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Woodland expansion and upland management strategy dilemmas for biodiversity and carbon storage in the Cairngorms national park

Michel Valette[1,2]*, Scott Newey[3], Kate Schreckenberg[1,4] and Terence P. Dawson[4]

[1]Leverhulme Centre for Wildfires, Environment and Society, Imperial College London, London, United Kingdom, [2]Centre for Environmental Policy, Imperial College of London, London, United Kingdom, [3]Game and Wildlife Conservation Trust, Groddie, United Kingdom, [4]Department of Geography, King's College London, London, United Kingdom

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EDITED BY
Vinicius Londe,
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Andrea Baggio Compagnucci,
Forestry Commission England, United Kingdom
Tyler Carney,
University of Florida, United States

*CORRESPONDENCE
Michel Valette,
m.valette20@imperial.ac.uk

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Nature-based solutions are increasingly advocated to mitigate climate change and biodiversity loss, while improving ecosystem resilience and providing additional ecosystem services. In Scotland, woodland expansion and restoration of degraded peatlands are expected to play a major role in meeting net-zero emissions by 2045 and have prompted debates about the impact of increased woodland cover and prescribed fire on the biodiversity and ecosystem services provided by upland landscapes. In alignment with national policy, the Cairngorms National Park, the UK's largest national park, has committed to an ambitious programme of woodland expansion and peatland restoration in a landscape dominated by heather moorlands that is predominantly managed through prescribed burning for game management. Using the Native Woodland Model and the InVest modelling platform, we assessed the effects of five land cover and land use change scenarios, with different levels of prescribed fire regulation and woodland expansion, to evaluate their benefits and costs on biodiversity and carbon sequestration. Results show that changing the extent and management of habitats will result in different carbon sequestration pathways, as well as biodiversity winners and losers. The scenario presenting greater benefits for the conservation of biodiversity also has lower above-ground carbon sequestration potential and a larger negative impact on red grouse habitats, thus being less profitable to sporting estates. Hence, trade-offs will be necessary to achieve optimal carbon sequestration and biodiversity gains, with a potential role played by the continuation of prescribed fires and traditional moorland management practices as well as complementary grants and support measures based on biodiversity benefits rather than carbon sequestration. The results from this study could support discussions regarding future management of the uplands, trade-offs between loss of carbon in soils, carbon sequestration in woodlands and conservation of biodiversity, as well as stakeholders likely to be affected.

KEYWORDS

woodland expansion, prescribed fires, prescribed burning, trade-offs, protected areas, muirburn, trees, moorland

1 Introduction

Anthropogenic climate change, erosion of biodiversity and associated losses of ecosystem services are jeopardizing human wellbeing and capacity to fulfill their basic survival needs across the globe (IPBES, 2019; IPCC, 2023). This has led to international commitments to limit global warming to 1.5°C (Paris Agreements), protect biological diversity (Convention on Biological Diversity) and restore 350 million hectares of degraded ecosystems (Bonn Challenge). Nature-based solutions, such as woodland expansions, restoration of peatlands and regulation of certain land management activities, such as grouse moors, farming and forestry, are expected to play a major role in climate change mitigation policies, based on their potential to benefit both biodiversity and climate while delivering additional ecosystem services, such as timber and fuelwood provision, water provision and purification, flood protection, and control of soil erosion control (Griscom et al., 2017; Seddon et al., 2020; IPCC, 2023). However, rapid upscaling of nature-based solutions could have some deleterious social and environmental impacts while failing to sequester carbon and provide desired ecosystem services, as shown by some large-scale and poorly designed tree-planting campaigns (Malkamäki et al., 2018; Fleischman et al., 2020; Seddon et al., 2021). The trade-offs between food production, different ecosystem services and benefits for biodiversity of nature-based solutions need to be acknowledged and negotiated, to optimize potential co-benefits while reducing and compensating their costs (Hua et al., 2022; Miralles-Wilhelm, 2023).

In Scotland, upland areas are expected to play a major role in the deployment of nature-based solutions to meet zero emissions targets of the national government (Scottish government, 2011). Over the last century, extensive areas of peatlands have been drained across the uplands for agriculture, forestry, and sheep farming: while they cover 20% of Scotland's land area, 80% of the peatlands across Scotland are considered degraded (Holden et al., 2004; Alonso et al., 2011; Scotland's environment 2019). Degraded peatlands are characterized by lower water tables, slower rates of peat accumulation, decomposition of organic matter and release of carbon. Maintenance and restoration of peatlands are considered essential if the UK is to meet its net-zero emissions objective and has led national and devolved governments to commit to restoration and sustainable management of its peatlands (NatureScot, 2015; Helm et al., 2020). The Scottish Government also committed to increasing woodland cover from 18% to 21% of the Scottish land area by 2032 (Scottish government 2018) with open upland habitats/ hill edge identified as areas most likely to support new woodland cover (Woodland Expansion Advisory Group, 2012).

The Scottish uplands comprise different habitat types including blanket bogs, rough grasslands, dwarf shrub heath (heather moorland) and montane habitats. They support many native species and communities of conservation priority, including some unique or important assemblages of breeding birds and vegetation communities confined to the British Isles (Thompson et al., 1995; Eaton et al., 2015). Uplands also provide a range of other crucial ecosystem services, such as storing large quantities of carbon in the soil or the filtration of the majority of freshwater across the UK (Chapman et al., 2009; Alonso et al., 2011). Uplands have important cultural and recreational values, with different stakeholders preferring distinct characteristics of the landscape such as increased woodland cover or the presence of certain species (Schmidt et al., 2017; FitzGerald et al., 2021). Divergent aspirations for the uplands among stakeholders and wider society have led to heated debates around many aspects of uplands management (MacMillan and Kirsty, 2008; Dinnie et al., 2015). This is the case of prescribed fires on heather moorland for red grouse management and woodlands expansion, two management measures that can have significant impacts on carbon sequestration and biodiversity (Thompson et al., 2016; Sotherton et al., 2017).

