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An assessment of future rewilding potential in the United Kingdom

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Abstract
Restoring ecosystems is an imperative for addressing biodiversity loss and climate change, and achieving the targets of the Kunming–Montreal Global Biodiversity Framework. One form of restoration, rewilding, may have particular promise but may also be precluded by requirements for other forms of land use now or in the future. This opportunity space is critical but challenging to assess. We explored the potential area available for rewilding in Great Britain until the year 2080 with a multisectoral land-use model with several distinct climatic and socioeconomic scenarios. By 2080, areas from 5000 to 7000 km^2 were either unmanaged or managed in ways that could be consistent with rewilding across scenarios without conflicting with the provision of ecosystem services. Beyond these areas, another 24,000–42,000 km^2 of extensive upland management could provide additional areas for rewilding if current patterns of implementation hold in the future. None of these areas, however, coincided reliably with ecosystems of priority for conservation: peatlands, ancient woodlands, or wetlands. Repeatedly, these ecosystems were found to be vulnerable to conversion. Our results are not based on an assumption of support for or benefits from rewilding and do not account for disadvantages, such as potential losses of cultural landscapes or traditional forms of management, that were beyond the modeled ecosystem services. Nevertheless, potential areas for rewilding emerge in a variety of ways, from intensification elsewhere having a substantial but inadvertent land-sparing effect, popular demand for environmental restoration, or a desire for exclusive recreation among the wealthy elite. Our findings therefore imply substantial opportunities for rewilding in the United Kingdom but also a need for interventions to shape the nature and extent of that rewilding to maintain priority conservation areas and societal objectives.

KEYWORDS
abandonment, ecosystem services, food security, land-use model, passive rewilding, restoration, scenarios

INTRODUCTION

Rewilding ecosystems that have been altered or degraded by human activity may make an essential contribution to reversing global biodiversity decline and accelerating land-based climate change mitigation through carbon sequestration (Svenning, 2020). Rewilding could also contribute to the Kunming–Montreal Global Biodiversity Framework, in particular, its second target to "ensure that by 2030 at least 30 per cent of areas of degraded terrestrial, inland water, and marine and coastal ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity" (Convention on Biological Diversity, 2023). Because of this potential contribution, rewilding is rapidly gaining political and practical prominence. As it does so, it is becoming associated with many different forms of conservation in different parts of the world, often distinct from its original focus on the establishment of large, connected reserves containing keystone and large carnivore species and without full knowledge of the benefits or drawbacks of all approaches (Perino et al., 2019).

The United Kingdom is one of the most nature-depleted countries in the world (Hayhow et al., 2019), where 71% of the land area is managed for agriculture (DEFRA, 2021). This makes rewilding particularly relevant in terms of repairing damaged ecosystems, and it has increasing prominence in policy and practice (Brown et al., 2011; DEFRA, 2022; Sandom et al., 2013; Sandom, Dempsey, et al., 2019). But the long-term degradation of UK ecosystems also poses challenges, not least because rewilding implies a substantial change to conditions that people have come to regard as natural, traditional, or otherwise appropriate (Mikołajczak et al., 2022). In its focus on ecosystem structure and functions, rewilding is not always intended or able to maximize elements of biodiversity that people may prioritize (Carver et al., 2021; van Meerbeek et al., 2019). Rewilding is often very controversial as a result, with passionate and subjective debates characterizing its implementation (Hodgson et al., 2018; Jones & Comfort, 2020; Thomas, 2022; Wynne-Jones et al., 2018). For these reasons, the United Kingdom makes a particularly useful case study within the broader context of the international development of rewilding because it highlights the pressures that might prevent large-scale rewilding and opportunities to support it.

Relatively flexible definitions of rewilding have emerged recently in the United Kingdom that acknowledge the need for the achievement of environmental objectives in or in close proximity to productive and cultural landscapes (Brown et al., 2011; Hall, 2014). In this context, Du Toit and Pettorelli (2019) identify rewilding as a process of "reorganizing and regenerating wildness in an ecologically degraded landscape, with present and future ecosystem function being of higher consideration than historical benchmark conditions." This should lead, according to Pettorelli et al. (2018), to "the self-sustaining provision of ecosystem services with minimal ongoing management." In their review of the concept, Carver et al. (2021) emphasize that "rewilding exists on a continuum of scale, connectivity, and level of human influence." Although proposals have been made to allow monitoring of the progress and extent of rewilding (Torres et al., 2018), others suggest that rewilding should not be tightly defined or measured and remain a somewhat exploratory process (Jepson et al., 2018), which makes definitive anticipation of its effects difficult.

These flexible definitions of rewilding also imply a need for land that can develop in relatively unconstrained and unpredictable ways, even where it might also continue to provide recreational, agricultural, or other benefits. By implication, rewilding areas are largely independent of societal demands for specific goods or ecosystem services, aside from long-term and loosely defined objectives for biodiversity recovery and carbon sequestration. (This is not to imply that rewilding schemes themselves do not have clear objectives and management practices; rather, these are not strongly constrained by demand for other land uses.) It is this definition that we adopted here, and we made no assumptions about the exact nature of areas with potential for rewilding other than their independence from extractive forms of land management.

This necessary independence has meant that rewilding in the United Kingdom has often occurred on large private estates, where landowners are motivated and able to take the land out of other forms of productive use (Jones & Comfort, 2020; Sandom, Wynne-Jones, et al., 2019). However, new land management subsidies and an influx of private investment in nature-based solutions mean that rewilding may soon become more widespread. In 2022, the UK Government announced plans to subsidize the restoration of 300,000 ha (3000 km^2) of wildlife habitat by 2042, with a special focus on wetland and peatland areas (DEFRA, 2022). At the same time, the marketization of biodiversity and carbon credits has created a major potential income stream for rewilding projects (Knight-Lenihan, 2020; Savills, 2022; Worrall et al., 2009). This has led to interest in (some form of) rewilding among farmers and other land managers, often alongside regenerative pastoral agriculture (Cusworth et al., 2022).

Despite this increasing interest, the potential extent of land available for rewilding in the future is highly uncertain. Many factors will determine this, including climate change impacts on farming and ecosystems, changing priorities for land use and conservation, and competing demands for land to produce goods for domestic or international use. The use of future projections to explore the scope for rewilding as these contextual factors vary is therefore a prerequisite for anticipating its potential ecological impacts. However, the implications of future land-use change, strongly driven as it is by requirements for food, timber, and other, especially provisioning, services, are relatively neglected, not least because of the difficulty of projecting these diverse land-use change drivers and outcomes.

