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A simulation-based approach to assess forest policy options under biotic and abiotic climate change impacts: A case study on Scotland's National Forest Estate☆

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ABSTRACT

The future provision of forest goods and ecosystem services is dependent, among other factors, on climate change impacts, forest management, and response to forest policies. To assess policy implementation targets for Scotland's National Forest Estate under climate change, we simulated forest growth through the 21st century - with and without the abiotic impacts of climate change, and with and without the biotic impacts of an important fungal disease. Eight different forest management trajectories were simulated under a climate projection, to assess the future provision of forest ecosystem goods and services. Climate change was represented by the IPCC RCP 4.5 projection, and the biotic impact of Dothistroma needle blight was predicted using a new vulnerability matrix. Indicators of three important goods and services: timber production, standing biomass, and biodiversity were measured in the simulation of forest growth and reported at decadal intervals using dynamically linked forest models. We found that both a broadleaved species trajectory and a Forest Enterprise Scotland selected species trajectory would improve standing biomass and biodiversity, but slightly reduce timber volume. Dothistroma needle blight could reduce standing biomass (by up to 3 t ha^{-1}) and timber volume (by up to 5 m^3 ha^{-1}), but the predicted impact is dependent on the type of forest management trajectory. Our findings show opportunities for diversifying forest management and tree species – and at the same time supporting forest policy to improve forest resilience under uncertain climate change and Dothistroma impacts. The forest simulation has been used to demonstrate and evaluate national strategic delivery of multi-purpose forest benefits in Scotland, and how species and management might be targeted regionally in Forest Districts, to maintain achievable national targets for timber production, carbon sequestration, and biodiversity under climate change.

1. Introduction

The sustainable multi-purpose management of forests in Europe involves the assessment of complex inter-related land management issues covering various aspects of environmental and biodiversity policy, as summarised in the EU Forestry Strategy (European Commission, 2013). Forests provide multiple benefits to the public. These benefits relate to the concept of ecosystem goods and services (Millennium Ecosystem Assessment, 2005) that quantify the goods or benefits people derive from functioning ecosystems. Forests have attracted much research and policy interest on the subject of ecosystem goods and services (e.g. Schroter et al., 2005; Bateman et al., 2013; Quine et al., 2011). Both managed and unmanaged forests provide a broad range of goods and services (Quine et al., 2011) compared to more intensive land management (e.g. intensive agriculture).

Both the UK Government (UK National Ecosystem Assessment, 2011 & 2014) and Scottish Government (Forestry Commission Scotland, 2006) have stated the need for a more sustainable ecosystems approach to land management. This requires policy implementation to guide land use and land management decisions with the aim of providing multiple ecosystem goods and services now and into the future. Forest management in Scotland has for several decades considered multi-purpose benefits

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(UK Forestry Standard, 2011) and this has led to a more targeted approach in the delivery of goods and services at different geographic scales (Forestry Commission Scotland, 2013b) through a 'strategic delivery' approach of ecosystem services. Testing strategic delivery requires an assessment of the current and future state of woodlands to understand how management choices (reflecting direction and ownership objectives) in different areas will influence forest goods and ecosystem service provision (Ray et al., 2015). Scotland's publicly owned National Forest Estate (NFE) is therefore a good case study for assessing the implications of policy implementation under climate change.

Forestry Commission Scotland's Climate Change Programme (2013a) outlines how the forest sector can become more resilient to the impacts of climate change. Approaches to adaptation in the UK and Scotland include: changes to species choice, increasing the area of native woodland, selecting more southerly provenances, conversion to continuous cover forestry and increasing forest tree species diversity (Hemery et al., 2015). Changes in forest management will also impact ecosystem goods and service delivery, including timber production, the ability to support biodiversity, and carbon sequestration (Ray et al., 2015; Beauchamp et al., 2016). As identified in Scotland's Adaptation Programme (Scottish Government, 2014) and in the 'Low Carbon Scotland – Second Report on Proposals and Policies' (Scottish Government, 2013), adaptation and mitigation strategies must be considered together. This will ensure that current mitigation efforts are well adapted to future climates, and that adaptation actions support mitigation measures; Scotland's forests must be resilient in order to deliver emissions abatement targets.

Scotland's forest industry has emerged rapidly over the course of a century (1900-to date), with a change in forest land cover from approximately 5% to 17% over the period. Its rapid emergence occurred in response to phases of forest policy (Harmer et al., 2015). Scotland's forest industry has been built on a few robust conifer species, e.g. Sitka spruce (*Picea sitchensis*), Scots pine (*Pinus sylvestris*), larch (*Larix decidua* and *Larix kaempferi*), and Norway spruce (*Picea abies*) (Quine and Ray, 2010). These were trialled on different sites and monitored with permanent sample plots, where they showed good growth on a range of often challenging site types.

An emerging issue of increasing concern to forests (Boyd et al., 2013), and forest managers (Petr et al., 2014), is the increased risk and impact of pests and pathogens. This is partly due to an increase in global trade (Pautasso et al., 2012; Roy et al., 2014) and partly climate change (Jung, 2009; Tubby and Webber, 2010) which together have increased the spread and the risk of colonisation of pests and pathogens. The dynamics of many host-pathogen interactions are influenced by climate, thus climate change has the potential to exacerbate or alleviate both the chances of establishment of new pathogens and the emergence of pre-existing ones (Sturrock et al., 2011; Pautasso et al., 2012). Foliar fungal pathogens are particularly sensitive to temperature and water availability for sporulation, spread and infection and are likely to be effective indicators of environmental change (Harvell et al., 2002; Garrett et al., 2016). Dothistroma needle blight (DNB) affects at least 109 Pinaceae taxa, primarily *Pinus* spp., and is considered one of the most damaging diseases of pines worldwide, causing premature defoliation, a reduction in yield, and in extreme cases tree death (Drenkhan et al., 2016). In Britain, DNB is caused by *Dothistroma septosporum* and has been particularly serious on Corsican pine (*Pinus nigra* ssp. *laricio*), but also on lodgepole pine (*Pinus contorta* var. *latifolia*) and Scots pine (Brown and Webber, 2008). It is thought that increasing precipitation in the spring and summer months along with warmer temperatures leads to a greater risk of infection (Woods et al., 2016).

Until recently, Scots pine, lodgepole pine and Corsican pine were being selected as suitable species for forest stands in the projected future Scottish climate (Ray, 2008). It is therefore of interest to forest policy and forest practice (Lindner et al., 2010) to consider pest and pathogen impacts in the context of changing climatic conditions and the maintenance of resilient forests into the future. This study is concerned with the potential impacts of climate change impacts, including DNB, on the delivery of forest policies and forest management.

