Fires in the uplands: future impact of prescribed fires and woodland restoration on biodiversity and carbon stocks in the Cairngorms National Park

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Moorlands and woodlands in the Cairngorms National Park. Source: M. Valette

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Abstract

The Cairngorms National Park (CNP) is the UK's largest national park and harbours a range of species of conservation concern. About 45% of the CNP is dominated by heather moorlands, with a significant part managed through prescribed fires for game management, and about 20% under woodland cover. The CNP Partnership Plan 2022-2027 has set a target to achieve net zero for the region by 2045 through an ambitious programme of woodland expansion and the restoration of degraded peatlands. There are debates in the CNP and across the UK, about the impact of increased woodland cover and prescribed fires (muirburn) on the biodiversity and ecosystem services provided by upland landscapes. Using the InVest modelling platform we assessed the effects of five land cover and land use change scenarios, with different levels of muirburn 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. 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 associated predator control.

Introduction

More than half of the Scottish landcover is classified as uplands, comprising different habitat types such as peat bogs, acidic grasslands, dwarf shrub heath (heather moorland), bracken, fen, marsh and swamp as well as inland rock and montane habitats (Scottish Government, 2011). Semi-natural in character, uplands support a large number of native species of conservation priority, including some bird species and vegetation types confined to the British Isles (Eaton et al., 2015; Thompson et al., 1995). Upland habitats also generate 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 (Alonso et al., 2011; Chapman et al., 2009).

Since the Medieval period, Scottish uplands have been heavily managed for agriculture, pastoralism and natural resource extraction, and the combined influence of grazing and pastoral fires led to the expansion of moorlands over forests and deterioration of peat bogs (Dodgshon and Olsson, 2006; Holl and Smith, 2007). In the late 18th and 19th centuries, the Highland Clearances and forced eviction of traditional tenants drastically transformed the Scottish uplands: traditional small-scale farms were consolidated into large landholdings, dedicated to sheep farming and then sporting estates (Hobbs, 2009; Holl and Smith, 2007; Wightman et al., 2002). Sporting estates are small-scall businesses on landholdings of significant size (usually more than 3 000 ha) with permanent staff employed to manage the land and assist sporting, most commonly deer stalking and driven red grouse, and to a lesser extent, pheasant and partridge shooting (Sotherton et al., 2009; Wightman et al., 2002). Sporting estates often rely on income from sporting and other activities such as livestock farming, forestry and nature-based tourism (Morran et al., 2014). Sporting estates employ a range of staff undertaking important landscape management measures, such as deer stalking, predator control and use of prescribed fires for game management, which can benefit rural communities and upland ecosystems (MacMillan and Leitch, 2008; Sotherton et al., 2009; Thompson et al., 2016).

Extensive areas of peatlands have been drained for agriculture, forestry, and sheep farming, especially over the second half of the 20th century when commercial forestry and sheep farming were subsidised by the government (Alonso et al., 2011; Fuller and Gough, 1999; Holden et al., 2004). Peatland cover has declined extensively over the last 100 years and now covers an estimated 20% of Scotland's land area, however, 80% of the peatlands in the UK are degraded (Alonso et al., 2011; Scotland's environment, 2019). Degraded peatlands are characterised 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 the government to commit to the restoration and sustainable management of its peatlands (Helm et al., 2020; NatureScot, 2015). Efforts to restore degraded peatlands often focus on the restoration of the water table through blocking grips (drainage ditches) and restoration of peat-forming vegetation such as *Sphagnum* spp. (Osborne et al., 2021). Recently, the "rewilding" discourse, a loosely defined concept aiming to restore the wilderness and ecosystem services of the upland regions, and native woodlands restoration efforts have gained momentum (Deary and Warren, 2017; Martin et al., 2021; Robbins and Fraser, 2003). These efforts are, in part, associated with the acquisition of large estates by new types of landholders interested in alternative land uses and carbon sequestration (Dinnie et al., 2015). However, the restoration of woodlands is seen by some as jeopardising tourism opportunities, traditional livelihoods and the biodiversity unique to open upland landscapes (Barnaud et al., 2021).

Uplands have important cultural and recreational values, with different interest groups preferring distinct characteristics of the landscape such as increased woodland cover or the presence of certain species (Fitzgerald et al., 2021; Schmidt et al., 2017). Divergent aspirations for the uplands among stakeholders and wider society have led to heated debates around many aspects of uplands management (Dinnie et al., 2015; MacMillan and Leitch, 2008). This is the case of prescribed fires for red grouse management and woodlands restoration (Sotherton et al., 2017; Thompson et al., 2016).

Driven grouse shooting is a type of land use covering about 12% of Scotland, where land managers use predator and parasite control, as well as habitat management including prescribed fires, to favour red grouse for sport shooting interest (Matthews et al., 2020; Robertson et al., 2017; Werritty et al., 2019). Prescribed fires for game management are described by some as an environmentally destructive practice benefiting private estates and hunting interests, and by others as a necessary intervention to maintain contrasting habitats, manage healthy ecosystems and increase income in remote communities in areas of otherwise low productivity (Matthews et al., 2020; Werritty et al., 2019). Prescribed fires, usually burnt in small patches/narrow strips, create a mosaic of stands of heather of different ages, providing both high-quality feeding and nesting habitats to grouse and other birds and some herbivore species, but also prevent forest regeneration and negatively impact some animal species (Mustin et al., 2018; Newey et al., 2016; Robertson et al., 2017). 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 (Heinemeyer et al., 2023; Holland et al., 2022; Worrall et al., 2013). Prescribed fires reduce the fuel load available for burning in wildfires, but poor fire management can also lead to escaped fires and prevent the regeneration of woodland cover (Santana et al., 2016; Worrall et al., 2013). About 40% of the burning associated with game management occurs on carbon-rich peatlands and frequently within protected areas, raising concerns about potential impacts on biodiversity and carbon emissions (Douglas et al., 2015).

Woodland restoration is widely advocated as a means to tackle climate change, increase biodiversity, improve delivery of ecosystem services and increase ecosystem resilience (Griscom et al., 2017; IPBES, 2019) Yet, woodland restoration is also controversial with debates around social inclusion, displacement of traditional livelihoods, and potential adverse effects on biodiversity depending on its location (Di Sacco et al., 2021; Holl and Brancalion, 2020). The Scottish Government have committed to increase woodland cover from 18% to 21% of the Scottish land area by 2032 (Scottish government, 2018), with open habitats identified as areas most likely to support new woodland cover (Woodland Expansion Advisory Group, 2012). 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., 2020; Ražauskaitė et al., 2020; Smyth, 2023). Moreover, the growing woodlands are at risk of wildfires and tree mortality and there are some uncertainties about their final carbon sequestration potential. Increased woodland cover could also lead to the degradation of the habitat quality of moorland-dwelling species by increasing the proximity of many areas to forest edges and associated predation (Wilson et al., 2014).

Case study and research questions

All land use and land management practices benefit and disbenefit 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). To examine the trade-offs between some 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 and land use interest including large tracts managed for driven red grouse shooting (including through the use of prescribed fires (Matthews et al., 2020)), commercial forestry, upland grazing, tourism and increasingly also rewilding and woodland restoration schemes (CNPA, 2022). Moreover, the Cairngorms National Park Authority (CNPA) published their management objectives and quantitative goals for woodland restoration, along with sufficient methodological detail to allow us to recreate realistic scenarios.

The location and design of woodland restoration 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 Holl, 2020). This is especially true across the UK, where most of the land is privately owned and woodland restoration efforts are implemented by individual landholders, often with government grant aid. In consultation with selected stakeholders, we developed and assess the effects of five scenarios for the future land use of the CNP, including three options for woodland restorations and two options for the future locations of prescribed fires for game management.

We used the Native Woodlands models (Towers et al., 2000) and InVEST (Sharp et al., 2014) to explore three research questions:

- How these land use scenarios affect the habitat quality for a selection of species representing the interest of different stakeholder groups within the park?

- How 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?

The Native Woodlands models combine 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). It has been used for developing the Cairngorms National Park Forest Strategy 2018 (CNPA, 2018) and other questions regarding native woodlands restoration efforts in Scotland such as the potential for carbon sequestration (Fletcher et al., 2021). InVEST (Sharp et al., 2014) is an open-source software suite for modelling ecosystem services with spatially explicit outputs, allowing users to visualise areas that could be favoured or disadvantaged by different management scenarios (Sharp et al., 2014). InVEST has been used in diverse contexts for the landscape-level analysis of ecosystem services trade-offs such as habitat vulnerability assessment or carbon sequestration (Bagstad et al., 2013; Posner et al., 2016).

Methods

Scenarios of future land use in the Cairngorms

The five scenarios for the future woodland restoration efforts and restriction on the use of prescribed fires within the Cairngorms national park, are based on the Cairngorms National Park Forest Strategy 2018, the Partnership Program 2022. In February and March 2023, the research teams conducted semi-structured interviews with nine stakeholders in and around the Cairngorms National (including land managers and staff of governmental and non-governmental institutions involve into CNP management and/or associated research), to collect contextual information, inputs on the design the scenarios of future possible land-use and potential impact on biodiversity and ecosystem services.

Prescribed fires

By prescribed fires for game management (hereafter called prescribed fires), we include all fires that are intentionally lit to maintain habitat quality for game species, especially red grouse. At the time of this study there was little regulation of prescribed fires and burning was carried out under a voluntary "muirburn code" (NatureScot, 2021). We included in this definition prescribed fires that escape/extend beyond the intended area, as long as the intensity and severity of fires remain similar to usual prescribed fires. This definition of prescribed fires excludes fires that burn at higher intensity and/or severity than intended (and thus potentially damaging moorlands), prescribed fires to create fire breaks, used mainly for wildfire prevention, woodlands regeneration and other types of prescribed fires that are used less frequently in the park.

