Ecosystem services provision from alternative management options was modified to Ireland's western peatland forests under future development scenarios

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Abstract

A forest decision support system to include impacts of climate change, dynamic assortment prices and Ecosystem Service (ES) indicators and used it to model forest management of a peatland forest landscape in the west of Ireland. Alternative Forest Management Models (aFMMs) were developed for unfertilised blanket bog sites. They focused on low-stocking lodgepole pine, Sitka spruce and birch mixtures, and bog restoration. These aFMMs were implemented in a linear programming-based decision support system that already contained current FMMs (cFMMs). ES provision results when using only cFMMs were compared to those when both cFMMs and aFMMs were used.

Using an objective to maximise Net Present Value (NPV), the aFMMs were established on sites with poor to marginal productivity. Their use led to improvements in NPV, biodiversity, water quality, landscape aesthetics and reduced windthrow risk, while harvest volume and carbon storage decreased. Compared to the increased demand for wood, the climate change factors (i.e. accumulated temperature, moisture deficit, detailed method of aspect scoring, and continentality) which affected productivity had relatively little impact on forest management and most ES provision levels. This was partly because the impact of increased temperature, moisture deficits and exposure on species productivity was low. Policy restrictions meant limited opportunity to diversify the forest landscape by planting different species, causing lodgepole pine to become dominant in all scenarios and resulting in similar ES provision trends for all scenarios. However, increased biomass demand and policies to mitigate climate change resulted in intensified management, lower uptake of aFMMs, and, generally, lower ES provision levels.

Keywords: *forest planning, Remsoft Woodstock, sustainable forest management, climate change, blanket peat.*

Introduction

Irish forest cover was reduced to just 1.5% in 1908. With a view to establishing a viable sawmilling industry in Ireland, State afforestation in the 20th century focused

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on purchasing marginal agricultural land for public afforestation (Gray 1963, Neeson 1991, OCarroll 2004). Since the 1980s, the State has also offered financial incentives for private landowners to afforest their land. These initiatives have increased forest area to 11% (770,020 ha) by 2017 (Forest Service 2018). The quality and potential of forest land varies greatly, especially with regards to the one third of Ireland's forest that is located on blanket peat (Forest Service 2018). Various provenances of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and lodgepole pine (*Pinus contorta* Douglas) have been used for the afforestation of blanket peats. This is due to their relatively higher productivity especially on sites with poor growing conditions (Renou and Farrell 2005). However, establishing Sitka spruce on blanket peat without the use of fertiliser is difficult (Carey and Hendrick 1986). With more restrictive environmental forest policy and certification rules (Forest Service 2017, PEFC (Ireland) Ltd. 2014), as well as concerns about operational impacts on water quality (Cummins and Farrell 2003, Moorkens et al. 2013, McCarthy Keville O'Sullivan Ltd. 2018), fertiliser use is now restricted in many areas. This is especially relevant for catchment areas with freshwater pearl mussel (*Margaritifera margaritifera* L.). Even with measures such as digging drains and repeated application of phosphatic rock fertiliser, there is no guarantee that the result will be a stand that produces commercial timber. The management of many blanket peat forests is marginally profitable at best, even with fertiliser application (Tiernan 2007). These factors have led to a preference for Lodgepole pine on blanket peat sites. Historically, establishing peatland forests involved open furrow ploughing to a depth of ca. 300-400 mm, at a spacing of 2 or 4 m, and planting on the plough ribbons providing an elevated planting position. This combined with waterlogging being commonplace means that many sites are at risk from wind damage. With all of these factors in mind, there is a clear need to evaluate the future management of Ireland's blanket peatland forests.

Introduction of sustainable forest management strategies in Ireland, e.g. *Growing for the Future* (DAFF 1996), focused on economic, ecological, and social services (Mulloy 1997). These Ecosystem Services (ESs) are defined as goods and services that contribute to human well-being (Reid et al. 2005). ESs are used around the world to assess forest status, as well as gauging the economic, environmental, and social performance of the forest industry. Assessing sustainable forest management performance can be simplified by using measurable ES indicators, which are tied to the three pillars of sustainable forest management, i.e. the economic, ecological and social values (Biber et al. 2015, Nobre et al. 2016). Preferably, this is done using a forest management decision support system. The benefit of using such a system has become especially obvious when evaluating alternative forest management options or assessing the impacts of global factors such as climate change and changes in global timber markets (Nordström et al. 2019).

Climate change projections for Ireland show that average Sitka spruce productivity will decline (Cabrera Berned and Nieuwenhuis 2017, Keenan et al. 2017). Without fertiliser application, sawlog production from Sitka spruce will not be possible on most peatland sites (Lundholm et al. 2019). Rather than producing large volumes of low value pulpwood (Corrigan and Nieuwenhuis 2017), the provision of other ESs from these forests could be considered. Proposed alternative management options for forested peatlands and adjacent mineral soil sites include long-term retention of forest, natural regeneration (preferably using broadleaves), retention of unplanted areas, restoration of natural bog habitat through rewetting, planting with native species, and planting with lodgepole pine at low stocking levels (Tiernan 2007, Renou-Wilson and Byrne 2015).

This study assessed the implementation of alternative forest management options for peatland forests using a forest management decision support system. It considers the effects of a dynamic bioeconomy and the impacts of climate change on forest productivity. The provision of ESs from these alternative management, or alternative Forest Management Models (aFMMs),were then compared with the provision levels produced by the current (c) FMMs.

Materials and methods

Study area

The Barony of Moycullen was chosen as the Case Study Area (CSA). It is located just west of Galway city, Co. Galway, in western Ireland (Figure 1). The size of the CSA is 77,500 ha, with a total forest area of 10,230 ha. Atlantic blanket peat soils underlie 82% of the forest area, with the remainder being located on gleys and lithosol mineral soils (Lundholm et al. 2019). Most of the afforestation took place in the 1970s and 1980s using ploughing, drainage, fertilisation and planting. Some stands are now on their second rotation. The dominant species are Sitka spruce and lodgepole pine, occupying 41.0% and 29.1% of the CSA's forests, respectively. Other conifers and broadleaves make up 10.4% of the forest area, and 19.5% consists of open land and unstocked forest. The Owenriff catchment, one of Ireland's eight priority freshwater pearl mussel catchments, is located in the CSA (Moorkens et al. 2013). The area is frequented by Galway locals, Irish and international tourists looking to explore and recreate in Connemara.