Rewilding, a loosely defined concept around the restoration of wilderness and ecosystem services, is gaining momentum nationally and internationally. The context of the Scottish uplands, woodland expansion, peatland restoration and a move away from intensive livestock grazing and game bird management dominate rewilding initiatives (Robbins and Fraser, 2003; Deary and Warren, 2017; Martin et al., 2021). These efforts are, in part, associated with the acquisition of large estates by new types of landowners interested in woodland expansion, restoration of native ecosystems and carbon offsetting schemes (Hobbs, 2009; Dinnie et al., 2015). In Scotland, the expansion of woodland is controversial with debates around social inclusion, displacement of traditional livelihoods, optimal location for woodland expansion, ecosystem services provision and potential adverse effects on biodiversity (Hobbs, 2009; Burton et al., 2018; Burton et al., 2019). Tree planting or establishment on soils rich in organic matter can lead to considerable soil carbon loss, which might not be compensated by tree growth for several decades (Friggens et al., 2020; Matthews et al., 2020a; Ražauskaitė et al., 2020; Baggio-Compagnucci et al., 2022; Smyth, 2023). Moreover, growing woodlands could accumulate carbon at a slower rate than expected due to changing climatic conditions and are exposed to diverse risks such as wildfires and wind damage (Hermoso et al., 2021; Baggio-Compagnucci et al., 2022). Increased woodland cover could lead to loss, and degradation of the habitat quality of moorland-dwelling and other open habitat species by conversion to woodland and increasing the proximity of many areas to forest edges and associated predation (Wilson et al., 2014).

Prescribed fire is an essential aspect of land management, along with predator and parasite control, to allow driven red grouse shooting, an important economic activity for sporting estates in the uplands (Werritty et al., 2019; Matthews et al., 2020b). Sporting estates are small-scale businesses on landholdings of significant size (usually more than 3,000 ha), employing a range of staff undertaking habitat and wildlife management activities, such as deer stalking, grazing management for livestock, predator control, and prescribed burning for game management (MacMillan and Kirsty, 2008; Sotherton et al., 2009; Thompson et al., 2016). Between 30% and 40% of the burning associated with game management in the UK occurs on carbon-rich heather moorlands and peatlands and frequently within protected areas, raising concerns about potential impacts on biodiversity and carbon emissions (Douglas et al., 2015; Spracklen and Spracklen, 2023; Shewring et al., 2024)). Prescribed fires are usually burnt in small patches/narrow strips, creating a mosaic of stands of heather of different ages, providing both high-quality feeding and nesting habitats to grouse and other ground nesting birds, and some herbivore species, but also preventing forest regeneration and negatively impacting some

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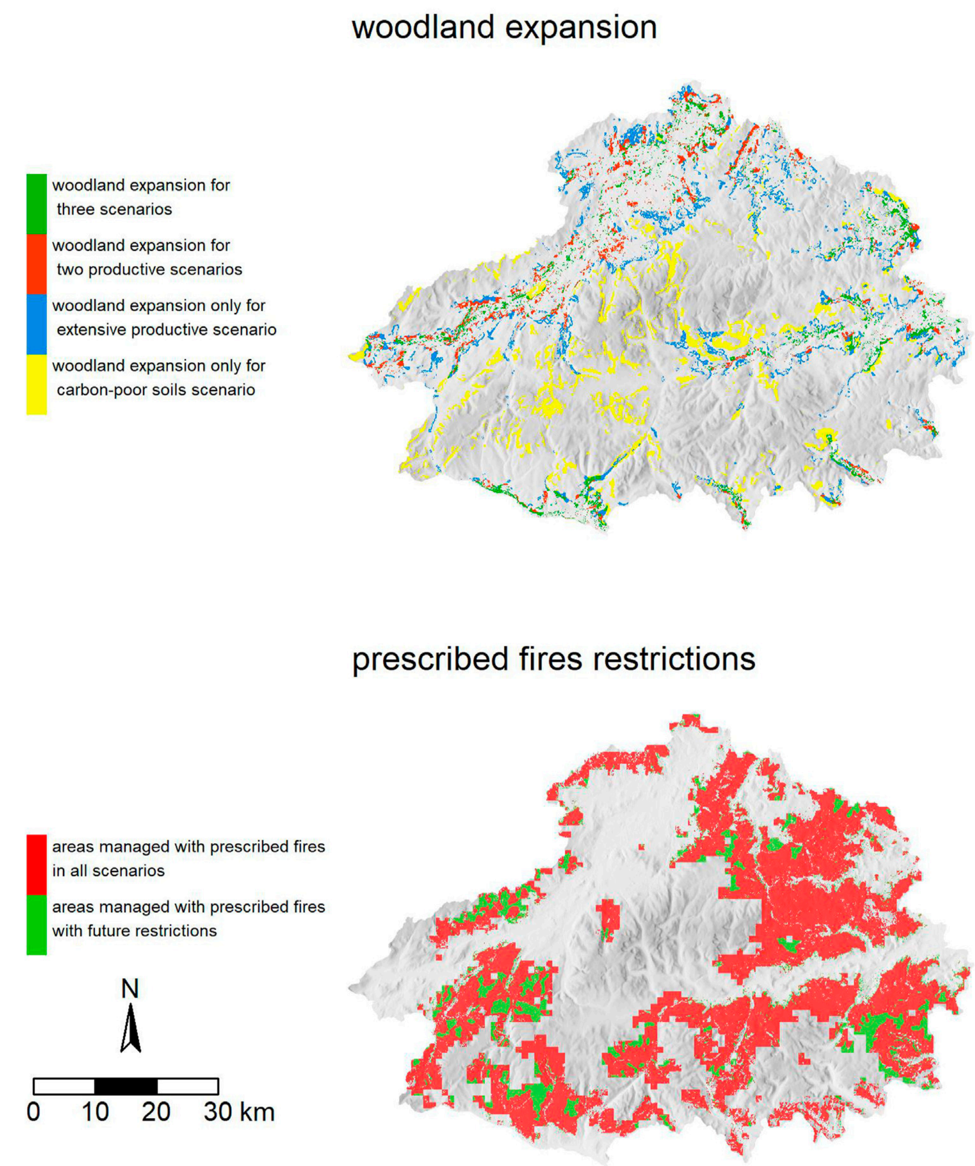

FIGURE 1
Management options for the use of prescribed fires. Areas in green represent areas currently burned where the use of prescribed fires could be restricted. Red areas show where burning can be undertaken and which would be unaffected by the management options explored.

animal species (Newey et al., 2016; Robertson et al., 2017; Mustin et al., 2018). There is conflicting evidence about the impact of prescribed fires on peatlands and peat-forming vegetation, as well as long-term consequences on their carbon storage capacity, which is conditional on the spatial extent and timescales being examined (Worrall et al., 2013; Holland et al., 2022; Heinemeyer et al., 2023). Prescribed fires reduce the fuel load available for burning through wildfires, but prescribed fire is inherently risky and can also lead to escaped fires, which can sometimes damage and degrade the wider landscape (Worrall et al., 2013).