The current extent of prescribed fires was assessed using the dataset from McLeod and Newey, 2018, unpublished (see Matthews et al. 2020 for details) at a 1-kilometre resolution, 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. We used the Scotland Land Cover dataset from 2020 (Space Intelligence 2020) to retain only areas covered by peatlands, heather and grasslands, the land cover types that are commonly managed through prescribed fires for red grouse management. This resulted in circa 182 000 hectares of moorland within the CNP managed through 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 1km 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).

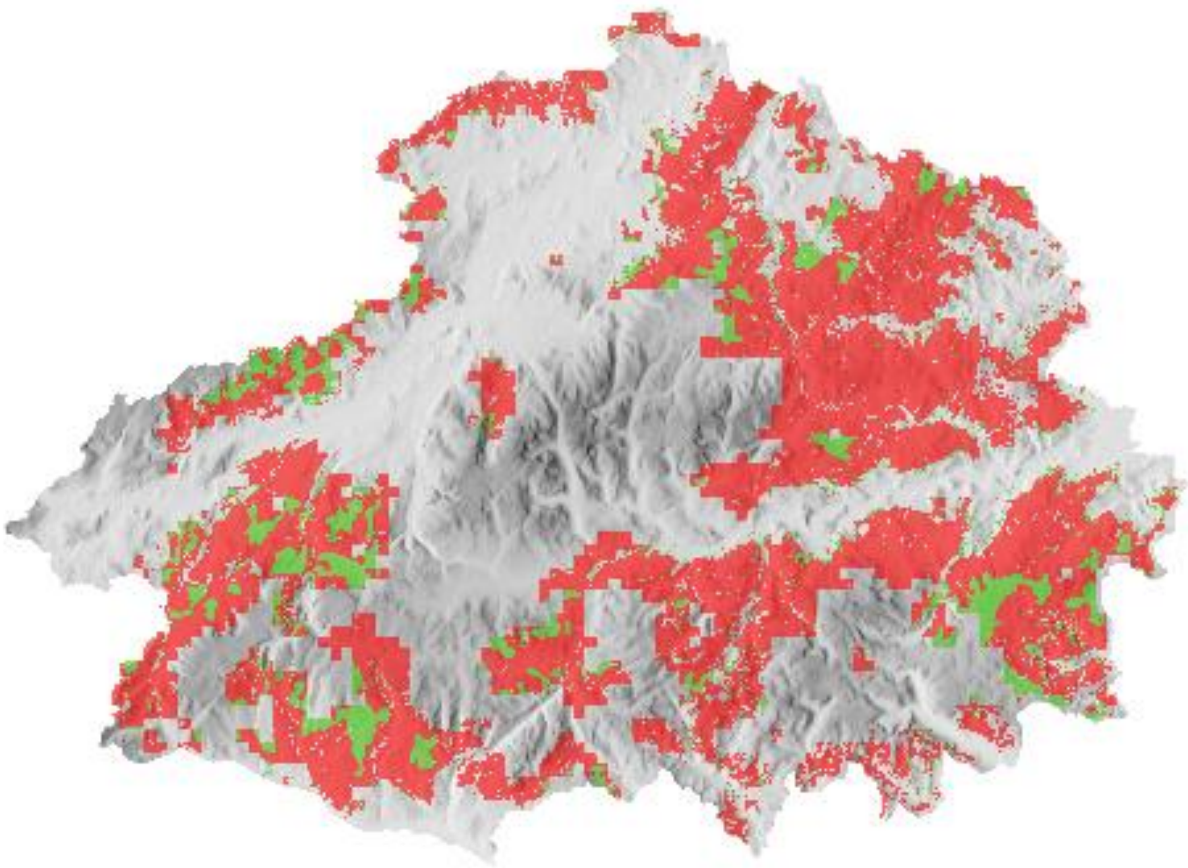

Figure 1. Management options for the use of prescribed fires. Areas in green represent areas currently burned where the use of prescribed fires could be restricted. Red areas show where burning can be undertaken and which would be unaffected by the management options explored.

We developed an alternative management option with increased restrictions on the use of prescribed fires, based on potential modifications to the muirburn code and fire risks assessment used by some landholders within the CNP. Forthcoming prescribed fire legislation will likely ban fires on peats deeper than 40 to 50 centimetres. Thus, we used the peatland soil map of the James Hutton Institute to constrain use of prescribed fires on deep peats[1]. We also added constraints on slopes steeper than 30 degrees and within 5 meters of water courses, constraints which already exist in the muirburn code. Finally, we added a constraint to prohibit burning within 50 meters 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. While prescribed fires are recognized as an important tool to favour the regeneration of native species in the CNP, regular fires for game management could hamper woodlands regeneration and are designed differently. Applying these constraints resulted in ~155 000 hectares of moorlands that could be managed through prescribed fires under possible future restrictions.

Woodland restoration

The Cairngorms Partnership Plan details a woodland restoration target of 35 000 hectares by 2045, including 10 000 hectares of natural regeneration without fences and mainly native woodlands. As most of the CNP is privately owned, we used insights from interviews during our scoping visit to determine where woodlands restoration efforts are the most likely to occur. We identified the following principles:

- Some landholders will restore woodlands in the most productive areas
- Some landholders consider restoring 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 woodlands restoration of the CNP Forest Strategy 2018 (CNPA, 2018). Peatlands soil map (The James Hutton Institute, 2020) and top organic soils content map (The James Hutton Institute, 2020) were used to identify areas with potential deep peats and carbon-rich soils, which would be avoided in the extensive woodlands restoration efforts on carbon-poor soils. The National scale land capability for forestry map (The James Hutton Institute, 1988) was used to identify the most productive forestry areas, with 24 915 hectares identified as being of land capability class F5 or below (used in priority) and an additional 68 311 hectares identified as of land capability class F6. As one of the management objectives of the CNPA is to maintain pastoralism, we also constrained woodlands restoration on the mesic grasslands category, containing pastures, identified by Scotland Land Cover dataset from 2020 (Space Intelligence 2020). Finally, we used the proximity-based scenario generator of

[1] *This dataset is the best source of data available on a large scale. However, land managers will probably need to manually survey their lands to identify these areas on their land, and our dataset might underestimate areas of deep peat soils covered by dry heather.*

InVEST to model the restoration of woodlands from existing stands. This resulted in the creation of three woodlands restoration options:

- **Limited woodlands restoration effort:** target of 17 500 hectares of woodlands restoration (half the objective of the Cairngorms Partnership Plan 2022 for 2045)
- **Extensive woodlands restoration efforts on productive areas:** 35 000 hectares of woodlands restored (objective of the Cairngorms Partnership Plan 2022 for 2045)
- **Extensive woodlands restoration efforts on carbon-poor soils:** 35 000 hectares 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.

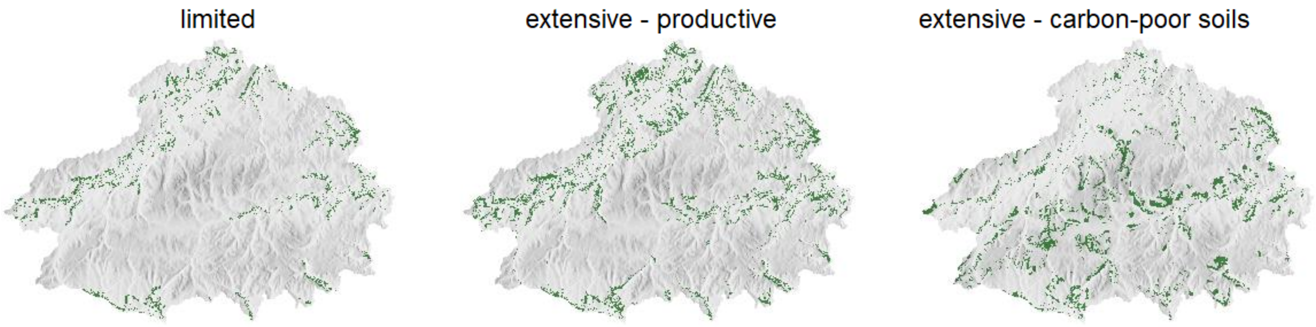

Figure 2. Three scenarios for woodlands restoration of the Cairngorms national park.

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

Name of the scenario	Woodland restoration	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 restoration	35 000 ha on most productive areas	No	11 084 ha (-6%)
Scenario 3: productive restoration and prescribed fires restrictions	35 000 ha on most productive areas	Yes	34 722 ha (-19%)
Scenario 4: carbon-sensitive restoration	35 000 ha on carbon-poor soils	No	12 210 ha (-7%)
Scenario 5: carbon-sensitive restoration and prescribed fires restrictions	35 000 ha on carbon-poor soils	Yes	38 219 ha (-21%)

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

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 restoration efforts and was used for the elaboration of the map of priority and sensitive areas for woodland restoration in the Cairngorms National Park Forest Strategy (CNAP, 2018).

Existing woodlands in the Cairngorms National Park are composed mainly of native species, even for commercial forestry with Scot pines plantations, and the CNPA objective is that >80% of woodland restoration 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 restoration scenarios. The proportions of NWM types restored in each scenario will also be used to calculate potential carbon sequestration, as potential above-ground biomass of NWM types ranges from 10 to 85 tC ha-1.

Habitat species modelling

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 specified 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)

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

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

We first created a list of species 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 restoration 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.