We conducted an initial geographical assessment of the potential locations for rewilding in Great Britain (excluding Northern Ireland because required input data were unavailable). We use a high-resolution and cross-sectoral model of the British land system that links local conditions to land management decisions and to national to global driving conditions (Brown et al., 2022). Our objectives were to define plausible extents of land areas available for rewilding (in the sense of being surplus to requirements for the production of food and timber) in the absence of additional policy interventions. We explored the temporal and geographical distribution of these areas and evaluated the feasibility of targets for protection and rewilding of land in the United Kingdom.

METHODS

Model and scenarios

We use the CRAFTY-GB model of the British land system (Brown et al., 2022) to explore the scope for rewilding under a range of future climatic and socioeconomic conditions defined by the widely applied RCP–SSP (representative concentration pathways–shared socioeconomic pathways) scenario framework (O'Neill et al., 2017). The model is formally documented and evaluated in File S2. The RCPs are defined by radiative forcing levels in the year 2100 of 2.6, 4.5, 6.0, and 8.5 W·m^{-2} relative to preindustrial levels. The SSPs describe social and economic conditions until 2100 that complement the RCPs and go beyond single-driver or trend-based analyses in constructing alternative but plausible futures containing realistic ranges of land-use drivers that can be integrated across scales, from local to global (Table 1). The specification and downscaling of the RCP–SSP to the United Kingdom are described in File S2.

TABLE 1 Overview of the scenarios applied and their implications for rewilding, which are derived from the model results and the UK-SSP (shared socioeconomic pathways) and RCP (representative concentration pathways) narratives.

Scenario (SSPs and SSP-RCP pairs)	SSP descriptions*	Implications for rewilding
SSP1 – sustainability (paired with RCP2.6)	UK-SSP1 shows the UK transitioning to a fully functional circular economy as society quickly becomes more egalitarian leading to healthier lifestyles, improved well-being, sustainable use of natural resources, and more stable and fair international relations. It represents a sustainable and cooperative society with a low carbon economy and high capacity to adapt to climate change.	SSP1 produces extensive rewilding potential areas (RPAs) (slightly smaller only than those in SSP2) with large geographical spread and large patch sizes. Intensive agricultural areas (pastoral and arable) decrease, whereas multifunctional "sustainable" agriculture increases. Demands for ecosystem services from natural and sustainably managed systems grow substantially, particularly for carbon, biodiversity, and recreation. The scenario narrative suggests an emphasis on natural processes and limited human impact in rewilding areas: "Semi-natural habitats in both the lowlands and uplands are effectively restored…[and] land abandoned by agriculture is either converted to semi-natural habitat and nature reserves, or allowed to transition towards rewilding" (UK Climate Resilience Programme, 2021).
SSP2 – middle of the road (paired with RCP 4.5 & RCP 8.5)	UK-SSP2 is a world in which strong public–private partnerships enable moderate economic growth but inequalities persist. It represents a highly regulated society that continues to rely on fossil fuels, but with gradual increases in renewable energy resulting in intermediate adaptation and mitigation challenges.	SSP2 produces the largest RPAs of any scenario, with similar geographical spread as SSP1 but smaller patch sizes. This is possible through intensification and increased efficiency in agriculture, leading to a decrease in agricultural area. Large increases in forest area, partly to satisfy very high timber demand and partly through land sparing, also imply space for rewilded areas without substantial human pressure. "Land use planning concentrates on agricultural intensification (both in the rural areas and in the cities through vertical farming), integrating forestry with agriculture, and addresses competition between sporting land uses in the uplands and the provision of wider public goods. The establishment of PES for woodlands supports their expansion in the uplands…The population no longer relies only on rural areas for food production, reducing land use conflicts and freeing up more land for conservation" (UK Climate Resilience Programme, 2021).
SSP3 – regional rivalry (paired with RCP 6.0)	UK-SSP3 is a dystopian scenario, with increasing social and economic challenges triggering international tensions, nationalization in key economic sectors, job losses, and, eventually, a highly fragmented society with the United Kingdom breaking apart. It represents a society where rivalry between regions and barriers to trade entrench reliance on fossil fuels and limit capacity to adapt to climate change.	SSP3 produces very small RPAs, and these are concentrated in the north of Scotland. Agricultural area increases as production efficiency declines and food shortages develop. Land-use changes occur frequently and heterogeneously, with divergence between independent states of England, Wales, and Scotland. All areas of land subject to human pressures, implying large challenges for rewilding. "To compensate for reduced yields, the agricultural area expands significantly as growing food for survival becomes a priority for all people. This has highly detrimental effects on biodiversity. National Parks and other protected areas de facto disappear by the 2060s and many wildlife populations become extinct" (UK Climate Resilience Programme, 2021).
SSP4 – inequality (paired with RCP 4.5)	UK-SSP4 shows how a society dominated by business and political elites may lead to increasing inequalities by curtailing welfare policies and excluding the majority of a disengaged population. The business and political elite facilitate low carbon economies, but large differences in income across segments of UK society limit the adaptive capacity of the masses.	SSP4 produces intermediate RPAs but with a high proportion of abandoned land in them. They are also concentrated in certain parts of the country. Large, homogeneous, agricultural areas develop in lowlands, with conservation and recreation management in upland areas and loss of marginal land uses. Declining pasture area, but expansion of bioenergy on arable land helps to drive increase in arable area and intensity at expense of forest areas. Technology also contributes to land-sparing effect; "In rural areas, large-scale agricultural intensification coupled with vertical farming in cities starts to free up land for other uses" (UK Climate Resilience Programme, 2021). However, recreation is likely to have substantial impacts in rewilded areas: "Land-owners shift…to high-value tourism and recreational sporting activities, such as hunting and fishing, for the elite and higher paid skilled workforce from the UK and overseas….Agriculture in the Welsh uplands is marginalised and the National Trust is privatised with corporations taking over such areas, in addition to Welsh beaches, as private playgrounds for the paying elite…vast areas of land are taken over by elite landowners in northern and southwest England" (UK Climate Resilience Programme, 2021).

