A Greener Future for All

COILLTE

Forests for Climate

Report on Carbon Modelling of the Coillte Estate

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UNIVERSITY OF LIMERICK
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Preamble

This report details the assessment undertaken to determine the current Greenhouse Gas (GHG) profile of Coillte's existing managed forest estate and to identify and assess the GHG mitigation potential of silvicultural management options based on a number of assumptions set out in the report.

The system boundary is defined as the Coillte managed forest estate and does not consider the importation of timber from potentially unsustainable sources or the substitution of fossil-based materials to replace lost timber flows. It is also necessary to note this analysis does not extend to, or include; climate adaptation, resilience of the estate, changes in productivity due to climate change, or the carbon sequestration and climate mitigation potential of afforestation.

Further research, analysis and pilot studies would need to be undertaken to provide a deeper understanding of various aspects such as: emission factors (e.g. on second rotation sites, organo-mineral soils and fen peats as well as how these emission factors change over time); the climate effect of rewetting and bog restoration over time; and wood products and life cycle analysis and would require the collaboration of a range of organisations including Government agencies, third-level institutions and other stakeholders.

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Executive Summary

Urgent emission reductions or enhancement of removals are required to ensure that CO_2 stabilisation is reached in the short term, and in turn ensure that global warming is limited to 1.5 to 2 degrees Celsius[1]. The Paris Agreement, the EU Land Use Land Use Change and Forestry (LULUCF) Regulation and the Climate Action Plan 2021[2] identify the importance of afforestation and forest management mitigation actions to reduce global warming to below 1.5 degrees Celsius. The EU “Fit for 55” package aims to underpin this policy by setting out an ambitious carbon neutral pathway for the EU by 2050. However, while the Climate Action Plan considers additional afforestation measures, forest management measures also have an important role to play in climate mitigation as they likely have a lower abatement cost and higher short-term mitigation potential.

The national Managed Forest Land (MFL), which includes the Coillte forest area, is estimated to transition from a net removal of CO_2 to a net emission over the coming decades due to a decline in forest growth increment associated with management for wood production, an increase in harvest and continued emissions from peatland forests[3]. This study seeks to characterise the future greenhouse gas (GHG) profile of the existing Coillte managed forest estate under a business-as-usual scenario, and to identify management options to improve the CO_2 capture potential of the Coillte estate. Identified mitigation measures, such as extended rotations, reduced thinning and low impact silvicultural systems were incorporated into a decision tree to derive a balanced land-use system, hereinafter referred to as the New Forestry Model, incorporating timber, nature, social amenity and climate change mitigation services. Comparisons between the business-as-usual and the New Forestry Model scenario, based on the delta C approach, facilitated the estimation of how forest management, and a balanced land-use management system, could contribute to the national effort toward meeting the EU burden sharing agreement.

The GHG profile estimates include emissions and removals from biomass, deadwood, litter, mineral and organic soils, as well as removals from harvested wood products (HWP) and product substitution. This was done using a harmonised modelling framework using Remsoft and the Canadian Forest Service Carbon Budget Model (CFS-CBM) hereinafter referred to as CBM. CBM is the GHG model framework used in the national GHG inventory and for submissions to the EU. Significant improvements were made in harmonising timber forecast data from Remsoft for use in CBM using data transcript procedures. This facilitated a more accurate calibration of model runs and GHG profiles that reflect age class structure changes observed in Remsoft simulations.

The GHG profile for the business-as-usual scenario, which reflects continuation of current management practices, showed that the estate provided an initial removal of 900 Gg CO_2 eq in 2021. However, there is a consistent decline in removals and a transition to net emissions by 2045. Emissions continue to increase to ca. 1,000 Gg CO_2 by the end of the century. The trend is driven by increases in the level of harvest, a decline in biomass increment and continued emissions from drained organic soils[3,4]. The decline in biomass increment is associated with age class shifts due to clearfelling and

[1] IPCC (2018) IPCC, 2018: Global warming of 1.5°C.- Special Report. Global Warming of 1.5 ºC — (ipcc.ch)
[2] Government of Ireland - Climate Action Plan 2021
[3] Black, K., Hendrick, E., Gallagher., G.,Farrington, P. 2012. Establishment of Ireland’s projected reference level for Forest Management for the period 2013-2020 under Article 3.4 of the Kyoto Protocol. Irish Forestry 69: 7-32
[4] NFAP, 2020. Ireland’s national forest accounting plan submission under the EU LULUCF regulation. https://www.gov.ie/en/publication/0ad4b-lulucf/

replanting and a decline in productivity of broadleaf stands which are predominately managed for ecological objectives and are not actively managed to maximise their full carbon sequestration capability. Comparison of the Coillte estate and the national Managed Forest Land (MFL) profile shows that the Coillte estate has a small impact on the observed emission profile for all MFL. This is because the share of Coillte land reduces from 89% in 2021 to less than 50% by 2050 due to transitions from the afforestation land to the MFL category over time.

A review of the literature and confirmatory modelling exercises identified several management alternatives, such as extensions of rotation ages and increased "no-thin" management, that can potentially increase C removals and, on peatland forests, delay the transition from a net removal to a net emitter. The extension of rotations increases the residence time of C in the forest and ensures maximum C capture is reached if grown to maximum mean annual increment (MMAI) before felling. Extended rotation also increased C capture by HWP and product substitution due to the fact that higher assortment outputs have a higher & longer storage potential. Particular attention was given to peatland forests since these pose the greatest emission threat in the future. Additional measures such as rewilding, long term retention, low impact silvicultural systems and rewetting (i.e. bog restoration) were assessed. All the measures, except for rewetting, are expected to have a positive mitigation potential. While rewetting can be considered beneficial from a biodiversity perspective, the analysis and other studies suggest that rewetting has a negative climate change mitigation outcome in the short to medium term; this is due to the CO_2 emissions from deforestation and methane emissions, which far outweigh the emission reductions from organic soils due to rewetting. However, it is important to note that the research related to rewetting forested peatlands in Irish conditions is limited and further research is required. Based on current research, rewetting does result in long term reductions in emissions from organic soils.

Assessment of implemented measures using a decision tree showed that the removals of C could increase by 2,000 to 3,000 $GgCO_2$ per year in the short-term, before then reverting to an emitter of ca 2,000 Gg CO_2 per year over the medium and longer term. However, this is only considered when the carbon objective is assessed in isolation and not balanced with delivering the multiple objectives of forestry, which includes forests for wood and the need for a sustainable supply of certified Irish timber, forests for people, and forests for nature. Furthermore, considering these carbon mitigation measures in isolation, and within a system boundary that does not consider the global impacts of importing timber from potentially unsustainable sources, serves to demonstrate that forest management measures potentially have a far greater short-term climate change benefit than afforestation, even if the current ambitious national afforestation target of 8000 ha per annum is achieved.

A New Forestry Model for the Coillte's forest estate has been developed that seeks to balance land-use between the timber, climate, recreation and biodiversity objectives. When compared to the business-as-usual scenario, it is estimated that the New Forestry Model scenario will represent an emission reduction saving of ca. 19 MT CO_2 over the period 2021 to 2100. This includes a reduction of ca. 863 Gg CO_2 for the period 2026-2030, which is a small contribution towards the EU burden sharing agreement. For the period, 2021-2050, it is estimated that the New Forestry Model will save ca. -3,500 Gg CO_2 over the business-as-usual (BAU) scenario. It is estimated that a large emission reduction would be realised towards the end of the century, when 8,161 Gg CO_2 emissions are saved in a short period (2080-2100). In summary, the analysis suggests that 60% of the removals occur between 2021 and 2080, and ca. 40% of the emission reduction occur between 2080 and 2100. It is well acknowledged that there are fluctuations between removals and emissions in MFL, which occur due to factors such as shifts in age-class structure, changes in productivity and other factors[5]. The GHG profile associated with the New Forestry Model scenario becomes a smaller emitter between 2050 and 2053 and then reverts to a net remover until 2060. Whereas the business-as-usual scenario, which has larger emissions over the full period and is estimated to become an emitter in the mid 2040s. Towards the end of the century, the New Forestry Model GHG profile reverts to a net removal of -41 Gg CO_2, which compares favourably to a net emission of 894 Gg CO_2 for the business-as-usual scenario.