Literature review on habitat preferences

For each species, we conducted a rapid literature review using Google Scholar on their habitat preferences. The interviews during the scoping visit highlighted the importance of not only prescribed fires but also predation on the abundance of moorland species, since the cessation of predator control and increase in woodland cover are likely to increase predation pressure on remaining moorlands, closer to woodland edges in which predators can seek refuge. Thus, we complemented our initial screening by researching each taxa's name and the impact of prescribed fires and impact of predation. We examined results from the first 50 publications on Google Scholar, and potentially more if there were additional results from studies in Scotland or North England. We selected results from peer-reviewed publications that described habitat preferences of the selected species in Scotland or North England, as well as impacts of prescribed fires and woodland restoration. We excluded data originating only from a single site, except for studies looking at the impact of predation within Langholm moors, as detailed studies from this quasi-natural experiment advance our understanding of the impact of predation control on moorlands species, and for mountain hares as most studies in Scotland only investigated one site. The final corpus of publications included 13 references for the red grouse, 11 for the curlew, 11 for the meadow pipit, 9 for mountain hare and 14 for black grouse and have been organised in tables summarising the main information that could be used for modelling habitat quality (see annex 1).

Model calibration

Based on the tables summarising the results from the literature review, we created a sensitivity table with the habitat preferences of each species for 7 different categories of land use (see Table 3). Each of the habitats was categorised as either unsuitable (0), low quality (0.33), medium quality (0.66) or high quality (1). Regarding the importance of the proximity between large patches of moorlands and woodlands for black grouse habitat, we used a different classification of the land use including 9 categories considering large patches of moorlands and proximity from the edges of the woodlands.

Woodland restoration may have had a negative effect on open habitat species directly through the loss of preferred habitat and indirectly through increased predation from predators that favour woodland habitats (Douglas et al., 2020, 2014; Watson and Wilson, 2018). We used the extent of woodlands to model the impact of predation from species/individuals that dwell in woodland and forage on adjacent moorlands, a phenomenon frequently mentioned during interviews. Based on the literature we calibrated predation effects to decrease exponentially from the edges of the woodlands and stop at 1 km distance from existing woodlands (Douglas et al. 2013). However, the predation effect was parametrised so as not to induce changes of more than 0.3 on habitat quality, so we could distinguish the change in habitat quality resulting from a modification of predations or land cover change.

For each species, we ran habitat quality models for our baseline scenario and each of the five land user/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 (>30%, corresponding to a change of land cover affinity), modest degradation of habitat quality (<30%, corresponding to a change in threat), no change, modest improvement of habitat quality (<30%, corresponding to a change in threat), important improvement of habitat quality (>30%, corresponding to a change of land cover affinity).

Habitat	**Red grouse**	**Curlew**	**Meadow pipit**	**Mountain hare**
PF heathland	High	High	Low	High
PF peatland	High	Low	Low	Medium
Heathland	Medium	Medium	Medium	Medium
Peatland	Medium	Low	Medium	High
Grassland	Low	High	High	Medium
Regenerating woodlands/scrublands	Low	Low	Low	Low
Others	No	No	No	No

Table 3. Sensitivity table for red grouse, curlew, meadow pipi and mountain hare. Sensitivity table of black grouse is presented in annex 1. PF = prescribed fires.

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) utilising land use categories and correspondence tables assigning land uses to corresponding carbon pools (Annex 2). 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 restoration and long-term storage capacity. We developed a land use classification and associated corresponding carbon values using different sources:

- <u>Above-Ground Biomass (AGB) and dead biomass for heather and peatlands:</u> we extracted values from the biomass accumulation curves of Santana et al. (2016) for the Kerloch site, located in North-East Scotland close to the NE border of CNP. AGB and dead biomass estimation for a 20-year fire return interval (typical rotation length cited during interviews) were used for heather and peatland managed with prescribed fires, while asymptote values were used for heather and peatlands managed without fires.

- AGB for woodlands: for mature woodlands, we used the values given for each of the 41 native woodlands potentially restored in Fletcher et al., (2021), based on canopy cover and an average AGB of 85tC/ha. 1km cell already classified as woodland were assumed to be mature and have a biomass equivalent to 85 tC/ha, the baseline for a mature woodland with 80% canopy cover in Fletcher et al. (2021), except for areas classified as young woodlands that were assumed to have a biomass of 10 tC/ha (similarly to scrubby woodlands with a canopy cover of about 10%, such as scattered Juniper). Areas classified initially as young woodlands and areas targeted for reforestation were assumed to be on average 30 years old after 40 years, assuming a constant woodland restoration effort. Based on the simplistic assumptions of a linear biomass accumulation, we assumed that AGB for 30 year-old woodlands would be about 30% of the final value.

- Below-Ground Biomass (BGB) for woodlands: we multiply AGB by the coefficients obtained from Table 4.4 of the IPCC guidelines (2006). We used the dominant type of woodlands to identify the relevant coefficient for each land use class.

- Soil carbon for woodlands: we used the average given for Scotland by Vanguelova et al. (2013) for minerals, organo-mineral and organic soils for 0-100 cm depth, derived from measures in 69 woodland plots in Scotland. During the scoping interviews, several stakeholders expressed concerns about the impact of woodland restoration on soil carbon content, an issue increasingly discussed in the literature on woodland restoration (Fletcher et al., 2021; Friggens et al., 2020; Matthews et al., 2020; Ražauskaitė et al., 2020). There is no detailed study in Scotland considering the impact of woodland restoration on soil-carbon regarding soil types, woodland types and woodland restoration approach to calibrate our model. Thus, we considered a decrease of up to 50% of carbon content in organic soils and 20% in organo-minerals soils, corresponding to the higher value found in Friggens et al. (2020), and tested the impact of other values of decrease in soil organic content. In a site within the CNP, Ražauskaitė et al. (2020) showed that the decrease in carbon is especially strong after 30 to 40 years before rising again, thus we apply the reduction coefficient only for the 40 years estimation.

- Soil carbon for other land use: we used the average value given in the scoping study of soil organic carbon stocks (Lilly and Baggaley, 2020).

- AGB, BGB and dead biomass for other land use: we used the generic values provided by the IPCC guidelines (2006),

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.

Results

Types of woodlands restored

Limited woodland restoration (scenario 1) resulted in the increase of surface cover by 38 NVC types, extensive woodland restoration in productive areas (scenarios 2 and 3) resulted in the increase of surface cover by 40 NVC types, and extensive woodland restoration on carbon-poor soils (scenarios 4 and 5) resulted in the increase of surface cover by 42 NVC types. Limited woodland restoration was the only scenario not associated with restoration of 'scattered Juniper' (Sc2) and lowland 'mixed broadleaved woodland with bluebell/wild hyacinth/dog's mercury' (W10/W8). Extensive woodland restoration on carbon-poor soils (scenarios 4 and 5) was associated with the restoration 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).

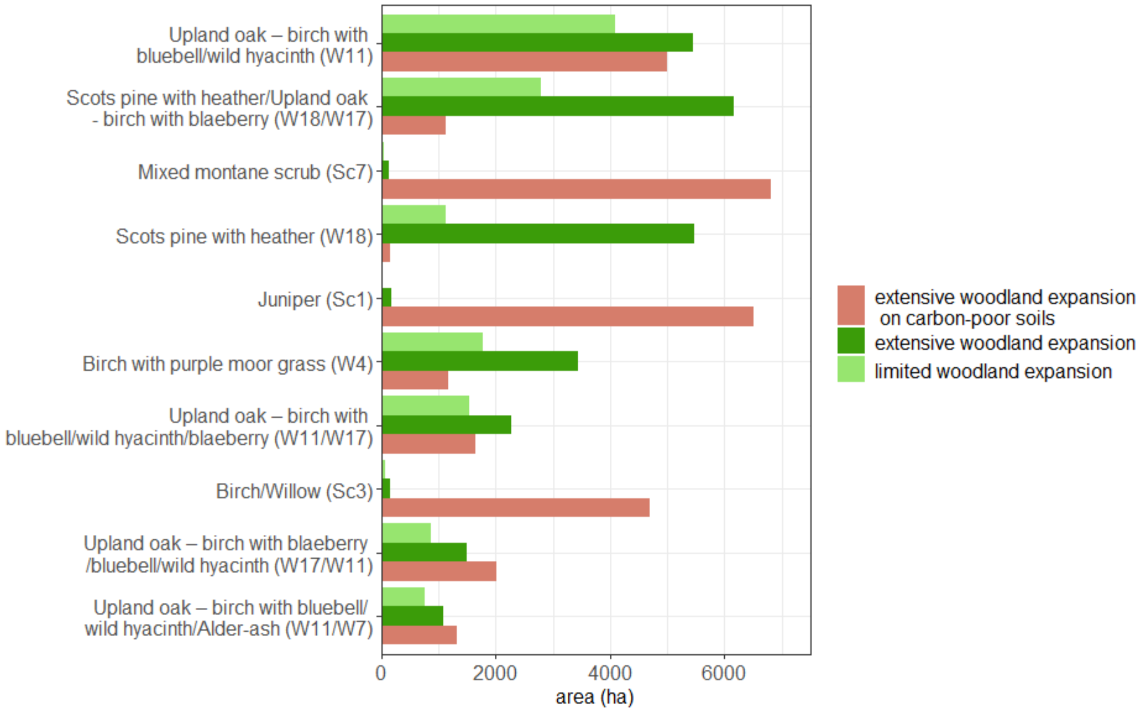

Figure 3. Area of the 10 woodland types (with corresponding National Vegetation Category-NVC) restored on larger areas according to the scenario with limited woodlands restoration (scenario 1), extensive woodland restoration (scenarios 2 and 3) and extensive woodland restoration on carbon-poor soils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

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

Habitat species modelling

The impacts of the different scenarios on habitat quality for red grouse, curlew and mountain hare were similar: limited woodland restoration scenario (scenario 1) led to a modest decline of habitat quality in about 12% of the CNP area and a stronger negative impact in about 2% of the CNP area. The scenarios with extensive woodland restoration (scenarios 2 to 5) led to moderate declines in habitat quality of around 20-25% of the CNP area, with stronger negative effects associated with woodland restoration on carbon-poor soils (scenarios 4 and 5, figure 4). 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, of up to 10% of the CNP for red grouse. Thus, the location of woodland restoration 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.

