

RESEARCH ARTICLE

Nature-based solutions for a changing world

The potential contribution of terrestrial nature-based solutions to a national 'net zero' climate target

Tom Bradfer-Lawrence¹  | Tom Finch¹  | Richard B. Bradbury^{2,3}  |
Graeme M. Buchanan¹ | Andrew Midgley¹ | Rob H. Field² ¹Centre for Conservation Science, RSPB
Scotland, Edinburgh, UK²Centre for Conservation Science, RSPB,
Sandy, Bedfordshire, UK³Conservation Science Group, Cambridge,
UK**Correspondence**Tom Bradfer-Lawrence
Email: tom.bradfer-lawrence@stir.ac.uk**Present address**Tom Bradfer-Lawrence, Biological &
Environmental Sciences, University of
Stirling, Stirling, FK9 4LA, UK**Handling Editor:** Nathalie Butt**Abstract**

1. Many national governments have incorporated nature-based solutions (NbS) in their plans to reduce net greenhouse gas emissions. However, uncertainties persist regarding both feasibility and consequences of major NbS deployment. Using the United Kingdom as a national-level case study, we examined the potential contribution of three terrestrial NbS: peatland restoration, saltmarsh creation and woodland creation.
2. While there is substantial political and societal interest in these three NbS, they also have strong potential for competition with other land uses, which will be a critical barrier to substantial deployment. We conducted a national mapping exercise to assess the potential area available for woodland creation. We then assessed the combined climate change mitigation potential to 2100 for the three NbS options under a range of ambition levels.
3. In line with the most ambitious targets examined, 2 Mha of land is potentially available for new woodland. However, climate change mitigation benefits of woodland are strongly dependent on management choices. By 2100, scenarios with a greater proportion of broadleaved woodlands outsequester non-native conifer plantations, which are limited by regular timber harvesting.
4. Peatland restoration offers the greatest mitigation per unit area, whilst the contribution from saltmarsh creation is limited by the small areas involved. Overall, the contribution of these NbS to the United Kingdom's net zero emissions target is relatively modest. Even with the most ambitious targets considered here, by 2100, the total cumulative mitigation from the three NbS is equivalent to only 3 years' worth of UK emissions at current levels.
5. *Policy implications.* Major deployment of nature-based solutions (NbS) is possible in the United Kingdom but reaching 'net zero' primarily requires substantial and sustained reductions in fossil fuel use. However, facilitating these NbS at the national scale could offer many additional benefits for people and biodiversity. This demands that policy-makers commit to a UK-wide strategic approach that

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prioritises the 'nature' aspect of NbS. In the push to reach 'net zero', climate change mitigation should not be used to justify land management practices that threaten biodiversity ambitions.

KEYWORDS

climate change, habitat restoration, mitigation, nature-based solutions, net zero, peatland, saltmarsh, woodland

1 | INTRODUCTION

Tackling the climate and nature crises is essential to achieve the sustainable development goals (UN, 2016). Most of the world's governments have pledged action via United Nations conventions, particularly the Convention on Biological Diversity (CBD) and the Framework Convention on Climate Change (UNFCCC). Signatories of the UNFCCC Paris agreement aim to reduce greenhouse gas (GHG) emissions to keep global temperature rises well below 2°C (Roe et al., 2019). Numerous actions have been proposed to achieve these goals, combining reductions in fossil fuel use with GHG removal from the atmosphere (Fekete et al., 2021). Among the latter, nature-based solutions (NbS) have gained considerable attention (Fargione et al., 2018; Seddon, Daniels, et al., 2020). If implemented appropriately, NbS provide important co-benefits including flood alleviation, improved livelihoods and biodiversity conservation (Chausson et al., 2020; Di Sacco et al., 2021; Seddon, Chausson, et al., 2020). The United Kingdom and its devolved governments have committed to reaching net zero GHG emissions by 2045 or 2050 (Priestley, 2019; Scottish Government, 2018; Welsh Government, 2021). The United Kingdom therefore provides a useful test case of the feasibility of a significant NbS contribution to a national net zero target.

There is growing appetite in the United Kingdom for substantial NbS use to reduce atmospheric CO₂, especially through peatland restoration, woodland creation and saltmarsh creation (Brandmayr et al., 2019; Climate Assembly UK, 2020). A range of targets have been proposed by governmental and non-governmental organisations (Brandmayr et al., 2019; Climate Change Committee (CCC), 2020; Woodland Trust, 2020). UK devolved governments are already committing funding to peatland restoration and tree planting, with Scotland's £350 million pledge (Scottish Government, 2020), and England's £640 million Nature for Climate fund (HM Treasury, 2020). However, there have been only limited assessments of the land-use change necessary and the climate change mitigation benefits that might be achieved by implementing NbS at the national scale (CCC, 2019, 2020; Matthews et al., 2020; Thomson et al., 2018). Significant questions therefore remain regarding the feasibility and potential contribution of these NbS to meeting net zero emissions targets. Other terrestrial mitigation measures include improved agricultural management of farmland carbon stores (Cardenas et al., 2019; Montgomery et al., 2020). Although these actions might

impact agricultural production, they are unlikely to necessitate widespread habitat change. We therefore focus our analysis on peatland, woodland and saltmarsh restoration and creation where there is the greatest potential for competition with other land uses.

Meeting proposed woodland creation targets would necessitate changing substantial areas of land use, but most UK land is already under agriculture or important for semi-natural open habitats. The devolved UK governments incorporate a degree of spatial planning in woodland expansion, with statutory agencies publishing woodland opportunity maps (e.g. Sing et al., 2013; Thomas et al., 2017; Welsh Government, 2020). However, these indicative maps do not consider spatial variation in existing soil carbon stores nor climatic influences on tree growth, both of which strongly affect potential for net carbon sequestration. A more detailed assessment including these factors has recently been published for Scotland (Matthews et al., 2020), but equivalents for the other UK nations are lacking.