Short term mitigation action is a preferable strategy to address climate change, given the long-term nature of CO_2 and temperature stabilisation in the atmosphere. While some short-term mitigation potential was achieved in the New Forestry Model scenario, it is considered that a more robust implementation of the identified mitigation measures, such as extended rotations, would result in further short-term climate benefits. This represents a common climate change mitigation dilemma, because short-term mitigation actions could impact directly on the supply of certified timber to the market and could potentially have significant, direct impacts on the forest sector and timber processing industry and may require the import of unsustainable timber. Furthermore, the importation of timber from potentially unsustainable sources may contribute to leakage effects at global level[6], i.e. the shift in carbon emissions from one country to another. The mitigation measures must therefore be balanced with other objectives such as biodiversity, recreation, species diversification and a sustainable supply of certified timber. Other measures, such as the sustainable management of the broadleaf woodlands to enhance their climate mitigate potential and further analysis and evaluation of low impact silvicultural systems for peatland forests should be considered.

It is important to note that the modelling undertaken in this report has been applied at a strategic scale and as such the proposed mitigation measures serve to provide general guidance in terms of the principles of forest carbon management. The implementation of any carbon mitigation measures would need to be fully evaluated to ensure that other aspects, such as for example, environmental objectives and legislative requirements, are fully considered in the decision-making process.

Finally, it must be acknowledged that there are still large gaps in the understanding of GHG dynamics in the forest sector system boundary. In particular, the quantification of the contributions of peatland soil emissions and product substitution is still evolving. The impact of extreme events and climate change on forests to capture C in the future is also very uncertain. In addition to these model and scenario uncertainties, there will also be operational challenges associated with the timing and extent of the implementation that may reduce or enhance further climate mitigation options in the New Forestry Model.

5 Böttcher, H., Kurz, W.A. and Freibauer A. (2008) Accounting of forest carbon sinks and sources under a future climate protocol—factoring out past disturbance and management effects on age–class structure. *Environmental Science and Policy* 11: 669-686.

6 Pan, W., Kim, M.K., Ning, Z. and Yang, H., 2020. Carbon leakage in energy/forest sectors and climate policy implications using meta-analysis. *Forest Policy and Economics*, *115*, p.102161.

1. Background

The Paris Agreement (COP 21) calls for the long-term conservation of forest carbon (C) stocks and the enhancement of forest sinks beyond the second half of the century. The EU vision towards C neutrality by 2055 (Fit for 55) outlines the role of land-use and forest sinks in meeting ambitious burden sharing agreements under a revised land-use land use change and forestry regulations (EU LULUCF regs)[7]. The impact assessment study presented in the EU LULUCF regulation identifies afforestation as the most expensive mitigation option and one with the lowest potential contribution to additional removals in the short term (2021-2030). In contrast, management of forest lands (MFL) is seen as the most cost effective with the largest mitigation potential across the EU. The Climate Action Plan sets ambitious targets for the LULUCF sector, but currently considers additional afforestation as the only forest related mitigation pathway. This is despite the EU LULUCF study findings, which instead highlight forest management as a key mitigation route.

This report focusses exclusively on the management of the existing Coillte managed forest estate and does not consider afforestation, renewable energy or other potential climate mitigation measures. The Coillte forest area currently represents ca. 86% of the Irish Managed Forest Land (MFL) area reported to the United National Framework Convention on Climate Change (UNFCCC) and will be subject to accounting rules set out in the EU LULUCF regulation over the period 2021-2030. However, MFL also includes private forest lands which were afforested more than 30 years ago, referred to as transitioning afforestation land. As a result of forests maturing across the national forest estate (both public and private) Coillte's contribution to the national MFL will consist of 50% of the MFL area by 2050. Ireland submitted a forest reference level (FRL) in a National Forest Accounting Plan (NFAP[8]) to the EC in 2020. The NFAP estimates that the total carbon stock in Irish forests is ca. 312 Mt carbon stored between trees, leaf litter and soils; but the NFAP and other studies[9] show that the greenhouse gas (GHG) profile of the national MFL area will transition from a net removal (sink) to a net emission (source) over the next 5 to 10 years. This transition to an emission is associated with several factors, including:

- A significant increase in the levels of harvest due to shifts in age class structures;
- A temporary decline in productivity due to a shift in age class structure to younger conifer stands that will be in a less productive phase of their development;
- A decline in productivity of the broadleaf estate as woodlands get older and become over-mature due to limited management;
- Continued emissions from peatland forests where the net carbon balance is negative.

[7] https://ec.europa.eu/clima/eu-action/forests-and-agriculture/land-use-and-forestry-regulation-2021-2030_en
[8] NFAP, 2020. Ireland's national forest accounting plan submission under the EU LULUCF regulation. https://www.gov.ie/en/publication/0ad4b-lulucf/
[9] Black, K., Hendrick, E., Gallagher., G.,Farrington, P. 2012. Establishment of Ireland's projected reference level for Forest Management for the period 2013-2020 under Article 3.4 of the Kyoto Protocol. Irish Forestry 69: 7-32

2. New Forestry Model objectives

The aim of the New Forestry Model is to provide a land use planning system for the Coillte managed forest estate for an 80-year horizon, that balances the multiple benefits of forests across four objectives:

- Forests for Wood – production of sustainably grown, certified timber with the potential to off-set fossil emissions through product substitution.
- Forests for Nature – to increase and enhance biodiversity across the estate.
- Forest for People – develop an increased recreational offering across the estate with an emphasis on urban community forests.
- Forests for Carbon – identify a suite of silvicultural and land-use management approaches that can be implemented across the managed forest estate to reduce overall emissions and increase removals. To meet the overall carbon objective, the following specific aims are included:
  - Identification of alternative management approaches designed to increase future climate change mitigation action;
  - Development of a decision support system to implement mitigation management practice in the strategic planning system (Remsoft) (see section 3.3.2);
  - Improved harmonisation of Remsoft and the Carbon Budget Model (CBM), the carbon modelling framework from the Canadian Forest Service;
  - Assessment of the mitigation potential using scenario analysis against a baseline (the business-as-usual scenario), including a final balanced New Forest Model scenario (i.e. determination of the difference between GHG profiles to assess the impact of implementing all land-use objectives);
  - Assessment of the contribution of the current and future management of the Coillte managed forest estate to the overall national climate change mitigation effort.

3. Approach

3.1 System Boundary

The system boundary used for the carbon component of the New Forestry Model project includes:

- Forest aboveground and belowground biomass, litter, deadwood and soil C pools;
- Harvested wood products (HWP) & Product Substitution based on additionality;
- Emissions from peat soils;
- Emission impacts from deforestation for rewetting of low productive peatland forests.

The following processes were excluded from the modelling framework:

- *Fertilisers, urea and fire emissions*, because of large uncertainties in future trends.
- *Deforestation emissions* (excluding those for rewetting).
- *Fossil fuel emissions* from harvesting, wood processing and management operations are excluded from the carbon modelling, but the production chain emissions are considered during the product substitution calculations associated with the HWP.
- Impacts of climate change on forest productivity, due to the complexity and uncertainty associated with the impacts of climate change (i.e. no stochastic model impacts have been integrated).
- The system boundary does not extend to consider the importation of timber from potentially unsustainable sources or the substitution of fossil-based materials to replace lost timber flows.
- Future afforestation potential.
- Climate adaptation or resilience measures.

3.2 Model scenario analysis

One of the aims of the carbon assessment was to develop landscape level assessments of GHG emission and reduction profiles for three main scenario outputs:

- **The business-as-usual scenario**: this is the baseline or business-as-usual scenario used to assess the impact of climate mitigation action.
- **The potential max carbon scenario**: this represents the potential maximum carbon capture scenario within the defined boundary, based on a carbon decision tree developed to optimise carbon capture. When applied in an isolated scenario, it omits all the other forest objectives – nature, wood and people and the impact on global C pools as a result of imports.
- **The New Forestry Model scenario**: this is a model where all objectives are incorporated in what is considered a balanced land-use model.

3.3 Modelling Framework

The estimation of GHG removals and emissions are based on the estimation of fluxes in the following pools:

- Forest biomass, litter, deadwood and soils, based on the CBM model using National Forest Inventory (NFI) data;
- Remsoft forecast outputs that include annual harvest volumes and associated land-use transitions over the 80-year period.
- Harvested wood products based on harvest assortments and recovery into sawn wood, pallet, stake, OSB and MDF.
- Product substitution based on product recovery and assumptions of additional product displacement.

