensions. We extracted the values of the three possible pairwise combinations (land + carbon potential, land + ecological potential and carbon + ecological potential) based on the extent of the hotspots of the overall rewilding potential (=20 % of land area with highest values). We classified the rewilding potential values of each dimension into 'low', 'medium' and 'high' categories based on the lower quartile, interquartile range and upper quartile. The pairwise comparison based on these three classes resulted in nine possible classes, highlighting synergies and trade-offs (low values for both dimensions meaning low synergies between those dimensions, low for one and high values for the other dimension indicating trade-offs between the dimensions, …).

For the next analysis step, we focused on the hotspots (=20 % of land area with highest values) per dimension to show synergies and trade-offs between the three dimensions, which also functioned as a first approximation for how the spatial pattern could differ if a different weighting of the three dimensions were applied. Therefore, we overlaid the individual maps showing the hotspots per dimension by using the ArcGIS tool 'Composite Bands'. The resulting multiband raster dataset was visualised as an RGB composite. Values without any overlap with other dimensions were visualised in the RGB colours (red, green, blue), whereas the intermediate colours of the RGB colour model were used to demonstrate synergies.

3. Results

3.1. European potential for climate-smart rewilding

The overall European rewilding potential (based on all three dimensions) has a mean value of 0.42 with most of the values being distributed closely around the mean (standard deviation = 0.09). Values at the extremes of the range (close to 0 or to 1) are rare. Mountainous regions, e.g., the Alps or the Scottish Highlands, as well as the Iberian Peninsula, parts of Scandinavia and the UK and the East of Europe show the highest values (Fig. 2d). In contrast, the rewilding potential is lower in Central Europe and Italy.

The rewilding potential per dimension shows distinct spatial patterns. The ecological potential, which covers geodiversity, natural water disturbance and landscape connectivity, has high values mainly in mountainous regions (Alps, Scottish Highlands, Pyrenees, Carpathians, etc.) and in the North and South of Europe (Fig. 2a). Regions with a low ecological potential are in Central Europe except for the Alps. The carbon potential, represented by potential carbon storage, has high values mainly in Central Europe ranging from the UK across France and Germany to the Czech Republic and Poland (Fig. 2b). Low values are found in Southern and Northern Europe. For the land potential, the North of Europe (mainly Sweden and Finland) and some smaller and disconnected regions in Spain, Poland, the Baltic States and in the Northeast of France (Fig. 2c) show the highest land potential. Regions with low land potential are among others along the Atlantic coast and in the Northern part of Italy.

3.2. Hotspots of rewilding potential

3.2.1. Distribution of rewilding potential hotspots

The threshold, marking the top 20 % of area with the highest rewilding potential (hotspots) in Europe, is at 0.49 (80th percentile), which covers around 800,000 km^2. The hotspots are unevenly distributed across the European countries. In the United Kingdom (UK), Lithuania (LT), Latvia (LV), Switzerland (CH), Austria (AT), Denmark (DK), Poland (PL), Slovakia (SK) and Estonia (ES) more than 20 % of the country areas fall within the European-wide hotspots. In contrast, in Slovenia (SI), the Netherlands (NL), Belgium (BE) and Luxembourg (LU) the potential contribution to the European-wide hotspots is less than 10 % of the country area (Fig. 3).

3.2.2. Main drivers of rewilding potential hotspots

Within the rewilding potential hotspots (Fig. 3a), the main drivers differ from region to region (Fig. 4). In more than half of the hotspots the ecological potential shows the highest values compared to the other two dimensions. It is the main driver for areas in the North of Scandinavia, the North of the UK, several regions of the Iberian Peninsula and in the Alps and the Pyrenees. The land potential is dominant on 33 % of the total hotspots with a rather scattered spatial pattern over Europe but an overall higher share of areas in Eastern Europe. The remaining 14 % of the hotspots can be explained by high values in the carbon potential, covering among others the South of the UK and smaller patches in Central and Western Europe.

3.2.3. Synergies and trade-offs of rewilding potential hotspots

The pairwise comparisons show the synergies and trade-offs between the different dimensions which underlie the rewilding potential hotspots at a given location (Fig. 5). For all three possible comparisons the highest share of areas can be explained by either having a medium value for both dimensions (13.0–14.4 %, light brown) or having high values for one dimension, while the second dimension only contributes low values (14.5–18.4 %, cyan and yellow).

