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Not seeing the carbon for the trees? Why area-based targets for establishing new woodlands can limit or underplay their climate change mitigation benefits

K.B. Matthews[a,*], Doug Wardell-Johnson[a], Dave Miller[a], Nuala Fitton[b], Ed Jones[b], Stephen Bathgate[c], Tim Randle[c], Robin Matthews[a], Pete Smith[b], Mike Perks[c]

[a] *The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, United Kingdom*
[b] *Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, Scotland, United Kingdom*
[c] *Forest Research, Bush Estate, Roslin, EH25 9SY, United Kingdom*

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ABSTRACT

Area-based targets for afforestation are a frequent and prominent component of policy discourses on forestry, land use and climate change emissions abatement. Such targets imply an expected contribution of afforestation to the net reduction of greenhouse gas emissions, yet the nature of afforestation undertaken and its geographical distribution means that there is considerable uncertainty over the eventual emission reductions outcomes. This uncertainty is reduced if the net carbon balance is calculated for all potential afforestation sites, considering climate, soil characteristics and the possible types of afforestation (species and management regimes). To quantify the range of possible emissions outcomes for area-based afforestation targets, a new spatial analysis method was implemented. This improved the integration of spatial data on antecedent land use with mapped outputs from forest models defining the suitability and productivity of eleven forestry management alternatives. This above ground carbon data was then integrated with outputs from the ECOSSE (Estimation of Carbon in Organic Soils – Sequestration and Emissions) model which simulates the soil carbon dynamics. The maps and other model output visualisations combining above and below ground carbon highlight where net carbon surpluses and deficits are likely to occur, how long they persist after afforestation and their relationships with antecedent land use, soils, weather conditions and afforestation management strategies. Using more productive land classes delivers more net sequestration per hectare and could mean greater carbon storage than anticipated by emissions reduction plans. Extensive establishment of lower yielding trees on low-quality ground, with organo-mineral soils could, though, result in net emissions that persist for decades. From the spatial analysis, the range of possible outcomes for any target area of planting is substantial, meaning that outcomes are highly sensitive to policy and implementation decisions on the mix of forestry systems preferred and to spatial targeting or exclusions (both at regional and local scales). The paper highlights the importance of retaining the existing presumption against planting of deep peat areas, but also that additional incentives or constraints may be needed to achieve the aggregate rates of emission mitigation implied by policy commitments. Supplementary carbon storage tonnage targets for new forestry would introduce a floor for carbon sequestration outcomes, but would still allow for flexibility in achieving an appropriate balance in the trade-offs between carbon sequestration and the many other objectives that new woodlands are expected to deliver.

1. Introduction

Commitments from governments to net zero carbon emissions means that, accepting there are activities such as agriculture that cannot be conducted without GHGs emissions, then the creation of carbon sinks is required (Rogelj et al., 2018). Afforestation is a prominent part of the public discourse on emissions abatement and widely cited as a policy option, with increased forest area or percentage of land cover specified as aspirations or targets.

This study describes a methodology that improves the estimates of

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* Corresponding author.
E-mail address: keith.matthews@hutton.ac.uk (K.B. Matthews).

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the contribution that areas of new woodlands could make to reducing emissions, and tests that methodology for Scotland. This builds on prior reporting (Matthews and Broadmeadow, 2009; Morison et al., 2012) with spatially explicit consideration of current land use, forest species suitability and improved soil modelling. Using this methodology, it is possible to evaluate the carbon dynamics outcomes of achieving existing areal afforestation targets, being explicit on both the net tonnage of carbon stored and by when this storage is achieved. The outputs of such analyses are potentially significant for forestry policy because they can, inform strategic decisions on the extent and nature of afforestation needed to achieve expected levels of emissions abatement, while still delivering on other policy commitments such as habitat restoration. More widely, in terms of land use policy, the methodology also provides a means to underpin the quantification of the cost to the public of the GHG emissions abatement delivered by afforestation measures compared with those in other land-based sectors such as agriculture.

1.1. *The policy context of the analysis*

The policy context for this analysis is defined by the Paris Agreement (within the United Nations Framework Convention on Climate Change) and by the European Union's Common Agricultural Policy (the CAP). The former commits member states of the EU (and others) to a minimum level of Nationally Determined Contributions (NDCs) to reduce GHG emissions (UNFCCC secretariat, 2019). The NDCs, or more ambitious voluntary commitments, are delivered through programmes of policies and proposals by EU member states or regions. The CAP provides financial support to farmers either directly through area based or production coupled payments (within the first Pillar of the CAP) or via agri-environmental and climate change schemes within the EU's rural development programmes (the second Pillar). While the details of the policy context referred to in this paper are EU and Scotland specific, the challenge of achieving a coherent land use policy that integrates the delivery of both climate change and agricultural objectives confront policy makers worldwide.

In Scotland the Climate Change (Scotland) Act (2009) commits Scotland to go beyond UK and EU greenhouse gas emission targets, with targets of 42% (revised to 43.66%) by 2020 and 80% reductions by 2050 (Scottish Government, 2009). These are ambitious targets and mean that all sectors will have to take actions, as outlined in the mandated Reports on Proposals and Policies. These reports, the third of which was published in 2018 (Scottish Government, 2018), prescribe, through emissions reductions targets, the balance of burden sharing per sector. Substantial headline progress has been made (46.7 Mt CO_2e for 2014 compared with 77.2 Mt CO_2e for the 1990 baseline), but in the forestry sector there have been periods when planting was lower than target rates e.g. in 2011 and 2015 predominantly, due to changes in grant schemes and concomitant reduced planting (The Committee on Climate Change, 2017). Existing forestry made an increasing contribution to sequestration of carbon from 1990 to 2002, the contribution remained fairly stable between 2002 and 2010 and then declined, with that decline predicted to continue; this reflects area, age and species mix of historic plantings (Scottish Government, 2018). Carbon storage by converting land from other uses to new woodlands has been declining since 1990 (see Fig. 1 in Supplementary Materials, derived from Salisbury et al. (2016)).

Land use policy measures directly financing greenhouse gas mitigation are limited to agri-environment climate and forestry schemes within the Scottish Rural Development Programme (SRDP) (Scottish Government, 2016b), part of Pillar 2 of the CAP, and peatland restoration. Relevant strategies and coordination initiatives that seek to balance multiple objectives include the Land Use Strategy (Scottish Government, 2016a) and the Scottish Forestry Strategy (Anon, 2018). Spatial targeting of new woodlands was supported by Indicative Forestry Strategies from 1990 and while the original instruments have now lapsed, there is renewed interest in refreshing them to reflect land use and forestry strategies and changed circumstances. For example, new woodland instruments are now available which underpin voluntary carbon payments through the Woodland Carbon Code (Forestry Commission, 2014).

For forestry in Scotland, the commitment has been is to create 100,000 hectares of new woodland from 2012 to 2022, with annual targets of 10,000 hectares per annum (Scottish Government, 2013). These area targets were the outcome of deliberations within a complex and contested policy environment, with tensions particularly between farming and forestry as effective drivers of rural development (Anon, 2012; Slee et al., 2014). The Climate Change Plan from 2018 confirms existing policy commitments and proposes increased rates of planting, from 2020 onwards, to 15,000 ha per annum by 2024/25 (Scottish Government, 2018).

Yet despite the existence of these afforestation targets, over the last decade the area of new woodland planted has exceeded 5,000 ha in only five individual years (Tatchell-Evans, 2016). Set against historic UK average planting rates of 25,000 $ha{\cdot}y^{-1}$ for 1950 − 90 and a maximum of 40,000 $ha{\cdot}y^{-1}$ in the 1970s (Cannell, 2003), the current targets are not demanding, yet by not meeting the targets there is an accumulating deficit in new woodland creation. Strong resistance to afforestation and particularly to increasing its share of funding within the second Pillar of the CAP is a deeply engrained attitude within Scotland's farming community with a strongly cultural and identity basis that emphasises food productivism (Burton, 2005). This resistance is further entrenched by capital land values, that are increased by the land's eligibility for area based payments under CAP Pillar 1 and via CAP Pillar 2 Less Favoured Area status (Grieve et al., 2016). There are clear opportunities for afforestation in Scotland with substantial areas of pasture land that is not grazed or very lightly stocked. In 2011, there were 49,683 ha of land capable of supporting improved grassland and 122,548 ha of land agriculturally suitable only for rough grazing that were recorded as having no domestic livestock, with a further 230,577 ha and 627,517 ha of land with such capabilities having stocking rates of less than 0.25 livestock units per hectare (Matthews et al., 2012). This means there is little or no likelihood that increased afforestation need compete substantially for land that would otherwise be used for food production.