The project initially sought to export the model scenario from Remsoft directly into CBM. However, this was not possible due to dynamic and complex transition rules used in the current Remsoft model. CBM cannot use dynamic transitions for management types. Therefore, a translator was developed to export the estimates and outputs from Remsoft into a format that could be used for simulation modelling in CBM using the Archive Index Database import approach to simulate landscape level GHG fluxes.

CBM simulations were calibrated using the Remsoft derived harvest volumes. Although the calibration ensured that the levels of harvest and age class dynamics are treated equally in both models, there is a potential risk that different volume or biomass increments models used by the two frameworks result in inconsistencies in the presumed available timber supply (Table 1). A statistical analysis elaborated in Section 4.3 demonstrates the close alignment achieved in calibrating the harvest between the two models, however it is acknowledged there could still be a misalignment between the increment/timber supply of the respective modelling frameworks. The models also apply different levels of aggregation of inventory data in terms of species and yield class groups, which define the state of the forest prior to model initiation (see Appendix I). A translator was developed to export and generate a consistent dataset that was used in CBM.

3.3.1 Carbon Budget Model

The Carbon Budget Model is a carbon modelling framework for stand and landscape level forest ecosystems. It has been under development by the Canadian Forest Service for over 20 years and is compliant with the requirements under the International Panel for Climate Change Good Practice Guidance for Land Use, Land-Use Change and Forestry[10]. There are numerous examples of its use globally[11], including in Canada, at European scale by the European Commissions' Joint Research Centre[12],the Czech republic, Poland and in Ireland.

The forecast scenarios were based on CBM simulations using target harvests and silvicultural rules obtained from the timber output scenarios generated using Remsoft (Figure 1). The calibration of the CBM model is done by matching CBM and Remsoft clearfell and thinning harvests using a model error threshold of 10% (Root Mean Square Error (RMSE) of 10%). HWP timber flows within the Irish market are calculated using the same recovery rates used for displacement calculations. However, it is important to note that the Remsoft assortment inflows to HWP and product substitution are adjusted

[10] IPCC (2003) Good Practice Guidance for Land Use, Land-Use Change and Forestry

[11] Kurz, W. et al (2009) CBM-CFS3: A model of carbon-dynamic in forestry and land-use change implementing IPCC standards. Ecological Modelling Vol. 220:4

[12] Pilli, R., et al. (2018) The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3): customisation of the Archive Index Database for European Union countries. Annals of Forest Science (75:71).

using the harvest ratio adjustment factor to ensure conservation of mass balance across all pools (Figure 1). The setup and initial configuration of CBM for Irish forestry and the state of the forest at model initiation was implemented using NFI data (see Appendix I).

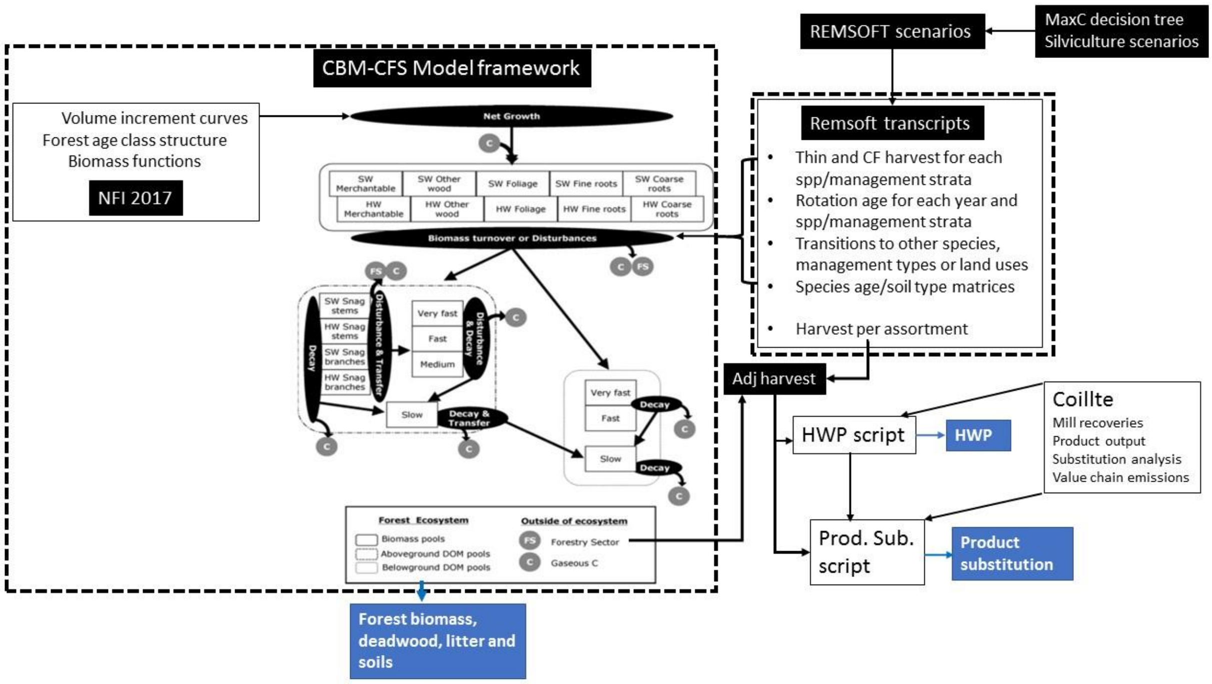

Figure 1 The model framework

Figure 1 shows the set-up of the CBM and Remsoft modelling framework with data flows and sources of data used to derive final outputs (blue boxes). Silvicultural scenarios were developed using a decision tree developed to maximise C capture across the estate (see Section 4.2). Harvest instructions, generalised silvicultural rules and forest transitions outputs are then imported from Remsoft into the CBM model to produce forest ecosystem flux estimates. The CBM model is calibrated using the expected harvest as defined by Remsoft. HWP and product substitution estimates are based on adjusted harvest assortments, mill recovery, product output and production chain emissions derived from an analysis of the Coillte wood chain.

Harmonisation of the frameworks is a challenging process due to differences in spatial resolution, stratification of forest types and growth models (Table 1). As a result, it is difficult to calibrate the Remsoft specified harvest in CBM. There is typically not enough available harvest from the Sitka spruce strata in CBM. To do the calibration, residual Sitka spruce harvests are then removed from other strata such as mixed conifer broadleaf mixtures and broadleaves (Remsoft does not model or harvest broadleaf volumes). This is considered appropriate considering the generalisation of the inventory database required as input into Remsoft, which is done based on first species and therefore a considerable spruce volume is included in mixed conifer strata. One of the key advances of this project was to improve the harmonisation of the datasets between the two models using a translator (Figure 3). More details regarding the calibration of CBM are provided in Appendix I.

Table 1: Major model framework attributes for CBM and Remsoft highlighting harmonisation issues.

Attribute	CBM	Remsoft
Sample framework	NFI 2017	Sub-compartment inventory 2021
Generalisation of species	Species cohorts (9) incl. BL, mixed CF/BL (see Appendix I)	Species by YC by management (no BL); pure stands only based on dominant SPP
Growth model	Chapmans based on NFI 2006-2017	Growfor
Harvest	Based on target and silvicultural rules, but target CBM=Remsoft	Based on defined CF and thinning ages
Optimisation	By changing sort type and species harvest (see Appendix I)	Complex true optimisation

3.3.2 Remsoft

Remsoft's Woodstock (hereinafter referred to as Remsoft) is a suite of forest modelling software used for strategic and tactical planning of forest resources is based on iterative, hierarchical modelling approach. It is widely used in the forest industry globally, but also in Ireland for the All Ireland Roundwood Production Forecast 2021-2040[13] as well as for other more regional studies[14]

The business-as-usual scenario is based on optimising the Net Present Value (NPV) of the entire forest asset with a range of management, environmental and other inputs. Figure 2 provides an overview of individual components that are used by the Remsoft optimisation engine. The harvest schedules are altered by the system for each of the 126,000 forest stands until the overall solution optimises value, subject to the constraints that includes harvest volume smoothing.