The objective of this study is to demonstrate whether public sector forestry in Scotland can make a contribution to greenhouse gas abatement and timber production while maintaining high biodiversity and other important benefits. The options are simulated by forest models under the uncertainty of climate change and a forest pathogen. Possible adjustments to forest management systems and to tree species choice are tested to ascertain the continued provision of these forest ecosystem goods and services.

2. Materials and methods

2.1. Study sites

In this study we focus on a forest growth and management simulation of the National Forest Estate (NFE) in Scotland and four forest districts in the north (North Highland District), south (Dumfries & Borders District), east (Moray & Aberdeen District) and west (Lochaber District) – (see Fig. S2 in online Supplementary material 1). These districts present different site conditions leading to variations in species composition, and different future climate change projections. Forestry Commission Scotland's stated policy of strategic delivery of benefits, plays on the strengths of different districts. For example, Lochaber and Dumfries & Borders are heavily focused on timber production, whilst Lochaber and Moray and Aberdeen have important recreation, biodiversity and community management interests. The current species composition of Scotland's forests (public and private sector combined), the NFE, and the four Districts are shown in Table 1 and Fig. S1 (online Supplementary material 1). The NFE represent the public forest managed by the Forestry Commission covering 471,000 ha, approximately 33% of the forested area (Forestry Commission, 2016), and it is comprised of a broad species selection with a variety of management systems. The conifer species composition of the NFE and private sector are similar, but the NFE has a smaller area of broadleaf forest than the private sector.

2.2. Input data

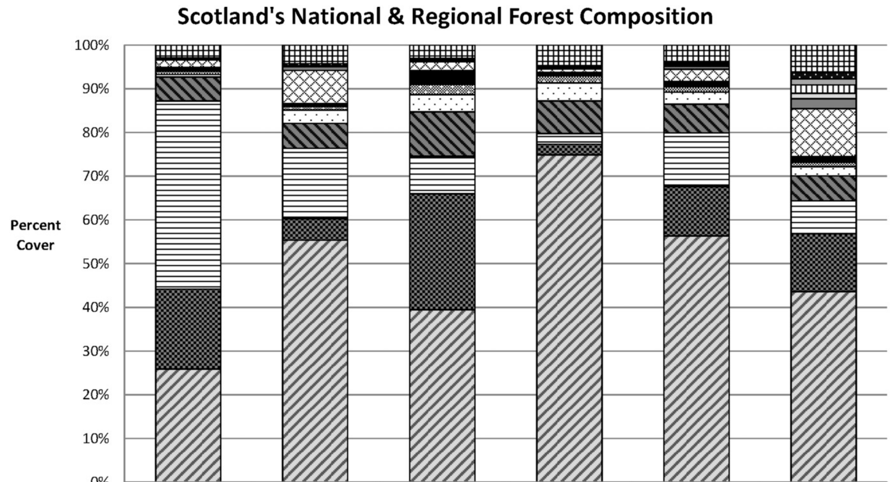
2.2.1. Spatial Forest inventory and soil data

The dynamically coupled models require spatially explicit forest inventory data showing the tree species, the age of the stand, and the current forest management system. This was possible using the Forestry Commission Sub-Compartment Database (SCDB) of the NFE. We used a digital soil map, based on a composite of the Soil Survey of Scotland soil associations mapped at a scale of 1:250,000 (Soil Survey of Scotland, 1981), combined with higher resolution soil type data for areas of public forest where a digital soil layer mapped at a scale of 1:10,000 was available. These soil data provided information about the soil quality in terms of soil moisture regime (SMR – soil wetness) and soil nutrient regime (SNR – soil fertility), where SMR and SNR are two of the six site quality factors used in the forest classification model, Ecological Site Classification (Pyatt et al., 2001).

2.2.2. Spatial climate data

To represent the future climate change impact on Scottish forests, we used the Representative Concentration Pathways (RCP 4.5) climate change projections of the IPCC Fifth Assessment Report (IPCC, 2014). The RCP 4.5 was matched to one single variant of the UK 11-member RCM Regional Climate Model (3Q14) using a Pearson correlation method (details in online Supplementary material 1). The projected 3Q14 variant provided daily simulated values of temperature, precipitation and potential evapotranspiration through the 21st Century. These were used to calculate monthly values for two of the the four climatic variables used in the forest model Ecological Site Classification, these were: Accumulated Temperature (AT – day degrees above 5 °C) and Climatic Moisture Deficit (MD – accumulated excess of potential evapotranspiration over precipitation in mm units).

Table 1
Current species composition of the four Forest Districts using data from the Forestry Commission Sub-Compartment Database; Scotland's National Forest Estate (NFE) "Public Sector", and Scotland's combined public and private forest "Scotland"(Forestry Commission, 2016). Values in the table are in hectares.



	North Highland	Lochaber	Moray & Aberdeen	Dumfries & Borders	Public Sector	Scotland
Other Broadleaves	1083.61	927.18	1309.18	1770.42	15000	73000
Alder species	37.98	91.69	58.74	21.16	1000	17000
Ash	1.54	46.32	25.54	29.17	1000	16000
Sycamore	116.28	0.83	33.56	53.58	1000	22000
Beech	8.9	14.82	132.77	54.3	1000	15000
Oak species	33.03	192.44	104.23	156.53	3000	26000
Birch species	637	1659	874.7	296.82	11000	128000
Other Conifers	314.68	157.16	1381.59	298.65	5000	14000
Douglas Fir	286.33	167.15	1044.87	613.11	5000	12000
Norway Spruce	235.49	684.24	1742.22	1608.54	11000	25000
Larches	2043.55	1249.88	4431.02	2823.57	26000	66000
Lodgepole Pine	16199.61	3544.64	3783.8	960.75	49000	88000
Scots Pine	6884.81	1080.73	11621.08	926.06	45000	154000
Sitka Spruce	9756.73	12187.81	17345.07	28688.19	225000	507000