The issue with windthrow on blanket peat soils is exacerbated by the CSA being situated on the headland of the Atlantic Ocean (Ní Dhubháin et al. 2001). The intensive site preparation causes the peat to oxidize and release CO_2 (Byrne and Milne 2006), while the application of fertiliser introduces an additional eutrophication risk. With these factors in mind, there are only a limited number of potential management systems available in the area, which include a very limited number of eligible tree species. At the same time, complex ES interactions will take place at the stand and landscape level depending on the management options used. This makes it an interesting location for assessing the long-term sustainability of forest management on peatland. The complexity of this landscape and its uses are similar to those of many afforested peatland landscapes along the western European seaboard, making the results from this study relevant for a much larger area.

Forest management decision support system

A forest management decision support system, called the ALTERFOR model, was developed using Remsoft Woodstock, a software system used for strategic and tactical forest planning and management by Coillte Forest and worldwide (Walters 1993). The model used linear programming optimisation, with an objective function to maximise Net Present Value (NPV) from mill-gate timber sales over a 100-year planning horizon, using a 5% discount rate - commonly used in Irish forestry (Tiernan 2007, Corrigan and Nieuwenhuis 2016, Teagasc 2019). The model start year was 2016.

The ALTERFOR model was developed specifically for Irish forestry, incorporating local and country-specific management actions, and practices that are compliant with Irish forest policy and environmental policy. The model uses a combination of static yield tables created using GROWFOR for conifers (Broad and Lynch 2006), Forestry Commission yield tables for broadleaves and larches (Edwards and Christie 1981), and CARBWARE single-tree models for the Sitka spruce and birch mixture (Black 2016).

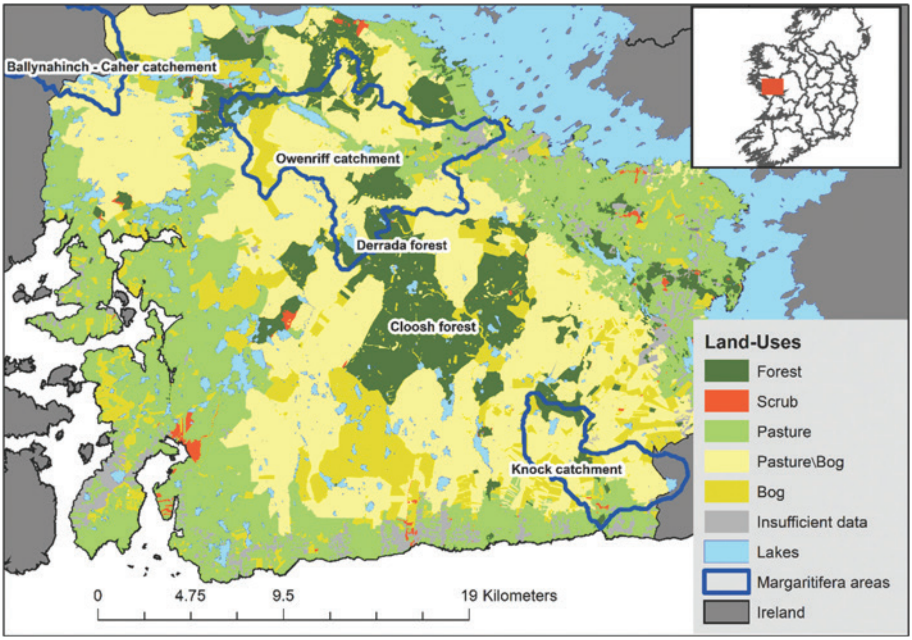

Figure 1: *The Barony of Moycullen delineated by its land-uses. Pasture\Bog refers to blanket bog utilised as commonage pastures. Adapted from Lundholm et al. (2019).*

Details on stand development, timber production, relevant costs and revenues associated with forest management actions, the global impacts from climate change (included as changes in species productivity), and dynamic timber prices (due to an expanding bioeconomy) have been presented in Lundholm et al. (2019). The complex methodologies used for quantifying ES indicators for timber, carbon storage, windthrow risk, biodiversity, water quality, and cultural values are detailed in Lundholm et al. (2020). The ALTERFOR model uses Sitka spruce Yield Class (YC, i.e. potential maximum mean annual increment) for all productivity measurements (including to retain productivity information after reforestation). Other species productivity was estimated from Sitka spruce YC using Tables 7 and 8 in (Phillips et al. 2009). These tables contain Sitka spruce YCs and the corresponding equivalent YC for a range of Irish species. Timber from conifer trees (except lodgepole pine) were assumed to be utilised as sawlog and pulpwood based on average tree size. Lodgepole pine timber was utilised as pulpwood, and all harvested broadleaf trees were considered to be fuelwood.

Ecosystem Services

The ES indicators were mainly based on stand metrics derived from yield tables, while some of the recreational attributes were assigned based on species, management intensity and stand structure at certain ages. ES indicator values were produced for each year, but the average annual ES provision levels over the planning horizon were used to simplify global scenario comparisons. The biophysical limits of ES provisions were derived from model runs using the cFMM BAU scenario, where the objective was to minimise and maximise the supply of each ES indicator separately. The minimum and maximum supply of ES indicators have been useful for stakeholder consultation (Corrigan and Nieuwenhuis 2017), and hence useful for this and future analyses. The ES indicators used were:

- **Forest industry ESs:** NPV, clearfell area, and harvest volume by assortments (Lundholm et al. 2019).
- **Carbon:** Carbon stock per area, including aboveground and belowground pools and deadwood pools, and harvested wood products pools, fossil fuel product substitution, and emissions from drained peatlands (Lundholm et al. 2020).
- **Windthrow risk:** CSA level average probability, based on Ní Dhubháin et al. (2009).
- **Biodiversity:** Indicators for biodiversity included large diameter wood volume, the area of old forest, coarse deadwood volume, and broadleaf volume. Broadleaf volume is the only reported biodiversity indicator, as it was shown to be the most indicative.
- **Water quality:** Phosphorus (P) leaching per hectare from all forest area with increased leaching in the four years after clearfelling, based on Mockler et al. (2016).