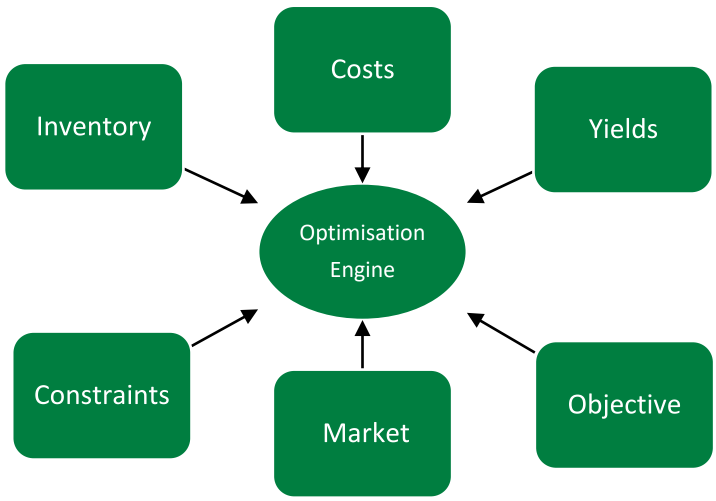

Figure 2 Components of the Remsoft Model

Constraints include sustainability of future volumes, year-on-year evenness of volume production, and felling in amenity and biodiversity areas. These are designed to provide for the long-term sustainability of the forest resource and to ensure the growing stock at the end of the cycle is higher than at the

[13] Redmond, J., Phillips, H., McDonagh, M., Sweeney, T., Fairgrieve, M., Malone, L. (2021) All Ireland Roundwood Production Forecast 2021-2040 – Methodology. (COFORD)

[14] Lundholm, A., Corrigan, E., Black, K., Nieuwenhuis., M. (2020) Evaluating the Impact of Future Global Climate Change and Bioeconomy Scenarios on Ecosystem Services Using a Strategic Forest Management Decision Support System. Frontiers in Ecology and Evolution 8:200.

start of the cycle. Adjustments to yield models are made to bring volume estimates and net harvest loss closer to those actually achieved.

The model can account for a number of economic, spatial and temporal factors in producing an optimal forecast, such as:

- the felling costs can vary considerably based on harvest type and tree size;
- the positive impacts that thinning can bring, in terms of increased tree size, can be weighed against the higher wind throw risk that thinning may cause, on a site-by-site basis;
- the total volumes of all products scheduled in any one year can be tracked and the haulage costs to, and capacities at each potential customer are included in the analysis;
- the increase in value which may accrue from retaining a stand for one extra year before clearfell can be weighed against the time value of money.

For the New Forestry Model additional objectives such as biodiversity, social and carbon objectives are included in the optimisation of Remsoft. To optimise for carbon, a framework for integrating Remsoft and CBM model runs was implemented, by:

- developing a carbon decision tree to be used by Remsoft (see section 4.2);
- the development of a translator script to export outputs from Remsoft into CBM for GHG profile simulations.

3.3.2.1 Remsoft translator

A translator was developed to export the estimates and outputs from Remsoft into a format that could be used for simulation modelling in CBM (Figure 3). These outputs included:

- Harvest volumes by species and period;
- Proportion of harvest from clearfell and thinning;
- Harvested Wood Product volumes;
- Species age class distributions;
- Clearfell ages for each year and species stratum;
- Transitions for other species or other land-uses;
- Soil type areas.

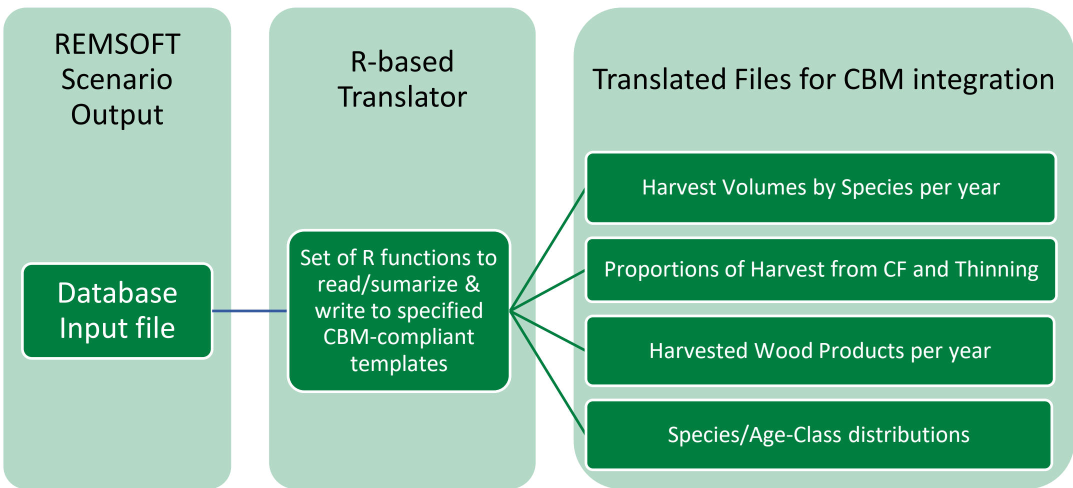

Figure 3 Remsoft to CBM-CFS Translator Process

3.3.3 Forest Carbon

CBM is a software framework that allows simulation of forest C budgets at the landscape level based on project specific inputs. A detailed description of CBM is given by Kurz et al.[15]. This framework has been selected due to its widespread use in Canada and other EU member states [16, 17, 18]. The model replaces the previously developed CARBWARE model used in Ireland [19; 20] because of a more complete treatment of dead organic matter pools. The model integrates NFI data (stands age, area, species, productivity classes and soil types), merchantable volume increment curves, equations to convert volume to biomass components, and data on disturbances, and simulates transfers of C between pools and the atmosphere (Figure 1). The equations and parameter values for growth, biomass to volume conversions, biomass components, turnover and C transfer functions for each species, management and disturbance type were defined in an Archive Index Database (AIDB, Kull et al.[21]). This database was reconfigured for the Coillte projection, using NFI and timber forecast data.

A detailed description of the set-up, calibration and running of the CBM is outlined in Appendix 1.

3.3.4 Organic soils

For the purposes of this assessment forest soils have been classified as organic soils (or peats) if the peat depth is greater than 40 cm and the organic content is greater than 20 per cent. Organic soils are further sub-classified as fens or blanket peats. If the organic or peat layer is less than 30 cm the soils are classified as organo-mineral (or peaty-mineral) soils.

Afforestation of organic soils results in a change in the GHG emission profile from a large CH_4 emission to large CO_2 and N_2O emissions due to drainage. The extent of emissions from soils following drainage is dependent on peat type, nutritional status, hydrology and previous land-use history. GHG studies in Irish peatland forests are limited in both number and the range of site types covered. The first study was that of Byrne and Farrell[22] who measured total soil respiration in a range of afforested sites on blanket peats and found a large range in values from 1 to 2.6 t C ha^{-1} yr^{-1}. The work by Byrne and Farrell was used to derive an Emission Factor (EF), 0.59 t C ha^{-1} yr^{-1} used for peatland forests in the national greenhouse gas inventory[23]. More recently, Jovani-Sancho et al.[24] investigated the soil carbon balance of forested blanket peatland in southwest Ireland. They assessed both soil carbon inputs and losses and found that afforested peatlands are a net soil carbon source of between 0.63 ± 0.92 t C ha^{-1} yr^{-1} and 3.09 ± 0.67 t C ha^{-1} yr^{-1}. The mean soil C loss across eight afforested sites was 1.68 ± 0.33 t C ha^{-1} yr^{-1}. This value has now been used for peatland forests in the national greenhouse gas inventory 2022 submission.

[15] Kurz, W.A. et al. 2009. CBM-CFS3: a model of carbon-dynamics in forestry and land- use change implementing IPCC standards. Ecol. Model. 220(4): 480–504. doi 10.1016/j.ecolmodel.2008.10.018.

[16] Grassi G. et al. 2018. Science-based approach for credible accounting of mitigation in managed forests. Carbon balance and management, 13(1), 8.

[17] Pilli R et al. 2018 Application of the CBM-CFS3 model to estimate Italy's forest carbon budget, 1995–2020. Ecol Modell. 2013;266(1):144–171. doi: 10.1016/j.ecolmodel.2013.07.007.

[18] Pilli R et al. 2017 Modelling forest carbon stock changes as affected by harvest and natural disturbances. I. Comparison with countries' estimates for forest management. Carbon Balance Manag. 2016;11(1):5. doi: 10.1186/s13021-016-0047-8.