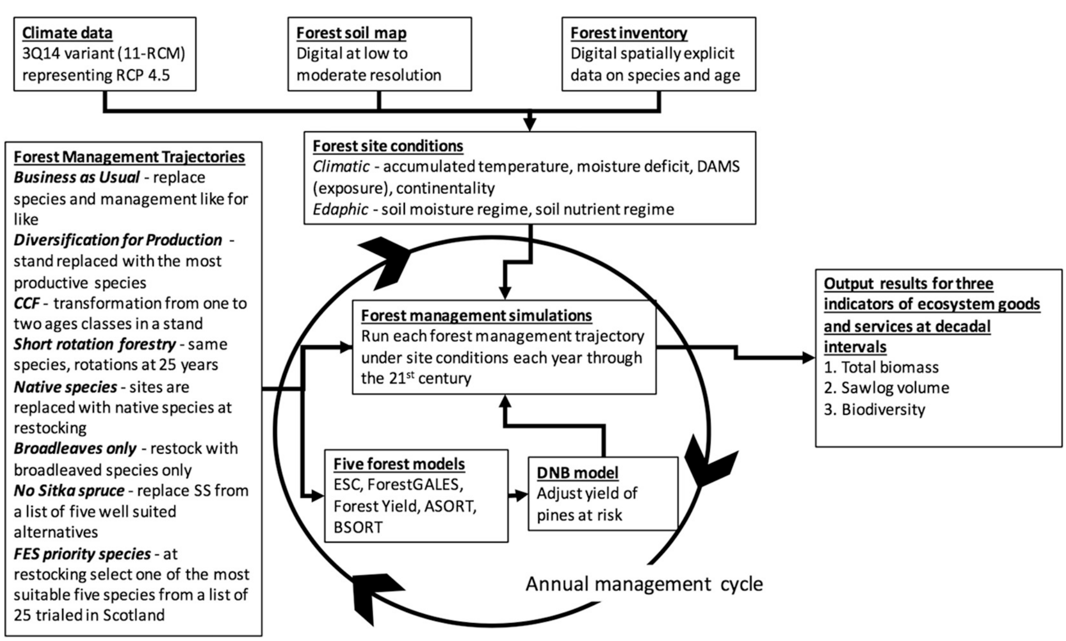


Fig. 1. Schematic diagram of the simulation method of forest management trajectory scenarios on the National Forest Estate of Scotland.

Table 2
Description of forest management trajectories with assumptions and constraints according rules dictated by site characteristics.

Forest management trajectory (FMT)	FMT description, assumptions and constraints Note: in all FMT types - Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) are retained to provide red squirrel habitat.
Business as usual (BAU)	No change in species, stands are replanted with the current species. Thinning in sub-compartments where DAMS < 16. For no thin sub-compartments replace existing species at year 50. For thinning sub-compartments start at year 20 and then every 5 years to year 50, then fell and replace.
Broadleaves only (BL2)	Allows replanting selecting the most suitable broadleaf species.
Continuous cover forestry (CCF)	No change in species composition, stands regenerated with the current species. If site conditions suitable, a heavy thinning intervention is simulated at 25 years. Sub-compartments DAMS ≤ 14 - marked FMA2 for conversion at year 50 - grow to year 50 thin to half the basal area. DAMS > 14 and ≤ 16 - thin as FMA 4 in BAU. Sub-compartments > 50 years classified as FMA 3 and grown to 100 years before felling.
Diverse species (DIV)	Selection of species using high predicted yield class for the site conditions from a selection of available 57 species in ESC. Continue same FMA allocation as in BAU, only species allowed to change after felling. Most suitable species for the sub-compartment site conditions for the rotation is chosen. No particular preference made for broadleaved trees or native trees. Sub-compartments > 50 years old allocated FMA 3 and felled at year 100.
Forest Enterprise Scotland priority species (FESP)	Selection by highest yield class from a management list of 19 priority species suitable for timber production in Scotland. Continue with the same FMA allocation as in BAU, only species allowed to change at time of felling. Broadleaves replace felled broadleaved stands, and larch and ash are excluded from replanting due to tree health limitations.
Native species (NAT)	Native species selected according to the suitability of the site for an NVC woodland type. Continue with the same FMA allocation as in BAU, only species allowed to change at time of felling. Norway spruce is replaced by Scots pine.
No Sitka spruce (NOSS)	Replacement species is selected at replanting, and available species are restricted to priority species with the addition of lodgepole pine (Alaskan) (*Pinus contorta* var. *latifolia*) and rowan (*Sorbus aucuparia*) and grand fir (*Abies grandis*) on moist lowland sites to ensure sufficient species diversity. Continue with the same FMA allocation as in BAU, only species allowed to change at time of felling
Short rotation forestry (SRF)	No change in species composition, stands are replanted with the current species. SNR > very poor, SMR > Wet, and DAMS ≤ 16, otherwise the site is classed as unthinned FMA4. Sub-compartment stands are felled and replaced at age 25 years.

DAMS – wind exposure, SNR – soil nutrient regime, SMR – soil moisture regime, FMA – Forest Management Alternative stand type.

2.3. Forest simulation using dynamically coupled models

2.3.1. Forest management trajectories under climate change projections

We ran the coupled forest models to simulate tree growth, carbon sequestration, biomass, timber production and biodiversity on the NFE. The method builds on previous work described by Ray et al. (2015). A schematic diagram (Fig. 1) summarizes the simulation method. Three spatial datasets were used to simulate forest management through the 21st century: climate projections at decadal intervals (2020s, 2030s, 2040s etc); forest soils set as constants for the simulation; forest inventory data – initialised using the 2016 SCDB. The SCDB inventory was updated within each annual cycle of the model simulation to reflect changes in the forest structure and its management under eight different management trajectories. The forest management trajectories are comprised of management systems and decision rules designed to implement different forest policy directions. They were created by applying specific forest management systems to forest SCDB data in the simulation. For example: ‘Broadleaves only’ (Table 2) attempts to change species choice to broadleaved species when the opportunity arises at restocking; ‘No Sitka spruce’ attempts to remove and replace Sitka spruce stands with a mix of suitable alternative high yielding conifer and/or broadleaved species at the time of restocking. The trajectories simulated (Table 2) were: business as usual, species diversification for production, continuous cover forestry using a shelterwood system of two age components, short rotation forestry, native species selection, broadleaved species selection, species diversification without Sitka spruce, and finally species selection using Forest Enterprise Scotland's selected species for diversification.

2.3.2. Forest management alternative simplification of the Forest inventory data

The eight forest management trajectory types specify rules to simulate the different forms of forest management applied to the SCDB. To facilitate the diverse range of silviculture and species described by the SCDB, we simplified the forest inventory silvicultural descriptions into Forest Management Alternatives (FMA). Forest Management Alternatives, described by Duncker et al. (2012), provide a means of classifying differences in management intensity. They described five FMA types ranging from FMA type 1 Forest Reserve with no management, to FMA type 5 intensive single species short rotation forestry. Production forestry in Scotland is largely described by FMA types 3 and 4: “combined objective forestry” and “intensive even-aged forestry”, respectively. “Close to nature forestry”, FMA type 2, is increasing in Scotland in the form of continuous cover forest management, but has limited potential due Scotland's high wind exposure climate. The FMA classification seeks to describe forest management intensity using criteria such as type of regeneration, level of machine operation, ground preparation, and size of harvesting coupes. As the forest model simulation progressed on an annual cycle, rules were applied at the appropriate time in the rotation (Table 2) to the FMA types of the SCDB to maintain the selected forest management trajectory, and the forest inventory SCDB was updated. Any changes required by the forest management trajectory (thinning, felling, etc) were controlled by the rules applied to the SCDB to describe the particular forest management trajectory running in the dynamically coupled models.