Synergies with high values for the land and carbon potentials (dark red in Fig. 5a) cover 6.1 % of the area. They are mainly located in the middle of Europe with rather small patches ranging from Poland to

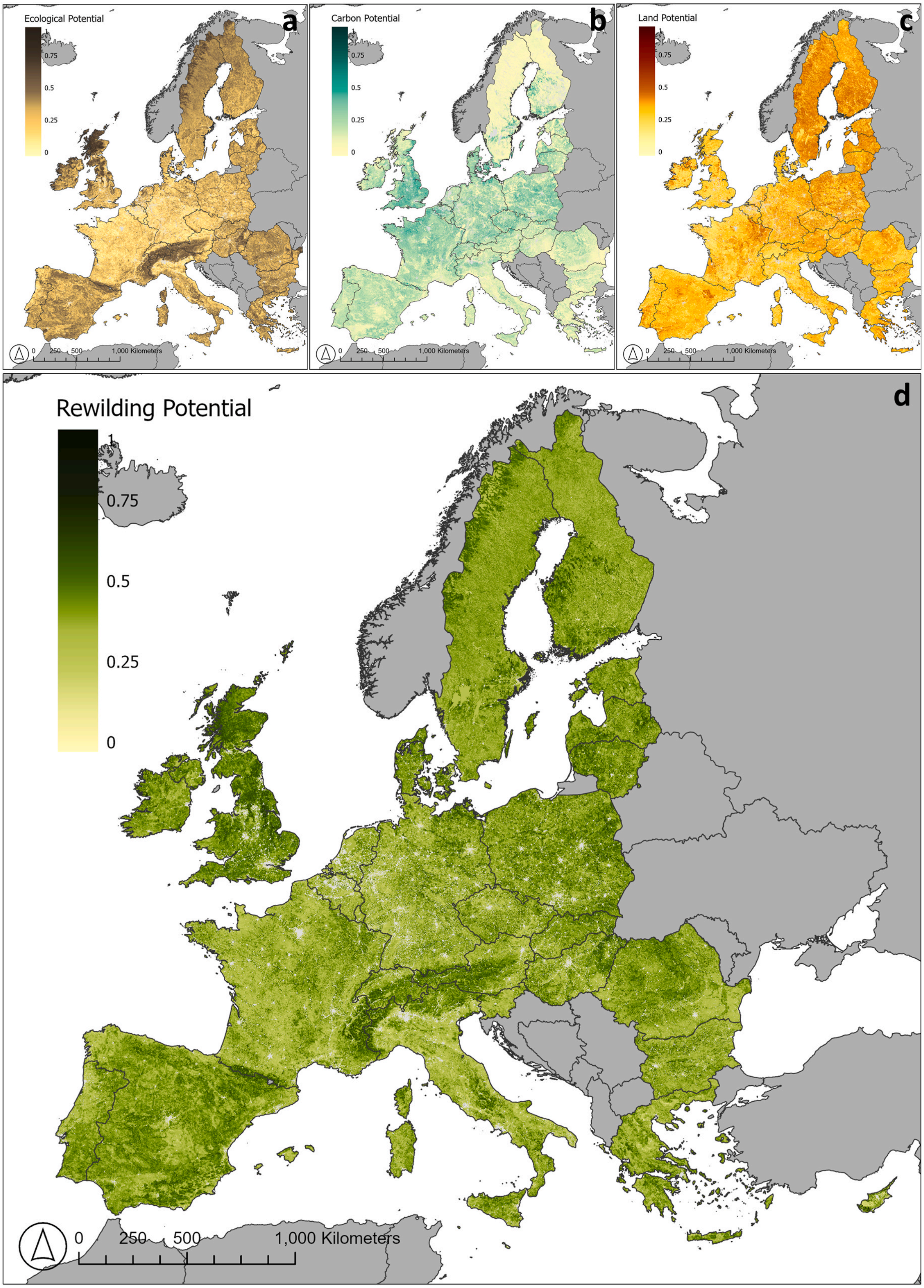

Fig. 2. a-d Rewilding Potential, based on (**a**) ecological potential, (**b**) carbon potential, (**c**) land potential and (**d**) all three dimensions combined. For Switzerland, the land potential is based on two instead of three indicators, as data on crop and forest productivity were missing.