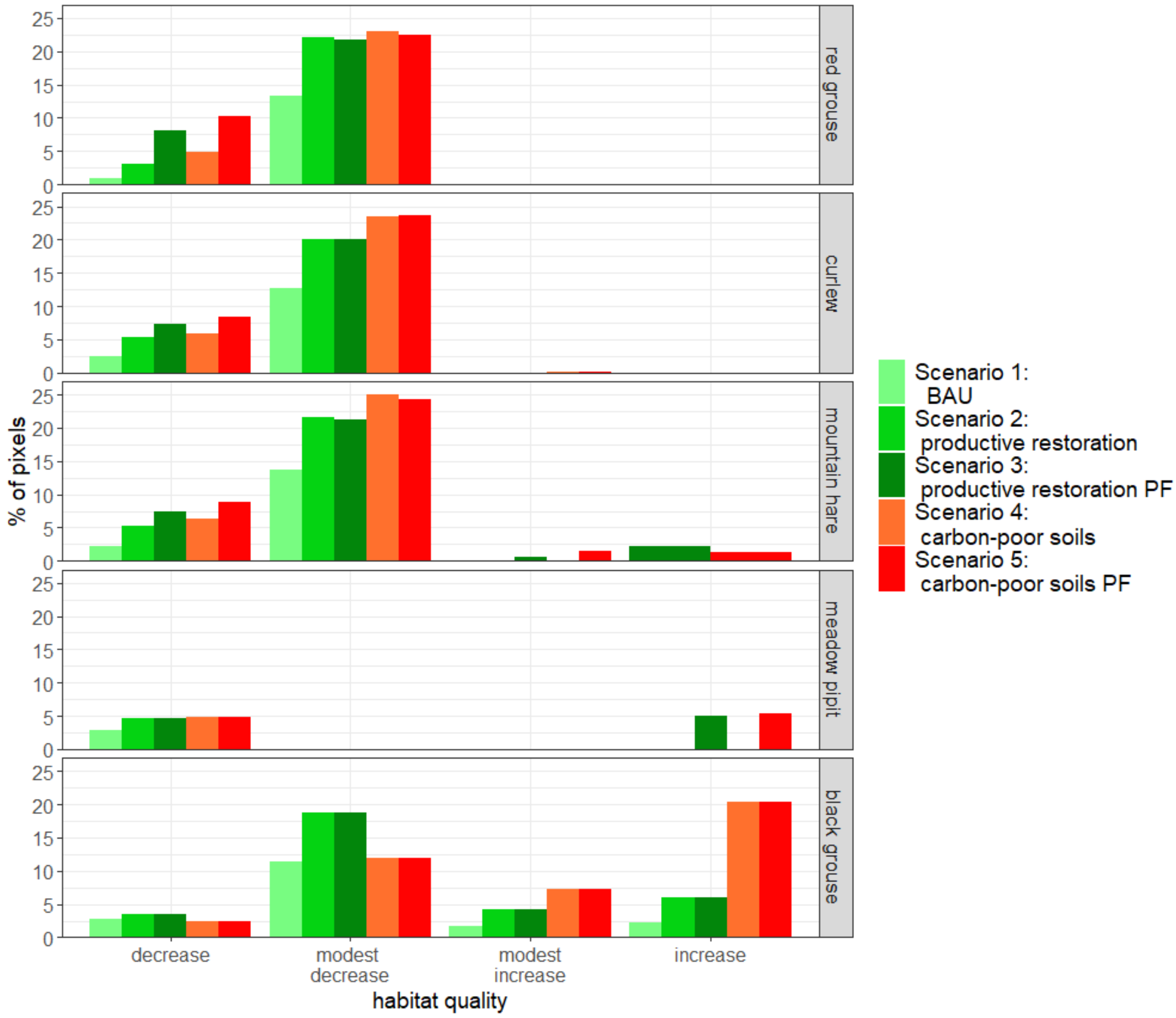

Figure 4. Proportions of the landscape that changed habitat quality for the 5 species assessed. Modest decrease and increase correspond to a change between 1% and 30% changes in habitat quality, while a decrease or increase corresponds to more important changes in habitat quality, only possible through changes in land use affinity (see Annex 3 for detailed spatial outputs).

For the meadow pipit, limited woodland restoration (scenario 1) leads to a decrease in habitat quality over an estimated 2.5% of the CNP area, with extensive woodland restoration (scenarios 2 to 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) lead to an increase in habitat quality in 5.5% of the CNP area (figure 4).

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

Carbon storage

Figure 5. Soil carbon loss and biomass carbon gain after 40 years (top) and after 100 years (bottom) for the different scenarios

Limited woodland restoration in productive areas (scenario 1) lead to a lower biomass accumulation than in other scenarios (figure 5). Extensive woodlands restoration in productive areas (scenarios 2 and 3) lead 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. Extensive woodlands restoration on carbon-poor soils (scenarios 4 and 5) led to the sequestration of about two-thirds of the biomass compared to woodlands restoration in productive areas but is already sequestering carbon after 40 years as there are no important soil carbon losses. Using different values of soil-carbon loss after woodlands restoration, we found that extensive woodland restoration 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 4). 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.

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

Table 4. Soil carbon loss after 40 years and total biomass in tons of carbon accumulated according to different soil carbon reduction coefficients after 40 years.

Scenarios	Number of NVC types restored and specific NVC	Impact habitat quality						Carbon storage (ktC)	
		change	*red grouse*	*curlew*	*mountain hare*	*meadow pipit*	*black grouse*	*40 years*	*100 years*
Scenario 1: BAU	38 - Birch, Oak and Scots Pine woodlands	*moderate*	-13%	-13%	-13%	0%	-10%	-550	1 627
		important	-1%	-2%	-2%	-3%	-1%		
Scenario 2: productive restoration	40 - Birch, Oak and Scots Pine woodlands	*moderate*	-22%	-20%	-22%	0%	-14%	-1 329	3 095
		important	-3%	-5%	-5%	-5%	2%		
Scenario 3: productive restoration and PF restrictions	40 - Birch, Oak and Scots Pine woodlands	*moderate*	-22%	-20%	-21%	0%	-14%	-1 217	3 208
		important	-8%	-7%	-5%	0%	2%		
Scenario 4: carbon-sensitive restoration	42 - Scrublands, Juniper and Willow	*moderate*	-23%	-24%	-25%	0%	-5%	359	2 330
		important	-4%	-6%	-6%	-5%	18%		
Scenario 5: carbon-sensitive restoration and PF restrictions	42 - Scrublands, Juniper and Willow	*moderate*	-23%	-24%	-23%	0%	-5%	478	2 449
		important	-10%	-8%	-7%	0%	18%		

Table 5. Resume of the impact of the different scenarios on woodland restoration, habitat quality of selected species and carbon storage. In the impact on habitat quality, the best overall scenario(s) for each species was highlighted in blue and the worst scenario(s) in red. For carbon storage, red indicates overall carbon losses and blue carbon sequestration, the darker the colour the most important gain/loss.

Discussion

Our analyses show that, based on current knowledge, each of the five scenarios assessed here is associated with benefits and disadvantages regarding their impact on biodiversity and carbon sequestration. 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 restoration) 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. 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 restoration and prescribed fires restrictions) shared many characteristics with the previous scenario but leads 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 restoration) 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 scrubs 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 restoration and prescribed fires 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. Scenarios 2 to 5, all sharing a similar target of restoring 35 000 hectares of woodlands, but with different locations in the landscape, have distinct outcomes on biodiversity and carbon sequestration. This highlights the need to support area-based woodland restoration pledges with guiding principles and safeguards to reach desired ecological and climatic impact, such as guidance on the priority areas to target (Brown, 2020).

Changes in land cover associated with the different scenarios are expected to have both direct impacts on moorland species through replacement of habitat types, and indirect impacts, through change 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 restoration will negatively impact ground-nesting birds, potentially across significant areas of the CNPA, especially when restoring woodlands on carbon-poor soils (scenarios 4 and 5). The cumulative impacts of both woodland restoration 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, it also affects the extent of land managed by gamekeepers and predation pressures on areas next to new forest edges.

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 vs prescribed fires remain unclear and the knowledge base is contested (Ashby and Heinemeyer, 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, and on very wet sites, reduce cranefly emergence, which has associated negative impacts on rare upland bird populations (Heinemeyer et al., 2023). However, cutting may be less effective at promoting long-term carbon sequestration as studies have highlighted the carbon accumulated through charcoal production during prescribed fires can effectively lock carbon up safely (Heinemeyer et al., 2018; Worrall et al., 2013). However, more evidence is required to understand the factors influencing charcoal production during prescribed fires, such as intensity and rate-of-spread of fires, to assess when it could be beneficial for carbon sequestration (Worrall et al., 2013).