2.3.3. DNB vulnerability matrix indicator evidence and approach

Our addition of a DNB vulnerability model was based on a body of literature that associates outbreaks of DNB with spring and summer rainfall, particularly above average amounts (Watt et al., 2011; Welsh et al., 2014). Exact values vary but Woods et al. (2016) surmise that rainfall in excess of 100 mm per month in the warmer months leads to outbreaks of DNB, which are far less likely to occur when rainfall is < 50 mm per month. In Britain, high levels of infection were observed (Murray and Batko, 1962) when total rainfall exceeded 315 mm from June to September, while no outbreaks were seen when total rainfall during this period was below 175 mm. Needle wetness is more important than total seasonal or monthly precipitation in the germination and infection of spores. Therefore, extended periods of needle wetness (e.g. due to frequent low-volume showers or mist) were assumed to lead to greater levels of disease than heavy downpours followed by long dry spells. The fungus is able to tolerate a wide range of temperatures, however, 16–20 °C is optimal for both infection and stomatal development (Gadgil, 1974, 1977). Overall, spring and summer rainfall along with temperature provide good indicators to estimate DNB severity.

The vulnerability of a forest to DNB impact depends not only on the environmental conditions but also the host (e.g. more or less susceptible

Table 3
Classified values of tree vulnerability to Dothistroma needle blight (DNB) based on a) climatic characteristics of a stand, b) tree species/provenance type, c) stand Forest Management Alternative (FMA), and d) the total vulnerability class and effect on stand yield, based on the sum of indices from a, b, & c.

a) Climatic characteristic with DNB vulnerability levels (1 – low, 2 – medium, and 3 – high)

AT MD	Subalpine	Cool	Warm	Very warm
Wet	1	2	3	3
Moist	1	2	3	3
Dry	1	2	3	2
Very dry	1	1	2	1

b) Tree species DNB vulnerability

	HIGH vulnerability	MEDIUM vulnerability	LOW vulnerability
Species	Corsican pine, lodgepole pine	Alaskan lodgepole pine, Scots pine	Sitka spruce, Douglas-fir
Shift	0	− 1	-2

c) FMA DNB vulnerability

	FMA1	FMA2	FMA3	FMA4	FMA5
No thin	0	0	+ 1	+ 1	0
Thin	N/A	-1	-1	-1	N/A

d) Total vulnerability index of forest stands to DNB – impact on YC reduction

Final Vulnerability Index	DNB Vulnerability Class	Yield Impact
0 or < 0	VERY LOW	None
1	LOW	Reduce YC by 10%
2	MODERATE	Reduce YC by 30%
3 +	HIGH	Reduce YC by 50%

N/A = thinning not performed in FMA 1 (Semi-natural reserve) and FMA5 (Short rotation forestry).

species) and pathogen (e.g. levels of inoculum in the area, virulence of strains) with the complex interaction between host, pathogen and environment. The effect of DNB infection of primary concern to foresters is a reduction in growth, with radial increment more severely affected than height, although in extreme cases mortality may follow. Studies generally agree that at least 25% of foliage must be affected before losses in growth are measurable (Christensen and Gibson, 1964; Hocking and Etheridge, 1967; Whyte, 1969). A study on *P. radiata* in New Zealand showed that there was a proportional relationship between disease level (percentage of foliage infected) and volume loss, so that, for example, an average disease level of 50% resulted in a volume loss of 50% after three years (Van der Pas, 1981). Once severely high levels of infection occur (i.e. 75% of foliage becomes affected) diameter increment practically ceases (Christensen and Gibson, 1964).

To calculate the DNB impact on forest stands, we used the current knowledge to modify the yield class (YC) of pine species according to a classification method based on climatic characteristics (Table 3a), conifer and pine species vulnerability (Table 3b), and the forest management alternative (Duncker et al., 2012) system used (Table 3c). Each table contains vulnerability values related to the potential DNB impact. We summed the values in the first three tables to obtain an overall vulnerability index, listed in the lookup table (Table 3d), which gives the yield adjustment applicable to the forest stand.

The DNB vulnerability model used the following assumptions: DNB affects only pines, DNB infection is present in all pine stands (even though that might not be the case), a change in species choice can be applied only as a change in forest management system – not as a response to infection, infected stands are retained until the end of the rotation, and timber quality is unaffected.

2.3.4. Dynamically coupled models and ecosystem goods and services indicators

The dynamically coupled forest models used in the simulation were: Ecological Site Classification (Pyatt et al., 2001), ForestGALES (Gardiner and Quine, 2000), Forest Yield (Matthews, 2008), ASORT (Rollinson and Gay, 1983) and BSORT (McKay, 2003; Broadmeadow and Matthews, 2004), and our new DNB vulnerability matrix model (Section 2.3.3).

1. Ecological Site Classification (ESC) is a forest site classification model using six site factors: - four climatic factors - accumulated temperature (AT -degree.days > 5 °C) which describes the growing season warmth; climatic moisture deficit (MD -mm) describing the relative wetness or droughtiness of the growing season; wind exposure (DAMS score); continentality (Conrad index): - and two soil quality factors - Soil Moisture Regime (SMR) or soil wetness; and Soil Nutrient Regime (SNR), or soil fertility. ESC predicts the site potential for a given species in the form of a general yield class.
2. ForestGALES is a wind risk model that calculates the risk of wind damage, either windthrow, or stem breakage, to forests stands.
3. Forest Yield provides estimates of various aspects of tree growth (height, diameter at 1.3 m) by stand age, for a range of tree species, yield classes and management prescriptions.
4. ASORT is an assortment model to provide estimates of potential timber production volumes.
5. BSORT estimates the tree size class distribution and through allometric equations the biomass per hectare by size components.

The models use the SCDB forest inventory and a set of rules (Table 2) based on forest management principles to form the eight forest management trajectories, applied to individual forest stand FMA types, and described spatially within a Geographic Information System, with and without both the climate change projections, and the effects of the DNB vulnerability matrix.