All land use and land management practices benefit and negatively impact some species, ecosystem services and associated stakeholders' interests. The "identification and assessment of costs, benefits and risks and their distribution and trade-offs" could help to reach more equitable governance of protected areas and increase conservation effectiveness in the long term (Schreckenberg et al., 2016). The location and design of woodland expansion initiatives will affect the ecological outcomes, as well as who will benefit from and bear the costs of investing in their management, thus it is essential to assess and discuss these trade-offs (Brancalion and Karen, 2020). This is especially true in Scotland, where 83% of rural Scotland is owned by private entities and woodland expansion efforts are implemented by landholders, often with government grant aid (Wightman, 2024).

To examine the trade-offs between different options for the management of the Scottish uplands, we chose the Cairngorms National Park (CNP) as a case study. This choice was motivated by the fact that the CNP represents a large upland region, with diversified land use including large tracts managed for driven red grouse shooting using prescribed fires (Matthews et al., 2020a),

TABLE 1 Summary of the different scenarios and impact on the moorlands managed through prescribed fires.

Name of the scenario	Woodland expansion	Prescribed fires restrictions	Reduction in moorland managed by prescribed fires
Scenario 1: BAU	17,500 ha (most productive areas)	No	3 346 ha (−2%)
Scenario 2: productive expansion	35,000 ha on most productive areas	No	11,084 ha (−6%)
Scenario 3: productive expansion and prescribed fires restrictions	35,000 ha on most productive areas	Yes	34,722 ha (−19%)
Scenario 4: carbon-sensitive expansion	35,000 ha on carbon-poor soils	No	12,210 ha (−7%)
Scenario 5: carbon-sensitive expansion and prescribed fires restrictions	35,000 ha on carbon-poor soils	Yes	38,219 ha (−21%)

commercial forestry, upland grazing, tourism and increasingly also rewilding and woodland expansion schemes (CNPA, 2022). Moreover, the Cairngorms National Park Authority (CNPA) published their management objectives and quantitative goals for woodland expansion, along with sufficient methodological detail to allow us to recreate realistic scenarios. In consultation with selected stakeholders (including land managers, staff of governmental and non-governmental institutions involved in CNP management and/or associated research), we developed and assessed the effects of five scenarios for the future land use of the CNP, including three options for woodland expansion and two options for the future locations of prescribed fires for game management. We used the Native Woodlands model (Towers et al., 2000) and InVEST (Sharp et al., 2014) to explore three research questions:

- How do these land use scenarios affect the habitat quality for a selection of species representing the interest of different stakeholder groups within the park?
- How do these land use scenarios affect the quantity and location of carbon stocks and sequestered carbon?
- What are the management implications of the outcomes of these land use scenarios on biodiversity conservation and carbon sequestration?

2 Methods

2.1 Scenarios of future land use in the Cairngorms

The five scenarios for future woodland expansion efforts and restriction on the use of prescribed fires within the Cairngorms National Park, are based on the Cairngorms National Park Forest Strategy 2018, and the Partnership Program 2022; CNPA 2018; CNPA, 2022). In February and March 2023, two of the co-authors conducted semi-structured interviews with nine stakeholders in and around the CNP (including land managers and staff of governmental and non-governmental institutions involved in CNP management and/or associated research) to collect contextual information on future land uses and potential impact on biodiversity and ecosystem services. Land managers were selected using convenience sampling, relying on information available online and networks of the research team. While not fully representative of the diversity of landholders in the CNP, the inclusion of governmental employees working with all types of actors across the CNP helped to ensure diverse points of view and land management practices were represented. Our final sample included staff employed for the management of estates covering 14% of the CNP, and staff supporting land management of estates covering 39% of the CNP. While a participatory elaboration of the scenarios would require a larger and longer engagement with stakeholders, these interviews were guided by research questions and explored different assumptions for creating the scenarios. Results from the interviews were used to identify areas most likely to be targeted for woodland expansions by landholders, the rationales behind these choices, and areas managed through prescribed fires. For the restrictions on the use of prescribed fires for game management (hereafter called prescribed fires), we created two management options (see Figure 1):

- Current prescribed fires use: estimated using the dataset from Newey et al. (2024); see also (Matthews et al., 2020b), which ascribed each 1-km OS grid square as "burnt" if any proportion of a square contained evidence of burning from visual inspection of satellite imagery covering the period from 2008 to 2017. Using the Scotland Land Cover dataset from 2020 (Space Intelligence and NatureScot, 2020), we retained only areas covered by peatlands, heather and grasslands, land cover types that are commonly managed through prescribed fires for game management. This resulted in circa 1,820 1-km OS grid squares (or 182,000 ha) with signs of prescribed fires, or about 40% of the CNP. This baseline overestimates the area of moorlands managed with prescribed fires due to the low spatial resolution of the dataset: in most 1 km cells only a fraction of land is burned. In addition, interviews indicated that land managers, following NatureScot advice, sometimes avoid using prescribed fires on sensitive areas such as deep peatlands, steep slopes, close to ridges or areas with protected species (annexe 1).
- Restrictions on prescribed fires use: an alternative management option based on potential changes to the muirburn code (a code which provides good practice

TABLE 2 Final list of species selected for habitat quality modelling (see annex 1).

Species	Priority list of CNPA	Scottish biodiversity list	IUCN status
Red grouse *Lagopus lagopus scotica*	No	Yes	Least concern
Curlew *Numenius arquata*	Yes	Yes	Near threatened
Mountain hare *Lepus timidus*	Yes	Yes	Least concern
Meadow pipit *Anthus pratensus*	No	No	Least concern
Black grouse *Lyrurus tetrix*	No	Yes	Least concern

guidance and statutory restrictions for burning and cutting of vegetation) and fire risk assessment already used by some landholders within the CNP. Prescribed fires legislation will potentially restrict use of prescribed fire on peats deeper than 50 cm, thus, we used the peatland soil map of the James Hutton Institute to constrain the use of prescribed fires on deep peats. We added constraints on slopes steeper than 30° and within 5 m of water courses, constraints which already exist in the muirburn code. Finally, we added a constraint to prohibit burning within 50 m of existing woodlands as a buffer to protect regenerating stands and create a smoother ecotone between woodlands and moorlands, one management objective of the CNPA. Applying these constraints resulted in −155,000 ha of moorlands that could be managed through prescribed fires under possible future restrictions.