[19] Black K. 2016. Description, calibration and validation of the CARBWARE single tree-based stand simulator. Forestry 86(1):55-68 doi: 10.1093/forestry/cpv033

[20] NIR 2021. National inventory report Greenhouse gas emissions 1990 – 2019. Reported to the United Nations Framework Convention On Climate Change, EPA, Dublin

[21] Kull, S.J. et al. 2016. Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3): Archive Index Database Table and Parameter Descriptions. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta.

[22] Byrne, K.A. & Farrell, E.P. 2005. The effect of afforestation on soil carbon dioxide emissions in blanket peatland in Ireland. Forestry, 78(3): 217-227

[23] Duffy, P., Black, K., Fahey, D., Hyde, B., Kehoe, A., Murphy, J., Quirke, B., Ryan, A.M. and Ponzi, J. (2021) National Inventory Report 2021. EPA

[24] Jovani Sancho, A.J., Cummins, T. & Byrne K.A. 2021. Soil carbon balance of afforested peatlands in the maritime temperate climatic zone. Global Change Biology. 27(15): 3681-3698.

There are large gaps in our knowledge of the carbon balance in Irish peatland forests. Data such as that reported by Jovani-Sancho et al. (2021) are required for at least all major peatland types (blanket bog, raised bog and fens). The available studies suggest that EFs may differ between these sites; however, given the uncertainty associated with the IPCC[25] default EF of 4.65 t C ha^{-1} yr^{-1}, it is appropriate to apply the value (i.e. 1.68 ± 0.33 t C ha^{-1} yr^{-1}) reported by Jovani-Sancho et al (2021) for Irish forests situated on blanket peats.

Data for other site types, such as raised and cutaway peats, is limited to the work of Byrne et al.[26] who measured soil respiration in an afforested cutaway peatland of residual woody fen/*Phragmites peat* overlying a sub-peat mineral soil consisting of glacial till and clay. It suggests that soil CO_2 emissions could be higher on these types of peat sites, which are more fertile. The rate of C loss due to decomposition of the residual peat, root biomass and forest floor was estimated to be 7.2t C/ha/yr. As in Byrne and Farrell, below-ground inputs of carbon, through litterfall and root turnover were not included. Nevertheless, it suggests that carbon losses from fen peat may be higher than in blanket peat.

On-site emissions from blanket peat soils due to drainage are calculated by Eq. 1 and are based on newly published EF data[24].

$$\Delta C_{So} = \sum_i \left(A_i \times EF_{soil_{(i)}} \right) \qquad [1]$$

where ΔC_{So} *is the onsite emission factor*, A_i is the area of peat soils in hectares, and $EF_{soil(I)}$ the on-site the emission factor for each organic soil category (i) in t C ha^{-1} yr^{-1}.

Two approaches were developed to assess how EFs would be included in the scenario analysis:

1. Approach 1 – considers a constant EF over time
2. Approach 2 – considers an exponential, age dependent decline in EFs over time (see Table 2).

The IPCC default constant EF of 2.26 tC ha^{-1}yr^{-1} is used for fens and cutaway peatland. Emissions from organo-mineral soils are assumed to be half that for blanket peats (see Table 2) & Duffy et al. (2021)[23].

A further assumption is the use of an exponential decay function to represent a declining emission from organic soils, as available soil C for decomposition becomes more recalcitrant over time.

The lack of research and empirical data on emissions from Irish forested peatlands means that it is not clear if peatland soil emissions stay constant or if the emission decline as forests get older as carbon in the soil pool becomes more resilient to decomposition. Most biogeochemical processes would point toward the exponential decay approach being the most realistic, but this has not been verified by the research community. It is also noted that there is no research information or published literature on the impact of site productivity on drainage emissions from organic soils in Irish forests, which could introduce uncertainty into the modelled outputs.

The constant EF and exponential decay approaches (Table 2) were applied under different model scenarios to test the impact on net GHG balance of peatland forests.

Off-site emission factors associated with run off were estimated using the IPCC default value of 0.31 tC ha^{-1}yr^{-1} or organic soil.

[25] IPCC., 2014. 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands. In: Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G. (ed.). IPCC, Switzerland.

[26] Byrne, K.A., Cabral, R. Farrell, E.P., 2007. Commercial afforestation. In: Wilson, D and E.P. Farrell. (eds.) 2007. CARBAL. Carbon gas balances in industrial cutaway peatlands in Ireland. Final Report. Bord na Móna.

Table 2: On-site emission factors (EF) used in the scenario analyses

	Approach 1	Approach 2		
Organic soil category (i)	Constant EF (tC $ha^{-1}yr^{-1}$)	Exponential decay function	EFsoil(i) year 1 (tC $ha^{-1}yr^{-1}$)	EFsoil(i) at steady state year 44 (tC $ha^{-1}yr^{-1}$)
Blanket peats	1.68	$Cstock_{t(n)}=Cstock_{(tn-1)}EXP(-0.03085)$ Initial stock $_{t1}$= 98.99 EF= $Cstock_{t(n)}-Cstock_{(tn-1)}$	3.01	0.79
Fens and cutaways	2.26	$Cstock_{t(n)}=Cstock_{(tn-1)}EXP(-0.03085)$ Initial stock $_{t1}$= 153.22 EF= $Cstock_{t(n)}-Cstock_{(tn-1)}$	4.65	1.23
Organo-mineral	0.84	$Cstock_{t(n)}=Cstock_{(tn-1)}EXP(-0.03085)$ Initial stock $_{t1}$= 49.1 EF= $Cstock_{t(n)}-Cstock_{(tn-1)}$	1.55	0.39

3.3.5 Harvested Wood Product model

The Harvested Wood Product (HWP) model is based on the product half-life decay model as outlined in the 2013 IPCC supplementary guidelines under the Kyoto protocol[27]. Projected HWP inflows and historical timber utilisation data were used to estimate harvested wood product (HWP) emissions/removals in Ireland using a model based on the 2006 IPCC Guidelines approach (Eq. 2 and 3).

$$C_{i+1} = e^{-k} \times C_i + \left[\frac{(1-e^{-k})}{k}\right] \times Inflow_i \qquad [2]$$

$$\Delta C_i = C_{i+1} - C_i \qquad [3]$$

where:

i = year.

C_i = the carbon stock in the particular HWP category (i.e. sawn wood or wood-based panels) at the beginning of year *i*, in kt C.

k = decay constant of first-order decay for HWP category given in units yr^{-1} (k = ln(2)/HL, where HL is half-life of the HWP pool in years. Default half-lives of two years for paper, 25 years for wood-based panels, and 35 years for sawnwood were used to estimate emissions resulting from products coming out of use.

$Inflow_i$ = the inflow to the particular HWP category (HWP_j) during year *i* in kt C yr^{-1}.

ΔC_i = carbon stock change of the HWP category during year *i*, in kt C yr^{-1}.

Harvested wood product inflows into the HWP pools from historical harvest and allocation of roundwood to construction, pallet and packaging, fencing, other and wood-based panels/OSB/MDF panels for the Coillte estate were obtained based on an analysis of domestic production from mill data for 2019 (source Coillte - Trade data/Industry estimates/Interviews[28], Table 3). The HWP categories are based on the product recoveries and market share data (Table 4).

[27] IPCC (2013) Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol
[28] Coillte. 2019 Woodflow Statistics, D. O'Toole (2020)

Table 3: Sawn wood recovery values based on percentage recovery from sawlog and stake

Process	Assortment	% recovery
Sawn Timber	Sawlog	49
Round stake	Stake	91
Residues from Sawn Timber	Sawlog	48

Table 4: Market share of finished products from Irish mills, associated conversion factors and half-life values for HWP categories[27].