Of the woodlands being established, 73% were planted under the Native Woodland option (Anon, 2012) of the Scottish Rural Development Program (SRDP) (2007 − 12) with a specification that means they are unlikely to contribute to future timber production (Lawrence and Edwards, 2013). The latest reports show that over the last five years in Scotland 14.3k ha of conifers and 18.1k of native woodlands have been planted (Forest Research, 2018) The prioritising of broadleaved and native species is shaped by commitments to the Aichi Targets for the conservation of biodiversity (Scottish Natural Heritage, 2016). Debate on the appropriate levels of financial support for afforestation and the balance between conservation and production-oriented woodlands continues to be shaped by stakeholders referring to earlier negative experiences in the 1980s, see for example RSPB Scotland (2018). The drivers behind this period of monoculture, tax-break-driven planting of iconic wilderness areas and the resultant environmental damage, stands of poor productivity or un-harvestable trees and the need to better understand how to restore or restock such sites, are reviewed by Sloan et al. (2019). Yet despite profound changes in forestry policy since this era, new plantings are still predominantly on some of the most marginal land, typically with higher carbon content soils which are less resilient to disturbance (Brown et al., 2014).

2. Materials and methods

2.1. *Summary of the approach*

The paper presents a new methodology to assess the consequences for carbon stocks of a change in land use to forestry and presents the

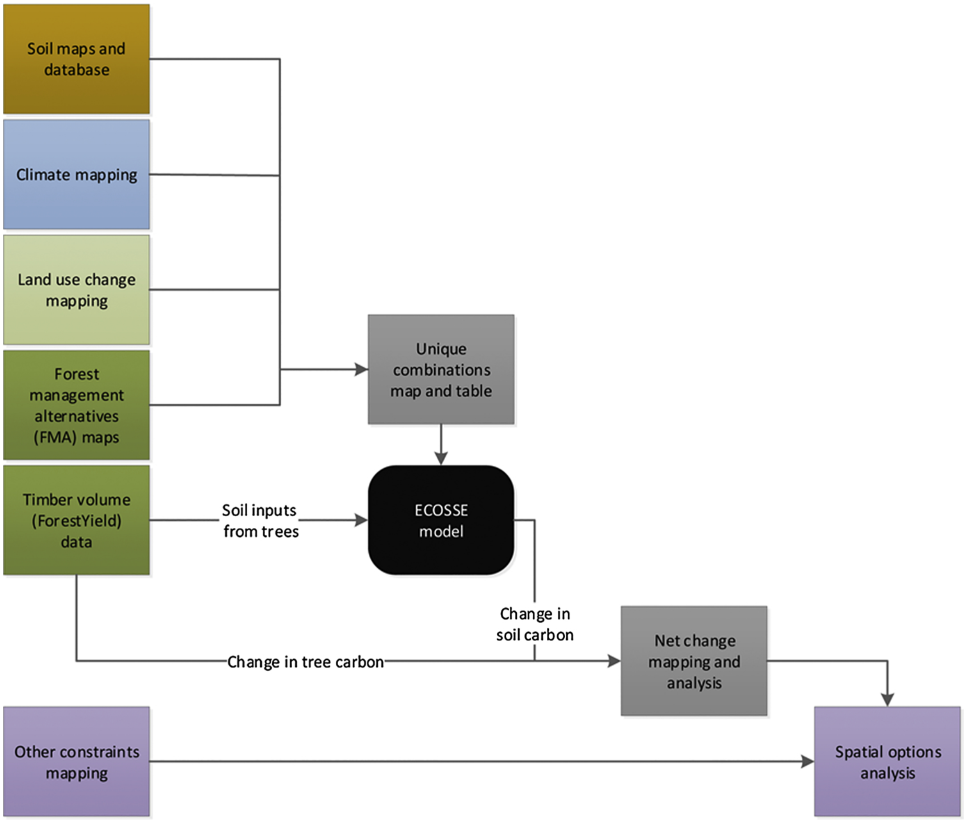

Fig. 1. The components of the change in net carbon stocks under afforesation analysis and their interactions.

implications for the use of the outputs from this approach using Scotland as a case study. Changes in soil carbon and the carbon stored within the woody biomass of the trees are integrated. Fig. 1 shows the components of the approach.

The Estimation of Carbon in Organic Soils – Sequestration and Emissions (ECOSSE) model took as its input unique combinations of climate, soils and land use data. The unique combinations maintain the higher granularity of the soils and land use datasets (1 ha cells) better than previously reported analysis (Matthews and Broadmeadow, 2009), while reducing the number of ECOSSE soil model runs needed (from 7 M to 0.2 M). ECOSSE generated rates of loss or sequestration of soil carbon for 5-year periods over a 100-year interval under diverse afforestation regimes.

Afforestation objectives and management regimes have been characterised by Duncker et al. (2012) using five archetypes, termed Forestry Management Alternatives (FMAs). Across the range of use intensities implied by these FMAs, eleven specific management regimes (termed here sub-FMAs) were used to assess the potential differences in the woody biomass component of carbon stocks. These define combinations of tree species, anticipated yields and management (rotation periods and thinning regimes). The sub-FMAs used characterise the broad range of types of afforestation likely to occur in Scotland (Mason and Perks, 2011). The Ecological Site Classification (ESC) model was used to map where sub-FMAs, where suitable and where threshold yields were met or exceeded (Pyatt et al., 2001), these are referred to in this paper as the sub-FMA opportunity (sub-$\mathrm{FMA_{OPP}}$) areas to distinguish the spatial patterns of where a sub-FMA could occur from the combination of species and management. The yield (timber volume) thresholds per sub-FMA are taken from ForestYield (Forest Research, 2001) which are derived from the yield tables of Edwards and Christie (1981). Within each sub-$\mathrm{FMA_{OPP}}$ area there will be areas that will achieve higher yields than the threshold for inclusion in the sub-$\mathrm{FMA_{OPP}}$ area, so estimates are conservative. Inputs from the trees to the soil (from leaf litter and woody debris) were specified per sub-FMA and used to scale the ECOSSE model of net primary production, driving soil dynamics (this detailed further in Section 2.3). Modelled above-ground tree growth volume (from ForestYield), expressed as carbon content, combined with change in soil carbon from ECOSSE provides an estimate of net change in carbon stocks.

2.2. Spatial data inputs

The soil mapping used is the 1:250,000 scale Soils Map of Scotland (James Hutton Institute, 2013). This map has national coverage, but smaller features within the landscape are not well represented. This makes it suitable for national and regional applications but not for site-specific decision-making. The soil parameters for ECOSSE are provided from the Scottish Soils Knowledge and Information Base (SSKIB) (Lilly et al., 2004). Each map unit (polygon) in the soil maps has estimated proportions of soil series whose typical characteristics are known. For a small area with thin or immature soils (e.g. rankers or lithosols for $<1\%$ of area) ECOSSE was set not to model the change in soil carbon.

The climate data used is a 5-km grid from U.K. Metrological Office, with daily values for the period 1960–2010 (Perry et al., 2009). The climate dataset has the lowest granularity and the signal from this variable can be visible in the map-based outputs as a line dividing two otherwise similar areas of soil and land use. Such artefacts are not frequently visible since differences within the more highly resolved datasets seem to have a greater effect on the estimates. ECOSSE and ESC can both use climate change data such as that provided by regional climate models but no attempt at 'future climate proofing' $\mathrm{FMA_{OPP}}$ areas or to assess the impact of climate change was implemented in this analysis.