- **Cultural services:** Recreational and Aesthetic value of the Forested Landscape (RAFL) index. The RAFL index was based on perceived preferred forest structures for recreation in Europe, drawing on findings on the scenic beauty of forests (Edwards et al. 2012b, Giergiczny et al. 2015) and the scenic quality of landscapes (Tveit et al. 2006, Ode et al. 2008).

Global scenarios

A control scenario and three global scenarios were assessed using the ALTERFOR model. Narratives for the global scenarios were provided by the International Institute for Applied Systems Analysis (Forsell and Korosuo 2016), using the using the Global Biosphere Management Model (Havlík et al. 2014). Climadapt (Ray et al. 2009) was used to scale the global scenarios down to the Irish level, for implementation in the ALTERFOR model. The four modelled scenarios were:

- **BAU** – Business as usual: Control scenario with no climate change or dynamic assortment prices implemented.
- **S1** – Reference: Future global development and emissions trend based on historical data, taking into account the EU policies and targets until 2020. Then continuing with some increase towards future biomass use. Temperature increase of 3.7 °C by 2100, compared to pre-industrial values. Climate scenario: Representative Concentration Pathway (RCP) 8.5. Increase in sawlog prices until 2040, then prices remain static. Increase in pulpwood price until 2030, then slight decline to around year 2040, after which prices were mostly static.
- **S2** – EU Bioenergy: Rapid development of EU bioenergy sector, considering the EU strategic aim at an 80% reduction in emissions by 2050, with also some global climate policies in place. Temperature increase of 2.5 °C by 2100, compared to pre-industrial values. Climate scenario: RCP4.5. Steep increase in sawlog prices in the period between 2070 and 2100. Slight pulpwood price increase followed by decline before 2060, followed by static prices.
- **S3** – Global Bioenergy: Global development toward the climate targets, climate policies are assumed to be taken into action globally, with both stringent EU policies and strong global climate mitigation through bioenergy deployment and sharp reductions in emissions. Temperature increase of 1.5-2.0 °C by 2100, compared to pre-industrial values. Climate scenario: RCP2.6. Steep increase in sawlog prices in the period from 2040 to 2060, then static prices. Pulpwood prices increase throughout the 100-year planning horizon.

Current Forest Management Models

cFMMs represent the species combinations, management systems, and management objectives associated with the current practices in the CSA. The utilisation of cFMMs represent the baseline forest management, FMM composition, and ES provision against which the aFMMs will be evaluated. All Irish forest management has been categorised into nine cFMMs. These are contained in three major groups (see below). Additionally, the annual clearfelled area before being reforested was included for reference, and broadleaf stands that could not be fully modelled due to lack of information on age and species were also included. It is assumed that the most suitable provenance was chosen, e.g. north costal in the case of lodgepole pine.

Group 1: Clearcutting conifer species

- **cFMM 1 Sitka spruce monoculture –** Stands made up of pure Sitka spruce, sometimes with a small portion of lodgepole pine. Eligible for clearfelling once the top height was between 18 and 26 m; this applied to all FMMs in the clearcutting conifer group.
- **cFMM 2 Sitka Spruce with diverse conifer mix –** Sitka spruce dominated stands, but with a portion of diverse conifers (Scots pine, larch, Douglas-fir, Norway spruce etc., i.e. any conifer species except lodgepole pine).
- **cFMM 3 Sitka spruce with broadleaf mix –** Sitka spruce dominated stands, but with a portion of broadleaf trees. These stands often included diverse conifers.
- **cFMM 4 Diverse conifers –** Stands dominated by diverse conifer species (Scots pine, larch, Douglas-fir, Norway spruce etc.)
- **cFMM 5 Lodgepole pine monoculture –** Stands made up of pure lodgepole pine, sometimes with a small portion of Sitka spruce.

Group 2: Nature conservation and biodiversity protection

- **cFMM 6 Buffer zones / setbacks –** Established around sensitive features and roads. Categorised into aquatic buffer zone, freshwater pearl mussel buffer zone, and road buffer zone.
- **cFMM 7 Native Woodland Site –** Designated as either Native Woodland Sites according to the National Parks and Wildlife Services, or Native Woodland by Coillte. This FMM also included forests established under the Native Woodland Establishment Scheme.

Group 3: Broadleaved forest

- **cFMM 8 Continuous Cover Forestry (CCF) broadleaves** – Managed without clearfelling, mainly Coillte forests due to their policy not to clearfell broadleaves.
- **cFMM 9 Clearfelling broadleaves** – Privately owned broadleaf stands that were eligible for clearfelling (as opposed to the mainly Coillte owned broadleaves in FMM 8) for timber production, and potentially reforested with different species. Eligible for clearfelling once the age was 60 years or older.

- **Unknown private broadleaves –** The area of private non-grant aided broadleaved forest in the CSA amounted to 340 ha. These areas lack species, stocking and age information and have therefore been omitted from the model. A multi-resources inventory would allow them to be included in future implementations.

Clearfell area

- **Area clearfelled in each year –** Although not representing an FMM, the annual area of clearfelled land was tracked in the ALTERFOR model. Clearfelled land had to be reforested.

Alternative Forest Management Models

Stakeholder interviews were held to identify aFMMs to model. During workshops, the stake- holders were later informed about the aFMMs' impacts on ES provision levels in the landscape and their feedback was recorded. Five aFMMs were developed and implemented in the ALTER- FOR model. These are presented below.

<u>Low stocked lodgepole pine aFMMs</u>

The three low-stocked lodgepole pine aFMMs had very simple management schedules and all were eligible for use on forested blanket peat sites, without the use of fertiliser. For reference, lodgepole pine planted at 2,500 stems ha^{-1} cost €2,589 ha^{-1} to establish and was eligible for use on sites with Sitka spruce YC 18-30 (Lundholm et al. 2019). GROWFOR was used to produce yield tables for all the lodgepole pine aFMMs.