The Cairngorms Partnership Plan (CNPA, 2022) details a woodland expansion target of 35,000 ha by 2045, including 10,000 ha of natural regeneration without fences and a focus on native woodlands. As most of the CNP is privately owned, we used insights from interviews during our scoping visit to determine where woodland expansion efforts might most likely occur. Conditional on our limited stakeholder engagement, we identified the following principles:

- Some landholders will restore woodlands in the areas with higher growing potential of planted woodlands to maximize above-ground biomass accumulation
- Some landholders will restore woodlands in areas with low carbon-soil contents to avoid losses of soil carbon
- Landholders prefer natural regeneration on the edges of existing woodlands, if possible, without fences as it is cheaper and easier to implement than tree planting and fencing

We used the Native Woodland Model (Towers et al., 2000), land cover dataset (The James Hutton Institute, 1993) and Sites of Special Scientific Interest (NatureScot) for reproducing the map of potential areas for woodland expansion of the CNP Forest Strategy CNPA, 2018. Peatlands soil map and top organic soil content map from The James Hutton Institute were used to identify areas with potential deep peats and carbon-rich soils, which would be avoided in the extensive woodlands expansion efforts on carbon-poor soils. The National scale land capability for forestry map from The James Hutton Institute was used to identify the most productive forestry areas, with 24,915 ha identified as being of land capability class F5 or below (used in priority) and an additional 68,311 ha identified as of land capability class F6. As one of the management objectives of the CNPA is to maintain pastoralism, we also constrained woodlands expansion on the mesic grasslands category, containing pastures, identified by Scotland Land Cover dataset from 2020 (Space Intelligence and NatureScot, 2020). Finally, we used the proximity-based scenario generator of InVEST to model the expansion of woodlands from existing stands. This resulted in the creation of three woodland expansion options:

- Limited woodlands expansion effort: target of 17,500 ha of woodlands expansion (half the objective of the Cairngorms Partnership Plan, 2022 for 2045)
- Extensive woodlands expansion efforts on productive areas: 35,000 ha of woodlands restored (objective of the Cairngorms Partnership Plan, 2022 for 2045)
- Extensive woodlands expansion efforts on carbon-poor soils: 35,000 ha of woodlands restored (objective of the Cairngorms Partnership Plan, 2022 for 2045) but restricted to soils with less than 15% of top organic carbon content (mineral soils) and outside of areas classified as deep peat.

We combined the 2 management options for prescribed fires and the 3 management options for woodland expansion to create five scenarios (Table 1; Figure 1). We excluded the possibility of having only limited woodland expansion effort but supplementary constraints on prescribed fires, as it was assumed to be an unlikely scenario.

2.2 Types of woodlands restored

For assessing the types of woodlands restored according to each scenario, we used the Native Woodland Model (NWM). This model combines soil and land cover data with ecological requirements of different national vegetation types to predict the native woodland types likely to naturally regenerate in any given area of Scotland (Towers et al., 2000). This dataset was developed to assist native woodland expansion efforts and was used for the elaboration of the map of priority and sensitive areas for woodland expansion in the Cairngorms National Park Forest Strategy (CNPA, 2018).

Existing woodlands in the Cairngorms National Park are composed mainly of native species, even for commercial forestry with Scots pine plantations, and the CNPA objective is that >80% of woodland expansion efforts should be achieved with native woodland species. During the scoping visit, landholders expressed a strong preference for natural regeneration over planting. Thus, we assume the NWM would provide a good approximation of the future restored woodland habitats, and we analysed the overlap between NWM and our three woodland expansion scenarios. The proportions of NWM types restored in each scenario were also used to calculate potential carbon sequestration, as the potential above-ground biomass of NWM types ranges from 10 to 85 tC ha^{-1}.

2.3 Habitat species modeling

We first created a list of species (Table 2) which were selected based on their (a) interest across a range of different stakeholders, (b) their preferences for open habitats and sensitivity to changing habitats in terms of woodland expansion and changing fire regimes, and (c) the availability of evidence from the wider literature to substantiate their habitat use preferences. This list is neither exhaustive nor representative of all species of the CNP that could be positively or negatively affected by woodland restrictions or restrictions of prescribed fires, as such efforts are beyond the scope of this project.

We used the habitat quality module within InVEST to assess how the land cover change scenarios might affect the habitat quality and thereby the distribution of selected species. The habitat quality model operates with the following inputs:

- Current and future land cover (derived from satellite data and scenarios).
- Sensitivity table (derived from literature review).
- Threats tables (derived from interviews and literature review).

See Supplementary Data S1 for more details on the literature review on habitat preferences and the calibration of the model. For each species, we ran habitat quality models for our baseline scenario and each of the five land use/cover change scenarios and compared the change in habitat quality. We classified each grid cell of the output into one of the five categories: important degradation of habitat quality (corresponding to a change of land cover affinity), modest degradation of habitat quality (corresponding to a change in threat), no change, modest improvement of habitat quality (corresponding to a change in threat), important improvement of habitat quality (corresponding to a change of land cover affinity).

2.4 Carbon storage

To assess the change in carbon stock resulting from the different scenarios, we used the carbon sequestration and storage module of InVEST, which computes carbon storage into different pools (above-ground biomass, below-ground biomass, dead biomass and soils) using land use maps and correspondence tables assigning land uses to carbon pools (see Supplementary Data S2). We assessed changes in carbon storage for two periods, 40 and 100 years into the future, to understand the evolution of carbon storage after potential soil carbon loss due to disturbance during woodlands expansion and long-term storage capacity. We developed a land use classification and associated corresponding carbon values using different sources available, including an estimation of carbon sequestration by the different woodland types from the NWM (see annexe for more details). Potential loss of soil carbon was quantified by imposing a 50% decline in the carbon content of organic soils and a 20% decline in organo-minerals soils after 40 years, based on value from Friggens et al. (2020), before reaching the value for mature woodlands measured through 69 woodlands plots in Scotland by (Vanguelova et al., 2013) after 100 years.