The main source of land use data is the Integrated Administrative and Control System (IACS) administered by the Scottish Government. These data for 2014 are supplemented where necessary by earlier IACS data and by the (approximately) decadal datasets such as the National Forest Inventory 2011 (Anon, 2011) and the UK Land Cover Map 2007

(Morton et al., 2011). The coastline, inland water, urban and other infrastructural data are taken from Ordnance Survey MasterMap. The land use map is thus a composite in time and with some variation in scale of capture but does provide a high-resolution baseline from which options for afforestation can be assessed. Within this analysis the land use data were used as a 100 m (1 ha) grid, using the predominant land use per cell and generalised into four classes: cropping (including grassland used within a crop rotation); grasslands; semi-natural and forestry. These are the land use types that the ECOSSE model was parameterised to represent. The land use map used is shown in Supplementary Fig. 2.

2.3. Spatial application of the ECOSSE model

The ECOSSE model simulates soil carbon(C) and nitrogen (N) dynamics in both mineral and organic soils using climate, land use, land management and soil data, and simulates changes in SOC and soil GHG emissions. The model is described in detail in Smith et al. (2010a, b) and its main components are shown in Supplementary Fig. 3. The ECOSSE model has been thoroughly evaluated, and shown to simulate soil organic carbon (SOC) change, N_2O and CH_4 emissions reliably, for land use transitions in the UK using data from field sites, as described in Bell et al. (2012); Dondini et al. (2015; 2016a; 2016b) and Abdalla et al. (2014, 2016). The remainder of this section notes the changes to the ECOSSE model for its application to analysis of afforestation.

ECOSSE simulated the change in soil carbon dynamics for the afforestation options defined by each of the sub-FMAs. For each sub-FMA, simulations were run for all the unique combinations present in Scotland of climate, soils and antecedent land use (cropping, permanent grass and semi-natural land). ECOSSE was initialised to partition the SOC into the different organic matter pools assuming the SOC is at steady state under the land use at the start of the simulation. For the purposes of this study, previous historical land use changes were not considered. Nitrous oxide emissions and methane emissions were also simulated using the ECOSSE model, but emissions were negligible compared to the change in soil organic carbon – so these fluxes were omitted to simplify the narrative.

Following initialisation, the main simulation was executed. This started with land use change from the initial land-use type to the sub-FMAs. To implement this conversion, where there was a high water-table, as indicated by the soils database, the land was assumed to be initially drained. Soil cultivation carried out during land use change was then simulated. The model simulates soil cultivation for land use change from permanent grass and semi-natural land uses because these land-use types typically require ground preparation before trees are planted, whereas conversion from croplands assumes no additional disturbance since such fields are assumed to be regularly cultivated. The model simulates physical fragmentation of soil organic matter resulting from cultivation by moving a proportion of the C and N in the humus pool, which has a slow decomposition rate, to the decomposable plant material (DPM) and recalcitrant plant material (RPM) pools, which have faster decomposition rates (Smith et al., 2010a). Redistribution of soil organic matter during cultivation is simulated by homogenising the vertical distribution of the soil organic matter pools down to the cultivation depth. The simulated cultivation depth for conversion from semi-natural land uses and permanent grass is 0.5 and 0.3 m respectively, assuming normal cultivation (disturbance) practices.

After simulation of the cultivation associated with land use change, the model simulates soil dynamics for the unique combinations of climate, soils and land use within each sub-FMA_{OPP} area. The plant-soil inputs for the initial land uses are a modification of the established net primary productivity (NPP) model MIAMI (Leith, 1975), the modification takes into account the proportion of NPP that is returned to the soil under different sub-FMAs and also total NPP for different sub-FMAs. The balance and size of plant inputs from each sub-FMA, into the DPM and RPM plant matter pools in MIAMI are scaled and constrained by the Forest Research BSORT model and associated publications (McKay et al., 2003; Morison et al., 2012). The total plant inputs from each sub-FMA were also used to modify (scale) the modelling of forest plant input in the ECOSSE as follows. The default values for the plant inputs to the soils (from a generic tree species) were increased or decreased using each sub-FMA's yield and management practices. This allowed the estimation of plant inputs for each sub-FMA_{OPP} area. This maintains a degree of consistency between the plant and soil components of the system (each is responding to the same climate).

2.4. Forestry data and models

A range of options exists for forestry management with a gradient of intensity of intervention (Duncker et al., 2012). The broad classes of options, termed Forest Management Alternatives (FMAs), include: Unmanaged forest nature reserve; Close-to-nature forestry; Combined objective forestry; Intensive even-aged forestry; and Wood biomass production. Different FMAs have significantly differing objectives, from preserving natural processes without human intervention through delivering multiple benefits to maximizing biomass production or revenue from timber. The examples of forestry systems included within this analysis are defined as sub-FMAs and are presented in Table 1.

For each sub-FMA, a representative yield class is assigned, and timber volume is derived from ForestYield – a digital version of the Forestry Commission Forest Yield Tables (Edwards and Christie, 1981). The ForestYield model (Matthews et al., 2016) is built upon an extensive UK permanent sample plot network and has been reviewed against a stand level dynamic growth model (Lonsdale et al., 2015a) and shown to perform well for Scots pine (Lonsdale et al., 2015b). These values are then used to estimate the mass of carbon stored in the woody biomass (Morison et al., 2012). The standing volume model outputs are scaled using well-established and robust allometric relationships (Levy et al., 2004; McKay et al., 2003) and modified by wood density (Lavers and Moore, 1983) to convert wood volumes to dry weight, 50% of which is assumed to be carbon (Matthews, 1993). Estimates of carbon stocks per sub-FMA were produced assuming 'standard' initial spacings and grown under 'standard' management regimes. For this investigation, estimates from annual growth with standard management practices have been accumulated into five-year periods over a 100-year interval to match the ECOSSE outputs. The five-year periods have been derived from annual estimates to adequately represent stand growth in terms of changing vigour (increment) throughout tree life. Where thinning and rotational felling have occurred, the fate of the forest products and their substitution benefit has not been accounted for in this analysis (e.g. timber replacing concrete as a building material or replacing fossil fuels) so the estimates of net carbon balance are conservative.

3. Results

3.1. Maps

For each sub-FMA_{OPP} area and time interval, maps of the net rate of change in carbon stocks can be generated (in $\text{t·ha}^{-1}\text{·yr}^{-1}$). Example maps for four sub-FMA_{OPP} area at year 40 after planting are presented in Fig. 2. Each sub-FMA_{OPP} area is presented using a colour ramp for net change in carbon stocks from red at -3.59 $\text{t·ha}^{-1}\text{·yr}^{-1}$ to blue at 5.37 $\text{t·ha}^{-1}\text{·yr}^{-1}$. Darker colours signify more extreme values with the crossover at zero (close to white). The range and ramp are fixed across all sub-FMA_{OPP} areas and all periods making the maps directly comparable. The white areas are those not suitable for the sub-FMA_{OPP} species. The black areas (typically small and/or localised) are areas within the sub-FMA_{OPP} area with a land use that is not one of Cropping, Grasslands, Semi-Natural or Forestry. The yellow areas indicate where the characteristics of the soils mean that ECOSSE was set not to model

Table 1

Management prescriptions for minimal threshold modelled yield by species used to represent each of the 11 Forestry Management Alternatives.