Restoration of woodlands on carbon-poor soils is predicted to have benefits to the biodiversity specific to the Cairngorms and lead to increased cover of juniper, willow and other mountain scrub species specific to the uplands. This is expected to lead to an overall increase in the habitat quality for the black grouse. This woodland restoration scenario could also attract more mountain visitors, through an increase in native woodland cover, a favoured landscape attribute (Dick et al., 2022). Woodland restoration 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 increase proportions of scrub and open woodlands. Our model 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., 2020; 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, and of restoration techniques used on soil carbon to make accurate predictions on soil carbon response to woodland restoration. Interviews highlighted a preference for natural regeneration but most evidence of the loss of carbon 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. A further step in the analysis of the potential costs and benefits of the woodland restoration 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., 2019, 2014).

Woodland restoration on carbon-poor soils also presents trade-offs for landowners that government institutions could consider when promoting this strategy for safer 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 impact red grouse density and consequently rural incomes. Thirdly, it is associated with slower growing species and biomass accumulation that could restrain carbon credits accumulated. Together, these make the restoration of woodland on carbon-poor soils a less economically profitable option for landowners. It is important to understand the costs, benefits and constraints experienced by landholders who want to restore native woodlands and how this affects the design of their restoration initiatives. This would help to develop complementary support measures and payment for woodland restorations options that capture less carbon but yield other important co-benefits, like the recent emergence of payment schemes for woodland restoration.

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 (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 that could burn, potentially leading to important soil combustion and associated carbon emissions. There is evidence that prescribed fires for red grouse management could reduce fuel load and associated wildfire risks, there are still many uncertainties regarding the number of wildfires escaping from prescribed fires and the influence of the spatial configuration of prescribed fires on wildfire risks (Holland et al., 2022). It is important to consider not only the impact of prescribed fires on fire likelihood but also on fire size and intensity: lower fuel load connectivity could help to contain accidental fires and prevent them from damaging the soils and regrowing forest (Davies et al., 2019; Log et al., 2017). Another important role of prescribed fires for wildfire risks is the maintenance of teams of gamekeepers working with fires and owning fire-fighting equipment. Through regular use of fires, gamekeepers are accumulating extensive knowledge of fire behaviour and 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.

Conclusion

All the scenarios presented different trade-offs between the diversity of native woodland types restored, habitat quality for open-ground species, risks of soil carbon loss in the mid-term and sequestration of carbon in the long term. The difference in the outcomes of scenarios sharing a similar target of restoration 35 000 hectares of woodlands highlights the importance of the location of woodlands restoration efforts and complementary landscape management interventions, such as the use of prescribed fires, on future ecosystem services provided by the uplands.

While woodland restoration on productive soils results in higher carbon sequestration and lower declines in habitat for some open-ground species, it induces a decreased habitat quality of black grouse, important loss of carbon in the soils after 40 years and restoration of fewer scrublands, juniper and others rare types of vegetations. Woodlands restoration on carbon-poor soils, often located on steeper and more remote parts of the estates, could also increase the workload and cost of woodlands restoration. While the restoration of woodlands on carbon-poor soils presents some benefits for the conservation of the Scottish upland’s biodiversity and a safer pathway to capture carbon, it is likely to be the least favourable scenario for private landholders.

Our study shows that restrictions on prescribed fire use have a mixed impact on open-ground species, with a general decline in habitat quality for red grouse, curlew and mountain hare, and habitat improvement for meadows pipit, as well as a negligible impact on sequestration of carbon in biomass. The impact of prescribed fire restrictions is concentrated in parts of the park dominated by carbon-rich soil and will have a stronger economic impact on sporting estates in these areas, especially if they are unsuitable for mechanical mowing. There are still two critical aspects regarding the role of prescribed fires in the carbon sequestration in the uplands that need further investigation. First, the impact of prescribed fires on the production and storage of charcoal in the soils, which could lead to secure long-term storage of carbon. Second, the role of prescribed fires on the risks of severe wildfires, which is especially important in a landscape with significant woodland restoration efforts, an increasingly fire-prone climate and many visitors over summer.

Acknowledgement

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Annex 1: Literature review

A set of species were selected based on their (a) wide importance and interest across a range of different stakeholders, (b) their sensitivity to changing habitats in terms of woodland restoration and changing fire regimes, and (c) the availability of evidence from the wider literature to assign their habitat use preferences. An initial list was derived from a rapid review of the literature, including Werritty et al. (2019) and Holland et al. (2022) and a consultation of the CNP priority species list.

We include species that were anticipated to be both positively and negatively affected by the restriction on prescribed fires and woodland restoration. We also included species representing different ecological guilds and habitat preferences, and we considered the conservation status of the species in the UK, their presence on the priority species list of the CNP, and their value for sport and nature-based tourism, two essential economic activities within the CNP.

We only selected species for which we have peer-reviewed evidence available for habitat use preferences and the impact of prescribed fires and/or woodland restoration in Scotland and northern England, to assure the credibility of the results. We also selected species for which we could model appropriately current and future trends in the habitat quality module of InVEST. In the initial stage of the research, we considered including another two taxa: capercaillie, and arthropods. Stakeholders indicated that the conservation of capercaillies in the Cairngorms is strongly affected by woodland management, predator control and climate change. Thus, our modelling approach would not adequately predict the future distribution of capercaillie. While stakeholders express their interest to see the impact of prescribed fires on insects, especially butterflies, we excluded this taxon from the list as there is insufficient peer-reviewed evidence on habitat preferences and the impact of prescribed fires. We decided to include meadow pipits as they represent a major food source for many raptor species. The next sections include the main results from the literature review.

Red Grouse

The preferred habitat of red grouse is heathland (Brown and Stillman, 1993; Pearce-Higgins et al., 2006), followed by bogs and they are also present in flush, grass and bracken and young regenerating forest (Brown and Stillman, 1993; Hancock and Avery, 1998). Grassland is not suitable for nesting and could increase the risk of predation on broom (Campbell et al., 2002; Thirgood et al., 2002). Moorlands managed for red grouse have higher density due to vegetation management by prescribed fires (Newey et al., 2016; Picozzi, 1968; Robertson et al., 2017; Tharme et al., 2001) and predator control (Baines et al., 2008; Fletcher et al., 2010; Littlewood et al., 2019; Tharme et al., 2001). However, predation control efforts only have a limited effect due to predation by raptors (Fletcher et al., 2013).

Curlew

Curlews prefer grass, to a lesser extent heath and bracken and they are also accommodating of bog habitats (Brown and Stillman, 1993; Franks et al., 2017). Curlews are more abundant on grouse moors than other moors (Tharme et al., 2001), due to reduced predation (Baines et al., 2023, 2008; Douglas et al., 2014; Fletcher et al., 2010; Franks et al., 2017; Littlewood et al., 2019; Ludwig et al., 2019) and possibly heterogeneous vegetation structure created through prescribed fires (Douglas et al., 2017; Newey et al., 2016; Pearce-Higgins et al., 2006). Surrounding woodlands decrease curlew density, possibly due to predation (Douglas et al., 2014; Franks et al., 2017; Littlewood et al., 2019).

Meadow pipit

Meadow pipits prefer areas with grasslands, especially if mixed with heather and bogs, (Pearce-Higgins and Grant, 2006; Smith et al., 2001; Vanhinsberg and Chamberlain, 2001), and have a slight preference for bracken, heather and bogs (Brown and Stillman, 1993). Their numbers decrease in density in regenerating forests and they are negatively affected by nearby woodlands (Douglas et al., 2020; Hancock and Avery, 1998). They have lower densities on grouse moors, due to the negative impact of burning (Newey et al., 2016; Smith et al., 2001; Tharme et al., 2001). Their density is reduced by predation by raptors, which is limited on grouse moors (Amar et al., 2008; Baines et al., 2008). However, the impact of predators could have only a limited impact on adult population density (Fletcher et al., 2010).

Mountain hare

Mountain hares prefer restored or unburned blanket bogs, have a slight preference for managed heather, damaged/burned bogs and grasslands and mire, and they could accommodate young tree plantations (Bedson et al., 2022; Hewson, 1989; Hulbert et al., 1996; Hulbert and Iason, 1996; Rao et al., 2003a; Rao et al., 2003b). Mountain hares are present in higher densities on grouse moors, potentially due to the heterogeneous structure and presence of young heather for feeding and old heather to hide (Hesford et al., 2019; Hewson, 1989; Hewson and Hinge, 1990). Watson and Wilson (2018) highlighted a potential negative impact of culling for controlling tick-borne disease, but their study presents potential issues regarding the count methods for mountain hare and their culling requiring a license from NatureScot since 2021.

Black grouse

Black grouse show a preference for grassland and a slight preference for heather (Baines, 2008; Pearce-Higgins et al., 2016; Pearce-Higgins and Grant, 2006; Roos et al., 2016; Starling-Westerberg, 2001). They need large continuous patches of moorlands of at least 200 ha (Warren et al., 2019; White et al., 2015). They also thrive in forests which are less than 20 years old and need to have forest within 1.5 km of leks sites, but have low density in broadleaf woodland and commercial woodlands (Pearce-Higgins and Grant, 2006; Scridel et al., 2017; White et al., 2015, 2013). They usually penetrate only in the first 500 meters of the forest (Scridel et al., 2017). Black grouse are present in the same density, or lower extent, on grouse moors than others moors (Baines, 1996; Newey et al., 2016; Tharme et al., 2001), despite one study finding the opposite trend (Warren et al., 2019). This could be due to a limited impact of predation control measures, due to the importance of raptors, stoat and pine marten predation which are not well regulated on moors (Summers et al., 2004; Warren and Baines, 2002).