After the creation of correspondence tables with each land use and associated carbon stock, we reclassified current and future land use before running the models. We then merged the output of carbon stored in AGB, BGB and dead biomass as there were uncertainties in some studies about the repartition of carbon between the different components, and these three carbon pools are susceptible to external disturbance, such as intense wildfire or wind damage events.

3 Results

3.1 Types of woodlands restored

Limited woodland expansion (scenario 1) resulted in the increase of surface cover by 38 National Vegetation Classification (NVC) types, extensive woodland expansion in productive areas (scenarios 2 and 3) resulted in the increase of surface cover by 40 NVC types, and extensive woodland expansion on carbon-poor soils (scenarios 4 and 5) resulted in the increase of surface cover by 42 NVC types. Limited woodland expansion was the only scenario not associated with expansion of "scattered Juniper" (Sc2) and lowland "mixed broadleaved woodland with bluebell/wild hyacinth/dog's mercury" (W10/W8). Extensive woodland expansion on carbon-poor soils (scenarios 4 and 5) was associated with the expansion of scattered birch/willow (Sc4), scattered mixed montane scrub (Sc8), and alder-ash woodland with yellow pimpernel/upland oak-birch woodland with blueberry (W7/W17), but not with mosaics of upland oak-birch woodlands with bluebell/wild hyacinth and birch woodland with purple moor grass (W11/W4).

The different woodland expansion scenarios also led to important differences in the area of each NVC category (Figure 2). Both limited and extensive woodland expansion on productive areas (scenarios 1, 2, and 3) led to the expansion of large tracts of upland oak and birch woodlands with different vegetation associations (W11/W17/W4, Figure 2). Extensive woodland expansion on productive areas (scenarios 2 and 3) also led to important areas of Scots pine woodlands with heather (W18). While extensive woodland expansion on carbon-poor soils (scenarios 4 and 5) led to the expansion of more scrubland communities, with important areas of scrub, juniper and birch/willow association (Sc1/Sc3/Sc8), it had considerably smaller areas of Scots pine woodland with heather (W18).

3.2 Habitat species modelling

The impacts of the different scenarios on habitat quality for red grouse, curlew and mountain hare were similar: limited woodland expansion scenario (scenario 1) led to a modest decline of habitat

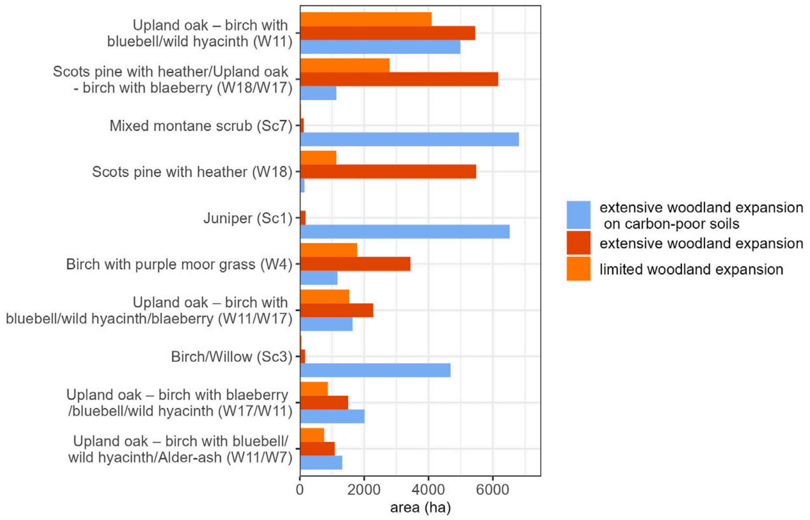

FIGURE 2
Area of the 10 woodland types (with corresponding National Vegetation Category-NVC) restored on larger areas according to the scenario with limited woodlands expansion (scenario 1), extensive woodland expansion (scenarios 2 and 3) and extensive woodland expansion on carbon-poor soils (scenarios 4 and 5).

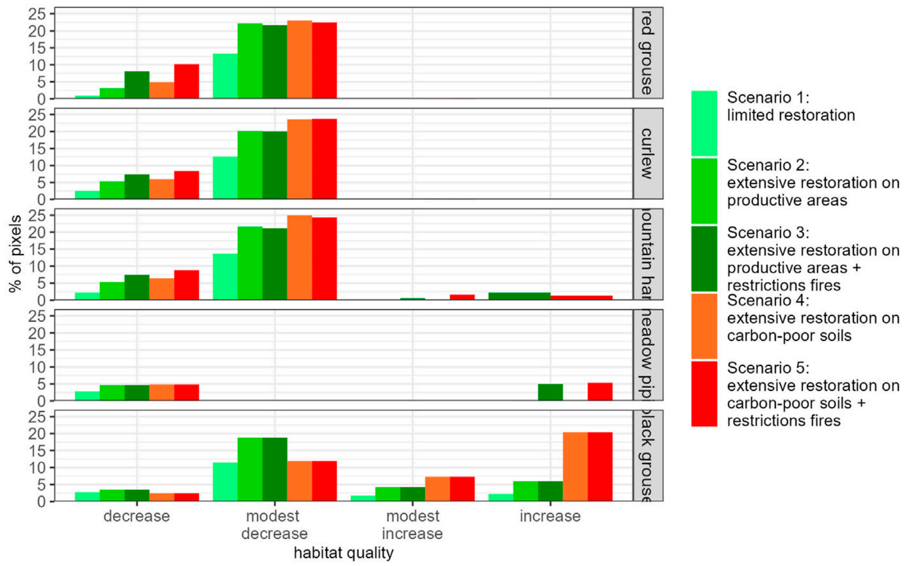

FIGURE 3
Proportions of the landscape that changed habitat quality for the 5 species assessed. Modest decrease and increase correspond to a change between 1% and 30% changes in habitat quality, while a decrease or increase corresponds to more important changes in habitat quality, only possible through changes in land use affinity (see Annex 3 for detailed spatial outputs).

quality in about 12% of the CNP area and a stronger negative impact in about 2% of the CNP area (Figure 3). The scenarios with extensive woodland expansion (scenarios 2–5) led to moderate declines in habitat quality of around 20%–25% of the CNP area, with stronger negative effects associated with woodland expansion on carbon-poor soils (scenarios 4 and 5, Figure 3). The two scenarios which included the restrictions on the use of prescribed fires (scenarios 3 and 5) led to larger areas showing strong declines in habitat quality for all species considered here, of up to 10% of the CNP for red grouse. Thus, the location of woodland expansion efforts appears to affect predation patterns on red grouse, curlew and mountain hare and have a broad and relatively low impact, while the restriction on prescribed fires leads to stronger impacts on smaller areas. Mountain hares also have some areas with a general improvement in their habitat quality, but they remain quite marginal.