- **Lodgepole pine for fibre – LP1600** was planted uniformly over the site, using 1,600 lodgepole pine seedlings ha^{-1}, and the stand was eligible for clearfelling once the top height was between 18 and 26 m, the standard normal clearfelling eligibility for conifers in the ALTERFOR model. The aFMM was eligible for use on blanket peat sites with Sitka spruce YC 8-20 and cost €1,689 ha^{-1} to establish.
- **Lodgepole pine for biodiversity – LP1100** was planted in dense groups, with open space in between, using 1,100 lodgepole pine seedlings ha^{-1}. After planting, the trees were left to develop freely, i.e. no further management interventions. The aFMM was eligible for use on blanket peat site with Sitka spruce YC 8-20 and cost €1,161 ha^{-1} to establish.
- **Nephin thin** was created by heavily thinning existing lodgepole pine dominated stands on blanket peat that were between 26 and 50 years of age to 500-550 stems ha^{-1}. After the heavy thin, the stand was left to develop freely. The action generated income from thinning the existing stand.

Modified Kronoberg

The idea for the Modified Kronoberg (**MKB**) aFMM originated from a review of the BOGFOR project (Black et al. 2017a, Black et al. 2017b) and was based on earlier trials established on cutaway bogs (Renou-Wilson et al. 2008). This management system could have potential use on blanket peat sites with peat depths of 0.5 m or less. These sites in the CSA were identified using peat depth from the Galway wind park Environmental Impact Statement (Fehily Timoney and Company 2011). The area of identified shallow peat sites of at least 1 ha was 186 ha.

MKB is established by planting a mixture of 50% Sitka spruce and 50% downy birch in alternating rows, at 2 by 2 m spacing, resulting in 2,500 trees ha^{-1} (Black et al. 2017a) in shallower peat and mineral peaty soils, where birch may grow (Horgan et al. 2003). After reforestation, which cost €2,568 ha^{-1}, three thinnings are applied at ages 21, 27, and 34 years, and the stand is eligible for clearfelling at age 40 only, as this was the harvesting age that resulted in the highest NPV. A detailed description of the MKB system and other Sitka spruce and birch mixtures, including management prescriptions, yield tables and financial analyses, can be found in Black et al. (this issue). The MKB yield tables were produced using CARBWARE (Black 2016), which can simulate growth for intimate mixtures with both inter- and intra-species competition.

Bog restoration

Suitable sites for bog restoration include areas with environmental policy designations, low YCs, and with the presence of certain *sphagnum* mosses and other indicator plant species (Neville 2017; *Pers. comm. to A. Lundholm*). However, due to a lack of suitable information, bog restoration was only an eligible option for clearfelled Coillte sites designated or adjacent to a SAC, a SPA, or both. The bog restoration aFMM was not restricted by YC, but all trees on site had to be removed prior to restoration, so the stand had to be eligible for clearfell and thus conform to the clearfell height requirement. The cost of bog restoration was €2,000 ha^{-1} (Coillte 2008). Revenues from clearfelled timber on the restoration site were calculated as normal and are not included in the bog restoration cost.

Results: aFMMs and global scenarios

The results focus on two aspects: forest composition, represented by Forest Management Model (FMM) proportions, and ESs provision. Each aspect will be presented as a comparison between the scenarios (BAU, S1, S2, and S3) using only cFMMs (identified as cFMM BAU, etc.) and using both cFMMs and aFMMs (identified as aFMM BAU, etc.).

Forest composition

The predominant change in forest composition over the planning horizon was from being dominated by Sitka spruce to being dominated by lodgepole pine, and the large increase in cFMM 6 - Buffer zone areas in both the cFMM and aFMM scenarios (Figure 2). In the cFMM scenarios, all harvested blanket peat sites were reforested using cFMM 5 - lodgepole pine monocultures (stocking of 2,500 stems ha^{-1}), with cFMM 6 - Buffer zones established where appropriate. The largest change in FMM areas occurred between 2027 and 2056, when cFMM

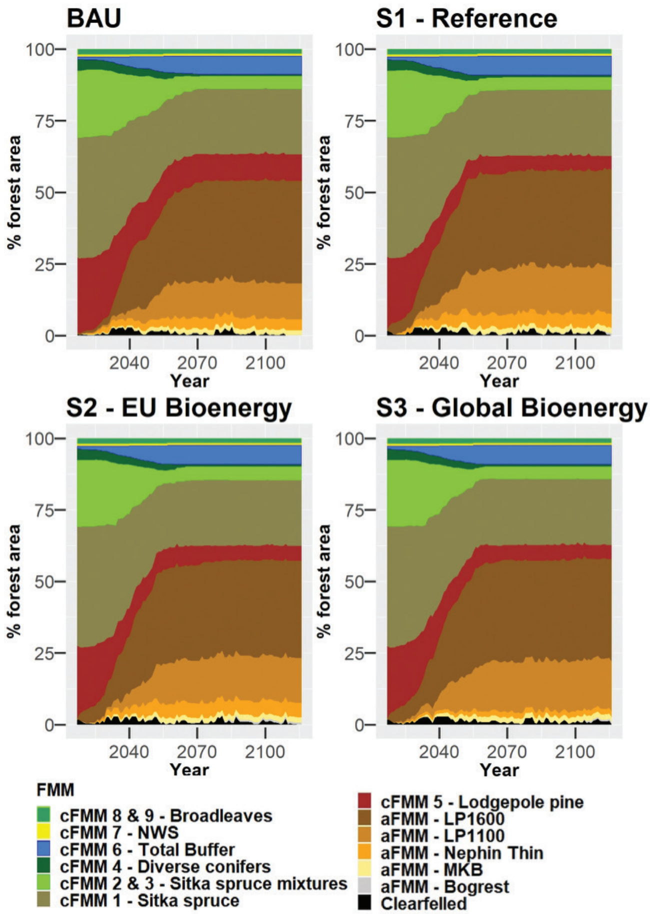

Figure 2: *Percentage of the forest area managed with different FMMs in the four aFMM scenarios: The Broadleaves group contains both privately-owned and Coillte-owned broadleaved forest. The Sitka spruce mixtures group contains all stands dominated by non-lodgepole pine conifers (including Sitka spruce), with broadleaves and/or non-lodgepole pine conifers as secondary or tertiary species. Sitka spruce and lodgepole pine refers to monoculture stands.*