(Continues)

TABLE 1 (Continued)

Scenario (SSPs and SSP-RCP pairs)	SSP descriptions*	Implications for rewilding
SSP5 – fossil-fueled development (paired with RCP 8.5)	UK-SSP5 shows the UK transitioning to a highly individualistic society where the majority become wealthier through the exploitation of natural resources combined with high economic growth. It represents a technologically advanced world with a strong economy that is heavily dependent on fossil fuels, but with a high capacity to adapt to the impacts of climate change.	SSP5 has larger RPAs than SSP4, but with an unusual geographical distribution and the smallest patch sizes of any scenario. Strong intensification occurs in agriculture (far beyond present-day levels) while increases in meat demand drive expansion of productive land uses into natural areas. Consequent abandonment in upland and marginal areas not under protection. Although this spares land for rewilding, environmental restoration has a low priority, and disruptive recreation takes precedence: "Former upland farms are re-wilded for tourism. Re-wilding is acceptable to local communities who see opportunities for income generation from tourism and food products such as game meat. By the 2060s, international tourism flourishes in these upland areas of the UK" (UK Climate Resilience Programme, 2021).

*Adapted from Brown et al. (2022) and narratives from UK Climate Resilience Programme (2021).

CRAFTY-GB is an agent-based model operating at a 1-km^2 spatial resolution and annual time step and is an application of the CRAFTY agent-based modeling framework (Murray-Rust et al., 2014). We embedded this model in the LandSyMM global modeling framework (Henry et al., 2022; Maire et al., 2022) (https://landsymm.earth/) to account for global change impacts on the British land system, including international trade. The model simulated land-use outcomes as the result of decision-making and competition among individual agents representing land users. A wide range of land uses and management intensities is available to these agents, and each produces a parameterized range of provisioning, regulating, cultural ecosystem services, and indicators for biodiversity and employment (the full list: food crops, fodder crops, grass-fed milk, grass-fed meat, bioenergy fuel, softwood, hardwood, biodiversity, landscape diversity [approximate variation in land cover in the land-use class], carbon sequestration, nonextractive recreation, flood regulation, employment, and sustainable production) (File S2).

Ecosystem service provision was determined by the form of land use and by a range of capital types that describe attributes of the land system at each modeled grid cell (human, social, financial, manufactured, and natural capitals, each composed of indicators detailed in File S2). The model was driven by (prescribed) societal demands for those services, which agents competed to satisfy, and by scenario-based variation in capitals arising from climatic and socioeconomic change. Agents were grouped into 17 agent functional types (Arneth et al., 2014) that capture the main forms of management and behavior relevant to British land-use change (File S2). Protected areas of 11 different types of designation and conservation land belonging to 5 different private organizations were included from the baseline and varied among the scenarios according to scenario storylines (e.g., being removed in some cases, retained in others, and influencing the level of management when present). The model is open-access and described in detail in Brown et al. (2022), including model development, calibration, evaluation, and application to the climatic and socioeconomic scenarios used here.

CRAFTY-GB runs under UK-specific versions of the RCP and SSP scenarios. The SSPs were specified for the United Kingdom as described in Pedde et al. (2021), Harmáčková et al. (2022), and Merkle et al. (2023). These substantial extensions of the global SSPs provide detailed narratives and quantifications of social, economic, and political developments across the United Kingdom until 2100 (Table 1) (UK Climate Resilience Programme, 2021). The narratives integrate national stakeholder knowledge on locally relevant drivers and indicators with higher level information from the European and global SSPs. The UK-SSPs were put in a global context with the LandSyMM global land system modeling framework to provide consistency with the broader SSP framework and to account for the United Kingdom's international trade in land-based commodities. The RCPs were specified for the United Kingdom with climatic conditions taken from the CHESS-SCAPE future climate data set (Lowe et al., 2019; MOHC, 2018). This data set covers several physical climate variables to 2080 at 1-km spatial resolution and time steps ranging from daily to decadal averages. Established RCP–SSP combinations (Table 1) (Brown et al., 2022) were used to cover a range of scenario uncertainty while prioritizing the pairing of particularly consistent RCPs and SSPs, with the middle of the road SSP2 being judged most applicable to multiple RCPs.

Identifying rewilding potential areas

Across the scenarios described above, we identified areas with potential for rewilding (rewilding potential areas [RPAs]) as those under management that is compatible with rewilding in 2040 and 2080. There were 2 classes that we assumed could be suitable for rewilding: unmanaged (abandoned or never-managed) land that is surplus to all modeled requirements and land managed to supply modeled demands for ecosystem services related to natural land (carbon, biodiversity, flood regulation, landscape diversity, and recreation and not food, fodder, fuel, timber, or other extractive services), which we labeled as *conservation*. The conservation class does not indicate a conservation designation and is not restricted to present-day conservation management. We assumed that recreation in these areas is consistent with rewilding, but scenario narratives included a range of activities, for example, hunting and mass tourism, that would affect rewilding management in different ways (see below and Table 1).

Very extensive pastoral management was not included in RPAs but was recorded as relevant. This third class was very broad, supplied small quantities of livestock products alongside a range of other ecosystem services, and covered much of the United Kingdom's most marginal agricultural land, including upland grazing, sporting estates, and seminatural areas. Despite being relatively unproductive for food and sometimes used for (or at least referred to as) rewilding (Carver et al., 2021; Gordon et al., 2021), this class of land is usually actively managed for agriculture and linked to traditional or cultural landscapes that may be of great significance to local communities (as demonstrated by the opposition to the Summit to Sea rewilding scheme in Wales [Jones, 2022]). Its potential for rewilding is therefore debatable and highly context dependent.

We did not attempt to prompt transitions to these land-use classes, so they emerge only as a response to the drivers embedded in the original scenarios: changes in demands for ecosystem services, capital levels, agent decision-making, and protected areas. Protected areas were not classified as RPAs by default because most have aims that are not broadly consistent with rewilding (IUCN National Committee UK Protected Areas Working Group, 2023; Starnes et al., 2021). Nevertheless, RPAs can and do occur in them and were recorded in those cases. Having identified RPAs and very extensive pastoral areas in different scenarios and time points, we checked their overlap with specific ecosystem types, focusing on (potential) wetlands, peatlands, and ancient (seminatural) woodland as high-priority habitats in the United Kingdom (JNCC, 2019). We did this to assess the scope for protection and restoration of these habitats, in line with government targets (DEFRA, 2022) but in the absence of specific interventions targeted in those areas (i.e., assessing their vulnerability to future pressures). We used habitat maps from a range of sources for this comparison (details in File S1). We mapped RPAs present in 2080 and identified hotspots of RPAs across all scenarios and their overlap with the ecosystem types. We also assessed patch sizes of RPAs and very extensive pastoral management (with R package terra [Hijmans et al., 2022]) to capture the broad variation across scenarios in land-use heterogeneity and its implications for the ability of these areas to function as rewilded landscapes.