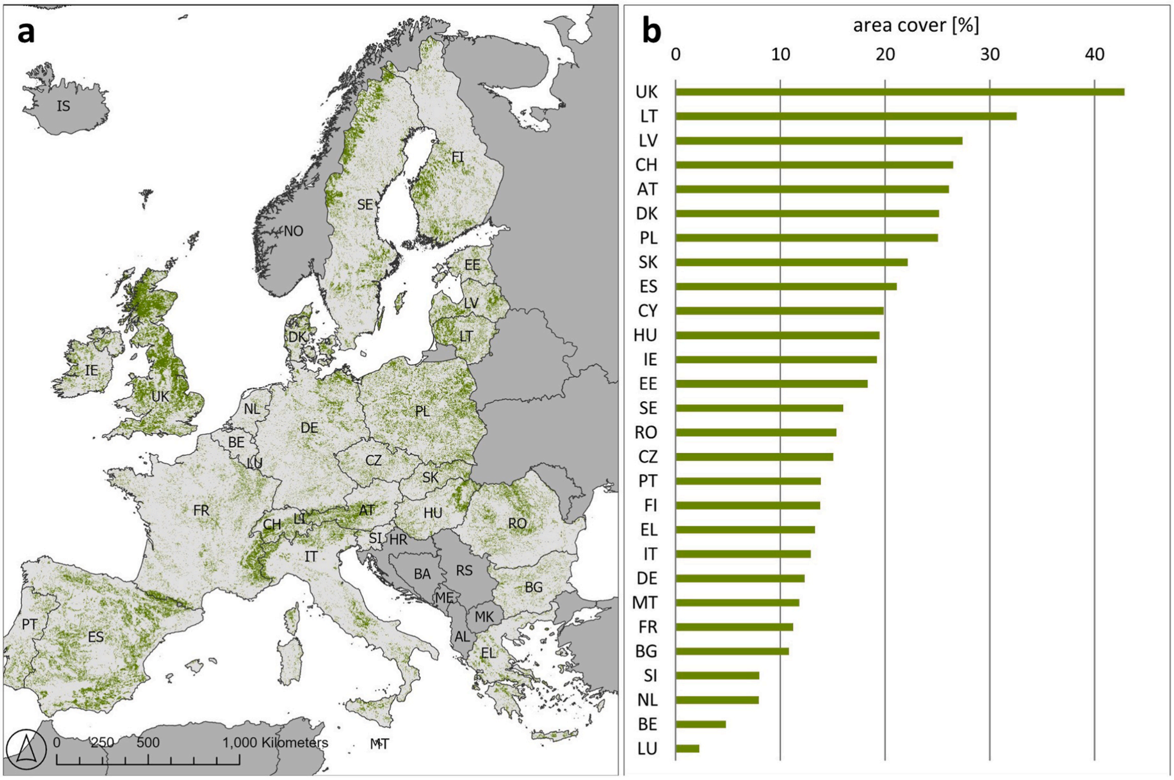

Fig. 3. Distribution of rewilding potential hotspots (20 % of area with the highest values) in Europe (**a**) spatially and (**b**) area covered per country compared to total area of country.

France. Some larger patches occur in Finland and northeast Spain. High values for the land and ecological potentials (dark red in Fig. 5b) explain 7.0 % of the high rewilding potential. They mainly occur in the North of Europe (Sweden, Finland, Northwest of Ireland and Baltic States), the Eastern Alps, and some smaller areas in the East of Hungary as well as on the border between Romania and Bulgaria. 5.0 % of the high rewilding potential can be explained by high values for the ecological and carbon potentials (dark red in Fig. 5c) including mountain ranges (Pyrenees, Alps), the United Kingdom and small patches in the Baltic States and Central and South of Spain.

Synergies with high values in all three dimensions are very rare, with a coverage area of only 0.3 % of the rewilding potential hotspots (Table S 2). Also, high values in two dimensions combined with middle values in the third dimension are rare with a total coverage of 3.1 % of the rewilding potential hotspots. However, high values in two dimensions are often accompanied by low values in the third dimension. For example, areas with high values in the ecological and land potential mainly show low values for the carbon potential (covering 5.6 % of the rewilding potential hotspots).

3.3. Rewilding potential hotspots per dimension

The threshold value for rewilding potential hotspots (20 % of area) per dimension is 0.44 for the land potential dimension, 0.33 for the carbon potential dimension and 0.47 for the ecological potential (Fig. 6a–c). When overlaying the hotspots of each dimension about half of Europe (50.2 %) is covered where at the same time it covers 98.7 % of the overall rewilding potential hotspots (Fig. 3a).

The majority of land falling into the top 20 % of one of the dimensions is covered by high values for one dimension only (85.2 %), with 30.9 % for the carbon potential (blue), 27.5 % for the land potential (red) and 26.8 % for the ecological potential (green) (Fig. 6d). The spatial distribution highlights the North of Europe for the land potential (Fig. 6a), whereas the carbon potential is allocated mainly in central Europe (Fig. 6c). Mountainous areas clearly show a high rewilding potential when considering the ecological potential (Fig. 6b). The Mediterranean region has overall a lower share of high rewilding potential of the three dimensions. However, more diverse and small-scale patterns regarding the different dimensions are evident. Synergies within the three dimensions (land, carbon and ecological potential) are rare: the hotspot grid cells overlap on 14.4 % for two dimensions and only 0.4 % for all three dimensions (Fig. 6c). Synergies between the land and ecological potentials (yellow) are found in the Northwest of Sweden and in Eastern Europe (Fig. 6e). The land and carbon potentials (pink) overlap in Eastern France, in the South of the Pyrenees and on some smaller patches in the UK. High values for the carbon and ecological potentials (cyan) occur in the middle of the UK with smaller patches distributed across Denmark, Northern Germany and Eastern Europe, often along rivers (Fig. 6e). Grid cells where all three dimensions overlap are rare and scattered across Europe without forming larger connected areas.