Here, we scrutinise existing UK NbS scenarios for climate change mitigation (Table 1), to determine:

1. What cumulative contribution can peatland restoration, woodland creation and saltmarsh creation make to reducing UK net emissions, both for the agricultural sector and overall?
2. After excluding inappropriate areas, whether there is sufficient land available to meet woodland creation targets?
3. How management choices affect carbon sequestration in woodlands, specifically, what are the consequences of selecting broadleaves managed for conservation versus conifers managed for timber production, ground disturbance during site preparation and rotational timber harvesting?

Logistical capacity, economic costs and socio-cultural acceptance of NbS-driven changes in land use are also critical (Foster et al., 2013; Hopkins et al., 2017; Tew et al., 2019), but are not formally assessed here. While accepting that these factors may further limit NbS deployment, it is still important to understand the baseline potential for NbS, as a component of a nation's overall GHG reduction strategy.

2 | MATERIALS AND METHODS

The NbS considered here (Table 1) include peatland restoration and woodland creation under a range of scenarios proposed by the UK

TABLE 1 Annual habitat restoration and creation rates under a range of targets for peatland restoration, and saltmarsh and woodland creation considered in this study. Peatland and woodland scenarios are taken from the Climate Change Committee sixth carbon budget (CCC, 2020). The saltmarsh scenarios are based on details in RSPB (2018)

NbS option	NbS details	Business-as-Usual	Headwinds	Balanced Net Zero Pathway	Widespread Engagement	Widespread Innovation	Tailwinds
Peatland restoration	Area of degraded upland peat restored	250,000 ha by 2030 in Scotland ^a	100% by 2050 ^b (1,438,143 ha)	100% by 2045 (1,438,143 ha)	100% by 2045 (1,438,143 ha)	100% by 2045 (1,438,143 ha)	100% by 2045 (1,438,143 ha)
	Area of afforested peat restored	0	0	20% by 2035 (87,858 ha)	20% by 2035 ^c (87,858 ha)	20% by 2035 (87,858 ha)	20% by 2035 (87,858 ha)
	Area of peat with industrial extraction restored	0	100% by 2035 (8,034 ha)	100% by 2035 (8,034 ha)	100% by 2035 (8,034 ha)	100% by 2035 (8,034 ha)	100% by 2035 (8,034 ha)
	Area of lowland peat under grassland restored	0	25% by 2050 (47,537 ha)	25% by 2035, 50% by 2050 (95,074 ha)	25% by 2035, 50% by 2050 (95,074 ha)	25% by 2035, 50% by 2050 (95,074 ha)	25% by 2035, 50% by 2050 (95,074 ha)
	Area of lowland peat under cropland—conservation rewetting	0	10% by 2050 (19,413 ha)	25% by 2050 (48,531 ha)	25% by 2050 (48,531 ha)	0	0
	Area of lowland peat under cropland—paludiculture	0	10% by 2050 (19,413 ha)	15% by 2050 (29,119 ha)	15% by 2050 (29,119 ha)	25% by 2050 (48,531 ha)	25% by 2050 (48,531 ha)
	Area of lowland peat under cropland—sustainable management	0	30% by 2050 (58,238 ha)	35% by 2050 (67,945 ha)	35% by 2050 (67,945 ha)	50% by 2050 (97,063 ha)	50% by 2050 (97,063 ha)
	Total peatland restoration area ^d	250,000 ha	1,590,776 ha	1,774,703 ha	1,774,703 ha	1,774,703 ha	1,774,703 ha
Woodland creation	Broadleaf:Conifer ratio ^e	39:61 (Scotland) 87:13 (England) 57:43 (Wales) 68:32 (Northern Ireland)	47:53 (UK)	67:33 (Wales & Northern Ireland) 80:20 (England) 50:50 (Scotland)	67:33 (Wales & Northern Ireland) 80:20 (England) 50:50 (Scotland)	33:67 (England, Wales & Northern Ireland) 25:75 (Scotland)	44:56 (UK)
	Creation rate ^f	15,000 ha per year	30,000 ha per year by 2035	50,000 ha per year by 2035	70,000 ha per year by 2035	50,000 ha per year by 2030	70,000 ha per year by 2035
	% of open ground	10%	15%	15%	20%	10%	15%
	Total woodland creation area ^g	495,000 ha	897,000 ha	1,431,750 ha	1,992,042 ha	1,438,250 ha	1,909,040 ha
Saltmarsh creation	Creation rate	45 ha per year	250 ha per year	250 ha per year	500 ha per year	250 ha per year	500 ha per year
	Total saltmarsh creation area	1,350 ha by 2050	7,500 ha by 2050	7,500 ha by 2050	15,000 ha by 2050	7,500 ha by 2050	15,000 ha by 2050

^aWhen CCC (2020) was published, the Scottish Government was the only UK administration to have made a firm commitment regarding peatland restoration. The CCC (2020), therefore, assumes peatland restoration only occurs in Scotland in the Business-as-Usual scenario, but occurs across the whole United Kingdom in the other scenarios.

^bApart from the Business-as-Usual scenario, the CCC gives all other peatland restoration targets as percentages of the total area of degraded peatland in the United Kingdom (Table S1). We determined areas of each category based on figures in ONS (2019), given here rounded to the nearest ha. Annual restoration rate of each category increased over time to represent increasing capacity (Tables S2 and S7).

^cWe also explored the impacts of restoring 100% of afforested peat (i.e. 439,292 ha) by 2050 in this scenario, see main text.