No	FMA Name	FMA definition[a]	Species and assumed Yield Class (YC)	Stand Carbon (t˙ha^{-1})		
		FMA Native[b]		**20**	**40**	**80**
1	Native Conifer	Scots pine [YC4_MT] {2.5} <CCF> - no harvest	**Scots Pine YC4**	0.3	3.0	30.11
2	Native Broadleaf	(2) broadleaf Sycamore, Ash and Birch [YC4_NT] {2.5} <CCF> - no harvest	**Sycamore, Ash and Birch (SAB) YC4**	8.0	44.7	93.3
		FMA Multi-Purpose		**20**	**40**	**80 (70 + 10)**
3	Multi-Purpose Broadleaf	(3) MultiP Productive broadleaf Sycamore, Ash and Birch [YC6_MT] {2.5} 80	**Sycamore, Ash and Birch (SAB) YC6**	11.7	37.1	70.0
				20	**40**	**80 (50 + 30)**
4	Multi-Purpose Sitka Spruce	(4) MultiP Sitka Spruce SS [YC12_MT] {2.0} 50	**Sitka Spruce YC12**	8.1	37.1	74.1
5	Multi-Purpose Conifer	(5) MultiP Alternative Conif [YC8 _MT] {1.7} 50	**Japanese Larch YC8**	17.9	38.5	74.9
		FMA Production		**20**	**40**	**80 (50 + 30)**
6	Production Douglas Fir	(6) Production Douglas Fir DF [YC18_MT] {1.7} 50	**Douglas Fir YC18**	33.7	71.6	141.2
7	Production Sitka Spruce	(7) Production Sitka Spruce SS [YC16_MT] {2.0} 50	**Sitka Spruce YC16**	15.8	49.2	97.6
8	Production Conifer	(8) Production Alternative Conif [YC10_MT] {1.7} 50	**Japanese Larch YC10**	23.0	44.4	86.8
		FMA Short Rotation Forestry		**20**	**40 (25 + 15)**	**80 (25 + 25 + 25 + 5)**
9	Short Rotation Aspen	(9) SRF ASPEN [YC10_NT] {2.5} 25	**Aspen YC10**	30.6	62.1	143.9
10	Short Rotation Rauli	(10) SRF Non-Native as Sycamore, Ash and Birch [YC12_NT] {2.5} 25	**Sycamore, Ash and Birch YC12**	43.8	88.5	191.7
11	Short Rotation Eucalypt	(11) SRF Non-Native as Sycamore, Ash and Birch [YC12_NT] {2.5} 25	**Sycamore, Ash and Birch YC12**	43.8	88.5	191.7

[a] FMA definition defined as: (ID Number.) Species [Yield Class_Thinning] {Spacing (in m)} <management > Rotation length.

[b] Both managed without harvest (i.e. Continuous Cover Forestry (CCF)).

the change in soil carbon (such as rankers or lithosols). The green areas are existing woodland showing no land use change. Maps for all the sub-FMAs across all time periods are presented at http://woodlandexpansion.hutton.ac.uk/.

3.2. Rate versus area charts

The rates versus areas charts presented for the same example sub-FMAs (in Fig. 3–6) provide a means of assessing the areas associated with particular rates of sequestration or emission and aid in the interpretation of the maps. This is particularly important since cartographical compromises may inadvertently over- or under-emphasise features. These charts are a way of showing the scope for positive carbon accumulation outcomes versus the extent of the whole sub-FMA$_{OPP}$ area and allow comparison between sub-FMAs.

The charts show an ordered (smallest to largest) set of net rates of change in carbon sequestration (in t·ha^{-1}·yr^{-1}), for each unique combination of land use, soils and climate, against the accumulated area of the unique combinations (ha). It does this for five periods 20, 40, 60, 80 and 100 years. For all sub-FMA charts the same numerical ranges for the axes are used, so both the relative magnitudes of change in carbon and the extent of the sub-FMA$_{OPP}$ areas can be judged. The characteristic stepping in the graphs is associated with changes in the antecedent land use – semi-natural (on organic and organo-mineral soils), grasslands and cropping (read from left to right of the graph). Within the semi-natural area there is a significant gradient from highly organic soils with the largest net losses to organo-mineral soils that can in some cases yield net positive rates of carbon sequestration after a period of losses.

3.3. Comparing overall performance between sub-FMAs

The extent of each sub-FMA$_{OPP}$ area and the area-weighted mean of net change in stored carbon per annum over 20, 40 and 80 years is given in Table 2. The table also presents change values for subsets of each sub-FMA$_{OPP}$ area defined by antecedent land use. The table highlights sub-FMA$_{OPP}$ areas where on average there are net losses of carbon, and which would require a presumption against planting, if avoidance of any loss were a priority. The potential effectiveness of such targeting measures is discussed in Section 4.2 and illustrated in the supplementary materials. The table highlights that if early contributions to carbon storage (<20 years) is required, then the range of sub-FMAs that can deliver this is limited, especially for semi-natural antecedent land uses.

3.4. Distribution of sequestration rates for 100,000-hectare permutations

To gain a better understanding of the likelihood of outcomes for each sub-FMA, the rates of carbon accumulation or loss per annum have been calculated for permutations ($n = 100{,}000$) of 100,000 ha of new woodland planting for each sub-FMA (termed here the sub-FMA$_{100}$ set). The distribution of the rates of change in carbon (t·ha^{-1}·yr^{-1}) for the sub-FMA$_{100}$ sets, drawn at random from the population of land parcels, provides an estimation of the most likely outcome, assuming proposals for planting are made at random and approved on the same basis. Fig. 7 summarises the distribution of average rates of change in carbon sequestration for the sub-FMA$_{100}$ sets. The figure shows the range of values that occur over 100 years at 20-year intervals. The central boxes show where 50% of the instances occur (25th to 75th percentile) and the ‘whiskers’ show the minimum and maximum values that were generated in each sub-FMA$_{100}$ set of permutations. The sub-FMA$_{100}$ sets are ordered based on their performance for the first 20 years.

3.5. Outcomes for combinations of sub-FMAs

The consequences for rates of carbon stock change of combining pairs of sub-FMA$_{OPP}$ areas are also presented. Given the additional area of afforestation is small relative to the land area potentially available (for most sub-FMA$_{OPP}$ areas), then it is possible to make a simplifying assumption that each of the sub-FMAs is not competing for the same land. This allows for combinations of sub-FMA$_{OPP}$ areas to be estimated by using the average rates per sub-FMA$_{OPP}$ area (as defined in Table 2)