Land cover category	Habitat preference
Grassland within 1.5km of woodlands large block of moorland (>200ha)	High
Grassland within 1.5km of woodlands small block of moorland (>200ha)	Medium
New native woodlands within 500 meters of moorlands	High
Old woodlands within 500 meters of moorlands	Medium
Heather within 1.5km of woodlands large block of moorland (>200ha)	Medium
Heather within 1.5km of woodlands small block of moorland (>200ha)	Low
Bogs within 1.5km of woodlands large block of moorland (>200ha)	Medium
Bogs within 1.5km of woodlands large block of moorland (>200ha)	Low

Table S1. Sensitivity table for the different land use category used for the black grouse. Sensitivity table of other species are available in the methods.

Reclassification of the land use

The first task was to reclassify the dataset from Space Intelligence into 6 categories relevant to the information contained in the literature review:

- Bogs and peatlands (code 2+3+4)
- Grasslands (code 5+6+7+8)
- Heathlands (code 12)
- Regenerating woodlands/Scrublands (code 9+10+11+13+17)
- Mature forest (code 14+15+16)
- Other (code 1+18+19+20+21+23)

We used the datasets on prescribed fires to identify areas managed for red grouse shooting and created 2 new sub-categories for heather moorland and peatland managed with prescribed fires. We used the 5 scenarios to create future land use maps of the Cairngorms: areas targeted for woodlands restoration efforts were identified as regenerating woodlands/scrublands, while regenerating forest from baseline scenario (code 17) were reclassed into mature forest, as the canopy should be close by 2040 (when the expected woodlands restoration objectives are met).

For black grouse, we didn't examine areas managed for red grouse as it seems to have only a limited impact on adult population density. Regarding the habitat requirement of the black grouse, we created new subcategories for grassland, heathlands and bogs which were within 1.5 km of forest edges, as well as another category for blocks of moorlands (grasslands+heather+bogs) that were bigger or smaller than 200 hectares. We also identified woodlands that were within 500 meters of moorlands.

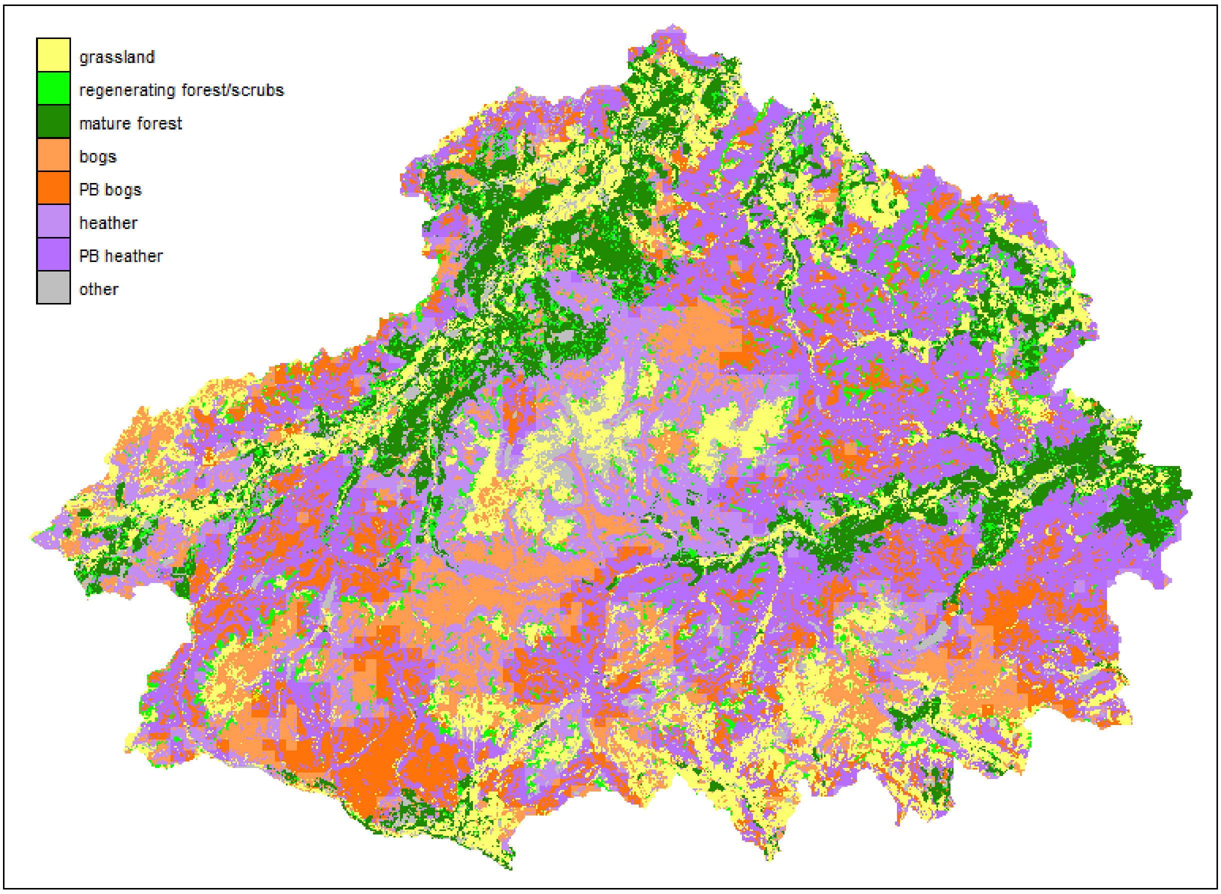

Figure S1. Map of the baseline scenario following reclassification. PB indicate the areas of bogs or heather managed through prescribed burnings.

Annex 2: Carbon table

40 years				
Land use categories	*Above-ground biomass*	*Below-ground biomass*	*Dead biomass*	*Soil*
scrubs mineral soils	10	5	1	151
scrub minero-organic soils	10	5	1	290
scrub organic soils	10	5	1	270
broadleaf mineral soils	26	12	5	151
broadleaf minero-organic soils	26	12	5	290
broadleaf organic soils	26	12	5	270
evergreen mineral soils	26	12	5	151
evergreen minero-organic soils	26	12	5	290
evergreen organic soils	26	12	5	270
other	0	0	0	0
bog	8	1	7	528
grassland	5	1	0	185
heather	8	1	7	290
bog prescribed fires	5	1	5	528
heather prescribed fires	5	1	5	290
bog mineral soils prescribed fires	8	1	7	151
heather mineral soils	8	1	7	151
bog mineral soils prescribed fires	5	1	5	151
heather mineral soils prescribed fires	5	1	5	151

100 years				
Land use categories	*Above-ground biomass*	*Below-ground biomass*	*Dead biomass*	*Soil*
scrubs mineral soils	10	5	1	151
scrub minero-organic soils	10	5	1	290
scrub organic soils	10	5	1	270
broadleaf mineral soils	85	39	5	151
broadleaf minero-organic soils	85	39	5	362
broadleaf organic soils	85	39	5	539
evergreen mineral soils	85	39	5	151
evergreen minero-organic soils	85	39	5	362
evergreen organic soils	85	39	5	539
other	0	0	0	0
bog	8	1	7	528
grassland	5	1	0	185
heather	8	1	7	290
bog prescribed fires	5	1	5	528
heather prescribed fires	5	1	5	290
bog mineral soils prescribed fires	8	1	7	151
heather mineral soils	8	1	7	151
bog mineral soils prescribed fires	5	1	5	151
heather mineral soils prescribed fires	5	1	5	151