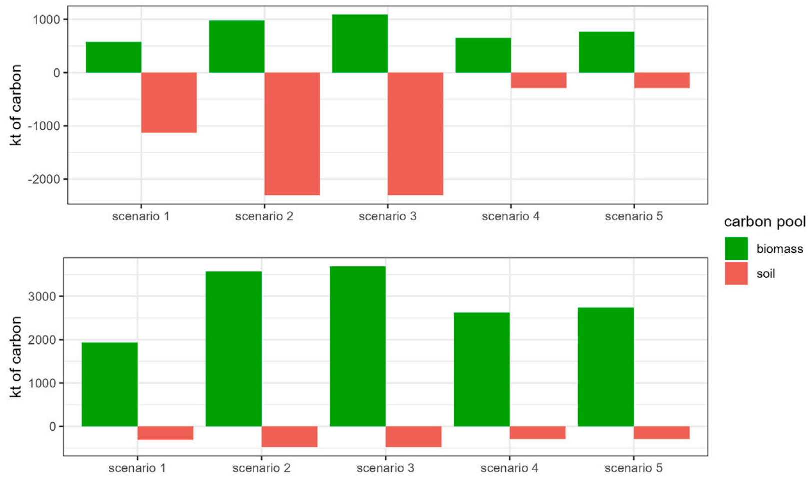

FIGURE 4
Soil carbon loss and biomass carbon gain after 40 years (top) and after 100 years (bottom) for the different scenarios.

TABLE 3 Soil carbon loss after 40 years and total biomass in tons of carbon accumulated according to different soil carbon reduction coefficients after 40 years.

Reduction coefficient	Scenario 1 (tC)	Scenario 2 (tC)	Scenario 3 (tC)
Organic 50% organo-minerals 20%	−1 126,778	−2,306,158	−2,306,299
Organic 25% organo-minerals 10%	−697 175	−1 296,441	−1 296,572
Organic 12.5% organo-minerals 5%	−497 257	−873 740	−873 864
Total biomass accumulated	576,026	977,106	1 089 448

For the meadow pipit, limited woodland expansion (scenario 1) led to a decrease in habitat quality over an estimated 2.5% of the CNP area, with extensive woodland expansion (scenarios 2–5) leading to a decrease in habitat quality in around 4.4% of the CNP area. Scenarios with restrictions on prescribed fires (scenarios 3 and 5) led to an increase in habitat quality in 5.5% of the CNP area (Figure 3).

For the black grouse, both limited woodlands and extensive woodland expansion scenarios on carbon-poor soils (scenarios 1, 4 and 5) led to a modest decline in habitat quality in around 10% of the area of the CNP, and the two extensive woodland expansion on productive areas scenarios (i.e., scenario 2 and 3) led to a decline in an estimated 18% of the area (Figure 3). All the scenarios also led to some improvement in habitat quality, but extensive woodlands expansion on carbon-poor soils (scenarios 4 and 5) led to larger areas experiencing a modest increase, in 7% of the CNP area, and an important increase in habitat quality, in 20% of the CNP area.

3.3 Carbon storage

Limited woodland expansion in productive areas (scenario 1) led to a lower biomass accumulation than in other scenarios (Figure 4). Extensive woodlands expansion in productive areas (scenarios 2 and 3) led to the largest accumulation of biomass in the long term but resulted in important carbon loss from the soils and net emissions after 40 years, due to woodlands expansions on organic and organo-mineral soils. Extensive woodlands expansion on carbon-poor soils (scenarios 4 and 5) led to the sequestration of about two-thirds of the biomass compared to woodlands expansion in productive areas but would already sequester carbon after 40 years as there are no important soil carbon losses. Using different values of soil-carbon loss after woodlands expansion, we found that extensive woodland expansion in productive areas is likely to compensate for soils-carbon loss through biomass growth for a decrease of soils-carbon in organic soils of about 12.5% and 5% in organo-mineral soils (Table 3). The restrictions on prescribed fires have only a minor impact on total carbon sequestration and biomass accumulation. However, this leads to a greater accumulation of biomass on carbon-rich soils.

4 Discussion

Our analyses show that, based on best current knowledge, each of the five scenarios assessed here yielded different trade-offs between the diversity of native woodland types restored, habitat quality for selected open-ground species, risks of soil carbon loss in the mid-term, and sequestration of carbon in the long-term. Scenario 1 (business-as-usual) has the least impact on red grouse and other moorland species, but also the lowest carbon sequestration potential. Scenario 2 (productive expansion) also showed limited impact on red grouse and other moorland species and, along with scenario 3, has the greatest carbon sequestration potential of the scenarios assessed as long as the trees are not felled before regeneration of carbon stock. However, scenario 2 also leads to a decline in habitat quality for meadow pipit and is associated with substantial short-term loss of soil carbon before woodlands reach maturity. Scenario 3 (productive expansion and prescribed fire restrictions) shared many characteristics with the previous scenario but led to a greater negative impact on red grouse and other moorland species. However, it has a positive impact on meadow pipits in certain areas of the CNP. Scenario 4 (carbon-sensitive expansion) is predicted to sequester the least carbon and negatively impact larger areas of red grouse and other moorland species habitats than scenario 2. But it also restores a higher diversity of vegetation types, including more scrub and mountain woodlands, with knock-on benefits for black grouse, and retains an important quantity of carbon in soils during woodland maturation. Scenario 5 (carbon-sensitive expansion and prescribed fire restrictions) is associated with the greatest negative impact on habitat quality for red grouse and other moorland species, but a positive impact on the meadow pipit.