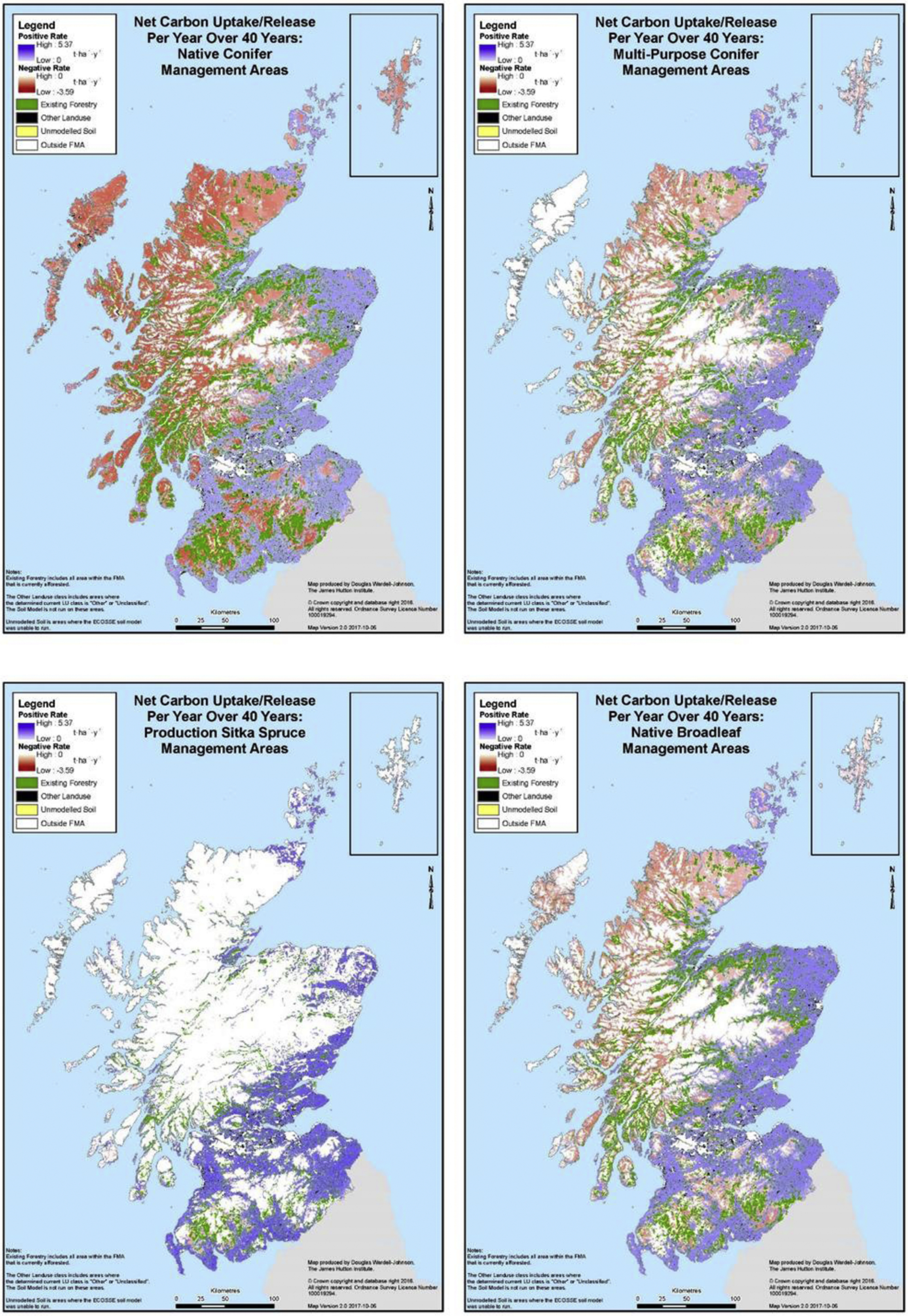

Fig. 2. Maps of carbon accumulation or loss characteristics for selected sub-FMA$_{OPP}$ areas.

and varying the relative proportions of each FMA. Two example outputs are presented, Table 3 for 50:50 ratios of sub-FMAs and Table 4 for 60:40 ratios of sub-FMAs. The cells in both tables present the average rate of accumulation or loss over 20 years in t·ha^{-1}·yr^{-1} of carbon for the sub-FMA$_{OPP}$ area combinations. Table 4 defines the accumulation or loss rates associated with each sub-FMA's use both as the larger and as

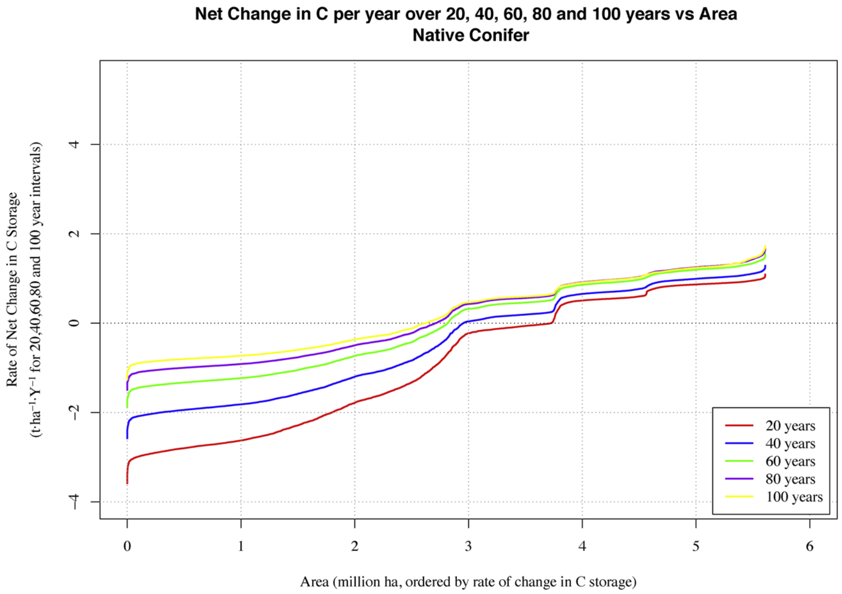

Fig. 3. Carbon accumulation or loss characteristics of the Native Conifer sub-FMA$_{OPP}$ area.

the smaller percentage. The cells are formatted to highlight where combinations result in losses, are neutral and see accumulation. The two tables highlight that decisions on the mix of sub-FMAs preferred for support by public policy will have a strong influence on the outcomes of afforestation in terms of changes in net rates of carbon accumulation or emissions. Since the analysis has used rates of change derived using all land in the sub-FMA$_{OPP}$ area, these values will have been inflated by using potentially large areas of land that, whilst included in the sub-FMA$_{OPP}$ area, are less likely to be proposed for afforestation. Using the semi-natural land only would reduce the rates but have the same pattern of interactions between the FMAs. Effective targeting within sub-FMA$_{OPP}$ areas remains essential if net losses are to be avoided.

3.6. Assessment of FMA combinations against a carbon sequestration target

If an assumption on a target in terms of tonnage of carbon is made rather than an area-based afforestation target, then it is possible to assess which of the combinations of sub-FMA proportions could meet such a target. Table 5 uses the 60:40 planting options and the average change in carbon stock rates, from Table 2 (for All Land, for the first 20 years) to assess the feasibility of achieving a 100-kilotonne target for net carbon storage per annum.

In Table 5 the blank areas show combinations that have no feasible way to meet the target since their combined rates are negative, based on stand carbon stocks (i.e. without including any substitution benefits). The remainder of the table shows the percentage of the 100,000 ha afforestation target area needed to deliver the 100-kilotonne target. For some combinations, the area required is less than the current 100,000 ha woodland planting target (those below the black line within the table), where the sub-FMAs are very efficient in delivering carbon accumulation. These tend to be production-oriented sub-FMAs which preferentially target lowlands with, for example, Sitka spruce and Douglas fir. These could to some degree offset other less effective or even loss-generating sub-FMAs and keep the area required below the 100,000 ha target. In other cases, where a combined planting option has a combined rate of carbon sequestration of less than 1.0

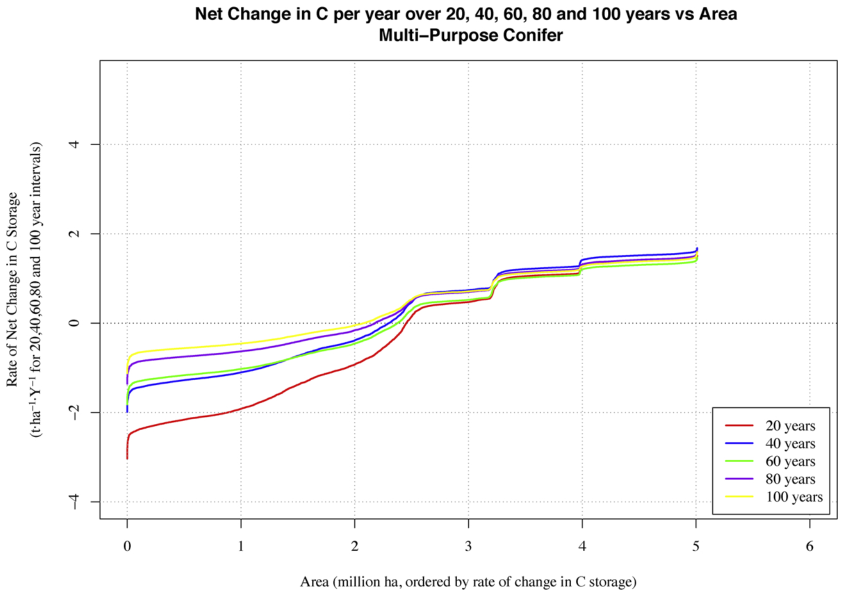

Fig. 4. Carbon accumulation or loss characteristics of the Multi-purpose Conifer sub-FMA$_{OPP}$ area.