For each of the forest management trajectories, we calculated three ecosystem goods and services indicators (online Supplementary

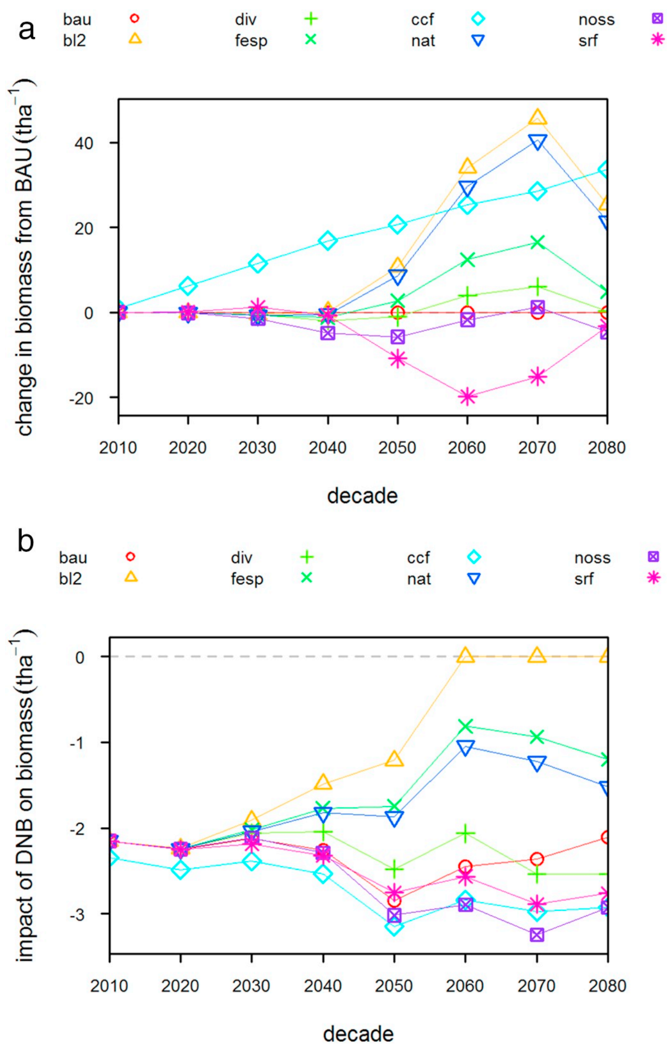


Fig. 2. Change in the provision of standing biomass on the (NFE) under climate change a) comparing forest management trajectories without DNB impact to business as usual (BAU) (standing biomass in the 2010 for BAU around 48.6 Mt), and b) changes due to DNB impact.

material 2): 1) standing biomass (t ha^{-1}), 2) harvested timber volume (m^3 ha^{-1}), and a forest biodiversity index (index ha^{-1}). Standing biomass is a good that stores carbon (regulating service) and when harvested, can be used as timber in construction (provisioning service), is used for pulp in making paper (provisioning service), or as biomass for renewable energy (provisioning service). When used in the latter way it also substitutes fossil fuel use (regulating service).

Biomass and timber volume were based on a predicted site yield from Ecological Site Classification and growth using Forest Yield, and then calculated using ASORT (timber volume) and BSORT (biomass). The biodiversity index used was based on a method developed by Humphrey et al. (2002, 2004), based on the age of a stand and its FMA type. The coupled model outputs have an annual time step, and results from the models were compiled and reported at decadal intervals.

3. Results

3.1. Changes in ecosystem goods and services on scotland's National Forest Estate

The findings highlight changes in the provision of three ecosystem goods and services under a single climate change scenario, using different forest management trajectories. In this section we present results for the NFE in Scotland at decadal intervals between the RCP4.5 climate projection and the baseline climate, exploring changes in standing biomass, timber production and biodiversity.

3.1.1. Biomass

The variability in standing biomass provision under different management trajectories on the whole NFE (Fig. 2a) shows that in the long term (50–70 years) an increase from the business as usual management will occur for native species, broadleaved species, and continuous cover forest management. This resulted in increases of up to 40 t ha^{-1} compared to business as usual. The continuous cover silviculture showed a steady increase through the period. However, broadleaves and native species management trajectories showed a steep increase from 2040 at which time business as usual (largely fell-restock systems) stands began to be felled at the age of maximum mean annual increment. In contrast, the largest reduction of up to 20 t ha^{-1} was projected for the short rotation forestry management, with modelled rotation lengths of only 25 years.

The diverse and small impacts of DNB depend on the type of forest management trajectory (Fig. 2b). At initialisation of the forest model simulation, DNB was predicted to reduce standing biomass across the NFE by approximately 2 t ha^{-1} (−1.7%). We see that some forest management trajectories improved the negative biomass impact of DNB, especially broadleaved and FE selected species (FESP) in Scotland– since these management trajectories gradually removed high risk species; Corsican pine and lodgepole pine. Broadleaved management (with reliance on birch species), was predicted to increase biomass compared to business as usual management, and may also mitigate DNB impacts.

In contrast, other management trajectories were projected to continue to maintain a reduced standing biomass compared to business as usual. These include: no Sitka spruce; low impact silviculture; and short rotation forestry – since these three management trajectories maintained both Corsican and lodgepole pine.

3.1.2. Timber Production

A decrease in timber volume (TDC17 – diameter above 17 cm) was projected across all management trajectories (Fig. 3a), mainly due to the currently optimised high timber production of fast growing Sitka spruce using fell-restock silviculture. Therefore, the current composition of tree species and management (business as usual) maintained the highest provision of timber. On the NFE, we predicted a 50 m^3 ha^{-1} reduction in timber production, if all stands suitable for short rotation forestry were transformed by the 2080s. In contrast, a general transformation to more continuous cover forestry projected little effect on timber production, since this management trajectory would be possible on a relatively small proportion of the NFE - forest stands not constrained by wind exposure. Diversifying species selection or selecting favoured FES species (FESP) would cause a small reduction in production by 2060 (< 10 m^3 ha^{-1}). This reduction was predicted to change to 20–25 m^{3}ha^{-1} by 2080, as slower growing species compared to Sitka spruce would become more widespread on sites for which they were more ecologically suitable. By gradually removing Sitka spruce from all stands at restocking, the production forecast would reduce by 10 m^3 ha^{-1} in 2060 and by 50 m^3 ha^{-1} by 2080, again because of replacement by lower yielding species.

The impact of DNB on timber volume was projected to be similar across all forest management trajectories until the 2060s (Fig. 3b), with the reduction of approximately 4 m^3 ha^{-1} (3%). Then, DNB impacts were shown to diverge with the most negative effects on short rotation forestry and business as usual and the least negative effects on broadleaved species management trajectories.