4. Discussion

4.1. Where could climate-smart rewilding be located in Europe?

We present here the first high-resolution European-scale mapping approach of the potential for climate-smart rewilding, considering ecological, carbon sequestration and socioeconomic aspects. We show that areas of high potential are scattered across Europe and are driven by different shares of the three dimensions that were considered in the analysis, which emphasises the high spatial variability in ecological diversity (Cervellini et al., 2021) and in the land-use history of Europe (Jepsen et al., 2015). For example, European mountains are characterised by a high geological heterogeneity and low landscape fragmentation (European Environment Agency; Swiss Federal Office for the Environment, 2011), providing different niches and refugia for species (Stein et al., 2014) leading to high potentials in the ecological

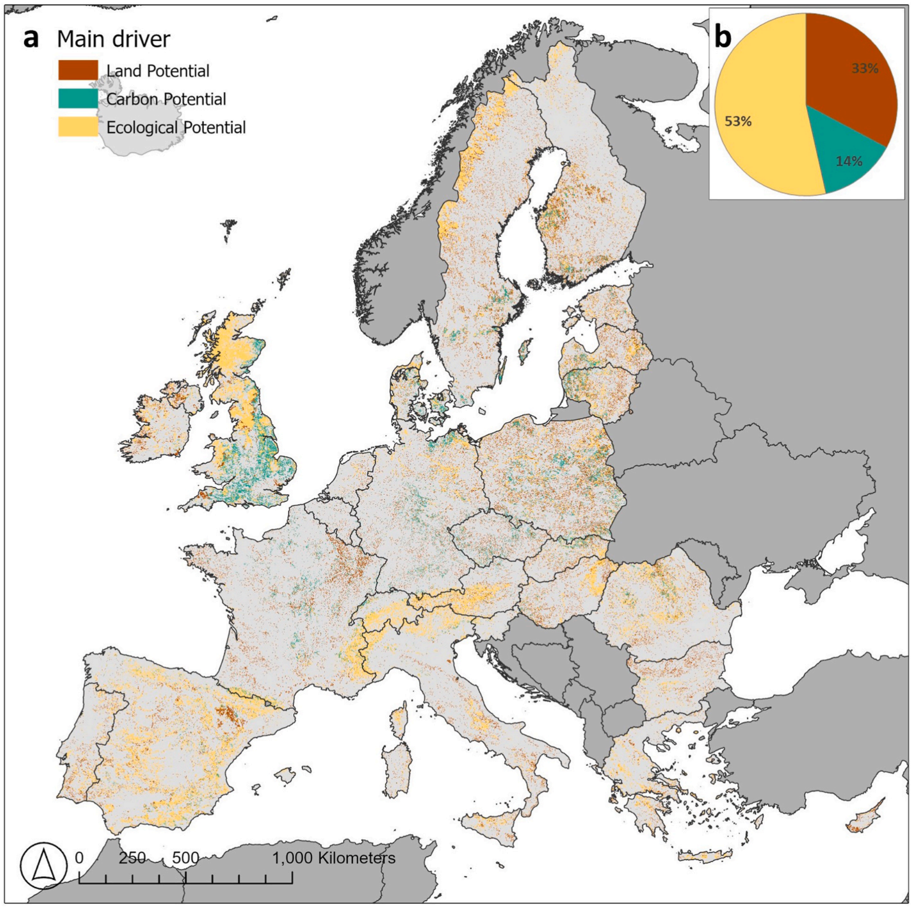

Fig. 4. Dominant dimension (highest value compared to the other two) being the main driver of the overall rewilding potential hotspots. (**a**) Spatial distribution of the main drivers, (**b**) distribution of rewilding potential hotspots (in percent).

dimension. In contrast, high values of the rewilding potential in Central and Western Europe including the South of the UK are mainly driven by a high potential for carbon sequestration, which indicates a long history of use and high levels of degradation of natural ecosystems (Walker et al., 2022a,b). However, these locations usually coincide with low land potential due to a high soil biomass productivity also explaining the long history of use (Tóth et al., 2013). A unique feature of high rewilding potential in Eastern Europe is the higher share of abandoned land arising from the collapse of the former Soviet Union (Prishchepov et al., 2013; Schierhorn et al., 2013), resulting in higher land potential. This land became available after the transition period from 1989 onwards, where the break-up of large collective or state farms was followed by privatisation, leading to smaller land units being managed by new landowners often with less experience and lack of equipment and other capital inputs (Pointereau et al., 2008).

The spatial variability in the drivers of the rewilding potential indicates that there is not a European-wide approach to realise climate-smart-rewilding in practice; instead, local and regional solutions will be required to turn the rewilding potential at a given location into actual rewilding projects. The trade-offs between the three individual dimensions (i.e., areas with high potential on our relative scale tend to score high only in one or two dimensions), further emphasises the enormous pressure on land through competing demands in a densely populated continent such as Europe (Grass et al., 2021). Hence, rewilding planning in Europe will always have to make compromises by deciding which objectives have the highest priority in a certain area. Our results can guide such decisions by giving an overview for Europe where there is high potential for rewilding by considering the main barriers and facilitators of rewilding. The answer to the question *'Where could climate-smart rewilding be located in Europe?'* will always depend on value judgements. Such values can differ depending on alternative visions of the future. The Nature Futures Framework (NFF), for example, describes three different visions of desirable nature-positive futures (Kim et al., 2023; Pereira et al., 2020). 'Nature for Nature' focuses mainly on nature's intrinsic values, 'Nature as Culture' prioritises the non-material benefits of nature for humans and 'Nature for Society' has the focus on nature's instrumental values. Depending on which vision society aligns with could influence how the priorities for rewilding are set, which would most likely differ within regions. In the Nature for Society vision, this could be an increased focus on the land potential, while in the Nature for Nature vision, higher importance could be given to the ecological potential. Here, an adapted weighting of the single indicators for deriving the rewilding potential could be used to explore rewilding potential across different value judgements, e.g. according to the three NFF visions.