1 - Sitka spruce monocultures, cFMM 2 and 3 - Sitka spruce mixtures, and cFMM 4 - Diverse conifers on blanket peat, were replaced with cFMM 5 - lodgepole pine monocultures and the aFMMs. Between 2057 to 2074, the only forest composition change was the replacement of fully stocked lodgepole pine stands with stands managed using the aFMMs. The aFMMs were established, to a varying degree, on all clearfelled blanket peat sites. LP1600 was the most commonly used aFMM, on around 3,300 - 3,500 ha (33-35% of the forest area), followed by LP1100 and Nephin thin. LP1100 was established to a lesser extent in the BAU scenario, 1,238 ha (13%), than in the global scenarios, at 1,625 ha (16%), 1,543 ha (16%), and 1,736 ha (18%) for S1, S2, and S3 respectively, and it took longer to establish the maximum feasible area of LP1100 in the S3 scenario than in the others. A drastically smaller area was managed using the Nephin thin in the aFMM S3 scenario, 191 ha (2%), while in the aFMM BAU, S1, and S2 scenarios the Nephin thin was established on 376 ha (4%), 475 ha (5%), and 498 ha (5%), respectively. The MKB aFMM was established to its full potential in all aFMM scenarios (186 ha or 2%), and there was minimal uptake of bog restoration because the NPVs of the other aFMMs were higher, but bog restoration was established on sites with higher productivity (i.e. where other aFMMs were not eligible) towards the end of the planning horizon. The area of restored bog was 4 ha, 70 ha, 67 ha and 62 ha in the BAU, S1, S2, and S3 scenarios, respectively. The model objective was to optimise NPV and since the lodgepole pine aFMMs had higher NPVs due to lower establishment costs than the other eligible reforestation options, these changes in forest composition were expected and largely due to the model assumptions, but they also reflect reality.

Net Present Value and harvest volume

The NPVs resulting from the aFMM scenarios, when compared to those from the equivalent cFMM scenarios (i.e. cFMM BAU compared to aFMM BAU, etc.) increased by 15%, 18%, 19%, and 12%, for BAU, S1, S2 and S3, respectively (Table 1). The NPVs resulting from the aFMM scenarios were €19.23 M, €27.82 M, €24.67 M, and €29.18 M for the BAU, S1, S2 and S3 scenarios, respectively. Compared to the result from the BAU cFMM scenario, the NPV increased by 16%, 68%, 50%, and 77%, for the four aFMM scenarios. Although the aFMM scenarios resulted in higher NPVs, it is worth noting that both aFMM S1 and S3 resulted in smaller clearfell areas and all aFMM scenarios produced smaller total harvest volumes than their cFMM counterparts, except for the BAU scenario (Table 1). Thin volumes were higher in the aFMM scenarios due to the use of the MKB and Nephin thin aFMMs. Thinning accounted for circa 1.5% of total harvested volume, as opposed to 0.3% in the cFMM scenarios.

Table 1: *Comparison of NPV, relative NPV, clearfell (CF) area, relative CF area, harvest volume, relative harvest volume and total harvested volume by assortments (pulp and stake and sawlog) resulting from the four cFMM scenarios and the four aFMM scenarios. Relative values are calculated using the cFMM BAU scenario values as reference values, e.g. aFMM BAU value divided by cFMM BAU value, etc.*

Scenario	NPV (€)	Relative NPV	CF area (ha)	Relative CF area	Harvest volume (m^3)	Relative volume	Pulp and stake (m^3)	Sawlog (m^3)
cFMM BAU	16,693,223	1.00	8,150	1.00	3,279,679	1.00	1,367,263	1,912,416
cFMM S1	23,608,992	1.42	13,114	1.61	4,522,287	1.38	2,748,047	1,774,241
cFMM S2	20,946,315	1.26	11,380	1.40	4,279,795	1.30	2,410,302	1,869,493
cFMM S3	26,064,704	1.58	16,488	2.02	5,277,293	1.61	3,282,690	1,994,603
aFMM BAU	19,230,147	1.16	9,642	1.18	3,432,511	1.05	1,514,423	1,920,183
aFMM S1	27,823,999	1.68	12,506	1.53	3,902,812	1.19	2,209,767	1,693,748
aFMM S2	24,868,301	1.50	11,640	1.43	3,803,294	1.16	1,997,039	1,806,808
aFMM S3	29,175,135	1.77	13,053	1.60	4,136,468	1.26	2,259,552	1,876,979

Ecosystem services provision

The differences in ESs provision between the cFMM and aFMM scenarios is presented by the average annual ES indicator values. Although graphs would highlight temporal differences in ES provision over the planning horizon, large temporal fluctuation can make it difficult to assess the total ES provision over the planning horizon. Therefore, the average annual values of the ESs indicators were calculated for all cFMM and aFMM scenarios, as well as the potential minimum and maximum supply of those ESs indicators, i.e. the biophysical limits of ES provision (Table 2).