Annex 3: Outputs from habitat quality model

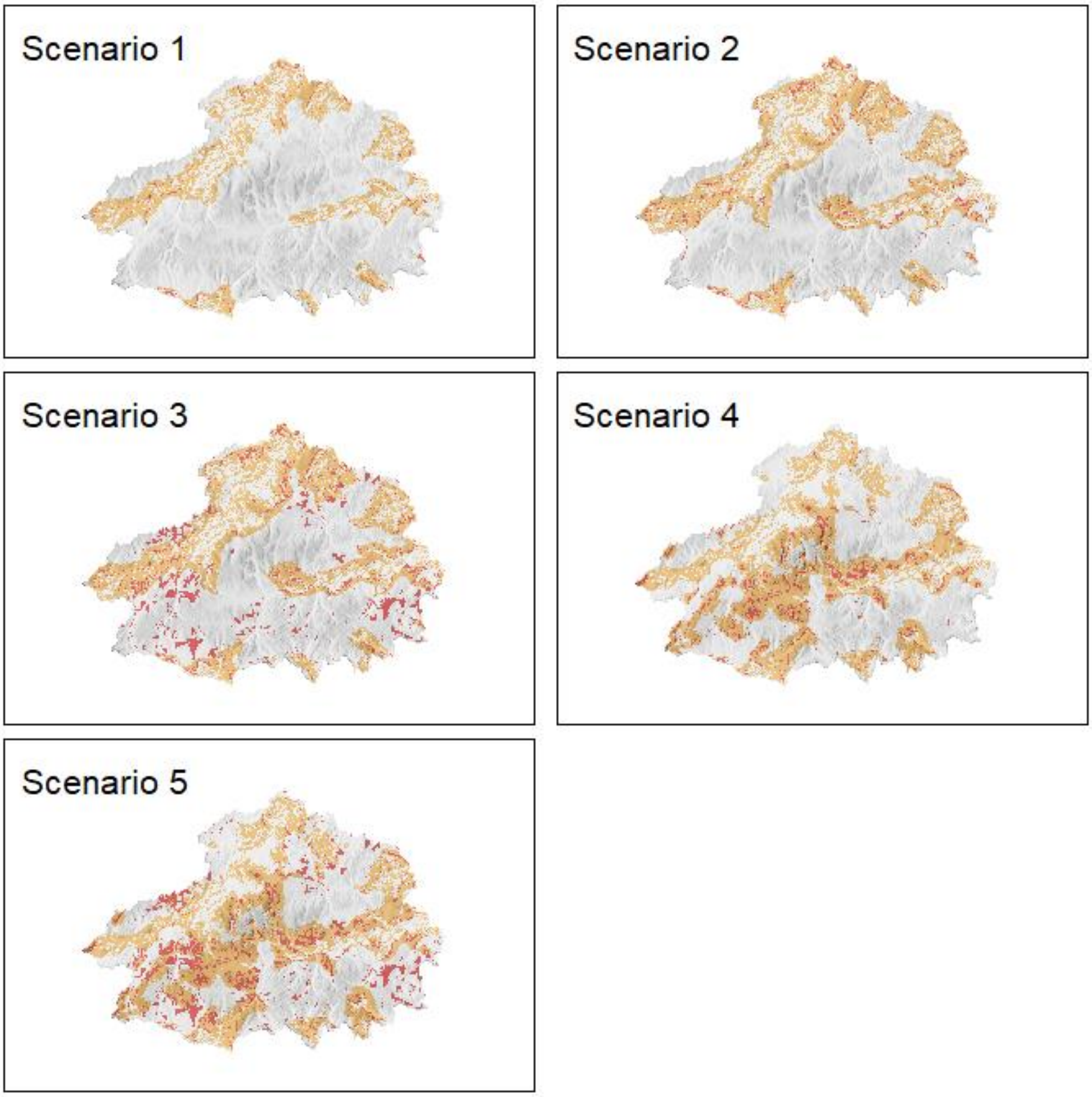

Fig S2. Change in habitat quality for red grouse. Dark red corresponds to a decrease in habitat quality, orange to a modest decrease in habitat quality, light green to a modest increase in habitat quality and dark green to an increase in habitat quality. Scenario 1: BAU, Scenario 2: productive restoration, Scenario 3: productive restoration and prescribed fires restrictions, Scenario 4: carbon-sensitive restoration, Scenario 5: carbon-sensitive restoration and prescribed fires restrictions

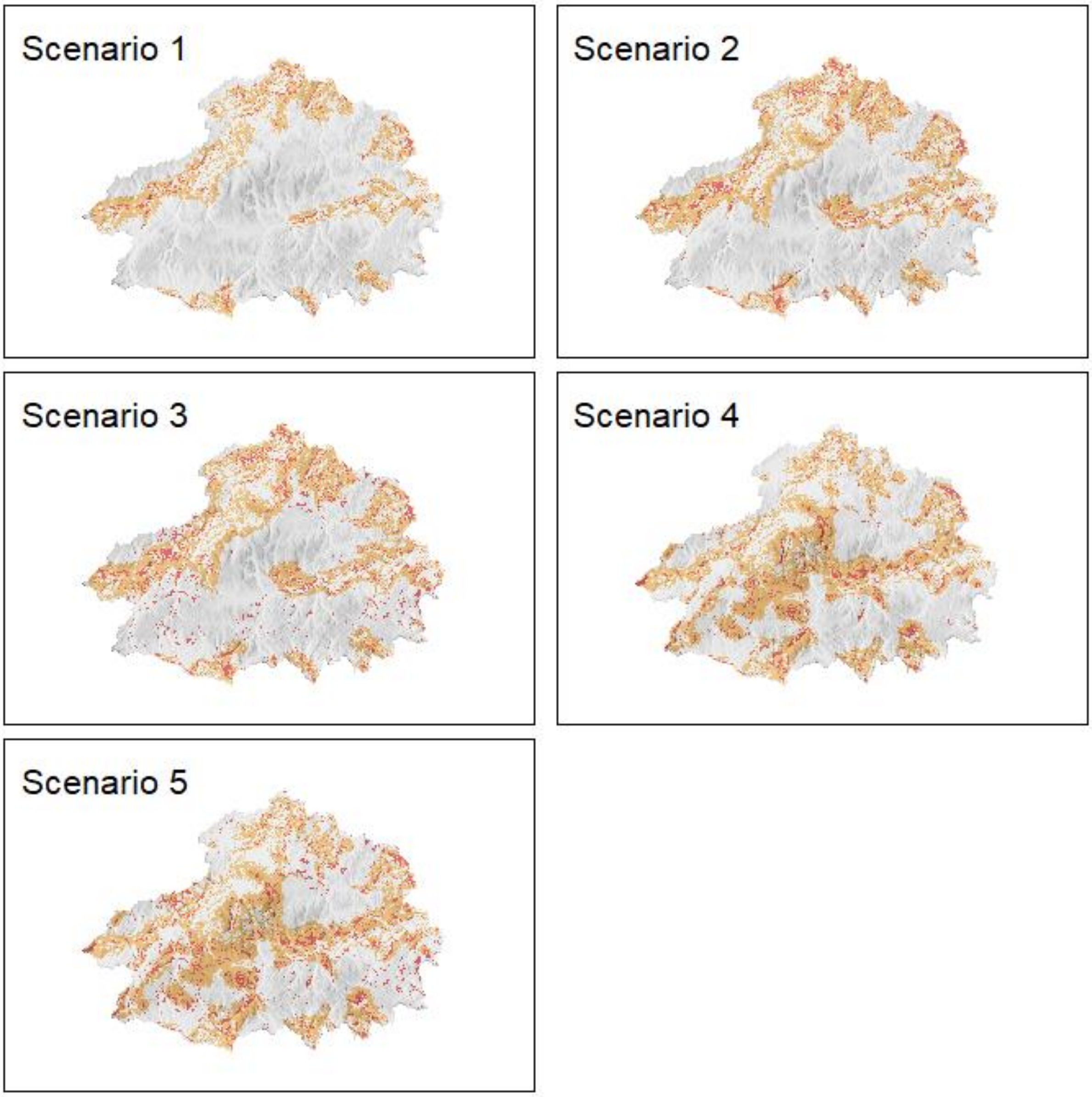

Fig S3. Change in habitat quality for curlew. Dark red corresponds to a decrease in habitat quality, orange to a modest decrease in habitat quality, light green to a modest increase in habitat quality and dark green to an increase in habitat quality. Scenario 1: BAU, Scenario 2: productive restoration, Scenario 3: productive restoration and prescribed fires restrictions, Scenario 4: carbon-sensitive restoration, Scenario 5: carbon-sensitive restoration and prescribed fires restrictions

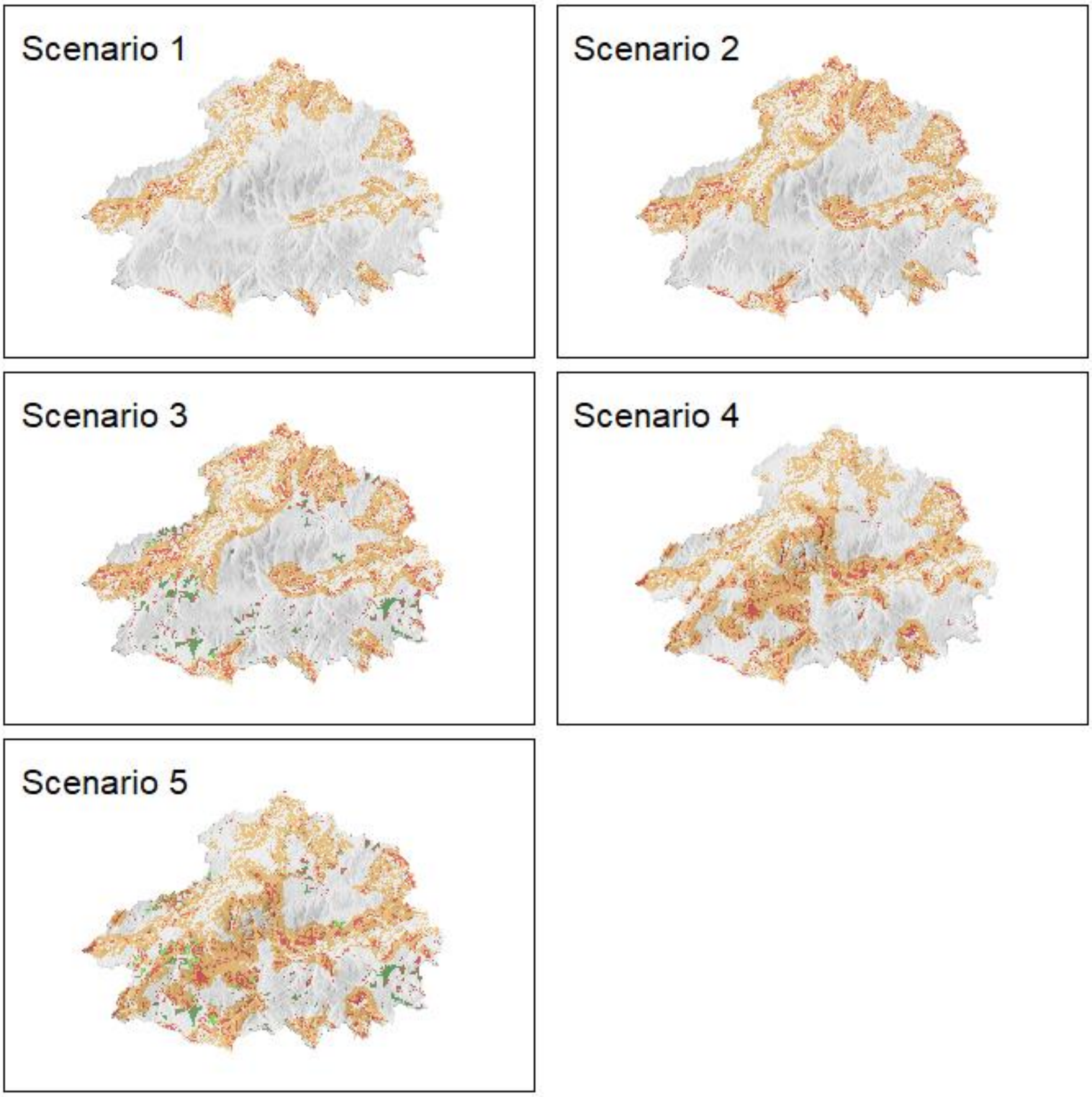

Fig S4. Change in habitat quality for mountain hare. Dark red corresponds to a decrease in habitat quality, orange to a modest decrease in habitat quality, light green to a modest increase in habitat quality and dark green to an increase in habitat quality. Scenario 1: BAU, Scenario 2: productive restoration, Scenario 3: productive restoration and prescribed fires restrictions, Scenario 4: carbon-sensitive restoration, Scenario 5: carbon-sensitive restoration and prescribed fires restrictions