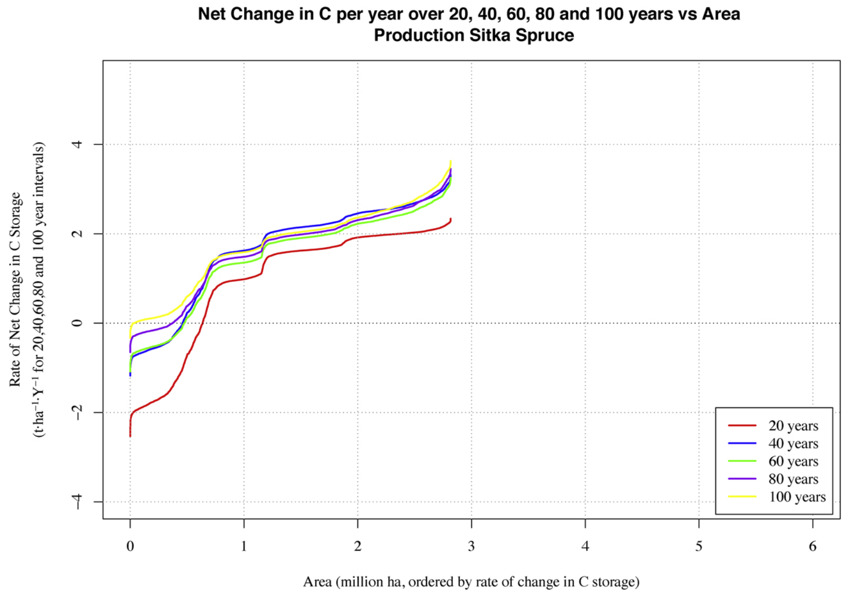

Fig. 5. Carbon accumulation or loss characteristics of the Prodcution Sitka Sprucer sub-FMA$_{OPP}$ area.

t·ha^{-1}·yr^{-1}, this requires an area larger than the 100,000 ha target. Even where a combination can achieve the target then the cost in terms of land take may be too large. This can be either in absolute terms, where the area required for the combination is larger than the sub-FMA$_{OPP}$ area (e.g. Native Conifers and Short Rotation Aspen), or in relative terms when set against other societal needs (since it takes too large a share of even an extensive sub-FMA$_{OPP}$ area).

4. Discussion

4.1. Features of the example sub-FMAs

The Native Conifer option with low timber yield (Fig. 3) shows a severely limited sub-FMA$_{OPP}$ area over which occur any gains in net carbon stocks for the first 20 years, with nearly 4 million ha below breakeven and, even by 40 years, nearly 3 million ha that still have negative net values. The chart also highlights the effect of the management regime for Native Conifer - continuous cover forestry with no clear fell and regeneration managed through selective thinning. This results in an increase in net carbon stocks up to 60 or 80 years depending on circumstances and then some later decline except in the least productive and highest carbon soils. Extensive afforestation on this basis is unlikely to make a significant contribution to carbon sequestration unless targeted on lowland farmland where, in practice, the opportunity costs and other socio-cultural factors make it highly unlikely to be adopted, see Hopkins et al. (2017) who elaborate this argument in detail.

For the multi-purpose conifer example (Fig. 4), the chart shows that even for a substantially more productive system than Native Conifers (Yield Class 8 rather than Yield Class 4), positive net carbon stock returns are achieved in just under half the FMA$_{OPP}$ area. The maximum rates of net gain are generally estimated at less than 1.0 t·ha^{-1}·yr^{-1} of carbon for rough grazing and above 1.0 t·ha^{-1}·yr^{-1} of carbon for improved grassland or cropland. The chart also shows the potential to generate artefacts by the choice of reporting period. A 60-year reporting period for this sub-FMA means a full rotation (50 years) plus another

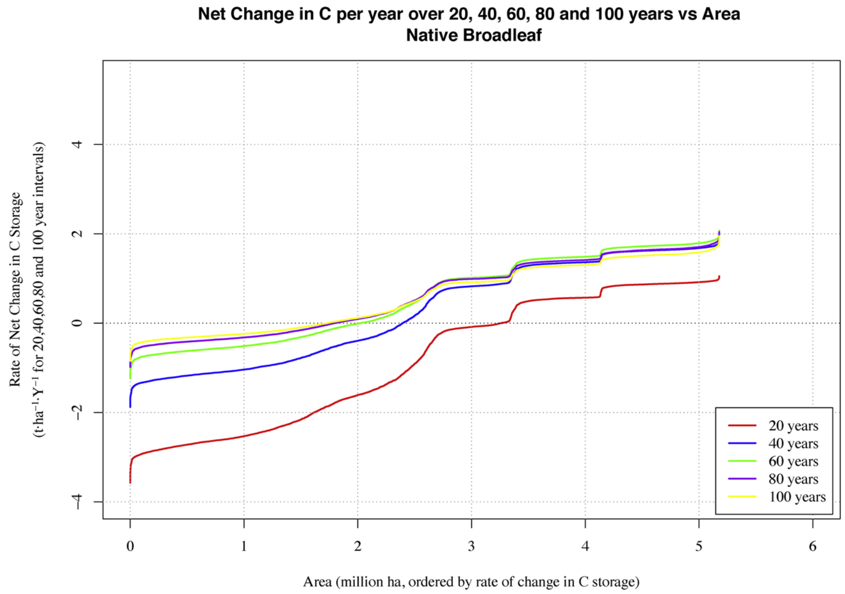

Fig. 6. Carbon accumulation or loss characteristics of the Native Broadleaf sub-FMA$_{OPP}$ area.

Table 2

Average change in carbon (t ha^{-1} y^{-1}) for each sub-FMA at 20, 40 and 80 years by antecedent land use.

Land Use Sub-FMA	All Area	t ha^{-1}·y^{-1} of carbon			Semi-natural Area	t ha^{-1}·y^{-1} of carbon		
Management	(M ha)	Net20	Net40	Net80	(M ha)	Net20	Net40	Net80
Native Conifer	5.6	−0.89	−0.45	0.11	3.6	−1.72	−1.12	−0.42
Native Broadleaf	5.2	−0.84	0.26	0.61	3.2	−1.74	−0.45	0.08
Multi-Purpose Broadleaf	4.4	−0.79	−0.07	0.12	2.5	−1.80	−0.85	−0.49
Multi-Purpose Conifer	5.0	−0.26	0.19	0.34	3.1	−1.13	−0.51	−0.22
Multi-Purpose Sitka Spruce	3.6	−0.20	0.64	0.73	1.8	−1.38	−0.30	−0.05
Production Conifer	3.1	0.60	0.84	0.89	1.5	−0.59	−0.12	0.11
Production Sitka Spruce	2.8	0.94	1.65	1.64	1.1	−0.39	0.52	0.64
Short Rotation Aspen	2.0	1.25	1.31	1.65	0.5	0.02	0.21	0.85
Short Rotation Eucalypt	1.8	2.10	2.14	2.40	0.4	0.72	0.91	1.50
Short Rotation Rauli	1.6	2.19	2.21	2.45	0.3	0.88	1.04	1.59
Production Douglas Fir	1.3	3.34	3.94	3.89	0.2	1.82	2.20	2.05
Land Use	Grasslands				Cropping			
Sub-FMA	Area	t ha^{-1}·y^{-1} of carbon			Area	t ha^{-1}·y^{-1} of carbon		
Management	(M ha)	Net20	Net40	Net80	(M ha)	Net20	Net40	Net80
Native Conifer	0.9	0.38	0.56	0.84	1.1	0.87	1.00	1.28
Native Broadleaf	0.9	0.40	1.22	1.29	1.1	0.88	1.63	1.65
Multi-Purpose Broadleaf	0.8	0.32	0.77	0.75	1.0	0.76	1.14	1.05
Multi-Purpose Conifer	0.8	0.94	1.12	1.08	1.0	1.39	1.51	1.41
Multi-Purpose Sitka Spruce	0.8	0.77	1.40	1.33	1.0	1.23	1.82	1.73
Production Conifer	0.7	1.39	1.45	1.38	1.0	1.81	1.82	1.70
Production Sitka Spruce	0.7	1.53	2.06	1.92	1.0	2.00	2.63	2.57
Short Rotation Aspen	0.6	1.42	1.47	1.74	0.9	1.80	1.79	2.01
Short Rotation Eucalypt	0.6	2.24	2.27	2.47	0.9	2.64	2.61	2.75
Short Rotation Rauli	0.5	2.27	2.29	2.48	0.8	2.63	2.61	2.75
Production Douglas Fir	0.4	3.06	3.71	3.68	0.7	3.91	4.55	4.52

ten years, so a second period of establishment losses is included.