The S1, S2, and S3 cFMM scenarios and all aFMM scenarios achieved higher NPVs than the biophysical maximum in the BAU cFMM scenario, due to the higher dynamic prices. Apart from the BAU scenario, the cFMM scenarios resulted in more harvested volume than the aFMM scenarios. The cFMM S3 scenario was the only one that resulted in harvest levels closest to the biophysical maximum, while in the other scenarios harvested volume reached between 59 and 75% of this maximum. In terms of carbon storage, the aFMMs underperformed when compared to the cFMMs and, in contrast to the situation at the model start year, the forest landscape became a carbon source towards the end of the planning horizon in the aFMM scenarios. This was due to carbon emissions from oxidising peat, the lower productivity of lodgepole pine compared to Sitka spruce, and that lower stocking levels of the lodgepole pine aFMMs. The cFMM scenarios generally resulted in the smallest possible broadleaf volume, and although the aFMM scenarios performed better in this regard, the

Table 2: *Ranges between the average annual biophysical minimum and maximum values for seven ES indicators under the cFMM BAU scenario, and the average annual ES indicator values for these seven indicators for the four cFMM and four aFMM scenarios. The average annual ES indicators are NPV, harvest volume (V_{Ha}), total carbon stock (C), average windthrow risk per hectare (Wi), broadleaf volume (V_{Br}), P leaching (P) and average RAFL index per hectare (Ra). The stakeholder preference for an increase (+) or decrease (-) in the indicator values is also included. The ES indicators use different numbers of decimal places based on the input data and the required levels of reporting detail.*

Scenario	NPV (€1,000s)	V_{Ha} (m^3 ha^{-1})	C (t ha^{-1})	Wi	V_{Br} (m^3 ha^{-1})	P (kg ha^{-1})	Ra
MIN	-44.8	0	85.64	0.307	28,368	0.566	0.392
MAX	166.9	59,873	175.09	0.734	63,981	0.608	0.633
cFMM BAU	166.9	32,797	125.43	0.552	28,477	0.585	0.621
cFMM S1	236.1	45,223	105.88	0.428	32,802	0.596	0.572
cFMM S2	209.5	42,789	110.84	0.481	28,955	0.592	0.585
cFMM S3	260.6	52,773	98.03	0.388	33,576	0.603	0.570
aFMM BAU	192.3	34,671	108.02	0.463	44,222	0.587	0.636
aFMM S1	278.2	39,421	95.37	0.412	43,365	0.593	0.625
aFMM S2	248.7	38,416	95.04	0.421	44,694	0.591	0.628
aFMM S3	291.8	41,781	94.38	0.405	40,402	0.594	0.614
Preference	+	+	+	-	+	-	+

broadleaf volume levels were still considerably below the maximum, even with the inclusion of the MKB in the aFMM scenarios. Furthermore, the aFMMs outperformed the cFMM scenarios in producing less P leaching, but it has to be pointed out that the range between the minimum and maximum possible P leaching levels was very narrow. The aFMM scenarios also outperformed the cFMMs scenarios in terms of RAFL indices, indicating a more aesthetically pleasing forest landscape according to the studies mentioned in the materials and methods section.

Discussion

Ecosystem Services provision

The increase in NPV in the aFMM scenarios was due to the harvesting of most of the available timber during the first part of the planning horizon, followed by the introduction of aFMMs with lower reforestation costs. Generally, the poorest sites were treated with the Nephin thin, which did not incur any re-establishment cost, or were planted with the LP1100 aFMM. Since Coillte and many private forest owners in Ireland manage their land with the view of maximising NPV, they should consider the financial benefits resulting from the implementation of the aFMMs on blanket peat sites. The aFMM scenarios performed worse than the cFMM ones for total harvest volumes and carbon stocks, but resulted in improvements in the windthrow risk, cultural services, biodiversity, and water quality ES indicators. This shows that some stakeholder ES requirements can be achieved by changed management approaches (including deforestation) on these site types, similar to the findings in Corrigan and Nieuwenhuis (2017).

Harvest volumes were reduced in all the aFMM scenarios. Many of the low-stocked lodgepole pine stands were either retained indefinitely or provided around 30% less volume when harvested, compared to fully stocked ones. Since fully stocked replanting would not be profitable on poor sites, even with fertiliser, the Lodgepole pine aFMMs were chosen as they allow the option to first extract existing sawlog timber (for example, Sitka spruce sawlog from cFMM 1) and then change the forest composition and re-designate the management objectives to provide a range of ESs, including timber, in the future.

Less carbon was stored in the aFMM scenarios than in the cFMM ones, with the only exception being S3, in which similar amounts were stored in both the cFMM and aFMM scenarios. Lower volume growth and less carbon stored in harvested wood products are contributing factors, but it is also due to many stands growing beyond the maximum available age in their yield tables, resulting in the last eligible yield value being used as a constant standing volume in the model. Bog restoration was the only option available in the model to reduce the carbon emissions from drained peat soils. However, this first requires deforestation which results in biomass and deadwood emissions from thestand and decreases potential biomass increment at the landscape level, resulting in negative implications for national greenhouse-gas and carbon accounting in the short term (Byrne and Milne 2006). Restored bog emit methane, which has a larger greenhouse gas forcing than carbon dioxide (Black and Gallagher 2010), so the greenhouse gas balance of restored bog, relative to continued plantation forestry, requires further investigation. Further barriers to bog restoration were its higher cost compared to those for the lodgepole pine aFMMs. There are likely more sites suitable for bog restoration in the CSA than were included in the model and identifying these sites would be beneficial for the future.

The decrease in windthrow risk was mainly due to low-stocked lodgepole pine trees not experiencing as much within-stand competition, resulting in trees with lower slenderness ratios (Pretzsch 2009). The windthrow risks for old growth, low-stocked retained stands are not known, and Atlantic storms are forecast to be more extreme in the future, due to climate change (Ray et al. 2008). Thus, overall windthrow will likely remain (and potentially increase) as a persistent management issue for many western peatland forests and the low-stocked forests are also likely to suffer windthrow in the future, but the extent of future impacts remains to be seen. However, as these trees are established at wider spacings and do not experience any thinning, they may be more stable (Scott and Mitchell 2005). It should be noted that the climate change and future windthrow scenarios in this study do not include extreme events, such as the impact of increased frequency and severity of storms.