For production, all forest management trajectories provided less timber in the future in contrast to business as usual, but DNB was projected to have a major impact on the business as usual management. Comparing the diverse species management (DIV) with the favoured

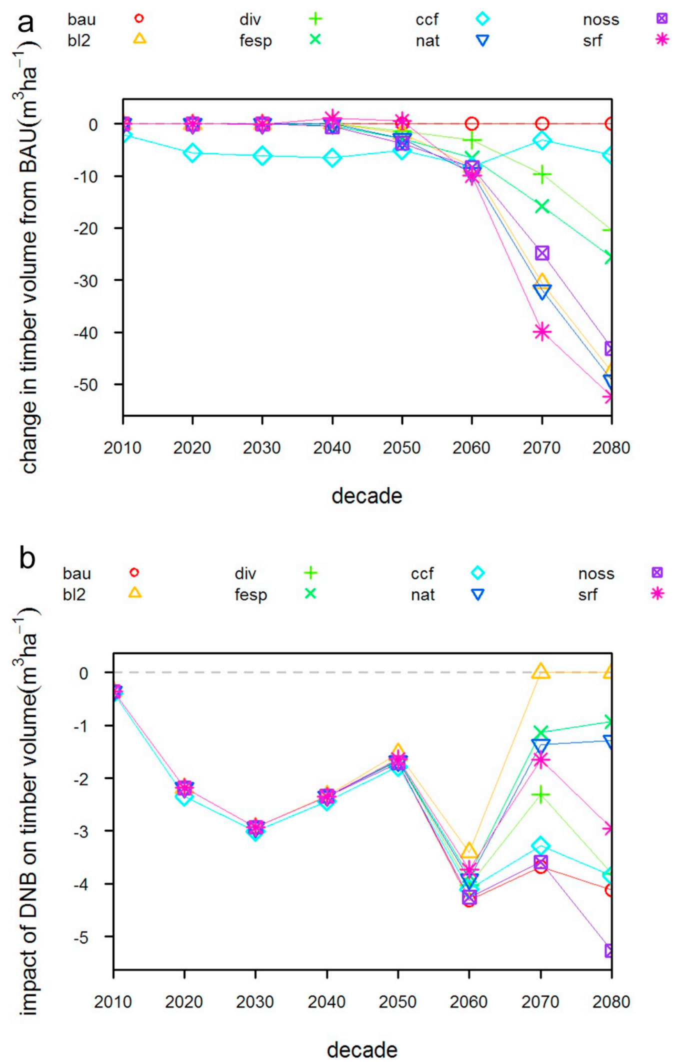


Fig. 3. Change in the timber volume production on the National Forest Estate (NFE) under climate change a) from BAU to other forest management trajectories without DNB impact (timber volume in the 2010 for BAU around 4.4 mil m^3), and b) due to DNB impact.

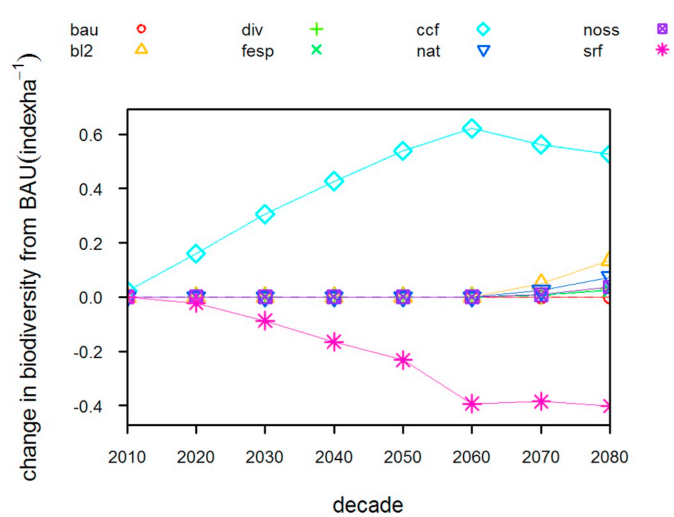


Fig. 4. Change in the provision of biodiversity on the NFE under climate change from BAU to other forest management trajectories without DNB impact.

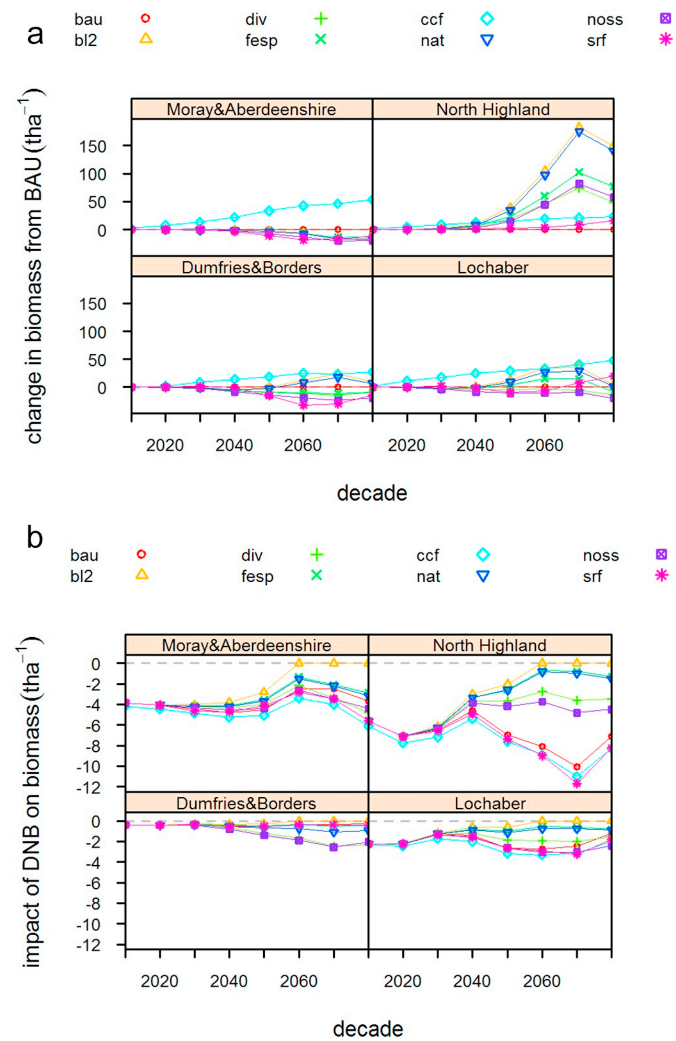


Fig. 5. Changes in the provision of standing biomass in four Forest Districts (Moray & Aberdeen (standing biomass in 2010 around 5.4 Mt), North Highland (standing biomass in 2010 around 3.2 Mt), Dumfries & Borders (standing biomass in 2010 around 4.8 Mt), and Lochaber (standing biomass in 2010 around 3.7 Mt)) under climate change a) from BAU to other forest management trajectories without DNB impact, and b) due to DNB impact.

species selection (FESP), the forest simulation showed the former would be impacted more severely by DNB as the latter FESP selection does not include Corsican pine or lodgepole pine.

3.1.3. Biodiversity

Fig. 4 shows changes (compared to the business as usual management system) in the provision of biodiversity – using a relative indicator (1 = low and 10 high). The main increase in biodiversity by up to 0.6 units was shown to occur for continuous cover management. In contrast, the main decrease, by up to 0.4 units, occurred for short rotation forestry, while other management trajectories ensured a similar provision of biodiversity to business as usual. DNB would have no impact on biodiversity using the remaining management trajectories, as the index is not sensitive to species changes in pine forests.

3.2. Changes in ecosystem goods and services for individual districts

In this section we present results showing changes in standing biomass, timber production and biodiversity index under climate change and for different management trajectories for four Forest Districts of the NFE (see Fig. S2 – online Supplementary material). The districts are Moray and Aberdeen in the east, North Highland in the north, Dumfries and Borders in the south, and Lochaber in the west of Scotland.