RESULTS

Locations and extents of RPAs

There were large areas of Britain that were not required to satisfy modeled demands for ecosystem services across the range of conditions described by the scenarios and that we therefore classified as RPAs (Figure 1). The extent of land under very extensive grazing was large in all simulations (larger than the RPA classes), potentially providing substantial further scope for rewilding.

Relatively little land was modeled as becoming available to rewilding through abandonment (being unmanaged for any purpose). The largest of these areas were in SSPs 1 and 4 (3700 and 4300 km^2, respectively). Conservation areas were more common and larger in extent than abandoned areas. The locations of these 2 classes were variable across scenarios, but conservation usually emerged near to but not in upland areas, where neither production nor traditional upland management was strongly competitive. Abandoned land was more dispersed, but also occurred outside the most productive agricultural areas (Figure 1). These spatial patterns were clearest in SSP1 (sustainability) and least clear in SSP3 (regional rivalry, where intense competition for land to satisfy food demands increased agricultural use). These 2 scenarios contained the largest patch sizes of RPAs and very extensive pastoral management, although SSP3 had substantially less than SSP1, almost all of which occurred in the very extensive class in northern Scotland (File S1). The SSP4 (inequality) had the greatest levels of abandonment because consolidation and intensification of the most productive agricultural areas meant that marginal production became uncompetitive (an emergent land-sparing effect anticipated by the scenario narrative [UK Climate Resilience Programme, 2021]), with patches occurring more widely but at slightly smaller scales than those in SSP3 (File S1).

Differences between SSP outcomes were not always as expected. For example, the large dietary shift away from livestock products in SSP1 (sustainability) did not spare land proportionately for rewilding because this scenario also contained preferences for the remaining meat consumed to be produced via less intensive, pasture-based methods that require more land. The SSP5 (fossil-fueled development) had a relatively large (but fragmented) extent of conservation area because of land-sparing intensification of lowland food production and the demand for recreation (rewilding in the scenario storyline).

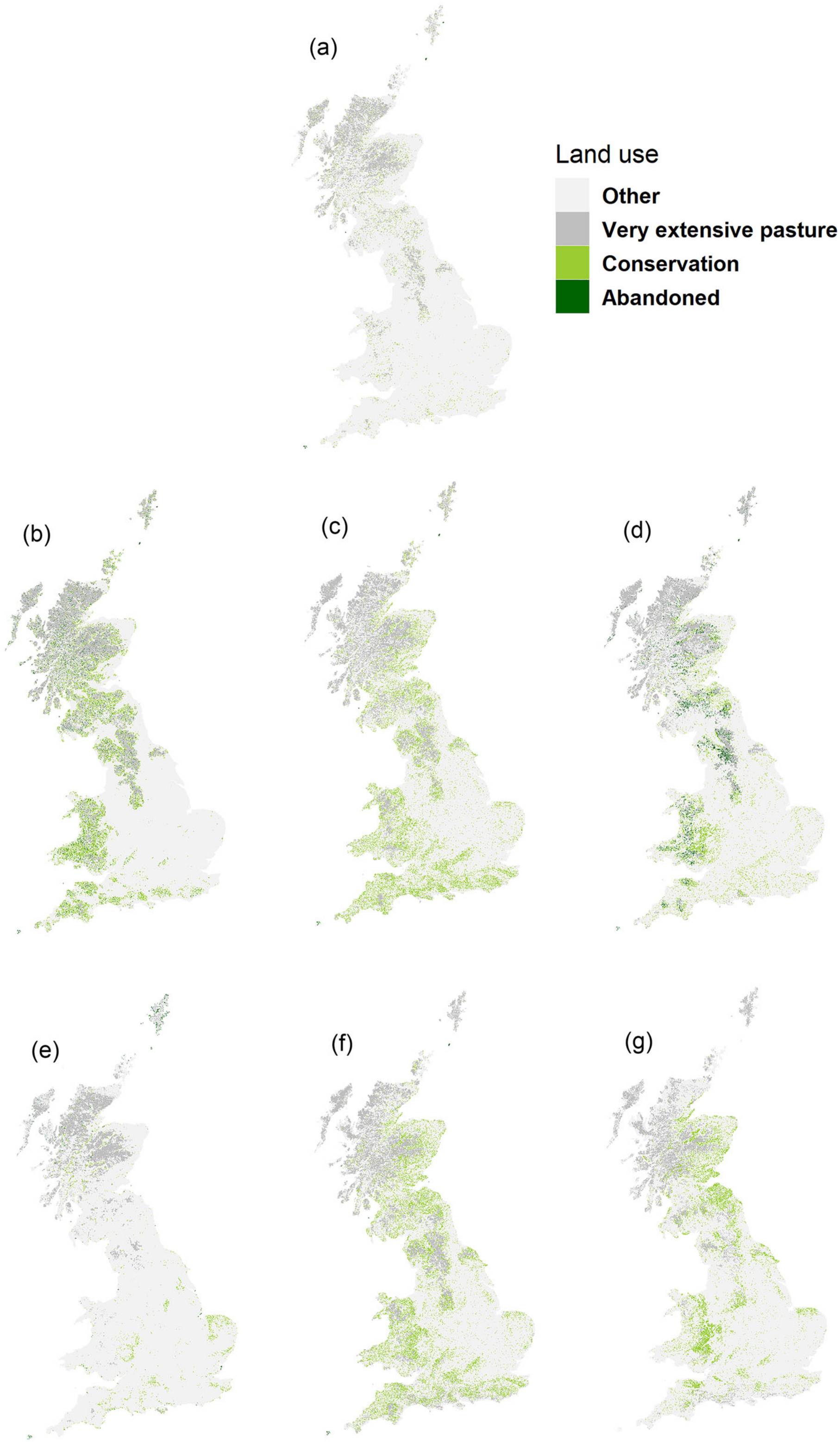

FIGURE 1 Areas of very extensive pasture, conservation management, and abandoned land in the baseline (a), and in 2080 across the simulated RCP–SSP (representative concentration pathways–shared socioeconomic pathways) scenarios: RCP2.6-SSP1 (b), RCP4.5-SSP2 (c), RCP4.5-SSP4 (d), RCP6.0-SSP3 (e), RCP8.5-SSP2 (f), RCP8.5-SSP5 (g).