Applying different rewilding approaches, adapted to a region's potential, could also help to overcome barriers associated with low rewilding potential in one dimension but higher values for other dimensions. This could, for example, include a greater focus on nature-based climate solutions (e.g. rewetting) in regions with a high carbon potential, or a more passive rewilding approach with low human intervention in areas where the ecological potential is high, enabling a good basic facilitation for successful rewilding. In areas with high land availability but low ecological potential, a more active rewilding approach would be needed to improve the basic facilitation, e.g., by initial intervention with species introduction or engineering work (Du Toit and Pettorelli, 2019). However, we are aware, that those examples can only help to define the overall emphasis on possible implementation

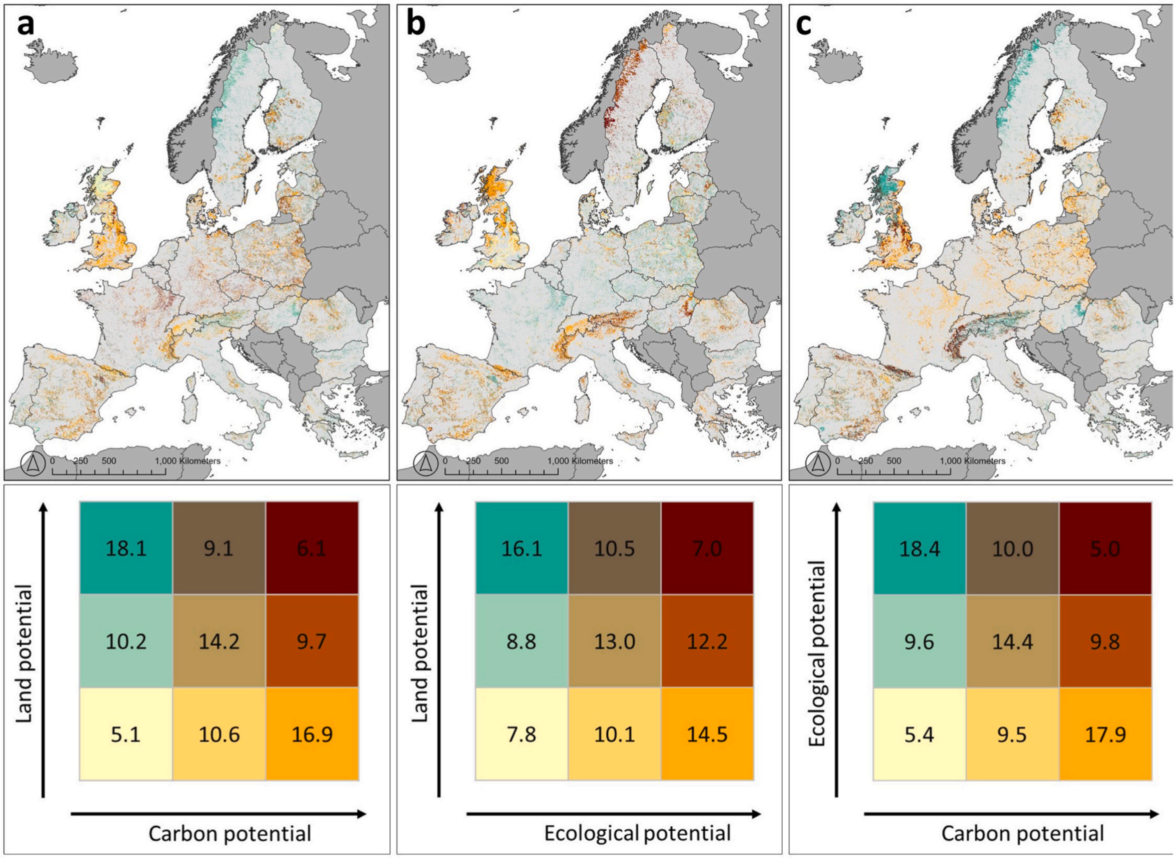

Fig. 5. Pairwise comparison of synergies and trade-offs between the ecological, carbon, and land potentials based on quantile classification on the 20 % of land with the highest overall rewilding potential values (hotspots). Comparison between (**a**) land and carbon potential, (**b**) land and ecological potential and (**c**) ecological and carbon potential. The percentages in the legend box indicate the share of pixels falling into each category, where bright yellow indicates low values for both dimensions, turquoise and dark yellow indicate high values for only one dimension, the darker and more towards red colours indicate more synergies between the two compared dimensions.