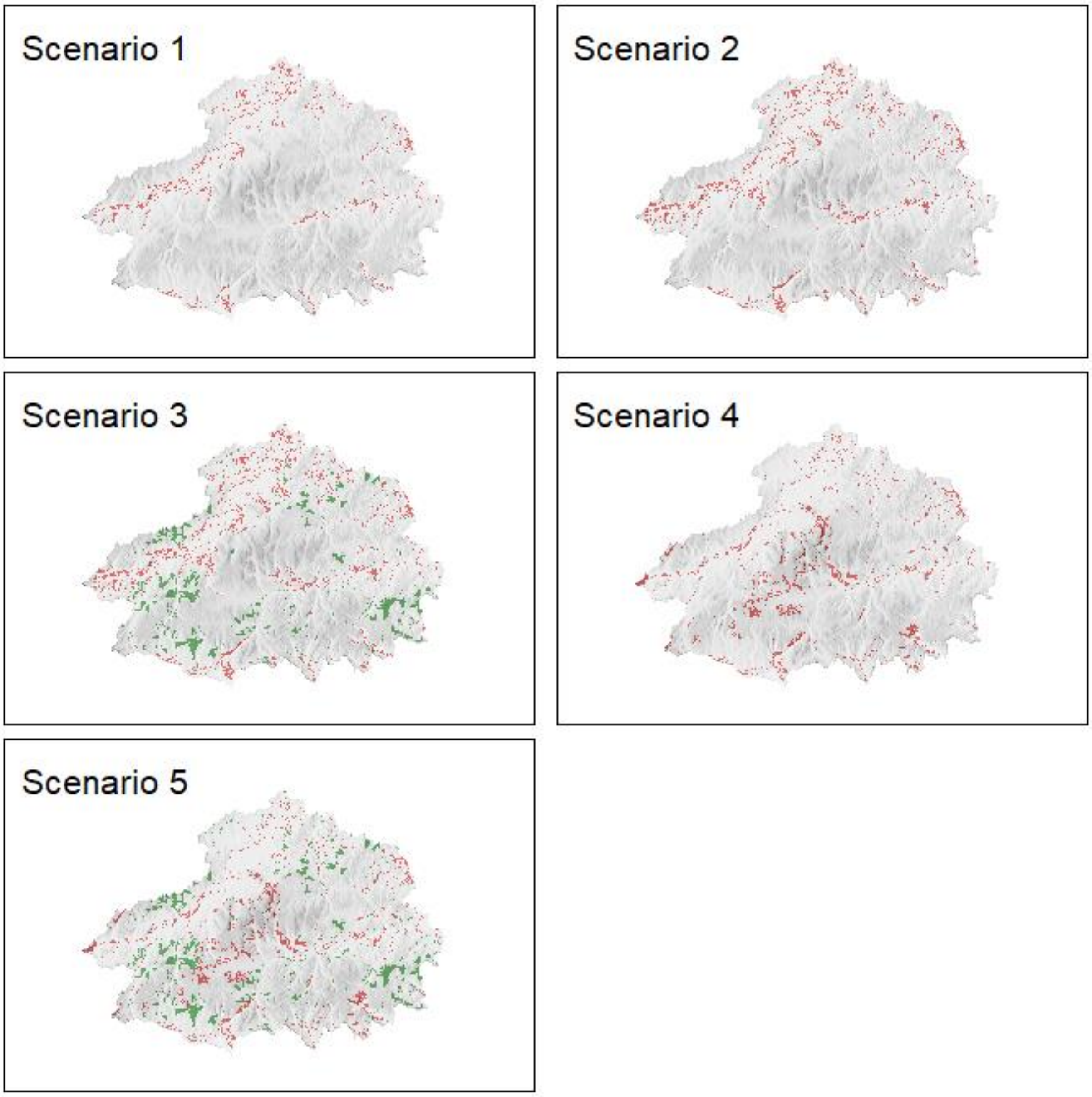

Fig S5. Change in habitat quality for meadow pipit. Dark red corresponds to a decrease in habitat quality, orange to a modest decrease in habitat quality, light green to a modest increase in habitat quality and dark green to an increase in habitat quality. Scenario 1: BAU, Scenario 2: productive restoration, Scenario 3: productive restoration and prescribed fires restrictions, Scenario 4: carbon-sensitive restoration, Scenario 5: carbon-sensitive restoration and prescribed fires restrictions

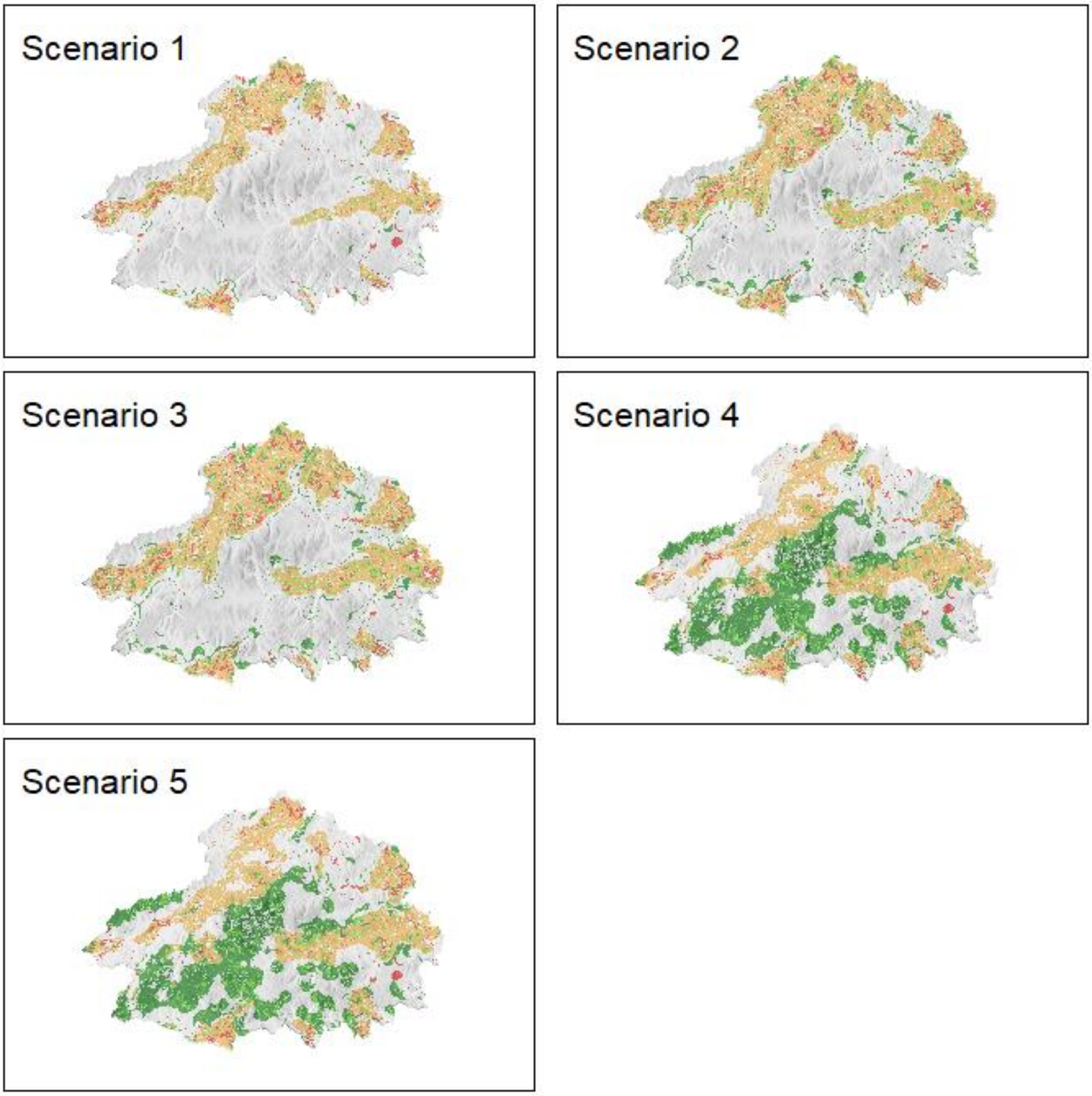

Fig S6. Change in habitat quality for black grouse. Dark red corresponds to a decrease in habitat quality, orange to a modest decrease in habitat quality, light green to a modest increase in habitat quality and dark green to an increase in habitat quality. Scenario 1: BAU, Scenario 2: productive restoration, Scenario 3: productive restoration and prescribed fires restrictions, Scenario 4: carbon-sensitive restoration, Scenario 5: carbon-sensitive restoration and prescribed fires restrictions

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