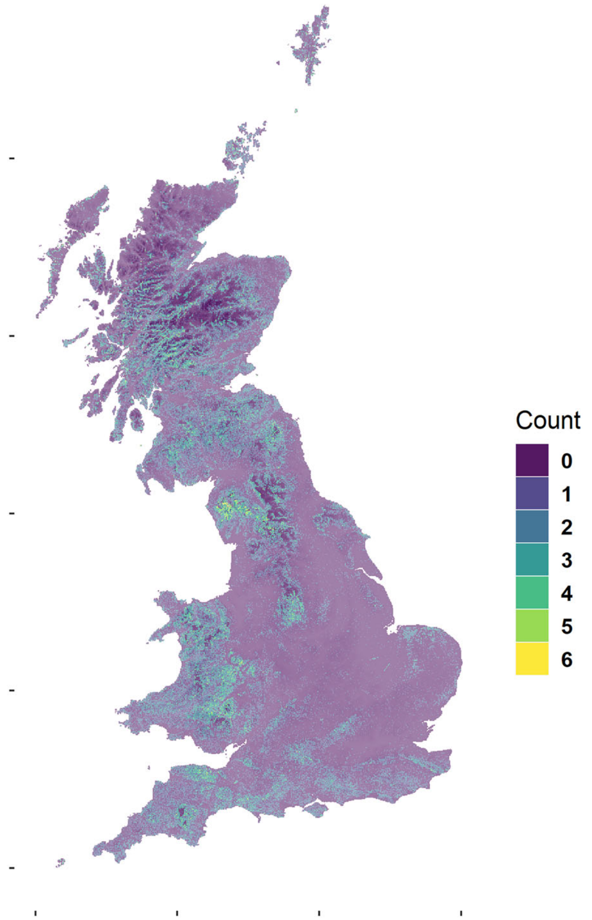

FIGURE 2 Rewilding potential areas (RPAs) across RCP–SSP (representative concentration pathways–shared socioeconomic pathways) simulations. The RPAs are represented by conservation management and unmanaged land in model results (very extensive pasture areas not shown). The heatmap was constructed by adding the number of times each cell is in one of these categories by 2080 across the 6 scenarios. Color opacity increases as elevation increases to highlight topography.

Despite the above differences between scenarios, clear hotspots of RPAs emerged across scenarios (Figure 2). Many of these hotspots were relatively close to urban centers, where demand for recreation could be satisfied (dependent on access in most scenarios) along with location-independent demands for carbon sequestration, water regulation, biodiversity, and landscape diversity. This outcome was also driven by the use of more remote areas for very extensive management, which included a number of uses, such as upland farming modeled as being not easily displaced. Many RPAs were also in cultural landscapes and designated areas.

Across scenarios, the extent of RPAs usually increased through time (reflecting a general increase in land productivity and supporting capitals and increasing demand for conservation in some scenarios). In SSPs 1 and 2, where scenario narratives (Table 1) suggest that rewilding could occur with limited human pressure, RPAs reached a total extent of over 25,000 km^2 by 2080. In SSPs 4 and 5, where scenario narratives suggest substantial human pressure for recreation, hunting, and tourism in RPAs, these covered approximately 17,000–20,000 km^2 by 2080 (Figure 3). In SSP3 (regional rivalry), their extent remained similar throughout the scenario, around 5000 km^2. For context, 20,000 km^2 is just under 10% of Great Britain's land area—nearly 7 times more than the government target of 3000 km^2 of habitat restoration by 2042 (DEFRA, 2022) and one third of the Kunming–Montreal Target 3 of 30% area protection, if applied to Great Britain (Convention on Biological Diversity, 2023). The extent of very extensive pastoral management (not part of the RPAs) remained similar to its initial value of 36,000 km^2 in SSPs 2 and 4, decreased to 24,000–25,000 km^2 in SSPs 3 and 5, and increased to 42,000 km^2 in SSP1.

Distribution with respect to ancient woodland, peatland, and wetland

The locations of RPAs in 2080 with respect to particular ecosystem types (ancient woodlands, peatlands, and [potential] wetlands) were also fairly consistent across scenarios (Figures 4 & 5). We separated out the results for wetlands because different sources gave very different locations and extents for these, based on differing definitions—from 9600 km^2 in the UK Land Cover Map (UK Centre for Ecology & Hydrology, 2016) to 75,000 km^2 in the Copernicus High Resolution Layer (Copernicus Programme, 2018). The latter, however, is intended to identify potential wetland areas (File S1) and so allowed us to assess the scope for wetland restoration in RPAs even where wetlands did not exist at the start of the modeled period. Similarly, the presence of peaty soils was indicated by the peatland data irrespective of its current condition.

Together, these 3 ecosystem types made up a small fraction of the total RPA area. Peatlands had substantial overlap with very extensive pastoral areas (around half of Britain's peatland area of nearly 30,000 km^2 [Artz, 2019] was in this class in results from SSPs 1, 2, and 4 [Figure 4b]), but there was very little overlap with the RPAs themselves. Ancient woodland was predominantly found in the conservation class, and abandoned land was usually not coincident with either peatland or woodland.

There were also some notable differences between scenarios. Ancient woodland was often coincident with conservation areas in 2080, but in SSP2 (middle of the road), ancient woodland had usually become managed for very extensive grazing. Much ancient woodland was lost to other land uses, with the largest extent being maintained in SSP1 (sustainability, where direct demand for native and natural woodland services exists) and SSP5 (fossil-fueled development, where woodland was indirectly spared by intensification elsewhere). The lowest extents were reached in SSP3 (regional rivalry) because agricultural expansion occurred in response to shortfalls in food production. This also affected peatland, which was least represented in RPAs in SSPs 3 and 5. New native woodland creation also occurred, peaking in SSP2 (middle of the road, paired with RCP 8.5), where the total extent of native woodland reached 66,800 km^2, around half of which was dedicated primarily to timber production. Some of these new native woodlands replaced non-native conifer plantations, especially in SSP1