HWP category	Market Share	Conversion factor to tC [Mg C.m^{-3}]	Half life (years)
Construction	48% of sawn timber	0.229	35
Pallet/Packaging	26% of sawn timber		
Fencing	25% of sawn timber plus round stake		
Other	1%		
OSB + MDF	85% of Pulp plus 30% of residues	0.269	25

3.3.6 Product Substitution

The implementation of the product substitution in the carbon modelling was based on the allocation of harvested timber volume to HWP products (Table 4 above) including energy, potential additional displacement of wood products, conversion and displacement factors provided by Holmgren (2021)[29]. Product substitution or displacement of energy intensive materials with wood products results in avoidance of emissions. However, in order for displacement to contribute towards climate change mitigation measures, the displacement must be additional to the current status quo. So additional Product Substitution (PS) can be calculated using Eq. 4 and 5.

$$PS = \sum Q_i \times DF_i \times PropA_i \qquad [4]$$

and

$$Q_i = V_i \times CF_i \qquad [5]$$

where Q_i is the quantity of a wood product category *i* expressed in tCO_2 eq., *DFi* is the displacement factor for products category *i* replacing and energy intensive material, expressed in tCO_2 per tCO_2 of the product category *i*; $PropA_i$ is the proportion of additional wood product *i* that substitutes energy intensive materials; V_i is the volume of wood product *i*, and CF_i is the conversion factor from volume to tCO_2 for product i (see Table 5). One key assumption associated with this process was the estimation of the proportion of additional volume substituting energy intensive materials ($PropA_i$); these values are assumed to be static (i.e. they do not change over the 80-year horizon) and are assumed to be representative of the current use of wood products in Ireland (Table 5).

[29] Holmgren, P. (2021) Benefits of Wood Product Substitution in Displacing Fossil Based Products, COFORD

Table 5: Product substitution parameters.

Wood product category (Q)	Vol. To CO_2 (CF)	Proportion of Additional Vol. Substituting Energy Intensive Materials (PropA)	Displacement Factor (DF)
Construction	316	0.15	1.85
Pallet/Packaging	171	0.05	1.57
Fencing	165	0.15	0.75
Other	7	0.00	0.00
OSB + MDF	870	0.15	1.35
Energy (Electricity, CHP)	418	0.10	0.36

4. Stand & Landscape Level Modelling

4.1 Carbon Mitigation Management Options

Stand and landscape level assessments were undertaken to develop an understanding of how carbon capture can be maximised on the estate, but the overriding challenge are the ongoing emissions from peatland forests. Various measures were examined to assess the impacts of emission from peatland forests, such as rewetting for bog habitat restoration, long-term retention, and conversion to native woodland under scenarios focusing on peatland redesign. All scenarios were developed using stand level CBM simulations and organic soil emission factors, as outlined in the methodology (section 3.3.4).

4.1.1 Peatland emissions

Eddy covariance and modelling studies[30] suggested that forest peatlands become a net sink after 4-12 years following initial afforestation. However, subsequent decomposition losses after clearfell and continued emissions from peat soils result in peatland forests becoming a net emission source after 1 to 3 rotations depending on productivity. The transition to net emission is suggested to occur earlier in low productive stands. This hypothesis was evaluated for Irish forests using the newly defined emission factors, assuming a steady state or exponential decay function for drained organic soils (see Table 2).

Figure 4 shows a typical profile of emissions and removals from all pools for a YC 18 Sitka spruce forest on blanket peatland, assuming a constant emission from soils of 1.68 tC $ha^{-1}yr^{-1}$. Blanket peatland emissions appear to be the major contributing factor influencing the overall GHG balance (yellow histograms in Figure 4). It was therefore important to establish which emission factors best represent peatland forests and when peatland forests become a net emission source so that an effective decision support system could be developed to minimise peatland emissions.

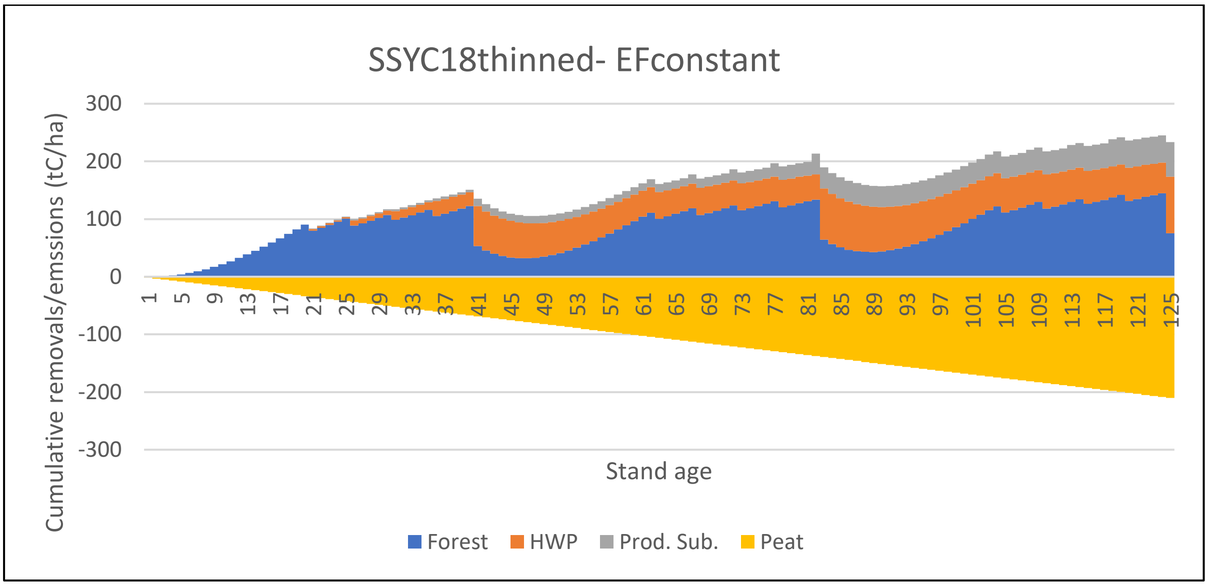

Figure 4 Cumulative removals and emissions of a Sitka spruce stand, YC 18 on blanket peatland forest over 3 successive rotations. C emissions are negative and removals are positive

[30] Hargreaves, K. J., Milne, R. & Cannell, M. G. R. 2003. Carbon balance of afforested peatland in Scotland. Forestry, 76: 299-317.

4.1.1.1 Blanket peats

The following analyses show the impact of the constant EF versus exponential decay EF across different forest types. For blanket peats, under the constant EF scenario, yield class 8 to 12 forests become a net emitter 80 to 140 years after initial afforestation (Figure 5). This means that YC 8 forests are likely to become a net emission source after the 1st rotation (ca. 55 years of age) and YC 12 stands a net emitter after 2nd rotation. The mean age after initial afforestation for the Coillte blanket peatlands is ca. 40 to 60 years, so it is likely that most of these lower YC forests will be a net emitters within the next 20 years if current management practice continues.

Under the exponential decay assumptions, YC 8 forest are projected to become a net emitter after the 2nd rotation, which means that most YC 8 blanket peat forest will become a net emission within the next 80 years. Higher productive forests, greater that YC 12, are demonstrated to be a net remover over 3 rotations (Figure 5 bottom panel).