^dThere are slight differences between the overall totals and the sum of individual category areas, due to rounding of the latter.

^eBroadleaf:conifer ratio for Business-as-Usual determined from 5-year mean ratios from FC (2019).

^fAll scenarios start at 15,000 ha of new woodland in 2021, creation rate then increases linearly up to the stated rate at 2030 or 2035, and that rate is maintained until 2050 (Table S7).

^gTotal area required includes open ground.

government's Climate Change Committee (CCC, 2020), and bespoke saltmarsh creation scenarios based on recent opportunity mapping (RSPB, 2018). In all scenarios, we assumed that restoration and creation began in 2021 at close to current implementation rates and increased linearly each year to the maximum rate shown in Table 1 and Table S2. All interventions were complete by 2050, but we forecast GHG emissions to 2100. To facilitate comparisons, we convert all emissions to Global Warming Potential (GWP_{100}), expressed as CO_2 -equivalents (CO_2e ; IPCC, 2007).

2.1 | Peatland restoration

As peatland condition is not comprehensively mapped in the United Kingdom, we could not spatially prioritise restoration. We therefore used the UK area estimates for different categories of degraded peatland from Office for National Statistics (ONS, 2019; Table S1) and restored each category in proportion to country-specific ONS area estimates (Table 1). We excluded areas of near-natural or rewetted bog and fen from our calculations. Deep peat soils covered by cropland and intensive grassland were treated as lowland peat, and domestic fuel extraction and the various degraded bog classes as upland peat (Thomson et al., 2018; Table S1). During the 20th century, large areas of peatland were afforested with commercial conifer plantations, which necessitated extensive ground preparation and drainage leading to much greater GHG emissions compared with undamaged peatlands (Table S1). However, CCC scenarios limit restoration of these afforested peatlands to only 20% of the lowest productivity plantations (CCC, 2020). Given the substantial emissions from these areas (Evans et al., 2017; see Supporting Information), we additionally explored the effects of restoring all afforested peatlands. For all scenarios, we offset emissions against the carbon sequestered in the trees on afforested peatlands and their derived harvested wood products (HWP; see Supporting Information).

To calculate restoration impacts, we used GWP_{100} values from Evans et al. (2017), except for paludiculture and sustainably managed cropland where we adapted values from CCC (2020; Table S1). Peatland GWP_{100} values include direct and indirect GHG emissions and DOC (Evans et al., 2017). Degraded upland areas were assumed to be restored to rewetted bog, and lowland areas to rewetted fen. In line with IPCC (2014), we assumed immediate switching of emissions from degraded to rewetted categories during the year of restoration. The annual area restored was gradually increased each year to represent growing capacity for restoration management (see Supporting Information).

2.2 | Woodland creation

We undertook a mapping exercise to identify potentially suitable areas for woodland creation, to assess the feasibility of national woodland creation targets (full methods in Supporting Information). Areas considered unavailable for woodland creation included higher

quality agricultural land and existing woodland (the modification of which could reduce agricultural or timber production, leading to offshoring of emissions), designated sites, priority habitats and peatlands (to avoid perverse outcomes for soil carbon or biodiversity) and existing buildings, infrastructure and archaeological features (Table S3). Some excluded areas were further buffered to limit possible negative spill-over effects of woodland creation, such as on peatland hydrology (FC, 2000), or to reduce predation in sites designated for conservation of wading birds (Wilson et al., 2014; see Supporting Information).

After excluding these areas, we found 530,280 distinct spatial units (henceforth termed polygons) that are potentially available for new woodland (mean 8.8 ha, *SD* 40.2 ha; see Supporting Information). We considered a representative range of tree species (Table S4), and for each scenario, we randomly assigned polygons to either broadleaves or conifers in line with the target ratios (Table 1). We assumed that new broadleaved woodlands would be established primarily for biodiversity conservation, while conifer woodlands would be managed using commercial forestry methods with regular timber harvesting. Differences between the two management approaches are detailed below.

New woodlands comprised species mixes as per the UK Forestry Standard (FC, 2017), that is, a primary species accounted for 75% of polygon area and open ground 10%–20% (Table 1). The remainder of each broadleaved polygon comprised a single secondary species, while conifer polygons included 5% broadleaves with a secondary commercial conifer species accounting for the rest. Primary and secondary species for each polygon were selected according to highest and next highest yield classes for the region, as a proxy for climatic suitability, derived from the Ecological Site Classification tool (ESC; Forest Research, 2011, 2020a; see Supporting Information for full details). Any polygons with an ESC-derived yield class below 4 for broadleaves or below 12 for conifers were assumed climatically unsuitable for woodland and excluded ($n = 11,397$; total area = 348,944 ha).

To maximise the climate benefits of woodland expansion while minimising impacts on agricultural output, we prioritised the order of polygon conversion to woodland. We categorised polygons as either lower soil carbon risk (mineral soils) or higher risk (organo-mineral soils) for woodland creation, as some recent evidence suggests that woodland creation on richer organo-mineral soils can trigger soil carbon losses that might at least partly counteract the benefits of sequestration by new trees (Friggens et al., 2020). Across all scenarios, we therefore prioritised establishment on polygons with mineral soils and then least productive land (i.e. highest Agricultural Land Classification/Land Capability for Agriculture grade). Broadleaved polygons were further ranked following the 'Lawton principles' (Defra, 2010), that is, prioritising sites adjacent to existing woodland, and then ordered in decreasing size (further details in Supporting Information). Conifer polygons were prioritised in the order of highest yield class, to maximise timber output and then decreasing size.