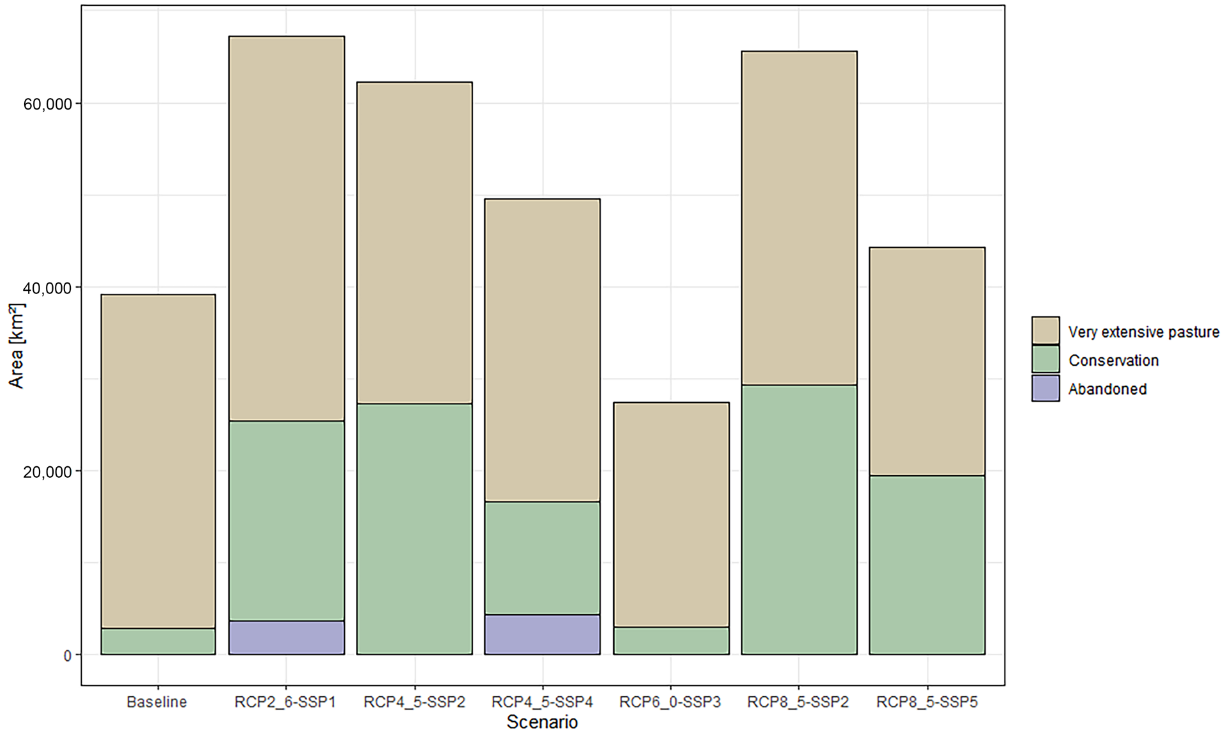

FIGURE 3 Areas of very extensive pasture, conservation, and abandoned land for each RCP–SSP (representative concentration pathways–shared socioeconomic pathways) scenario in 2080. Results for 2040 are in File S1.

(sustainability), where a near-doubling of native woodland extent (to just under 50,000 km^2) accompanied a near-total removal of non-native plantations. Where these native woodlands were managed for conservation, they were included in the RPAs.

The overlap of RPAs with (potential and actual) wetlands was proportionally similar among scenarios and data sets. In each case, most wetlands were located in very extensive pastoral areas, whereas the total wetland area in RPAs was largest in SSP1, smaller in SSPs 2 and 4, and smallest in SSPs 3 and 5. There were differences in the proportions of wetlands in conservation management and abandoned land in 2080. The Copernicus HRL data set suggested more potential wetlands under conservation management than on abandoned land, especially in SSPs 2 and 5, whereas EUNIS and CORINE data sets suggested more existing wetland on abandoned land, especially in SSPs 1 and 4. As with the other ecosystem types, SSP3 (regional rivalry) produced the smallest areas in RPAs based on all data sets.

DISCUSSION

Our analyses of future scenarios in the British land system accounted for a wide variety of land uses and ecosystem services and demonstrated the importance of considering national or even international requirements for land in assessments of future restoration potential. Our findings showed that substantial areas may be available for rewilding during the coming decades. These areas, of up to more than 27,000 km^2, are far in excess of government targets or existing projections and suggest that a substantial proportion of the Kunming–Montreal Global Biodiversity Framework's area-based targets (Targets 2 and 3) are achievable (Convention on Biological Diversity, 2023). The maintenance of food production alongside these large RPAs accords with previous studies' findings that the least productive 20% of the United Kingdom's farmland produces just 3% of calories and the least productive 10% just 1% of calories (see also, e.g., Aitkenhead et al. [2021] on the scope for peatland restoration with minimal agricultural trade-offs). These least productive areas overlap substantially with high-priority environments that host 90% of the best locations for carbon storage and 91% of the best nature areas in the United Kingdom (National Food Strategy, 2021; Thomas et al., 2013). These areas, and our RPAs, also occupy similar locations as the most habitat-rich areas of the United Kingdom as calculated in a European-scale analysis (Cervellini et al., 2021). In contrast, existing protected areas in the United Kingdom do not cover the highest biodiversity priority areas (Cunningham et al., 2021).

Although we found substantial scope for rewilding to occur where it may have ecological benefits and limited impacts on other land uses, we did not attempt to estimate its exact outcomes. Rewilding takes many forms in the United Kingdom, and its ecological effects are not yet fully understood, making anticipatory mapping of practices or outcomes very difficult. Exploring ecological and biological impacts within the opportunity space that we identified is a promising next step, but doing