The difference in the outcomes of scenarios 2 to 5, sharing a similar woodland expansion objective of 35,000 ha, demonstrates the importance of the location of woodland expansion efforts and complementary landscape management interventions, such as the use of prescribed fires, on future ecosystem services provided by the uplands. This highlights the need to support area-based woodland expansion pledges with guiding principles and safeguards to reach the desired ecological and climatic impact, such as guidance on the priority areas to target (Brown, 2020). Strategic spatial planning of woodland expansion could help identify priority areas and maximize the benefits of new woodlands for carbon sequestration, biodiversity and other ecosystem services (Bailey et al., 2006; Burke et al., 2023). Public forestry sectors in Scotland have responsibility for regulating and supporting woodland creation, thus the articulation between government programs and the interest of private landholders, owning most of the CNP and deciding on the location of future woodlands, is essential for maximizing different benefits of woodland expansion (Sharma et al., 2023).

Changes in land cover associated with the different scenarios are expected to have both direct impacts on moorland species through the replacement of habitat types, and indirect impacts, through changes in the distribution of predators, for example, (Wilson et al., 2014). In the absence of predator control, greater woodland cover is correlated with an increase in fox abundance and predation pressure, and a decrease in curlew numbers (Douglas et al., 2014). The results of our modelling suggest that the expected increase in predation pressure associated with woodland expansion will negatively impact ground-nesting birds across significant areas of the CNPA, especially when restoring woodlands on carbon-poor soils (scenarios 4 and 5). The cumulative impacts of both woodland expansion and restrictions on prescribed fires need to be considered together because while restrictions on prescribed fires would increase the habitat quality of certain species, such as the meadow pipit, they also affect the extent of land managed by game managers and predation pressure adjacent to new woodland cover.

Mechanical mowing might represent an alternative to prescribed fires to break up homogeneous stands and rejuvenate heather, but is confined to areas with gentle slopes, well-drained soils and terrain suitable for working with machinery (Heinemeyer et al., 2023). The cuttings should also be removed to prevent the build-up of fuel loads and subsequent wildfire risk, but this is expensive and time-consuming. Moreover, the relative benefits and disadvantages of mowing compared to prescribed fires remain unclear and the knowledge base is contested (Ashby and Andreas, 2020). Mowing has been shown to cause damage to the peat surface (micro-topography) though the impacts are poorly understood, may shift vegetation towards communities associated with increased methane emissions, increase concentration in dissolved organic carbon, and on very wet sites, reduce cranefly (Tipulid) emergence, which has associated negative impacts on rare upland bird populations (Heinemeyer et al., 2023). Mowing may be less effective at promoting long-term carbon sequestration as studies show the carbon accumulated through charcoal production during prescribed fires can effectively lock carbon up safely (Worrall et al., 2013; Heinemeyer et al., 2018). However, more evidence is required to understand the factors influencing charcoal production during prescribed fires, such as intensity and rate-of-spread of fires (Worrall et al., 2013).

Expansion of woodlands on carbon-poor soils is predicted to have benefits for the biodiversity specific to the Cairngorms and lead to increased cover of juniper, willow and other mountain scrub species specific to the uplands. The increased interface of moorland and woodlands is expected to increase the habitat quality for the black grouse. This woodland expansion scenario could also attract more mountain visitors, through an increase in native woodland cover in the uplands, a favoured landscape attribute for some visitors (Dick et al., 2022). Woodland expansion on carbon-poor soils also presents a safer pathway for carbon sequestration as it prevents soil carbon loss from planting on carbon-rich soils, however, it also has a lower final sequestration potential due to increased proportions of scrub and open woodlands, and lower potential payments for carbon sequestration.

Our research is based on the assumptions of a loss of carbon during the regrowth of woodland on organo-mineral and organic soils, in line with previous work in Scotland (Friggens et al., 2020; Matthews et al., 2020a; Ramcilovic-Suominen et al., 2021). However, there is still a lack of detailed understanding of the impact of the types of soils, types of woodland restored, and restoration techniques used on soil carbon to make accurate predictions on soil carbon response to woodland expansion. Baggio-Compagnucci et al. (2022) have shown that adoption of low-disturbance planting practices could significantly decrease soil carbon emissions, resulting in higher carbon sequestration potential in the Scottish uplands, while the choice of different tree species planted significantly impacts above-ground biomass accumulation and influence of climate change. Interviews highlighted a preference for natural regeneration but most evidence of the loss of carbon in soils originates from planted plots, which involve higher soil disturbances (Friggens et al., 2020; Ražauskaitė et al., 2020). The models in our study only consider the distribution of the biomass between the soils and the standing biomass, which could be more vulnerable to external disturbances such as wildfires and storm damage. Further steps in the analysis of costs and benefits of the woodland expansion scenarios would be to estimate their vulnerability to external disturbance, as upland areas might be more exposed to wind and lowland areas exposed to phyto-diseases (Mitchell et al., 2014; Mitchell et al., 2019). Moreover, climate change could reduce tree growth rates (Petr et al., 2014; Baggio-Compagnucci et al., 2022), increase risks of drought-induced tree mortality (Broadmeadow et al., 2005; Allen et al., 2010) and stand-replacing wildfires (Millar and Stephenson, 2015; Perry et al., 2022), all affecting carbon accumulation rates and carbon sequestration potential of different woodland expansion strategies.

Woodland expansion on carbon-poor soils also presents trade-offs for landowners that government institutions should consider if promoting this strategy to favor simultaneous carbon sequestration and biodiversity benefits. Firstly, carbon-poor soils in the CNP tend to be located in remote locations and on steeper slopes that could be challenging to access for large-scale fencing, tree planting and herbivore management. Secondly, increased predation pressures on moorland ground-nesting birds could negatively impact their breeding success, including high conservation priority species, and impact red grouse density and consequently rural incomes. Thirdly, it is associated with slower-growing species and biomass accumulation that could constrain accumulation of carbon credits and profits from forestry operations. Together, these could make the expansion of woodland on carbon-poor soils a less economically profitable option for landowners.