strategies of rewilding. Of course, when implementing a rewilding project, further adaptations to the local and regional conditions and needs as well as to different societal values have to be considered. The flexibility of the additive approach means that the weightings of the three dimensions can be modified to adapt the framework to specific applications or societal values. For now, we chose to weigh all three dimensions equally, since there is no clear evidence on which to base an alternative weighing scheme. In practice, weighing the relative importance of each dimension is a value judgement, the definition of which is not the purpose of the work presented here. Instead, the equal weighting provides a general overview considering the different aspects of rewilding (land availability, climate and ecology). However, the maps of the dimension hotspots do provide an indication of how different the overall rewilding potential would look if the dimensions were differently weighted.

4.2. Comparison to other studies

Our results are broadly in line with other studies. For example, a global study identifying priority areas for ecosystem restoration by Strassburg et al. (2020) also identified high restoration potential for Central and Eastern Europe, Eastern France and the North of the UK. Their results are also based on a multicriteria approach, including the dimensions of biodiversity conservation, mitigation of climate change and opportunity costs. Similarities mainly result from comparable patterns in the climate dimension, emphasising the important role Europe could play in carbon sequestration, as the carbon storage potential is higher than in many other world regions due to the high degree of land degradation. In contrast, the global perspective taken by Strassburg et al. (2020) identifies priority areas for biodiversity conservation mainly outside of Europe which highlights that ecosystem restoration and rewilding must be considered at the global scale to be effective for biodiversity conservation (Strassburg et al., 2020; Svenning et al., 2016). Within Europe, they identify the Mediterranean region with high priority for restoration, which aligns with the high values of ecological potential identified in our study. This is especially interesting, as their analysis is based on avoided extinctions per hectare when being restored, which indicates that the ecological potential hotspots identified in our analysis also have the potential to avoid extinctions and therefore directly contribute to fighting biodiversity loss. In contrast, the high rewilding potential for European mountainous areas identified here is not present in the results of Strassburg et al. (2020). This most likely arises from a focus on land converted from natural ecosystems to croplands or pasturelands which excluded forest areas that are dominant in European mountainous areas, such as the Alps. The high rewilding potential areas in Sweden, the North of the UK and the Iberian Peninsula also align with a study by Araújo and Alagador (2024). Given their focus on identifying the rewilding potential based on large areas with minimal human disturbances and the natural presence of key mammal species, it shows that those areas would also be suitable for passive rewilding with wild herbivore populations already present.

Studies investigating the potential of rewilding as a specific restoration approach are rare. Those that do exist often focus on a smaller scale by considering only the ecological benefits and needs of rewilding (Araújo and Alagador, 2024; Ceaușu et al., 2015; Zoderer et al., 2024), and do not utilise an interdisciplinary approach. With an ecological