We calculated carbon sequestration of each polygon using species- and yield-class-specific values extracted from the

Woodland Carbon Code (WCC) biomass carbon lookup table (v2.4; Jenkins et al., 2018). Sequestration values include all above- and below-ground biomass and litter, but not soil carbon (Randle & Jenkins, 2011). To account for impacts of woodland creation on soil carbon stores, we used polygon-specific soil carbon estimates (Field et al., 2020) and predicted changes following woodland creation depending on country, current habitat and woodland type (Bradley et al., 2005; see Supporting Information). Following the CCC scenarios, conifers were planted at a density of 1.5 or 1.7 m spacing, broadleaves at 2.5 m (Table S4) and all woodlands were thinned. Carbon in thinnings was assumed to be immediately lost to the atmosphere.

For conifers, we used a 40-year rotation (Moore, 2011) with a 3-year fallow period between rotations but acknowledge that a fixed rotation length is a simplification. Following end of rotation clear-fell, unharvested residues were assumed to be left on-site and decayed over time (Morison et al., 2012). Timber was apportioned to a range of harvested wood product (HWP) pools according to national statistics (FC, 2020). Our scenarios incorporated the carbon stored in these HWPs, with each product class having a different life span (Brown et al., 2018; IPCC, 2003; Moore, 2011; UNFCCC, 2003). Each year, a portion of HWP reached end of life and went to landfill, where some emissions continue (IPCC, 2006). Substitution effects of HWP are often considered in analyses like this, though potential emissions avoidance benefits may have been overstated 2–100 fold (Harmon, 2019). We include supplementary analysis with substitution but caution against its use (see Supporting Information).

2.3 | Saltmarsh creation

A previous study identified 318 potential managed realignment projects in the United Kingdom, totalling 29,996 ha potentially available for new saltmarsh habitat, replacing a range of terrestrial habitats (RSPB, 2018; Table S6). Area targets in Table 1 were adjusted by subtracting the estimated 105 ha of saltmarsh that will be lost each year to sea-level rise and coastal squeeze (Beaumont et al., 2014; ONS, 2016; RSPB, 2018). Although some mudflats would also be created, we assume that the entire realigned area would be converted to saltmarsh (see Supporting Information). We apply sequestration rates from Burden et al. (2019), which cover below-ground carbon only and do not include plant biomass. We did not spatially prioritise projects, as they will be driven by multiple considerations beyond climate change mitigation, such as hydrological and coastal geomorphology, and public acceptance regarding ceding land to the sea (Foster et al., 2013; Myatt et al., 2003).

For all three NbS, we determined the likely extent of land cover change on existing habitats (see Supporting Information). Our calculations did not include relatively minor emissions from restoration and creation activities such as fossil fuels for machinery, removal of existing site vegetation, seedling production in nurseries, fencing, herbicide, road construction and timber extraction (Lamb et al., 2016; Morison et al., 2012). Climate change is predicted to subject UK habitats to greater risks of pest outbreaks, fire and

windthrow (Ray et al., 2010). Although all these disturbances affect carbon sequestration and storage rates, precise impacts are uncertain and complex, and so we did not incorporate future climate change into our scenarios.

3 | RESULTS

3.1 | Peatland restoration

Under the Business-as-Usual scenario with minimal restoration, the United Kingdom's peatlands will release a cumulative 1,674 Mt CO₂e by 2100. Peatland restoration in the Widespread Engagement scenario would reduce this total to 1,011 Mt CO₂e, hence avoiding the emission of 663 Mt CO₂e by 2100 (Figure 1a; Table 2). Initially low rates of restoration mean climate benefits are limited until the 2040s, but scenarios begin to diverge post-2050. Differences in cumulative emissions among scenarios are largely driven by the fate of lowland cropland. Peatlands continue to be a source of net annual emissions, with interannual variation post-2050 driven by the flux dynamics of afforested peatlands (Figure 2a). Analysis of the emissions balance of afforested peatlands (see Supporting Information) suggested that Sitka spruce growing at the UK mean yield class in such locations is unlikely to sequester more carbon than is emitted from the degraded peat. Increasing the ambition for restoring afforested peatlands from 20% to 100% potentially avoids the emission of a further 74.5 Mt CO₂e (Figure 1a).

3.2 | Woodland creation

After excluding inappropriate areas, over 4.6 Mha are potentially available for woodland creation, although over 2.5 Mha are on higher risk organo-mineral soils where woodland creation may not result in net sequestration (Figure 3). Potentially available areas are not evenly distributed across the United Kingdom; although a greater proportion of total land in Scotland and Wales is available, there is a smaller proportion of lower risk soils. Our spatial prioritisation meant that new woodlands were only sited on lower risk mineral soils. Overall, at the UK level, there may be a sufficient area of lower risk mineral soils to meet even the CCC's most ambitious Widespread Engagement scenario, which entails nearly 2 Mha of planting by 2050.

By 2050, differences among the woodland aspect of the scenarios emerged, with Tailwinds having a cumulative net GWP₁₀₀ of -63.8 Mt CO₂e, 57% lower than the Balanced Net Zero Pathway at this point (Figure 1b; Table 2). The production forestry-orientated Widespread Innovation scenario had rapid initial growth rates, giving cumulative net GWP₁₀₀ of -12.7 Mt CO₂e, 9% lower than the biodiversity-orientated Widespread Engagement scenario in 2050. However, by 2100, substantially more sequestration had occurred as trees matured. The Widespread Engagement scenario then had a cumulative net GWP₁₀₀ of -111.5 Mt CO₂e, 23% lower than the