3.2.1. *Biomass*

As in Fig. 2a on the NFE, biomass provision was shown to increase gradually in all four districts (Fig. 5a) under the continuous cover forestry management trajectory, slightly more in Lochaber and Moray & Aberdeen than in North Highland and Dumfries & Borders due to a greater proportion of suitable sites for CCF in the former two districts. In Moray & Aberdeen, Dumfries & Borders and Lochaber the changes in biomass production among management trajectories were very similar to the NFE national results. In North Highland there was a large increase in biomass provision for native species selection and broadleaved species, largely because of the availability of suitable sites for native birch species under warmer climatic conditions, which is expected to improve the yield.

Three districts (Lochaber, Moray & Aberdeen, and Dumfries & Borders) showed a smaller proportion of lodgepole pine than North Highland, leading to an initial DNB impact reducing biomass provision by approximately 4 t ha^{-1}(Fig. 5b). In North Highland, a much larger reduction in biomass due to DNB was predicted for the business as usual, continuous cover and short rotation forestry (up to 12 t ha^{-1}). For these management trajectories the species present at initialisation was maintained through to 2080, leading to the continuation of large areas of lodgepole pine, and larger impacts from DNB. In Moray & Aberdeen, Scots pine is widely distributed, and the results showed a medium impact of DNB reducing biomass provision by approximately 4 t ha^{-1} which decreased slightly from 2060 and then increased slightly by 2080.

3.2.2. *Timber production*

Compared to business as usual, the forest simulation showed reductions in timber production volume for all management trajectories in Moray & Aberdeen, Lochaber, and Dumfries & Borders districts, with the largest reductions (50–100 m^3 ha^{-1}) in the latter district by 2080 (Fig. 6a). Lochaber and Dumfries & Borders have large proportions of Sitka spruce, and the results showed spatial differences in the way climate change and management trajectories interact between the south of Scotland (drier summers) and western Scotland (wetter summers), which caused the variation in the production volumes. Compared to business as usual, results for the FESP preferred species selection showed similar production targets as business as usual in Lochaber by 2070 and 2080 (20–25 m^3 ha^{-1}), but greater reductions in production in Dumfries and Borders in 2070 and 2080 (50 m^3 ha^{-1}). Similarly, results for the native species management trajectory showed production losses of 75–100 m^3 ha^{-1} in Dumfries & Borders, and $<$ 50 m^3 ha^{-1} in Lochaber.

Changes in Moray & Aberdeen followed a similar pattern to Lochaber, but in North Highland the results showed production benefits to be gained over business as usual in moving to FE preferred species (FESP), native species, species diversity, and broadleaved species management trajectories. DNB impacts were shown to be greater in Moray & Aberdeen, and North Highland (Fig. 6b) where Scots pine, Corsican pine and lodgepole pine are currently more extensively planted than in the other two districts. Unsurprisingly, in both districts a change to broadleaved species and/or native species was shown to reduce DNB impacts. Dumfries & Borders currently has much less pine and is largely unaffected by DNB.

3.2.3. *Biodiversity*

The same changes in biodiversity as described for the NFE (see Fig. 4) were shown to occur in each of the four districts (Fig. 7). Continuous cover systems produced increases in the biodiversity index and the short rotation forestry trajectory reduced the biodiversity index. The DNB vulnerability matrix model had no impact on the biodiversity index.

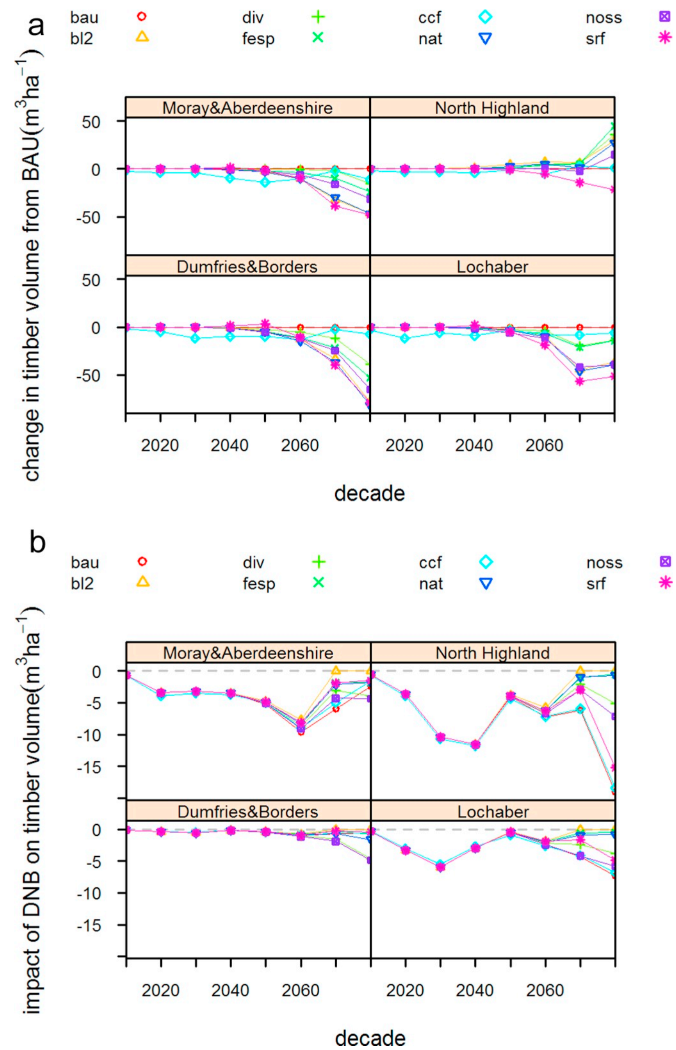


Fig. 6. Change in timber volume production in four Forest Districts (Moray & Aberdeen (timber volume in 2010 around 0.55 mil m^3), North Highland (timber volume in 2010 around 0.28 mil m^3), Dumfries & Borders (timber volume in 2010 around 0.43 mil m^3), and Lochaber (timber volume in 2010 around 0.39 mil m^3)) under climate change a) from BAU to other forest management trajectories without DNB impact, and b) due to DNB impact.