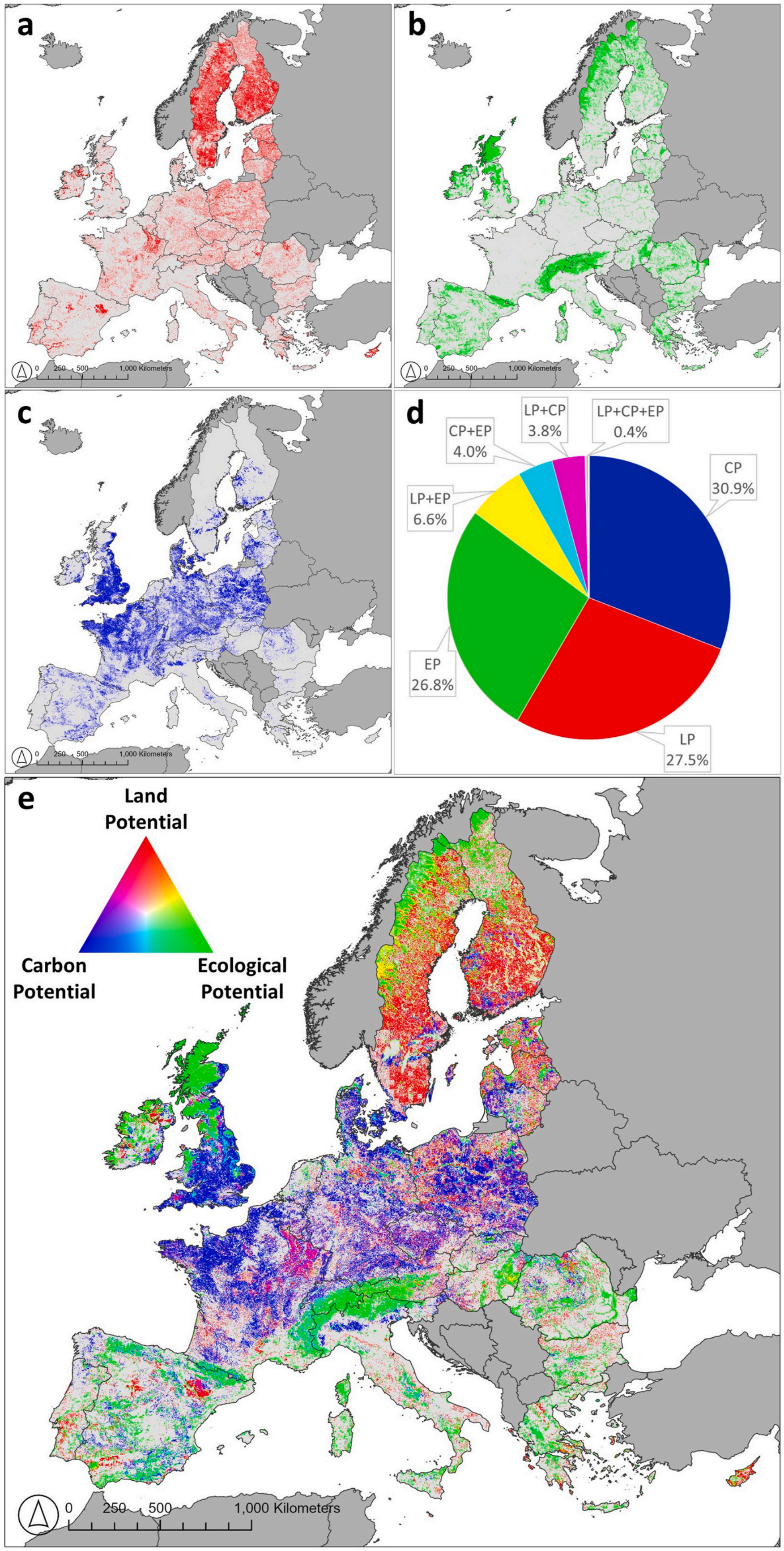

Fig. 6. Upper 20 % area showing highest rewilding potential (hotspots) based on (**a**) land potential (red), (**b**) ecological potential (green) and (**c**) carbon potential (blue). **e** Overlay of **a-c** maps showing no overlap in RGB colours and synergies in the intermediate colours (yellow, cyan and purple). **d** Showing the distribution in percent of the area per potential (EP = ecological potential, LP = land potential, CP = carbon potential) and their overlap, spatially shown in (**e**).

focus, the potential is often represented as wilderness described by indicators such as remoteness, artificial light, human impact, naturalness etc. Thereby, priority areas for rewilding are either identified if wilderness indicators are in an insufficient condition (Ceaușu et al. (2015) on projected abandoned land for Europe) or based on areas already showing a high wilderness quality (Zoderer et al. (2024) for the Alps) or derived from the natural presence of key mammal species (Araújo and Alagador, 2024 for Europe). The focus on wilderness areas is complementary to the approach taken here. We see a general potential for improvement through rewilding for the whole of Europe (with a focus on terrestrial land excluding urban areas), as almost all of Europe has been shaped or altered by humans (Tieskens et al., 2017).

4.3. Integrating rewilding into spatial planning in Europe

In the EU, environmental targets are often implemented at the national-level, which is also the case for the EU Nature Restoration Regulation (Regulation EU 2024/1991, 2024). The NRR sets a target to restore 20 % of land by 2030 and all land in need of restoration by 2050. While our mapping was not developed to match with the requirements of the EU NRR, our results still provide support in deciding which areas could be particularly important to restore when focusing on a process-oriented restoration approach. As the results show, each country has to cope with different rewilding potentials, thus with different basic conditions. While some countries have a higher share than 20 % of their land covered by rewilding potential hotspots, others have a lower rewilding potential. Countries with a larger share of areas with high rewilding potential should find it easier to allocate the amount of land needed to successfully implement restoration projects. Others with a lower share of areas with high rewilding potential will face more difficult starting conditions. Therefore, consultation between countries and across regions would be beneficial to jointly address the different sets of available potential and reach the best possible outcomes. This could, for example, be done by having a larger focus on carbon storage in one country versus a different focus on biodiversity in another country.

As our results show, national implementation of an area-based target would not necessarily overlap with the highest restoration potential identified on a continental scale (Fig. 3b). This also raises the question of whether the best implementation and outputs of the EU NRR restoration targets can be reached by providing an area target to each country instead of continental-wide implementation. In countries with less potential for rewilding, meeting the area target could make it harder to achieve the restoration target. This could lead to less successful results. For example, for overcoming the biodiversity crisis it is crucial that the status of the full spectrum of ecosystems is improved (Díaz et al., 2020). Ecosystems often extend beyond national borders, thus transboundary considerations are needed. Conversely, an advantage of country-specific targets is the flexibility for each country to implement restoration targets in a way that considers regional and local conditions and needs as much as possible (Hering et al., 2023). For the EU NRR this can be done within the National Restoration Plan each member state has to adopt, stating how they intend to achieve the targets (Regulation EU 2024/1991, 2024; Hering et al., 2023). We are aware that the decision on where to rewild or restore also has to consider several other aspects then those considered in the analysis presented here. Those range from the need to account for property rights, potential conflicts with existing or planned protected areas, trade-offs with other spatial plans and their aims as well as political values and the availability of financial resources.