The broadleaf volume biodiversity indicator improved when the aFMMs were used in the CSA. A study from Wales has found that utilising low-impact silviculture as a climate change adaptation strategy improved biodiversity, while changing to wood producing tree species that are more resilient to the future climate had little impact on overall biodiversity (Ray et al. 2015). Broadleaf volume increased in the aFMM scenarios, which resulted mainly from the use of the MKB aFMM. An important biodiversity improvement resulting from the use of the aFMMs, which was not measured but is relevant to the CSA, was increased landscape fragmentation due to the establishment of transition areas between fully stocked forest and open space, provided by the low-stocked lodgepole pine stands and buffer zones. The hen harrier, an endangered species in Ireland, requires a mixed landscape for hunting and nesting. Large areas of peatland forests, especially at pre-thicket stage, which fragment the open blanket bog landscape, are potential hen harrier habitats (Wilson et al. 2009, Caravaggi et al. 2019). Although there are no hen harrier SPAs in the CSA, they have been seen in the area and suitable habitat also exists to the west and north of the CSA (Ruddock et al. 2016). Facilitating suitable habitat could help to secure the future for viable Hen harrier populations in Ireland. Transition zones between open areas and the forest are also more generally important for biodiversity, providing habitat for mammals, birds, insects, and flora (Webb et al. 2010). They could also allow for natural regeneration of native scrub and tree species. Sites between blanket bog and peaty mineral soils should be targeted for these transition areas, since natural regeneration of many species on blanket bog is rare (O'Leary et al. 2001).

Although the results suggest that there would be a reduction in Pleaching in the aFMM scenarios, establishment of the aFMMs incentivised clearfelling of poor stands which would otherwise not be harvested. As a result, the aFMM BAU scenario produced higher total P leaching values than those in the cFMM BAU scenario. All land parcels in the model included a certain amount of P leaching, even if not recently clearfelled, resulting in very small overall differences in P leaching at the landscape level between the cFMM and aFMM scenarios. Buffer zones have been shown to reduce nutrient loading into watercourses (Kelly-Quinn et al. 2016), and the reduction potential is generally more affected by the topography than the vegetation in buffer zones (Ranalli and Macalady 2010). Including a greater level of spatial detail in the ALTERFOR model in the future would be an important improvement, especially if dynamic buffer widths were implemented to reduce P leaching in areas with higher loads.

The aFMMs created an aesthetically more pleasing landscape due to increased structural diversity, more broadleaves, less clearfelling, and stands that were more open, resulting in larger trees, older stands, and less harvest residue. The abovementioned aspects of forest landscapes have been found more attractive for recreation and improved aesthetics (Edwards et al. 2012a). Furthermore, forests with lower stocking and reduced management intensity increased the provision of recreation in a wider European context (Edwards et al. 2012b). Thus, the aFMMs could have a great appeal to tourists from the continent, provided there is good access to and within forest areas and proper linkages to the surrounding landscape, e.g. to the trails of the Western Way and the Galway Wind Way. The RAFL-index was a landscape average value and did not identify areas that had particularly high recreation potential. The opportunity exists to actively increase the RAFL-score in areas where the score is already high and also to improve the recreation potential along the existing walking trails in the CSA. Signages and interpretive material created by Coillte and government organisations (e.g. the Department of Agriculture, Food and the Marine, the National Parks and Wildlife Service, and the Environmental Protection Agency) could inform visitors about e.g. forest management, freshwater pearl mussel conservationand blanket peatlands protection.

Suitability and uncertainties associated with aFMMs

The yield modelling system, GROWFOR, used to generate many of the yield tables used in this study was calibrated using production-based stands. For this reason, a lower accuracy for older, lower stocked stands is to be expected and, in some cases, it was not possible to generate yield tables past the age of 60 years. In addition, the lower-stocked lodgepole pine aFMMs may not become fully established due to excess mortality from nutrient deficiency, waterlogging and windthrow, and hence may deliver different economic, cultural and biodiversity ESs provision levels than modelled. However, using yield tables outside of the range (of spacings and ages) for which they were constructed can still be useful for detecting regional trends when evaluating alternative management options (Frank et al. 2015). Trial sites of the aFMMs have been established in Ireland, so yield tables based on more accurate data of their development and mortality can be produced in the future.

The high pulpwood prices in the S3 scenario made it financially preferential to harvest the entire stand, replant it, and manage it for another rotation, rather than just heavily thin it once and establishing it as a Nephin thin aFMM. The transformation of a regular lodgepole pine stand using the Nephin thin aFMM was only an eligible option in the ALTERFOR model when the stand was between 26 and 50 years of age. This was done to limit the number of management options the model had to evaluate, and because there were problems producing reliable yield tables for very low-stocked stands. Allowing transformation at an older age would likely result in a greater area of Nephin thin. As of 2019, 97 ha of Nephin thin management had been established in Wild Nephin, Co. Mayo. Further expansion has ceased until the development of understorey vegetation and trees can be monitored and assessed. The main issue, so far, is rhododendron (*Rhododendron ponticum* L.) invasion. This issue could also become a problem in the LP1100 aFMM in the CSA. This may increase management costs through control and eradication measures, and prevent the development of native flora and biodiversity, one of the development objectives for the aFMMs.

The proposed MKB aFMM is based on modelled data using mixed species experimental data from a test site in Co. Offaly (Black et al. this issue), which was established in 2000 as part of the BOGFOR project (Black et al. 2017b). This test site is predominantly located on *phragmites* peat, cutaway raised bog and MKB established on blanket peats could develop differently. The approach in this study of selecting only shallow peat sites was adopted because drainage and nutrition problems could be less restrictive there for the growth of the species mixture, although peat composition would also affect site productivity and species compatibility. Field inventories and more detailed knowledge of the area would be necessary to find all sites suitable for the MKB aFMM. Peat depth is usually shallower around slopes and ridges and even if these areas would be too small, narrow, and fragmented to function as realistic management units for MKB, they may be suitable for establishing native broadleaf trees and scrubs, if the grazing issue of deer and sheep could be overcome (Rooney and Hayden 2002).

Bog restoration had higher NPV than the re-establishment of lodgepole pine at 2,500 stems per hectare, largely since it was cheaper to establish. However, the three low-stocked lodgepole pine aFMMs had higher NPV than bog restoration as they all had lower establishment costs and some of them also involved income from timber harvesting. The income from harvesting standing timber before restoration will also have to be taken into account, so it is not justified financially to establish bog restoration on poor sites with standing timber of low value and volume. Thus, bog restoration was mostly scheduled on sites with higher productivity (i.e. Sitka spruce YC >20), which were not eligible for the establishment of the lower-cost aFMMs, and it was only established towards the end of the planning horizon when it was not possible to fit another rotation in the planning horizon. However, if bog restoration was 50%-funded using biodiversity improvement funding (e.g. EU LIFE projects), it would be a more economic option than both LP1600 and LP1100 and the area of restored bog would likely increase drastically, assuming that suitable sites can be identified.