Understanding the decision process behind woodland creation by private landholders is important to adapt public forestry policy and influence the location of the new woodland creation, thus maximizing co-benefits between carbon sequestration, biodiversity and other ecosystem services (Thomas et al., 2015; Burke et al., 2023). In a study with sporting estates across Scotland, Bowditch et al. (2023) show that accessibility of different parts of the estates, the productivity of future woodlands and opportunity costs of alternative land uses are important determinants when estate managers choose the location of new woodlands. New woodland creation in Scotland has concentrated on marginal lands with carbon-rich soils (Brown, 2020). Woodlands are likely to continue expanding in these areas if the main incentive for their expansions is related to carbon markets as they have better sequestration potential. This could impede carbon-sequestration potential in the mid-term, due to soil carbon loss, and minimize benefits for the biodiversity of the uplands. However, payment for ecosystem services, such as the conservation of biodiversity, could incentivize private landholders to expand woodlands on carbon-poor soils and yield other important ecosystem services (Barry et al., 2014).

However, non-economic factors also play an important role in decisions regarding woodland expansions in the uplands (Thomas et al., 2015; FitzGerald et al., 2021; Bowditch et al., 2023). Development and support of existing partnerships between landholders, such as the Cairngorms Connect partnership, already proved pivotal to the expansions of woodlands in the CNP and could influence locations of future woodlands and common goals pursued by estate managers (Valluri-Nitsch et al., 2018; Gullett et al., 2023). Different types of woodland owners in the United Kingdom are currently prioritizing distinct objectives, such as the production of sawn timber, chipping or wood fuel, nature conservation or creation of recreative spaces, and could be affected by different policy instruments for the provision of public benefits (Urquhart and Paul, 2011; Raum, 2018). Productivist landholders could place a greater emphasis on financial return, and thus be especially receptive to financial incentives for conserving biodiversity or providing other ecosystem services with current low market values. Other types of woodland owners, such as conservation NGOs, tend to focus more on the recreational and environmental values of their woodlands and could be more inclined to expand woodlands on carbon-poor soils for aesthetics and biodiversity benefits if their financial models are sustainable.

Due to the increasing wildfire risks related to climate change, it is essential to consider the implications of future management scenarios on fuel build-up, vulnerability to wildfires and potential impact on ecosystem services (Santana et al., 2016; Arnell et al., 2021). While assessing the impact of different land use scenarios on wildfire risks was out of the scope of this study, future land use scenarios are predicted to lead to an increasing overlap of carbon-rich soils and important biomass stocks at risk of wildfire, potentially leading to important soil combustion and associated carbon emissions. A recent analysis shows that, between 2015 and 2020, 96% of wildfires in Scotland occurred outside of areas managed with prescribed fires for red grouse management, suggesting an overall important reduction of wildfire risks related to prescribed fires (Fielding et al., 2024). This, along with other evidence, suggest that fires for red grouse management could reduce wildfire risks, but there are still uncertainties around the influence of the spatial configuration of prescribed fires on wildfire risks (Holland et al., 2022; Fielding et al., 2024). It is important to consider not only the impact of prescribed fires on wildfire likelihood but also on wildfire size, intensity and severity: lower fuel load connectivity could help to contain accidental fires and prevent them from damaging the soils, vegetation and regenerating forest (Log et al., 2017; Davies et al., 2019). Another important role of prescribed fires for wildfire risks is the maintenance of teams of gamekeepers skilled in working with fires and owning fire-fighting equipment. Through regular use of fires, gamekeepers are accumulating extensive knowledge of fire behavior and the use of prescribed fires (Davies et al., 2019). They are also often first responders to wildfires on the moorlands and can fight these fires before they reach higher intensity and severity, a role especially important due to the remote locations of many moorlands. The majority of wildfires in Scottish moorlands were identified on peatland, areas that will be affected by further restrictions on prescribed fires and which are storing huge amounts of carbon: it is thus essential to consider alternative wildfire risk reduction strategies in these areas (Fielding et al., 2024).

5 Conclusion

Land is increasingly managed for multiple, sometimes contradictory or even conflicting, management objectives, for example; woodland expansion for biodiversity conservation and carbon sequestration, employment and income for local communities through sporting or ecotourism, and conservation of endangered or endemic species. This is particularly the case in upland areas which provide a range of critical ecosystem services, where land use may be constrained by climate and soils, and at least in the UK are often under different types of private and public ownership.

Here, through the analysis of some of the biodiversity and carbon sequestration potential for a range of different scenarios, we show that there are trade-offs between carbon sequestration, habitat quality for open habitat dwelling species and expansions of diverse and rare vegetation types. None of the scenarios explored would advantage all the management objectives, and there were always some objectives, and associated stakeholder groups, advantaged and disadvantaged.

The current carbon market design, focusing on above-ground sequestration of carbon, would incentivize woodland expansions on areas yielding limited benefits after 40 years due to soil carbon losses, and restore a lower number of native vegetation types. However, woodland expansion on carbon-poor soils is limited by several economic factors and would likely require different incentive mechanisms to reach safer carbon sequestration pathways and restoration of a higher diversity of vegetation types. Restriction on prescribed fires will have only a marginal impact on above-ground carbon sequestration, but will negatively impact some open-ground dwelling species, and could impact wildfire risks on carbon-rich peatlands.

While we argue that this emphasizes the need for evidence-based decision-making, we acknowledge that there remain many knowledge gaps and areas of contested knowledge. Our study focuses on the impact of woodland expansion on carbon sequestration and biodiversity, but the impact on other important ecosystem services provided by the uplands, such as water filtration and flood control, should also be investigated further.

Ultimately policy decisions will be made on political and economic grounds taking into account the scientific evidence. In such cases, we suggest that it is critical for successful policy implementation that decision-makers must fully engage with stakeholders and local communities and embrace different ways of knowing to identify consensus and areas of disagreement.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://zenodo.org/records/10835942?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6IjkxZWY1N2JiLTg5NTMtNDBhNi1iYTA2LWE1NmU5NzY3ZmQzNiIsImRhdGEiOnt9LCJyYW5kb20iOiIxZTM0OTM1NjMyOWUwZmEzY2U2NWQ2Y2M5OTBhYmMxOSJ9.WhF2M4E5VvgxOuBkTO8reHt4QzYvCwTdgLoabTkI-vvAMAiZ7bY6hXtQa5eY1irrm-h-6BcJlJvf3NOCUEfQ.

Author contributions

MV: Writing–review and editing, Writing–original draft, Visualization, Software, Methodology, Investigation, Formal Analysis, Data curation, Conceptualization. SN: Writing–review and editing, Validation, Supervision, Resources, Methodology, Conceptualization. KS: Writing–review and editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. TD: Writing–review and editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1411659/full#supplementary-material

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