4.4. Discussion of methods and future work

A constraint in this study was the availability of spatial data covering as much of Europe as possible at a resolution of at least 1 km^2. As many datasets were only available at the EU-scale, we were not able to cover all of Europe with our analysis but had to reduce the spatial extent to the EU26 + 2 countries. We included Switzerland, even though data were missing for one indicator (land productivity). Based on a sensitivity analysis (Appendix A: Figure S 2, Table S 3), the impact on the overall rewilding potential of missing one out of eleven indicators is minor, so we decided that the importance of presenting the rewilding potential for Switzerland is larger. Furthermore, the set of indicators and calculation methods used here influenced the calculated rewilding potential. For the ecological potential we aimed to highlight areas that have the right conditions for successful rewilding to happen. While we included water disturbance potential as a key disturbance factor, we acknowledge that other disturbances, such as fire regimes, snow cover dynamics, and land-use changes, could also play an important role. However, data availability (e.g., fire) and the occurrence on a more regional and not continental scale (e.g., snow dynamics mainly relevant in mountainous regions, fire mainly in the Mediterranean) pose challenges for incorporating these disturbance processes in a large-scale analysis. Additionally, natural disturbances are stochastic events that vary across locations and with different intensities (Franklin et al., 2000) which makes them hard to predict and to define in datasets. Another limitation in the ecological potential is that we did not include any biodiversity metrics directly. While our analysis incorporated landscape fragmentation and neighbouring habitat richness as indicators, we recognise that these are proxies and do not fully capture the complexities of biodiversity. However, present-day biodiversity data highlight current biodiversity hotspots, which are important for identifying areas for nature conservation, but not for identifying areas for rewilding. Including the neighbourhood, similar to the approach used for the habitat richness, could help to overcome this issue by stating that high biodiversity in the neighbourhood of a target cell would lead to an increase of the rewilding potential. However, such analyses are presently constraint by the availability of biodiversity datasets on a continental scale covering a significant number of taxonomic groups as well as the open discussion on which biodiversity metrics fits best to describe rewilding. Here, data on vertebrates could be of special interest in future research, as vertebrates are often guiding rewilding initiatives.

For the calculation of the climate-smart rewilding potential we used a min-max-normalisation for the indicators and the single dimensions, and an additive approach to combine the indicators first and then the three dimensions. Thereby, we show a relational comparison between the different areas within Europe, evaluating the lowest values occurring within Europe as the worst and the highest values as best. Another option would be to define optimised ranges for each indicator, based on objectives or hypotheses. However, the decision on the range would always be based on assumptions and such thresholds are difficult to find as spatial allocation studies on rewilding are still very rare.

To facilitate the analysis of the highest rewilding potential in more detail including analysis of trade-offs and synergies, we focussed a substantial part of our study on the hotspots of the rewilding potential. We defined hotspots by selecting the 20 % of land with the highest rewilding potential. We see those areas to be of particular interest when thinking about where to rewild in a way that reduces trade-offs and achieves multiple co-benefits. The value of 20 % was inspired by the EU Nature Restoration Regulation target of restoring at least 20 % of land by 2030, while at the same time an area-based threshold enables direct comparisons of the spatial distribution of dimensions despite the differences in their values. Other approaches for selecting hotspots for rewilding could result in different results. An alternative method could focus on covering various ecosystems with the same share of area. For example, this has been done at a global scale using the extent of different biomes (Strassburg et al., 2020), and at a regional scale using the extent of ecoregions (Zoderer et al., 2024). In Europe, legislation is mainly focused on national implementation, hence we did a continental and national analysis instead of focusing on the coverage of different ecosystems.

The framework presented here provides for the first-time large-scale maps on the climate-smart rewilding potential of Europe. These maps can be used as a baseline for future projections in land-use change models and expanded to explore future pathways and policy options. Furthermore, the developed spatial approach can be revised by exchanging the indicators if better spatial data with e.g., a higher resolution or a more detailed methodology becomes available. Additionally, we suggest that the developed spatial approach can be adapted to other regions or scales by adopting the indicators to best reflect the underlying regional conditions.

CRediT authorship contribution statement

Judith Kloibhofer: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Reinhard Prestele:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization. **Georg Leitinger:** Writing – review & editing, Supervision, Conceptualization. **Mark Rounsevell:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Helmholtz Excellence Recruiting Initiative and the European Union's Horizon Europe research and innovation programme under grant agreement No. 101081251. Views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Furthermore, we would like to thank Karina Winkler for providing updated HILDA+ data including processing of land abandonment data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125084.

Data availability

The data that support the findings of this study are openly available in Zenodo at DOI 10.5281/zenodo.14224439.

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