Alternative management of peatland forests

The aFMMs were developed for use by foresters in combination with cFMMs, and thus the results of the aFMM scenarios regarding NPV, forest composition and ES provision levels should be assessed based on the corresponding levels in the cFMMs scenarios. The aFMMs were developed to operate within the biophysical and policy limits of the western peatland landscape, meaning they had to fulfil certain criteria:

1. Successful establishment on blanket peat soils was necessary for wide applicability.
2. They must conform to current forest policy and certification guidelines, even if requiring case-by-case justification and approval.
3. They should be attractive to forest managers and stakeholders and provide a better mixture of ESs (including NPV) than the cFMMs.

In theory, the aFMMs allow foresters to: grow biomass on marginal sites, extract existing sawlog volumes and reforest at a lower cost, increase the area of open space where native trees and shrubs could regenerate, improve the aesthetics of the forest landscape for recreation, and restore bog habitats - while producing a higher NPV from mill gate sales. There are no policy restrictions preventing heavy thinning followed by indefinite retention, or against mixing Sitka spruce and birch, but the lodgepole pine fibre and biodiversity aFMMs and bog restoration (deforestation) require case-by-case approval by the Forest Service (Forest Service 2017). Hopefully, this case-by-case justification and approval process will become streamlined, considering the ES benefits that are associated with establishing lodgepole pine at lower stockings on blanket peat soils. The aFMMs focus heavily on lodgepole pine since it is the species with the best establishment and growth success on unfertilised blanket peat and is not as susceptible to grazing by sheep and deer as other tree species. Other studies regarding peatland forest management have concluded that productive, profitable peatland forests should continue to be managed, while alternative management should focus on unproductive and unprofitable sites (Tiernan 2007). Some potential alternative management models that were not included in this study were: leaving failed reforestation sites unplanted; no replanting; natural regeneration; and seeding with native scrub species (Tiernan 2007, Renou-Wilson and Byrne 2015, DAFM 2018). Some of these alternative management models were difficult to quantify or justify for inclusion in the model, e.g. no replanting would result in vast unplanted areas. Perhaps this would be the best management strategy for many peatland sites, but it goes against the reforestation requirement and the national objective of increasing the forest area (DAFM 2014). Deforestation also results in carbon emissions under the Kyoto protocol and the EU regulation on land use, land use change and forestry (LULUCF). More research is required to assess carbon emissions and ES trade-offs when considering alternative land uses for existing peatland forests, such as deforestation and bog restoration.

Policy makers, forest managers, environmentalists and other stakeholders all have different ideas and perceptions of the ideal forest landscape, the ESs that are most important, and the forest management models that should be used (Marques et al. 2017). The most pragmatic and realistic approach to integrate these different views is to use a combination of cFMMs and aFMMs to achieve a preferred outcome, but this combination will vary depending on the management objectives for the specific forest landscape – managing for one ES could reduce the supply of another (Biber et al. 2015). Pareto frontier methods could be used to visualise all feasible management outcomes and the associated ESs provision levels, allowing forest managers and stakeholders to select the combinations of FMMs that produce the preferred combination of ESs (Marques et al. 2017, Marto et al. 2018). Due to tighter environmental constraints, stricter certification rules and society's environmental focus, it is likely that the forests in the Cloosh area and other western peatland forests will be less intensively managed in the future. However, if climate change mitigation efforts increase the future demand (and price) for biomass (as represented in the S3 scenario), these forests could remain or become important sources for this biomass. Intensified harvesting combined with utilisation of wood for bioenergy (i.e. the S3 scenario) lead to overall smaller carbon stocks than harvesting and storing carbon in long-lived wood products such as sawn wood. Thus, forests with lower stocking and generally shorter rotations, while using harvested biomass for bioenergy are likely to be unsuitable climate change mitigation actions, even if this would be an appropriate financial response to mitigation policies. The future role of western peatland forests in the mitigation of climate change will largely depend on the global demand (and price) for biomass, national mitigation strategies, utilisation of wood in harvested wood products, adaption of actions to reduce the impact of climate change on species productivity, and alternative land-use policies. However, a focus on biomass production will conflict with and possible reduce the provision of biodiversity, water quality, and recreation, as demonstrated by this study.

Conclusion

The implementation of the alternative aFMMs in the decision support system suggests an increase in the provision levels of most ESs compared to the levels achieved by only using the current cFMMs, both under current and future climate conditions. The aFMMs have both benefits and drawbacks, in terms of increasing the supply of ESs, as they improved NPV, water quality, some aspects of biodiversity and reduced windthrow risk. However, the aFMM modelling results led to a reduction in harvested timber volumes and in carbon storage, demonstrating the presence of ESs trade-offs and making it very unlikely that all ES provision levels can be improved simultaneously across the landscape.

Segregating the provision of ESs in different parts of the landscape, depending on the biophysical conditions, is possibly the best way to improve ES provisions of western peatland forests. More intensive management techniques (e.g. fertilisation, genetic improvement) could be used to produce faster growing trees on the more fertile peatlands, producing more (sawlog) timber and storing more carbon. These sites should be selected based on spatial, social and biophysical characteristics, e.g. distance from water bodies, location relative to tourist pressures, drainage etc. However, as has been shown in this study, and in real life through eutrophication and (perceived) historical forestry-related impacts on water quality and freshwater pearl mussel habitat, this will have a detrimental effect on several other ESs.

The improvements in NPV resulting from the implementation of the aFMMs may make them attractive to forest managers in the CSA and the wider peatland forests, whose main objective is to produce an income for the forest owners, and this could indirectly lead to an improvement in the provision of many other ESs. Test sites have been established that will increase knowledge of the actual performance of the aFMMs which, in line with adaptive forest management, can lead to necessary modifications in their design and implementation. These test sites can also serve as an educational tool to spread knowledge of the aFMMs to forest managers and stakeholders operating in the western peatlands.

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