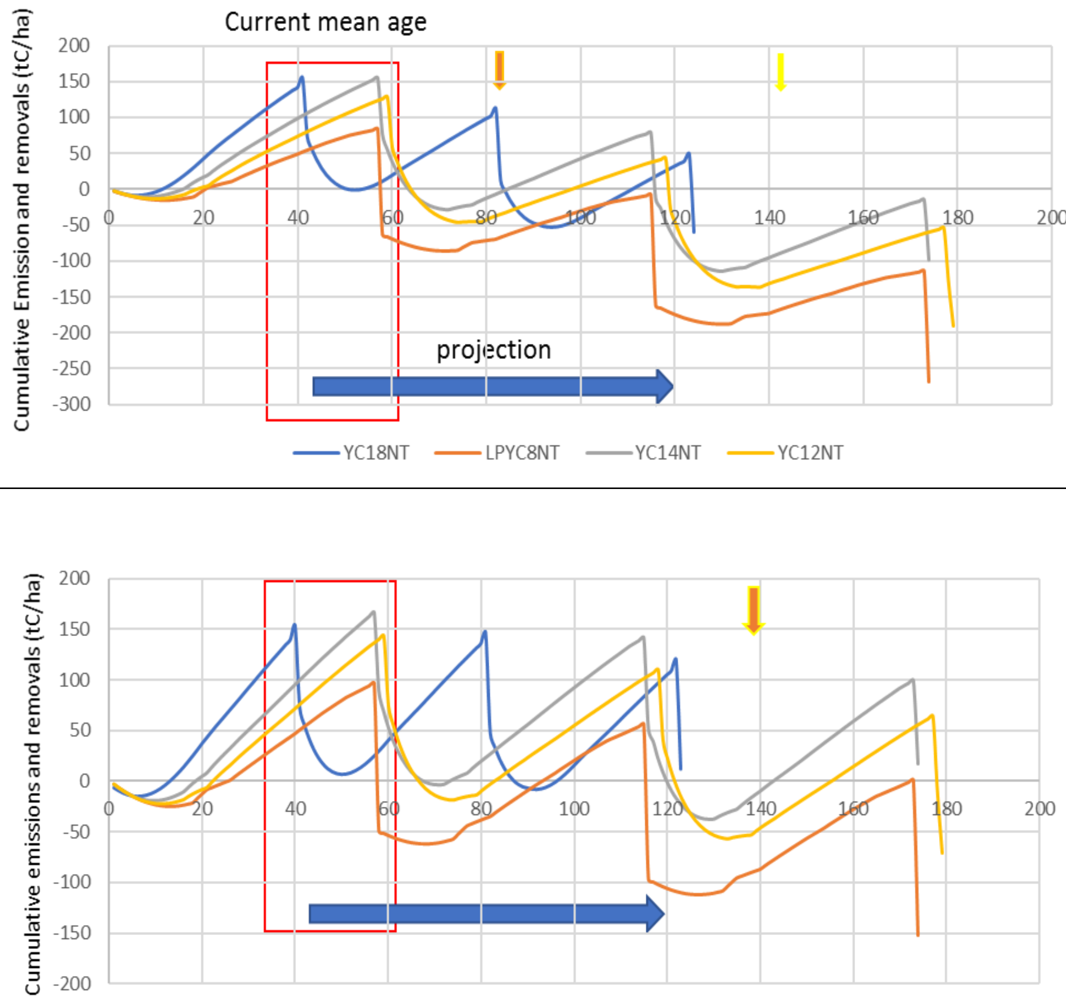

Figure 5 Cumulative emissions and removals for all pools using a constant emission factor (EF) (top panel) and an exponential decaying EF (bottom panel) for different blanket peat forest types over 3 successive rotations: YC 12, 14 and 18 Sitka spruce and Lodgepole Pine YC 8, all with no prescribed thinning operations.

The vertical arrows show where the corresponding forest type becomes a net emission.

The results suggest that blanket peatland forests with YC 8 and below are likely to become a net emission source, even in the exponential decaying EF scenario. Therefore, efforts to minimize emission should be directed to alternative silviculture and land-use measures for less productive forests.

Silvicultural options such as thinning and clearfelling can be considered for forest with a YC above 8 as it is demonstrated that they are net removers over three rotations.

4.1.1.2 Fen peats

For fen and cutaway peats a constant EF of 2.26 tC $ha^{-1}yr^{-1}$ is used as well as an exponential decay function applied to this EF. Under this scenario, yield class 8, 12 and 14 forests become net emitters after the 1st rotation. YC 18 forests are estimated to become net emitters after 90 years (Figure 6). Under the exponential decay assumption, YC 8 and 12 forests become a net emission source after the 1st and 2nd rotations, respectively.

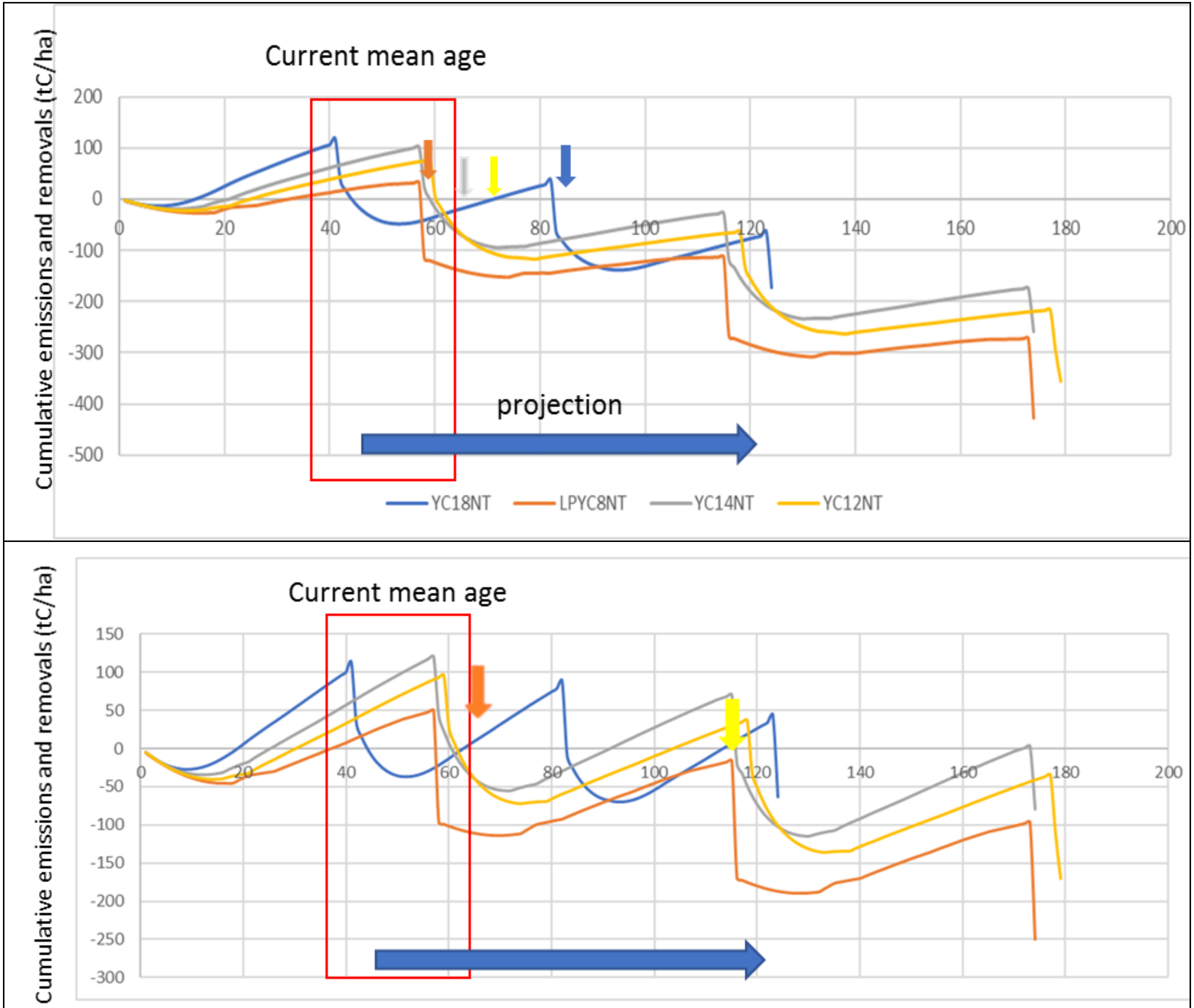

Figure 6 Cumulative emissions and removals for all pools using a constant emission factor (EF) (top panel) and an exponential decaying EF (bottom panel) for different fen forest types over 3 successive rotations: YC 12, 14 and 18 Sitka spruce "no-thin" (YC12, 12, 14, 18) and lodgepole pine YC8 "no-thin" (NT).

The vertical arrows show where the corresponding forest type becomes a net emission.

The results suggest that fen peat forests with a YC less than or equal to 10 are likely to become a net emitter within the next 80 years, even under the exponential decay EF scenario. Therefore, efforts to minimize emissions should be directed to alternative silviculture and land-use measures for these forest types. Standard silvicultural options can be considered for forest with a YC of 12 and above as it is demonstrated that they are net removers over three rotations.

4.1.1.3 Organo-mineral soils

Organo-mineral soils comprise mostly of peaty gleys and peaty podzols. These often support high yield class stands. Under the constant EF scenario, it is projected that YC 8 stands will become a net emitter after 3 rotations. For the exponential decay scenario, all forests with a YC 8 and higher will still be a net remover after 3 rotations (Figure 7).