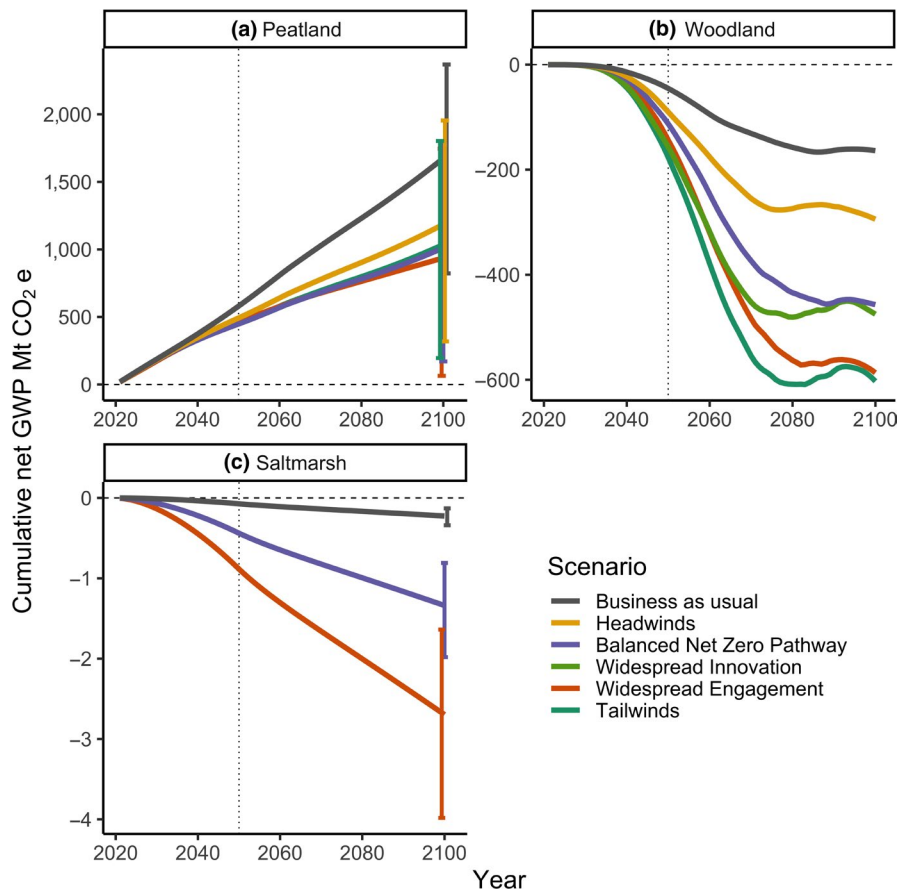


FIGURE 1 Net GWP_{100} for three NbS options under a range of scenarios. Restoration and creation are complete by 2050, shown by the dotted vertical line. For (a) peatlands, 95% confidence intervals are shown by the error bars at 2100, representing cumulative uncertainty. The Widespread Engagement scenario includes restoration of 100% of afforested peatlands. For (b) woodlands, no measures of uncertainty in sequestration are provided by the Woodland Carbon Code. For (c) saltmarshes, error bars show cumulative uncertainty as mean values ± 1 SD. Sequestration under Headwinds and Widespread Innovation follow Balanced Net Zero Pathway, and Tailwinds follows Widespread Engagement

Widespread Innovation scenario. The Tailwinds scenario offered maximum woodland sequestration overall, with -602.9 Mt CO_2e sequestered by 2100.

Most differences in mitigation potential among scenarios stem from woodland management choices. Over the century, greater sequestration is possible with broadleaves managed for biodiversity rather than conifers managed for timber (Figure S5). Initially similar per-hectare sequestration rates diverge as intensive forestry management limits long-term sequestration in conifers. Consequently, mean cumulative net GWP_{100} over 100 years for yield class 6 broadleaves is -328.2 t CO_2e per ha, while yield class 18 conifers harvested on a 40-year rotation store a mean of -281.7 t CO_2e per ha (see Supporting Information). These values do not include the impacts of site preparation. Moderate site preparation causes a soil carbon deficit, but this amounts to only -3.1 Mt CO_2e of lost mitigation by 2100 in the production forestry-orientated Widespread Innovation scenario. Rotational harvesting of conifers to meet timber demand results in foregoing an additional -330.8 Mt CO_2e from the Tailwinds scenario by 2100. In this scenario, HWP substitution could potentially provide an additional -152.9 Mt CO_2e of hypothetically avoided emissions by 2100 (see Supporting Information). All woodland scenarios offer the greatest net annual sequestration in the 2060s, before this declines in the 2080s (Figure 2b). This is due both to unharvested broadleaves reaching maturity, while production conifer

forestry becomes limited by rotational harvesting and losses from HWP.

3.3 | Saltmarsh creation

Despite a net loss of 60 ha per year in the Business-as-Usual scenario, higher initial rates of sequestration in new saltmarsh are sufficient to offset these losses and result in net cumulative and annual sequestration (Figures 1c and 2c). However, contribution of saltmarsh creation to the United Kingdom's net zero target is limited by the small areas available. Even under our higher ambition scenarios, with coastal realignment at 11 times the current annual rate, cumulative net GWP_{100} is only -2.7 Mt CO_2e by 2100 (Table 2).