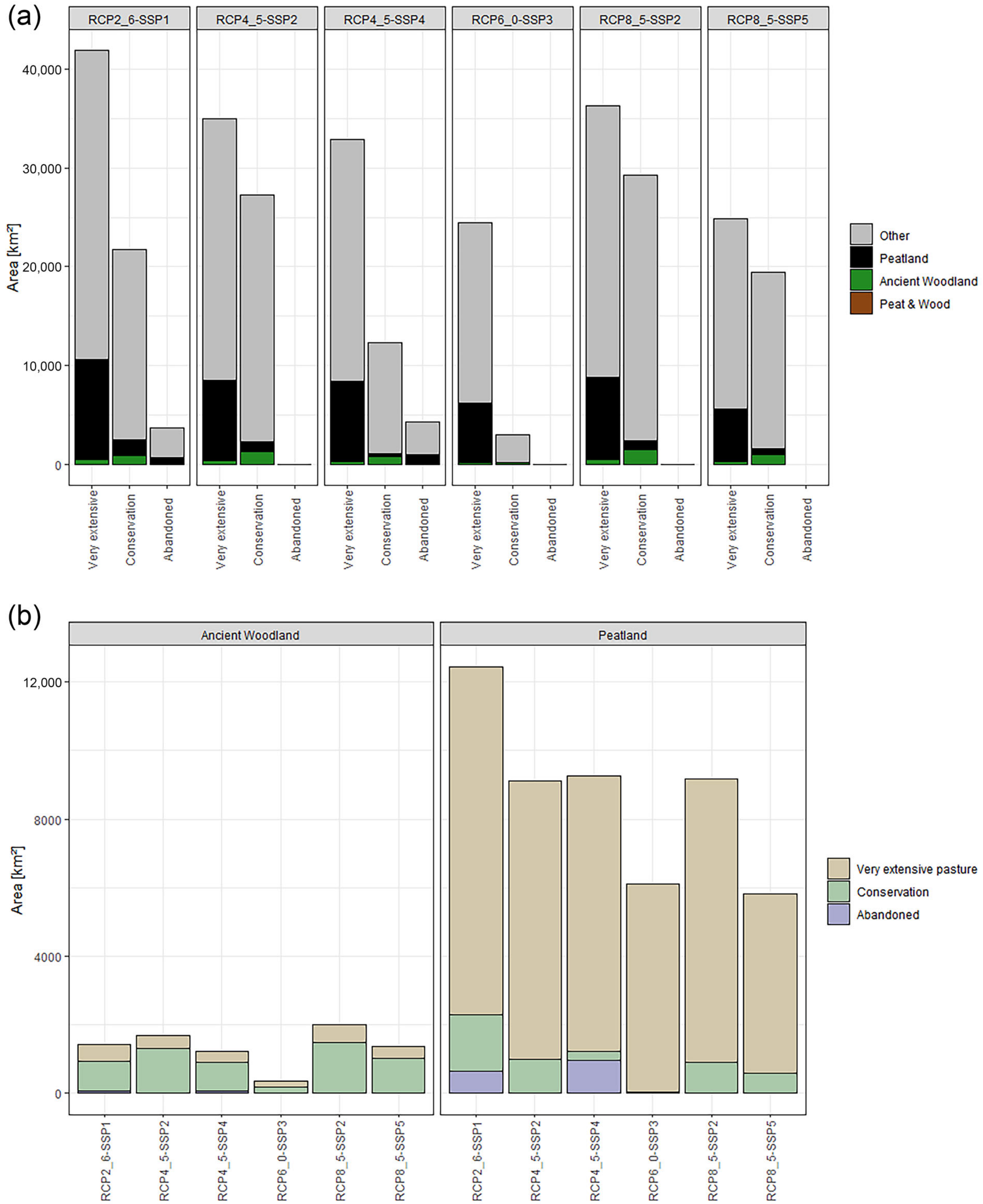

FIGURE 4 Coverage of ancient woodland and peat (classified as of base year) in rewilding potential areas (conservation and abandoned land) and very extensive pastoral areas in 2080 across RCP–SSP (representative concentration pathways–shared socioeconomic pathways) scenarios. Results for 2040 are in File S1.

this rigorously will require higher resolution modeling than we performed, both spatially and ecologically.

Nevertheless, the size and distribution of potential rewilding sites we identify have strong implications for forms of rewilding, as do the details contained in scenario narratives (Table 1). From the limited but relatively aggregated and untouched natural areas in SSP1 (sustainability) to the small, fragmented, and touristic areas in SSP5 (fossil fueled development), scope for natural pro-

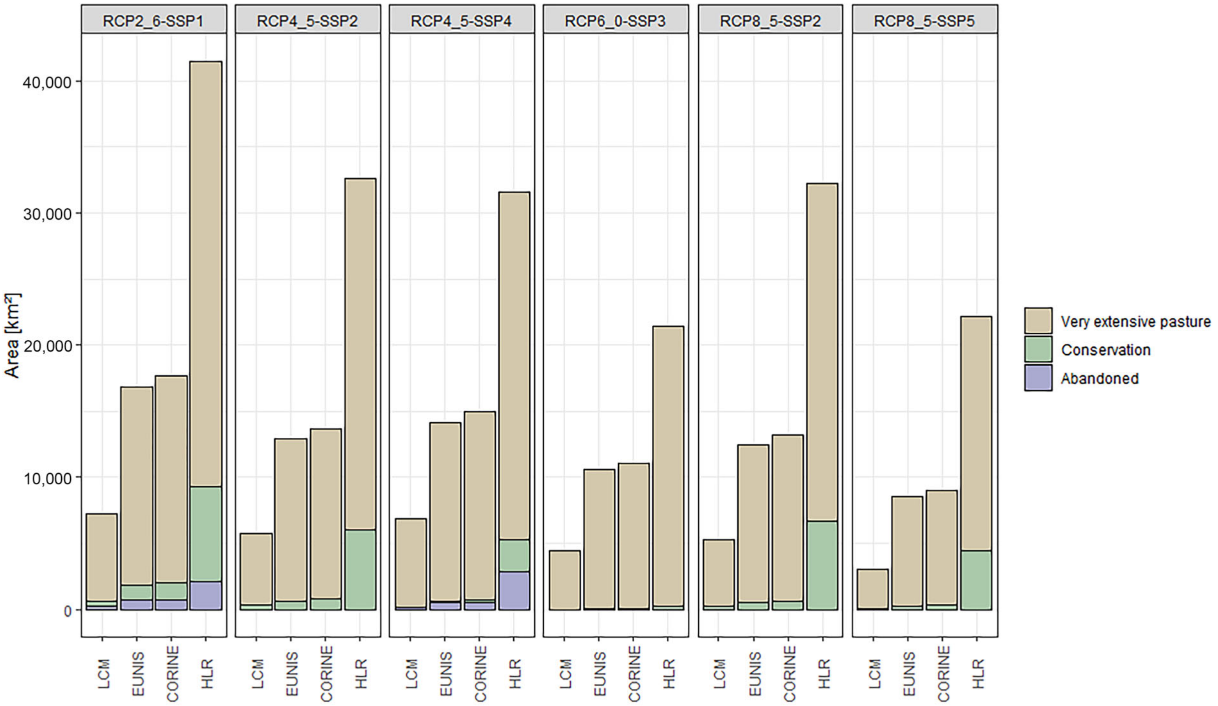

FIGURE 5 The coverage of current and potential wetlands in rewilding potential areas (conservation and abandoned land) and very extensive pastoral areas in 2080 across RCP–SSP (representative concentration pathways–shared socioeconomic pathways) scenarios and across 4 different wetland data sets (LCM, land cover map 2015 [UK Centre for Ecology & Hydrology, 2016]; EUNIS, ecosystem types of Europe 3.1 [European Environment Agency, 2019a]; CORINE, CLC 2012 Accounting layer 20 [European Environment Agency, 2019b]; HRL, Copernicus High Resolution layer, Water & Wetness 2015 [Copernicus Programme, 2018]). Further details and results for 2040 are in File S1.

cesses to occur across large geographical extents clearly varied a great deal (File S1). The SSPs 1 and 2 (middle of the road) produced large RPAs by 2080 with similar geographical distributions but quite different patch sizes (Table 1; File S1). The SSPs 4 (inequality) and 5 implied significant recreational pressure on RPAs, but in SSP4, this was prompted by a desire for exclusive recreation, including hunting, among elites. The SSP4 storyline also reflected current debates about control over land in Scotland, in particular, and the extent to which natural capital markets might exacerbate inequalities in land ownership that are already very high by global standards (Brown et al., 2011; Sharma et al., 2023). Indeed, much of the movement toward rewilding in the United Kingdom has been generated by conservation charities, companies, and wealthy individuals (Jepson et al., 2018; Jones & Comfort, 2020).