The Production Sitka spruce chart (Fig. 5) and map (Fig. 2 bottom left) highlight the smaller area of Scotland that would support a production-oriented Sitka Spruce regime, with an assumed Yield Class of 16. This narrowing of scope when combined with the larger stand biomass means that a substantial majority of the sub-FMA$_{\mathrm{OPP}}$ area can achieve positive net carbon stock values. Net change above 1.0 t·ha^{-1}·yr^{-1} of carbon is commonplace and can reach 4.0 t·ha^{-1}·yr^{-1} of carbon. The modelled scenario is Yield Class 16 Sitka spruce, whilst plantations on good quality soils, in Scotland, can produce Yield Class 26 (Mason and Perks, 2011). Carbon sequestration benefits from afforestation with productive conifers in this study, expressed as net ecosystem productivity (NEP) averaged across 80 years, were 2.25 t·ha^{-1}·yr^{-1} of carbon and are close to those reported in other published studies for Sitka spruce which range from 1.8-2.6 t·ha^{-1}·yr^{-1} of carbon for Yield Class 14 and 20, respectively (Mason et al., 2009; Minunno et al., 2010). The increase in sequestration benefit compared to multi-purpose Sitka spruce, in this study, reflects both improved yield and a reduction in the area of organo-mineral soils included in the sub-FMA$_{\mathrm{OPP}}$ area with a reduction in soil disturbance losses.

The Native Broadleaves option (Fig. 6) covers an extensive area but again close to half of the area sees a net depletion of carbon stocks. For cropping, grasslands and semi-natural antecedent land uses on lower carbon soils, there are no further gains beyond 60 years and some cases

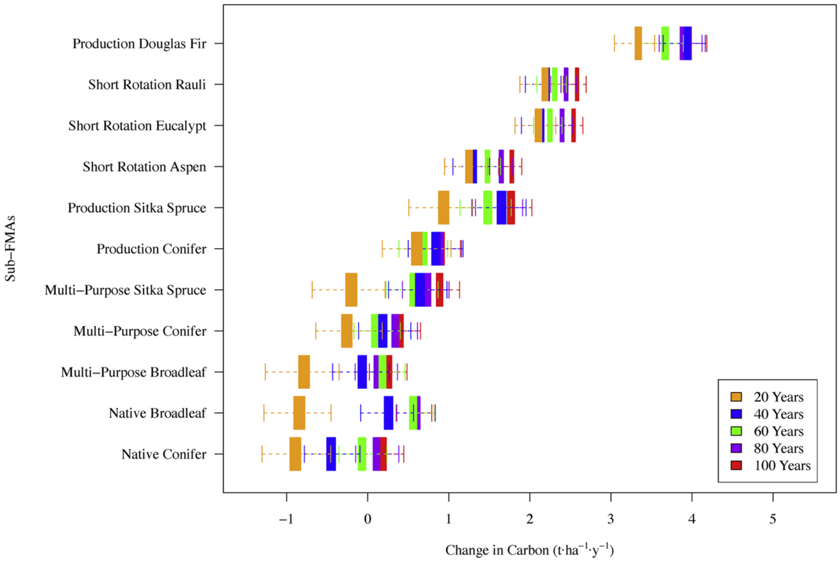

Fig. 7. The distributions of average carbon sequestration rates per annum for permutations of 100,000 ha of each sub-FMA$_{\mathrm{OPP}}$ area at 20, 40, 60, 80 and 100 years.

Table 3
Average change in carbon for pairs of sub-FMA's combined at 50%:50%.

		Percentage 50%										
	Sub-FMA Net 20 change in carbon (t ha^{-1}·y^{-1})	Native Conifer	Native Broadleaf	Multi-Purpose Broadleaf	Multi-Purpose Conifer	Multi-Purpose Sitka Spruce	Production Conifer	Production Sitka Spruce	Short Rotation Aspen	Short Rotation Eucalypt	Short Rotation Rauli	Production Douglas Fir
Percentage 50%	Native Conifer	−0.89										
	Native Broadleaf	−0.87	−0.84									
	Multi-Purpose Broadleaf	−0.84	−0.81	−0.79								
	Multi-Purpose Conifer	−0.58	−0.55	−0.52	−0.26							
	Multi-Purpose Sitka Spruce	−0.55	−0.52	−0.49	−0.23	−0.20						
	Production Conifer	−0.14	−0.12	−0.09	0.17	0.20	0.60					
	Production Sitka Spruce	0.02	0.05	0.07	0.34	0.37	0.77	0.94				
	Short Rotation Aspen	0.18	0.20	0.23	0.50	0.52	0.93	1.09	1.25			
	Short Rotation Eucalypt	0.61	0.63	0.66	0.92	0.95	1.35	1.52	1.68	2.10		
	Short Rotation Rauli	0.65	0.67	0.70	0.96	0.99	1.40	1.56	1.72	2.15	2.19	
	Production Douglas Fir	1.22	1.25	1.27	1.54	1.57	1.97	2.14	2.29	2.72	2.76	3.34

Table 4
Average change in carbon (t ha-1 y-1)for pairs of sub-FMA's combined at 60%:40%.

		Percentage 60%										
	Sub-FMA Net 20 change in carbon (t·ha-1·y-1)	Native Conifer	Native Broadleaf	Multi-Purpose Broadleaf	Multi-Purpose Conifer	Multi-Purpose Sitka Spruce	Production Conifer	Production Sitka Spruce	Short Rotation Aspen	Short Rotation Eucalypt	Short Rotation Rauli	Production Douglas Fir
Percentage 40%	Native Conifer	−0.89	−0.86	−0.83	−0.51	−0.48	0.01	0.20	0.39	0.91	0.95	1.64
	Native Broadleaf	−0.87	−0.84	−0.81	−0.49	−0.46	0.03	0.22	0.41	0.93	0.97	1.66
	Multi-Purpose Broadleaf	−0.85	−0.82	−0.79	−0.47	−0.44	0.05	0.25	0.43	0.95	1.00	1.69
	Multi-Purpose Conifer	−0.64	−0.61	−0.57	−0.26	−0.23	0.26	0.46	0.65	1.16	1.21	1.90
	Multi-Purpose Sitka Spruce	−0.62	−0.59	−0.55	−0.24	−0.20	0.28	0.48	0.67	1.18	1.23	1.92
	Production Conifer	−0.29	−0.26	−0.23	0.09	0.12	0.60	0.80	0.99	1.50	1.55	2.24
	Production Sitka Spruce	−0.16	−0.13	−0.10	0.22	0.25	0.74	0.94	1.12	1.64	1.69	2.38
	Short Rotation Aspen	−0.04	−0.01	0.03	0.34	0.38	0.86	1.06	1.25	1.76	1.81	2.50
	Short Rotation Eucalypt	0.31	0.34	0.37	0.69	0.72	1.20	1.40	1.59	2.10	2.15	2.84
	Short Rotation Rauli	0.34	0.37	0.40	0.72	0.75	1.24	1.44	1.62	2.14	2.19	2.88
	Production Douglas Fir	0.80	0.83	0.86	1.18	1.21	1.70	1.90	2.08	2.60	2.65	3.34

Table 5
Percentage of the 100,000 ha area needed to deliver an examplar 100 kt per annum target for accumulated carbon over 20 years using combinations of pairs of sub-FMAOPP areas and a 60%:40% ratio.