3.4 | Combined restoration and creation

Enacting the Widespread Engagement scenario plus 100% restoration of afforested peatland could provide up to $-1,326.8$ Mt CO_2e of cumulative climate change mitigation by 2100 (Table 2). This scenario would entail the conversion of 3.4% of arable land and 7% of improved grassland (Table S6). Cumulative climate change mitigation for all NbS options is greatest from the 2070s. Lowest annual emissions from peatlands occur during the second half of the century,

TABLE 2 Cumulative net GWP₁₀₀ in 2050 and 2100, in Mt CO₂e, for a range of NbS scenarios. Peatland restoration values are avoided emissions relative to the Business-as-Usual scenario. Woodland creation values include impacts of timber harvesting but not substitution. For comparison, UK net annual emissions in 2018 were 451 Mt CO₂e (BEIS, 2020)

	2050					2100				
	Peatland restoration	Woodland creation	Saltmarsh creation	2050 Total	Peatland restoration	Woodland creation	Saltmarsh creation	2100 total		
Business-as-Usual	0	-45.3	-0.1	-45.4	0	-163.8	-0.2	-164.0		
Headwinds	-87.4	-90.1	-0.4	-177.9	-488.8	-294.4	-1.3	-784.5		
Balanced Net Zero Pathway	-132.1	-112.6	-0.4	-245.1	-662.9	-457.0	-1.3	-1,121.2		
Widespread Engagement	-132.1	-143.7	-0.9	-267.3	-662.9	-586.7	-2.7	-1,252.3		
Widespread Engagement plus 100% restoration of afforested peat	-119.7	-143.7	-0.9	-264.3	-737.4	-586.7	-2.7	-1,326.8		
Widespread Innovation	-126.4	-156.4	-0.4	-283.2	-638.8	-475.2	-1.3	-1,115.3		
Tailwinds	-126.4	-176.4	-0.9	-303.7	-638.8	-602.9	-2.7	-1,244.4		

while woodlands offer the greatest annual sequestration during mid-century. However, the three NbS in combination offer a maximum annual sequestration rate of only -9.1 Mt CO₂e, equivalent to just 2% of the United Kingdom's net annual emissions of 451 Mt CO₂e in 2018 (BEIS, 2020) (see Supporting Information).

4 | DISCUSSION

The highest ambition scenario could reduce net emissions by -264.3 Mt CO₂e by 2050 and a further -1,062.5 Mt CO₂e between 2050 and 2100. The cumulative 2100 total of -1,326.8 Mt CO₂e is equivalent to around 3 years' worth of the United Kingdom's current total annual net emissions, and 30 years' worth of net emissions from the agriculture sector (BEIS, 2020). Thus, whilst NbS present an important component of the United Kingdom's climate change mitigation strategy, they do not negate the need for substantial and sustained reductions in GHG emissions across all sectors (CCC, 2020; Smith et al., 2016). The United Kingdom's combination of limited land area and high economy-wide emissions relative to other countries likely underlies the lower potential of NbS for national climate change mitigation, compared to the global picture (Griscom et al., 2017; Roe et al., 2019). Despite this, NbS offer many additional societal and ecological co-benefits if enacted with care, including biodiversity conservation, regulation of water flows and quality, improved recreational opportunities and adaptation to climate change (Seddon, Daniels, et al., 2020). However, the dominant NbS narrative, particularly around woodland creation, strongly emphasises climate change mitigation. Given the modest mitigation potential of even highly ambitious UK NbS targets, compared to national emissions, this emphasis risks undermining the co-benefits provided by natural and semi-natural habitats. Any NbS-driven land use change must prioritise potential co-benefits to avoid perverse outcomes in which relatively modest climate change mitigation undermines nature and other societal objectives.

The delay before substantial benefits accrue highlights both the urgency with which NbS should be deployed but also that these potential land use changes will have to last for decades. A long-term view is essential to understand potential benefits and the full impacts of management choices. Our analysis highlights the critical importance of restoring degraded peatlands, which in their current state will emit more GHGs (1,674 Mt CO₂e cumulative emissions by 2100) than potential new woodlands could sequester (up to 603 Mt CO₂e cumulative sequestration by 2100). However, if all afforested peatlands were restored, new plantations would be required elsewhere to maintain current timber production, leading to greater land demand than forecast by CCC (2020). For woodlands to help address the climate crisis, careful deployment means targeting lower risk soils, minimising ground disturbance during establishment and prioritising broadleaved woodlands managed for conservation.

Our woodland opportunity map (Figure 3) is indicative rather than prescriptive. Any site will need careful assessment for potential impacts on local communities, existing biodiversity and soil