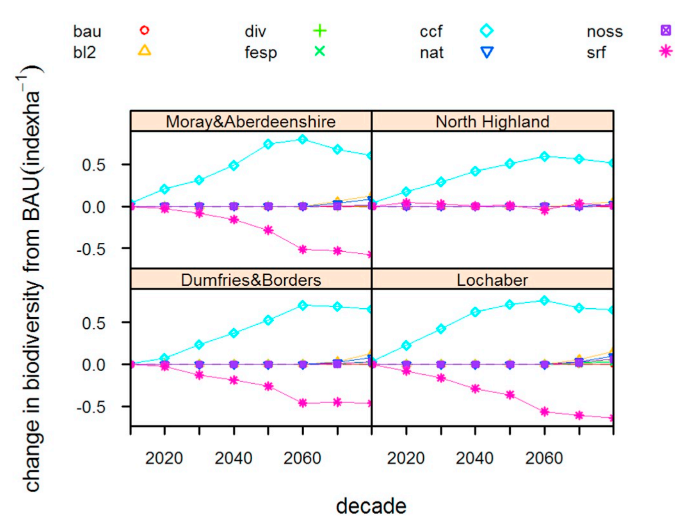


Fig. 7. Change in the provision of biodiversity in four Forest Districts (Moray & Aberdeen, North Highland, Dumfries & Borders and Lochaber) under climate change a) from BAU to other forest management trajectories without DNB impact, and b) due to DNB impact.

4. Discussion

4.1. Sensitivity of ecosystem goods and service delivery to changes in management choices, climate and disease

This study investigated ways in which the public sector forestry in Scotland can make a contribution to greenhouse gas abatement and timber production while maintaining high biodiversity and other important benefits. Scottish forest policy encourages species and forest management diversity, and the use of strategic targeting to meet multiple objectives. The results show the National Forest Estate's implementation of policy will deliver these intended benefits. In particular, given an RCP4.5 climate projection, with associated abiotic and DNB impacts, the production forecast could be maintained, or would suffer only small reductions. This outcome could be achieved by increasing the use of continuous cover forestry systems and by introducing more Forest Enterprise Scotland favoured species (FESP). Such a change would also maintain the forest biodiversity index. The combined abiotic and biotic analysis is an example case study that will help policy developers assess the sensitivity of forest ecosystem goods and services to changes in climate and pathogens (Lindner et al., 2010), and improve understanding of trade-offs resulting from different policy and practice decisions (Seidl and Lexer, 2013).

Our dynamically coupled forest model predicts that DNB could reduce standing biomass (by up to 3 t ha^{-1}) and timber volume (by up to 5 m^3 ha^{-1}). The impact is dependent on the type of forest management systems applied and introducing FESP would reduce this impact.

We demonstrated how interactions between management systems and abiotic and biotic climate impacts differ among regions in Scotland. In North Highland and in Moray & Aberdeen particular changes in species and silvicultural management (less pine more broadleaved species; more continuous cover systems) would improve biomass provision and timber production, and at the same time relieve the current impact of DNB, and improve biodiversity in forests.

4.2. Use of simulation tools in understanding forest policy implementation

There are relatively few models that can examine policy options and forest management scenarios together. Notable examples include the European Forest Information Scenario model (EFISCEN) (Schelhaas et al., 2015), which has been used to analyse large scale applications of climate change abiotic effects (Hanewinkel et al., 2012; Verkerk et al., 2014) and also regional forest biotic disturbances (Seidl et al., 2009) with the patch-based model PICUS (Lexer and Hönninger, 2001). For national and district analyses where detailed FMA descriptions, soil types, and climate scenarios are available, our dynamically coupled model approach can examine the effects of implementing forest policy in different ways, in different places and at different times into the future. The approach can accommodate the effects of forest planning on policy targets, by accumulating goods and services to regional and national scales.

The decision support tool used in this study is not intended to be used by forestry professionals alone, but jointly with forest scientists to assess scenarios and future implications of current policy and practice. This will enable capacity building (Grainger, 2012) and help manage uncertainty (Petr et al., 2014) within the National Forest Estate and, with modifications, within private forests.

The novelty of the forest model simulation is the multi-scale temporal view of forest policy implementation and future outcomes. The decision support tool uses ecosystem service indicators to appraise the combinations of forest management, and climate change abiotic and biotic impacts and can explore the notion of resilient forests meeting their intended delivery of ecosystem goods and services into the future (Ray et al., 2015).

It has been argued (Buizer and Lawrence, 2014), that recommendations for mitigation have used a more quantitative approach than recommendations for adaptation. This is because adaptation is concerned more with changing forestry professional's frames on tree species selection and/or silvicultural systems. Our approach uses high resolution spatial data in a multi-scale analysis which can provide recommendations tailored to forest regions and ecosystem services. Such results can be used in novel action expiration charts (Petr et al., 2016) for knowledge exchange with forestry professionals. The combination of simulations with the action expiration chart methodology also partly answers the Buizer and Lawrence (2014) recommendation to "engage with both the social and ecological complexity and value conflicts" in climate change adaptation discourse, through a dynamic spatial and temporal scenario assessment.

4.3. Opportunities for stakeholder involvement in simulation assessment

The mix of policy, management objectives, economic benefits and natural science is very much a multidisciplinary complex system (Costanza, 2001) involving forest policy makers, practitioners and scientists. It is in this area of uncertainty and mixed objectives that the simulation approach shows much potential. Our results have been used in discussions at the national level on forest policy, and at the forest district level regarding maintaining the multiple objectives of forestry. This has helped show how Forestry Commission Scotland's 'strategic directions' policy can target regional resources to provide particular benefits at the national level (Forestry Commission Scotland, 2013b), rather than each district being expected to deliver on 'aspirational targets' for all 'key commitments'. The work has helped inform the potential of alternate land management plans at the district scale to deliver recreation and biodiversity benefits (Beauchamp et al., 2016) requested in community discussions.

5. Conclusions

If large forestry enterprises, ignore information on likely abiotic and biotic impacts of climate change, and ignore policy recommendations, there is a risk of loss of production and a reduced resilience of forest stands. Scotland's National Forest Estate delivers important forest ecosystem goods and services (Ray et al., 2016; Sing et al., 2015), and we have shown under the uncertainty of climate change, how spatio-temporal scenario forest model simulations can inform solutions for the targeted delivery of benefits (Forestry Commission Scotland, 2013b). Furthermore, we have shown how forest model simulations can explore scenarios and show differences in the interactions between forest management trajectories, species choice, abiotic and biotic impacts. Our results support the policy of targeted delivery, and this leads us to believe that better informed decisions will improve future forestry objectives and strategic delivery, compared to trial and error management.

Our decision support tool currently extends to Scotland's National Forest Estate, which covers one third of Scotland's forest area. The principles of our findings can not be extended to the remaining area, due differences in species composition between the public and private ownerships (see Supplementary material) due to the underlying differences in soil and climatic conditions; so we plan to develop private sector case studies. In addition, other pest/pathogen models could be developed and incorporated to test combined abiotic/biotic climate change impacts.

Our approach applied single forest management trajectories across the National Forest Estate to assess and compare the impact of one trajectory with others. In practice, the forest simulation would test land management plans and strategic plans where different forest management trajectories could/should be spatially targeted to meet forest objectives and ecosystem goods and service provision.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2017.10.010.

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