		Percentage 60%										
	Sub-FMA (% of 100,000 ha required to meet a 100 kt target)	Native Conifer	Native Broadleaf	Multi-Purpose Broadleaf	Multi-Purpose Conifer	Multi-Purpose Sitka Spruce	Production Conifer	Production Sitka Spruce	Short Rotation Aspen	Short Rotation Eucalypt	Short Rotation Rauli	Production Douglas Fir
Percentage 40%	Native Conifer						18130%	489%	255%	110%	105%	61%
	Native Broadleaf						3894%	445%	243%	108%	103%	60%
	Multi-Purpose Broadleaf						2069%	405%	230%	105%	100%	59%
	Multi-Purpose Conifer						385%	218%	155%	86%	83%	53%
	Multi-Purpose Sitka Spruce						355%	208%	150%	85%	81%	52%
	Production Conifer				1144%	835%	165%	124%	101%	66%	64%	45%
	Production Sitka Spruce				455%	396%	136%	107%	89%	61%	59%	42%
	Short Rotation Aspen			3622%	290%	265%	116%	94%	80%	57%	55%	40%
	Short Rotation Eucalypt	327%	298%	270%	146%	139%	83%	71%	63%	48%	46%	35%
	Short Rotation Rauli	296%	271%	248%	139%	133%	81%	70%	62%	47%	46%	35%
	Production Douglas Fir	125%	121%	116%	85%	82%	59%	53%	48%	39%	38%	30%

a degree of decline in net carbon. For higher organic content soils, the rate of loss declines steadily over the period but for some is still substantial even after 100 years, even with no further management disturbance. New upland native broadleaf afforestation should be promoted through natural regeneration or low impact cultivation, which minimises soil disturbance losses and is managed long-term as a carbon reserve (Broadmeadow and Matthews, 2003). Even with this management regime, carbon accrual will be slow due to the low yield of native broadleaves on poor soils in upland sites. Productive broadleaves on better soils can, however, deliver net carbon sequestration early in their rotation and can be integrated into farmland management, using otherwise lightly utilised land or as shelterbelts or agroforestry.

In all cases the net mitigation benefits of new woodlands are larger if the substitution benefits from the uses of harvested wood products are considered within the overall accounting. Such benefits are though reported in GHG inventories as reductions in emissions from other sectors such cement or iron and steel production (Eurostat, 2017). These substitution effects can be substantial, with Sathre and O'Connor (2010) estimating an additional 2.1 tonnes of carbon emissions are potentially avoided per tonne of harvested wood product used. Substitution benefits are most significant when wood is used in items with long lifespans (e.g. in construction) and when the materials can also be retrieved and used as a fuel source at end-of-life (Matthews and Broadmeadow, 2009; Matthews et al., 2007). The 2030 and 2050 dates by which emission reductions are desired, however, means that for new woodlands these substitution benefits will in practice accrue only from thinning rather than end of rotation harvest, except for short rotation coppice-based systems. For climate change mitigation policy, the focus must be on how well the forestry performs in terms of the carbon embodied in both the trees and soils.

4.2. *Whole FMA summaries*

The key element to highlight from the whole FMA summaries is that for conversion from semi-natural land use, most sub-FMAs are estimated to see net losses for the first 20 years and, even by 80 years, some (four) are still on average net emitters or are only just breaking even. In early years, even for some production-oriented sub-FMAs such as Production Sitka spruce, net losses occur, especially on organo-mineral soils, and this would mean that such new plantings would not positively contribute to mitigation within the time frames of the commitments in the Climate Change (Scotland) Act. This means that, for most sub-FMA$_{OPP}$ areas, there is the need to be very careful in approving any land with semi-natural vegetation for afforestation in such circumstances. There will be areas that can generate higher rates of net carbon accumulation than are assumed by the yield threshold for each sub-FMA$_{OPP}$ area, but realising such opportunities requires careful targeting and policies that favour the most productive regions within sub-FMA$_{OPP}$ areas.

The need for targeting to avoid carbon loss from new afforestation is recognised by a statutory general presumption against planting new woodlands on deep peat soils, that is those with more than 50 cm of peat in the top 100 cm of profile (Morison et al., 2010). When such soils are excluded from the sub-FMA$_{OPP}$ areas this does increase the mean value for net change in carbon, but it does not eliminate the risk of afforestation resulting in net carbon loss. The effects of excluding the deep peats are quantified in Supplementary Materials Table 1.

4.3. *Distribution of rates for 100,000 ha*

The range of potential outcomes per sub-FMA is narrow for the permutations of 100,000 ha sized sub-sets of unique combinations drawn at random from the sub-FMA$_{OPP}$ area (Fig. 7). The distributions of potential outcomes are close to normal, meaning the averages from the whole sub-FMA$_{OPP}$ area summaries provide a fair indication of the likely outcomes in the absence of other interventions. It also highlights that on average by 40 years all but two sub-FMAs are making positive, even if in some cases marginal, contributions to carbon sequestration. Yet the question must be how relevant such a delayed and or marginal contribution would be to achieve the high-level national objective of an 80% reduction in emissions. One answer may be that achieving the last 10% of an 80% reduction is likely to be the most difficult, requiring either substantial technological or behavioural change and offsetting may be more efficient were investment made now.

Using permutations of land parcels assumes that applications for planting are made at random from the population and that approvals are equally undiscerning. There is potential to make the assumptions more realistic by tailoring the permutations to reflect historic patterns of planting by land quality. Brown et al. (2014) clearly show the strong bias in favour of afforestation of land with the lowest land capability for agriculture (LCA 6.3, land capable of supporting only rough grazing - see Supplementary Materials). Part of this bias is simply in the availability of land, with LCA 6.3 being the most extensive. So, by chance, one would expect around 45% of woodlands to fall on LCA6.3. The Brown et al. (2014) data identify that for LCA classes 5.2 and 5.3 (land capable of supporting improved grassland) actual woodland percentages are 12–15% whereas the percentage would be ~6% by chance. Woodland is, however, underrepresented in the higher quality (lower numbered) LCA classes, for example LCA 3.2 having 6% rather than 10%. It is also interesting to note that for new woodlands (2004 − 13 in the Brown et al. (2014) data) there is more of a bias towards poorer quality land when compared with earlier plantings. Continuing with historical planting patterns is likely to further limit the likely contribution of forestry to emissions mitigation. Altering the distribution of future planting is likely to require rebalancing priorities within forestry and agriculture policies and changes to payment regimes.

4.4. Combinations of FMAs

The combinations of sub-FMA tables highlight the variety of hard and soft constraints in operation and show one way in which the options for combining sub-FMAs may be quantified. Hard constraints occur where the combinations cannot deliver the target since they result in negative accumulation rates. Softer constraints are highlighted when the combinations result in required planting areas above (and in some cases well above) the current planting targets. While not an absolute constraint like the sub-$\mathrm{FMA_{OPP}}$ area, an increase in required area with a fixed support budget would likely mean less support per unit of area unless other sources of funds were added, e.g. through a carbon-cap-and trade system for emissions from agricultural land. Since the current area target has been challenging to meet with existing funding levels, it is unlikely that without additional funds these combinations requiring even larger areas could be achieved. Where combinations require larger shares of the sub-$\mathrm{FMA_{OPP}}$ area, this also makes their success less likely since, given the voluntary nature of afforestation, it is highly unlikely that the larger shares required will become available, without a change in policy or other circumstances.

5. Conclusions

There is substantial potential for new woodlands to make a strongly positive contribution to GHG emission abatement in Scotland and elsewhere. The importance of afforestation for carbon sequestration may be in offsetting emissions from sectors where an emissions reduction to 80% of 1990 levels or achieving carbon neutrality by 2050 is biophysically or financially impractical. The potential value of new woodlands is recognised by policy makers but is often framed as an overarching area-based target.

The paper has highlighted the limitations of area-based targets as an indicator of carbon sequestration outcomes and the potential for area-based targets to unintentionally generate undesirable outcomes. The range of possible outcomes for any area of planting is substantial, meaning that outcomes are highly sensitive to other macro policy decisions, for example on the strategic mix of forestry systems preferred and to micro-scale targeting decisions that favour particular forestry management alternatives and/or their spatial distributions.

For area-based targets to be effective in ensuring GHG emissions abatement outcomes they need to include explicit supporting assumptions on the minimum anticipated extent or rate of carbon sequestration delivered across the area of new woodlands. Otherwise a combination of land manager preferences, budgetary limitations, and the unintended consequences of other land use or agricultural policies can lead to the afforestation of less productive land, on soils with higher organic matter contents, that in the worst cases results in net emissions of carbon for decades. Any increase in a target area requires an increased budget since otherwise reduced rates of support per hectare could potentially mean less rather than more planting, or new plantings being restricted to those that deliver predominantly nature conservation outcomes. Supplementary carbon sequestration extents or rates for new forestry would introduce a floor for carbon storage outcomes but would still allow for flexibility in achieving an appropriate balance in the trade-offs between carbon sequestration and the many other objectives that new woodlands are expected to deliver.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2020.104690.

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