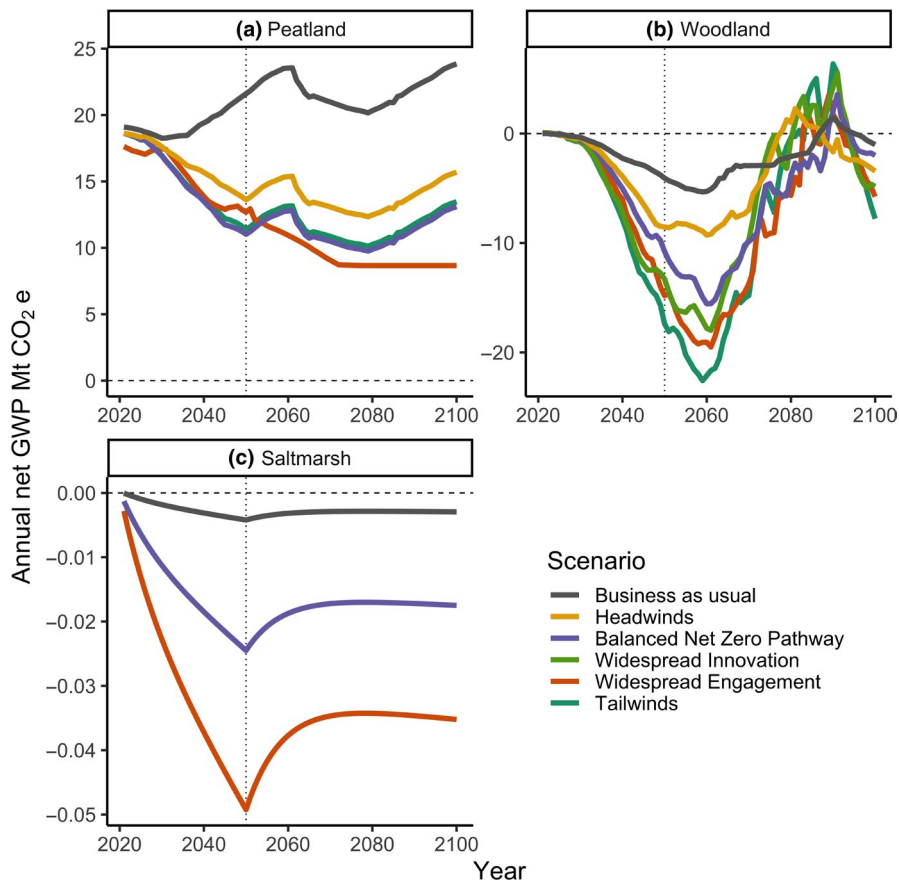


FIGURE 2 Annual GWP_{100} for three NbS options under a range of scenarios. For (a) peatlands, the Widespread Engagement scenario includes restoration of 100% of afforested peatlands. For (c) saltmarsh, sequestration under Headwinds and Widespread Innovation follow Balanced Net Zero Pathway, and Tailwinds follows Widespread Engagement. For context, UK annual emissions in 2018 were 451 Mt CO_2e (BEIS, 2020)

carbon prior to woodland establishment. Depending on the management aims, it may also be desirable to consider a much broader selection of tree species than we were able to assess here. In particular, Scots pine *Pinus sylvestris* is a key component of native woodlands in Scotland, and where appropriate could be considered as a candidate species for woodlands managed for biodiversity conservation.

Our mapping suggests there is sufficient potentially suitable land available to meet the CCC's ambitious woodland creation targets, but enacting NbS at the suggested scale will have wide-ranging and long-lasting impacts. Even though our mapping avoids woodland creation on higher grade farmland, conversion of any agricultural land will reduce overall production, unless accompanied by increased efficiencies and/or demand changes elsewhere in the food system (Finch et al., 2020). Societal attitudes towards such changes will vary. Removal of land from agriculture can be culturally sensitive, and not necessarily compensated for by increases in other non-exclusive land uses and co-benefits such as flood alleviation and recreation (Hardaker et al., 2021; Kirchhoff, 2012). Moreover, although woodland-associated species should benefit from major woodland expansion, open habitat species may decline (Burton et al., 2018; Lamb et al., 2019; Warner et al., 2021), while increases in restored peatland area should benefit wading birds (Wilson et al., 2014). Wider assessments of such broad-scale NbS-driven land-use change impacts on agriculture and biodiversity are urgently needed (Finch et al., 2020).

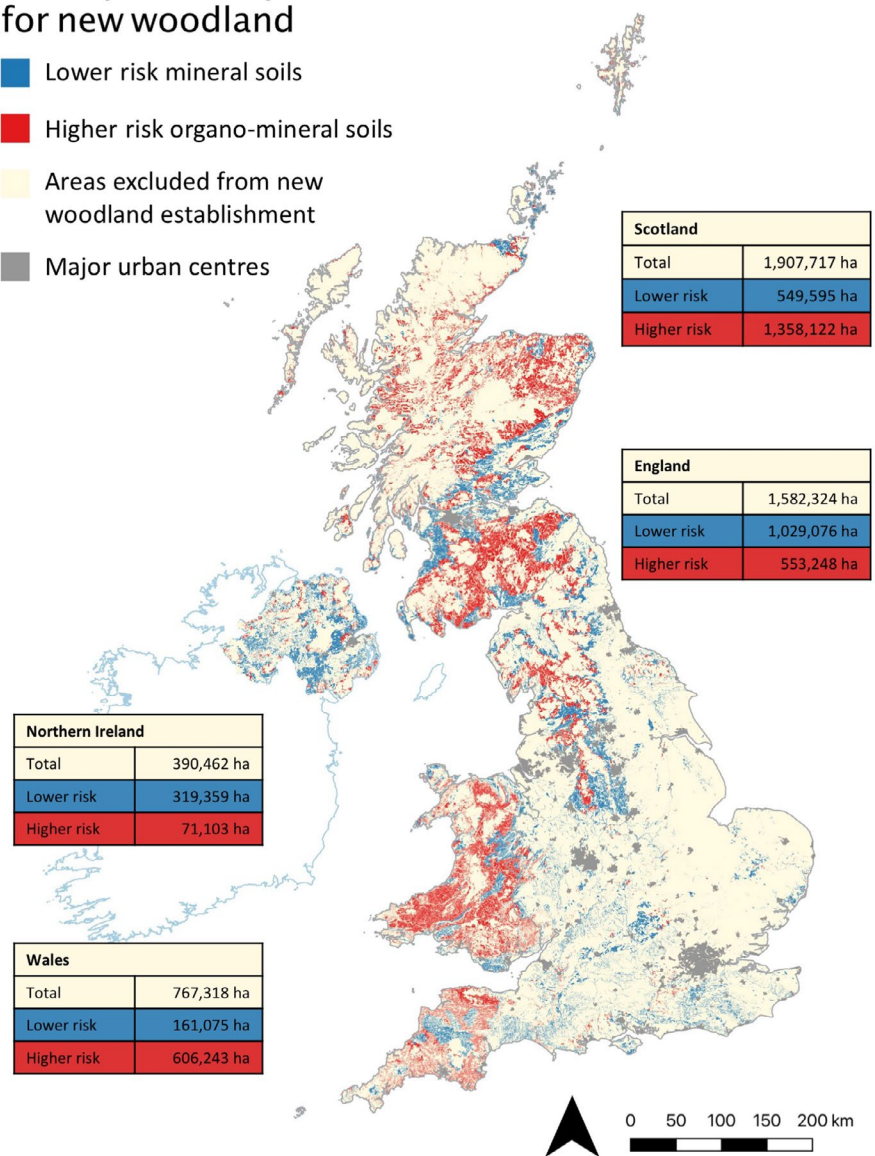
There are uncertainties in our projections, notably regarding the net sequestration benefits of woodland creation, because impacts on soil carbon stores are poorly quantified. Some recent evidence suggests carbon stores in some organo-mineral soils may be adversely affected by woodland establishment, potentially reducing net sequestration (Friggens et al., 2020), although this may recover over longer time-scales (Vanguelova et al., 2019; Xenakis et al., 2021). Given the urgency of the climate crisis, a precautionary approach is probably advisable where climate change mitigation is the primary driver of habitat change; in such cases, woodland creation should focus on mineral soils to give the greatest chance of net sequestration this century. However, carbon stores in organo-mineral soils vary widely, so some higher risk areas in our mapping may still be appropriate for woodland creation, especially when motivated by other goals such as flood alleviation or biodiversity conservation.