Another important current debate in land management is highlighted by SSP3 (regional rivalry). In this scenario, political and societal dysfunctions reduce food production, trade, and security. This results in most of Britain's land area being used in some way for agriculture by 2080. A renewed focus on domestic food security in the United Kingdom and other countries parallels this narrative in the present day and has already reduced the scope for conservation in some cases (Kovács et al., 2022; Morales et al., 2022). A requirement for farmers and landowners to "mitigate any negative impacts" of environmental restoration on food production has recently been introduced to a flagship UK government funding scheme (DEFRA, 2023). The tendency to constrain conservation for food production may be offset by increased levels of demand and financial support for carbon sequestration and biodiversity restoration in the future, but the impacts are likely to depend on the metrics and regulations applied and may be limited if these are inadequate (Knight-Lenihan, 2020; zu Ermgassen et al., 2021).

The RPAs we identified also indicate possible challenges for specific habitats and ecosystem services. The RPAs overlap to some extent with the areas modeled as abandoned in 2040 by Ceaușu et al. (2015), who highlight their deviation from potential natural vegetation. Passive rewilding of abandoned land can take many years to have benefits for vegetation and bird communities (Broughton et al., 2022), and positive ecological impacts are tempered by negatives in some situations (Quintas-Soriano et al., 2022; Sandom, Wynne-Jones, et al., 2019; Warner et al., 2021). Carbon sequestration benefits are likely to be large but are nevertheless uncertain (Bell et al., 2023), particularly because climate change impacts could reverse some gains. This is a major risk in high-emissions scenarios, where carbon stocks and biodiversity are at serious, early, and potentially abrupt risk (Ferretto et al., 2019; Trisos et al., 2020; Yumashev et al., 2022). These challenges could be particularly great for priority habitats, such as ancient woodlands and peatlands, most of which were outside our modeled RPAs, and large areas converted to agricultural or other new forms of management in our simulations. This implies that targeted measures may be needed to preserve the largest carbon and biodiversity stocks in Britain's land system, even as rewilding may emerge elsewhere in the absence of such measures. In this context, it is notable that protected areas in the United Kingdom have disputed value for biodiversity conservation, and a recent report by the Protected Areas Working Group of the IUCN National Committee UK concluded that only 5 types of site designation out of 23 can be considered to fully comply with the IUCN protected area definition and therefore to contribute to the Kunming–Montreal 30×30 targets (Cooke et al., 2023; Cunningham et al., 2021; IUCN National Committee UK Protected Areas Working Group, 2023; Starnes et al., 2021).

There is also a wide range of plausible social implications of our findings. Positive and negative social effects of rewilding have been recorded, and many cases provide examples of both (García-Ruiz et al., 2020; Jones & Comfort, 2020; Krauß & Olwig, 2018; Martin et al., 2021; Navarro & Pereira, 2012; Wynne-Jones et al., 2018). In the United Kingdom as globally, areas of priority for ecological restoration often overlap with the areas of relative socioeconomic deprivation, suggesting a fundamental need—and, potentially, an opportunity—to generate benefits for people and nature in these locations (Löfqvist et al., 2022). Social implications also contribute to uncertainty in our identification of RPAs, particularly given the active management and cultural significance of almost all land areas in the United Kingdom. The suitability of areas under very extensive management is most contestable, and there is no guarantee that land abandonment as modeled here would not be deliberately averted to preserve existing landscapes by, for instance, changes to land management subsidies.

Our findings depend on model assumptions, design, and input data, many of which stem from exploratory scenario narratives that are not probabilistic in nature (Brown et al., 2022). Based on previous sensitivity analyses, we know that CRAFTY is most sensitive to scenario-based factors (File S2), so our application of several scenarios provides a sketch of key uncertainty space. We did not model any form of support for rewilding beyond that already contained in the UK-SSP narratives or explicit opposition to it. We also did not model ecosystem services provided by unmanaged (abandoned) land or investment from carbon and biodiversity markets that are anticipated to fill a putative but disputed £50–100 billion funding gap for UK nature-based targets in the next 10 years alone (Community Land Scotland, 2023; GFI, eftec, Rayment Consulting, 2021).

Another source of uncertainty is the tenacity of modeled agents, especially those practicing very extensive management. Although this accords with the lack of land abandonment in the United Kingdom (in contrast to other parts of Europe) and the maintenance of upland agriculture through subsidy support, passive rewilding through abandonment does happen, and some studies suggest that it is likely to increase substantially in the United Kingdom in future (Broughton et al., 2021; Dax et al., 2021; Fayet & Verburg, 2023). The RPAs frequently emerged relatively close to population centers, where they satisfied demands for recreation without impinging on very extensively managed land. We assumed that recreation in managed natural land is consistent with rewilding, but potential inconsistencies clearly do exist, particularly with rewilding that seeks to create undisturbed natural areas or reintroduce large carnivores. Additionally, the presence of large private estates in many extensively managed areas provides scope for more production, recreation, or restoration focused management—and ad hoc changes in these—depending on the individual preferences and resources of landowners (Table 1).

Overall, many questions remain open about how rewilding could, should, and will be implemented in the United Kingdom and elsewhere. Answers to these questions depend greatly on the land system context within which rewilding occurs, as our analysis demonstrates. There appears to be significant scope in the United Kingdom to implement rewilding in some form and so, perhaps, to further develop answers to these questions. Large-scale rewilding could occur under a range of future conditions without impinging on essential land-based goods and services. Nevertheless, the extent to which it affects other objectives, positively or negatively, and the extent to which policy and market-based interventions can shape those effects, requires and justifies further attention.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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