Semi-natural woodland established for the long term is likely to be better than production forestry for both climate and biodiversity (Burton et al., 2018; Warner et al., 2021), and probably have greater public support (Climate Assembly UK, 2020). However, this does not mean production forestry cannot contribute to climate change mitigation in the United Kingdom nor do we seek to question the economic and societal importance of the sector (CJC Consulting, 2015). Given the United Kingdom is the second largest net importer of timber in the world (Forest Research, 2020b), there are legitimate concerns about how this trade impacts other countries (Mayer et al., 2005) and calls to increase domestic timber supply (Welfle

FIGURE 3 Areas potentially available for new woodland in the United Kingdom. Lower risk areas are mineral soils, where woodland establishment is likely to result in higher net carbon sequestration. Higher risk areas are organo-mineral soils, where woodland establishment might trigger substantial losses of soil carbon, potentially counteracting sequestration in trees

Areas potentially available for new woodland

- Lower risk mineral soils
- Higher risk organo-mineral soils
- Areas excluded from new woodland establishment
- Major urban centres



et al., 2014; WWF-RSPB, 2020). While increasing domestic timber production on land that could be used for semi-natural woodlands will likely reduce total potential carbon sequestration, this might be partially offset by reducing timber import emissions. Furthermore, although over half of HWPs currently have a service life of less than 15 years, changes in forestry management practices and market improvements leading to better HWP use could boost the mitigation potential of production forestry (Sathre & O'Connor, 2010).

Although we highlight the potential of NbS to contribute to the United Kingdom's climate change mitigation effort, and demonstrate the feasibility of large-scale habitat change, considerable barriers remain. Notably, the United Kingdom lacks capacity for major scale deployment of NbS. Recent historical rates of peatland restoration are only 3,200 ha pa (ONS, 2019), while tree planting across the United Kingdom in 2019 totalled 13,400 ha (FC, 2020). Increasing these rates to meet the proposed

scenarios will require an increase in the number of skilled workers, and infrastructure investment such as tree nurseries for raising seedlings (Fargione et al., 2021). Recent pledges by the UK government amount to only £12 billion for a 'green industrial revolution', despite the CCC estimating £22 billion is required annually to reach net zero by 2050 (CCC, 2019; HM Government, 2020). Substantial further investment will therefore be required to deploy NbS at any meaningful scale. Upland peatland restoration is likely to be cheapest per hectare (ONS, 2019), though climate change mitigation potential from lowland peat is generally much greater per unit area. Woodland creation using planting is more expensive than peatland restoration, as trees must first be grown in nurseries. Woodland established using natural regeneration is much cheaper but offers slower initial sequestration and requires proximate seed sources. Moreover, these habitats still require management interventions such as the control of deer browsing

pressure (Gill & Morgan, 2010; Lamb et al., 2016). Coastal realignment has the highest costs of the NbS studied here, although the co-benefits such as reductions in flooding of coastal settlements are particularly important in building resilience to a changing climate (Kiesel et al., 2020; MacDonald et al., 2020).

The UK needs to urgently increase rates of carbon and biodiversity-focussed peatland restoration and woodland creation and improve the long-term use of HWP. However, avoidance of perverse outcomes can be made more certain by emphasising the 'nature' in NbS. Climate change mitigation cannot be used as an excuse for land management practices that damage biodiversity (Girardin et al., 2021). The twin climate and ecological crises are inextricably intertwined, and one cannot be resolved without the other (Leclère et al., 2020). Forthcoming changes to UK agricultural and rural support funding represents a pivotal opportunity to encourage positive change for the natural environment and progress towards net zero, ensuring public money does support public goods. NbS and other negative emissions technologies could be important in mitigating climate change but can only offer a meaningful contribution in the context of rapid and sustained reduction in the use of fossil fuels.

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CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

AUTHORS' CONTRIBUTIONS

All authors were involved in study conception and designed the methodology; T.B.-L. led the data analysis and wrote the first manuscript draft. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The woodland opportunity map is available from the University of Stirling DataSTORRE <http://hdl.handle.net/11667/179> (Bradfer-Lawrence et al., 2021).

ORCID

Tom Bradfer-Lawrence  <https://orcid.org/0000-0001-6045-4360>

Tom Finch  <https://orcid.org/0000-0003-1122-8513>

Richard B. Bradbury  <https://orcid.org/0000-0002-1245-2763>

Rob H. Field  <https://orcid.org/0000-0002-0194-6872>

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the Supporting Information section.

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