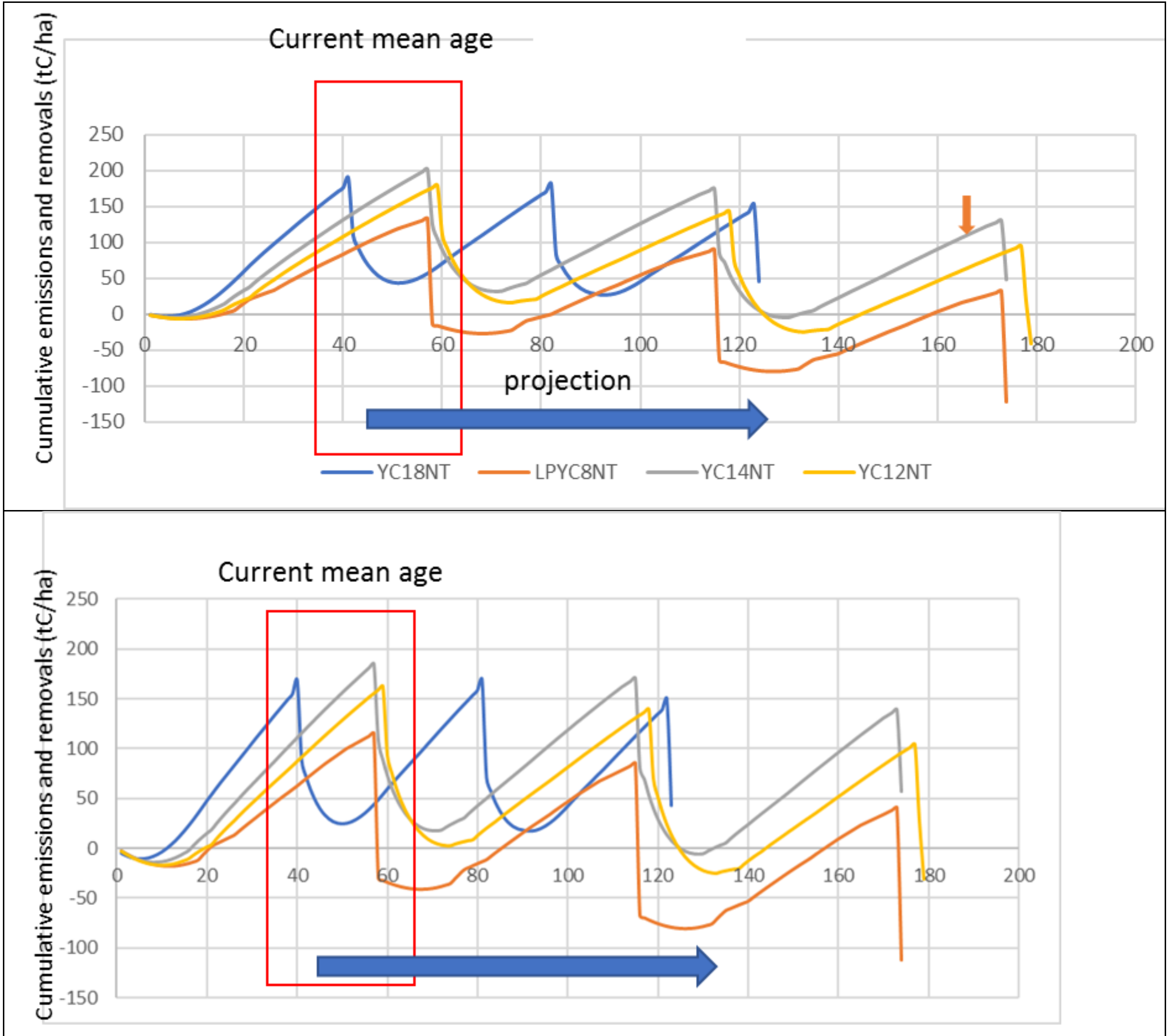

Figure 7 Cumulative emissions and removals for all pools under a constant emission factor (EF) (top panel) and an exponential decay (bottom panel) for different organo-mineral forest types over 3 successive rotations: YC 12 14 and 18 Sitka spruce "no-thin" (12,14,18) and lodgepole pine YC8.

The vertical arrows show where the corresponding forest type becomes a net emission.

The results of these scenarios for organo-mineral soils suggest that a threshold of YC 6 or less should be redesigned (alternative land-/silviculture) in order to minimize emissions from these stands. Standard silvicultural options can be considered for forest with a YC of 8 and above.

4.1.2 Silviculture

Management of the conifer estate generally involves thinning or "no-thinning" options with clearfell and replanting at commercial rotation ages, where the clearfell age is 20-30% lower than the age of maximum mean annual increment (MMAI). Although premature clearfelling provides an opportunity to normalise age class distributions and, in some cases, a better economic return, there is a potential to forego increment and in turn, additional carbon capture. Therefore, extension of rotations to MMAI is an option to improve carbon capture in productive forests of the estate but equally, this needs to be considered as part of a model that balances the multiple objectives of our forests (wood, nature, people and climate).

Emissions from the biomass, litter, deadwood and soils C pools are associated with felling (see Figure 4). It has been suggested that these could be reduced by alternative silvicultural management approaches to forests, such a continuous cover forestry (e.g. irregular structured forests) or shelterwood type systems, which reduce clearfell intensity. However, the scientific literature remains inconclusive on the efficacy of CCF as a carbon management and climate mitigation measure – a review of this topic is provided in Appendix III. Furthermore, there are currently no modelling frameworks and/or long-term experimental data for CCF systems available for the UK or Ireland to inform associated carbon modelling of such systems.

Thinning is a common forest management practice on wind firm sites. It involves the systematic/selective removal of a proportion of trees growing in a forest stand and provides more growing space for the remaining trees. This provides both an early supply of timber and income for the owner, as well as increasing the yield of timber over the stand's lifetime. The removal of trees creates gaps in the forest canopy that increase light penetration to the forest floor as well as altering soil moisture and temperature, which contributes to the yield increase.

A meta-analysis of results from 53 peer-reviewed publications did not find notable effects of thinning on soil moisture, fine root biomass and soil carbon stocks[31]. Conversely, litterfall was reduced following thinning (-23.7%), while soil temperature (+8.7%) and soil respiration were increased (+29.4%). Of note is the finding that thinning significantly increased soil respiration in both broadleaved (+35.6%) and mixed forest (+9.3%), but not in coniferous forest due to the more recalcitrant nature of the litterfall.

Studies on the effect of thinning on the forest carbon balance in Ireland are limited. Olajuyigbe et al.[32] investigated the influence of thinning, microclimatic factors and plant productivity on CO_2 losses from thinning lanes in a first rotation Sitka spruce stand in Co. Laois. The study found an increase in soil moisture content in thinning lanes as well as a short-term increase in soil CO_2 emission in thinning lanes compared to the forest stand. Stand model comparison of thin versus "no-thin" management of forest and HWP storage generally suggest that "no-thin" management provides a higher carbon store when compared to thin scenarios[33,34] Similar findings have been reported for forest management options in the USA[35]. However, the impacts at landscape level remain unclear.

For lower YC stands that are generally not thinned, extension of rotation was considered in two scenarios (Figure 8):

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[31] Zhang, Z., Guan, D., Li, W., Sun, D., Jin, C. Yuan, F., Wang, A. & Wu, J. 2018. The effects of forest thinning on soil carbon stocks and dynamics: a meta-analysis. Forest Ecology and Management, 429: 36-43.

[32] Olajuyigbe, S., Tobin, B., Saunders, M. & Nieuwenhuis., M. 2012. Forest thinning and soil respiration in Sitka spruce forest in Ireland. Agricultural and Forest Meteorology, 157:86-95.

[33] Black, K. 2008. Ireland's forest carbon reporting system. In: Hendrick, E. and Black, K. (Eds), Proceeding of COFORD conference on: Forestry, Carbon and Climate Change - local and international perspectives. COFORD, pp 14-20.

[34] Duffy, C., O'Donoghue, C., Ryan, M., Styles, D., Spillane, C. 2020. Afforestation: Replacing livestock emissions with carbon sequestration. Journal of Environmental Management 264, 110523.

[35] Clark, J., Sessions, J., Krankina, O., Maness, T. 2011. Impacts of thinning on carbon stores in PNW: a plot level analysis. Final Report on Impacts of Thinning. Oregon State University.

- Biological rotation (MMAI) was compared to the commercial rotation for a YC 12 Sitka spruce stand.
- Succession to birch woodland in peatland sites. In the case where a site may be suitable for native woodland conversion, conifer stands (YC 12) were converted to birch woodland over three stages, starting at 45 years by opening 25% of the stand and planting coupes of birch. The final stage was completed at year 75. Natural succession of the birch/spruce canopy was then assumed to occur.

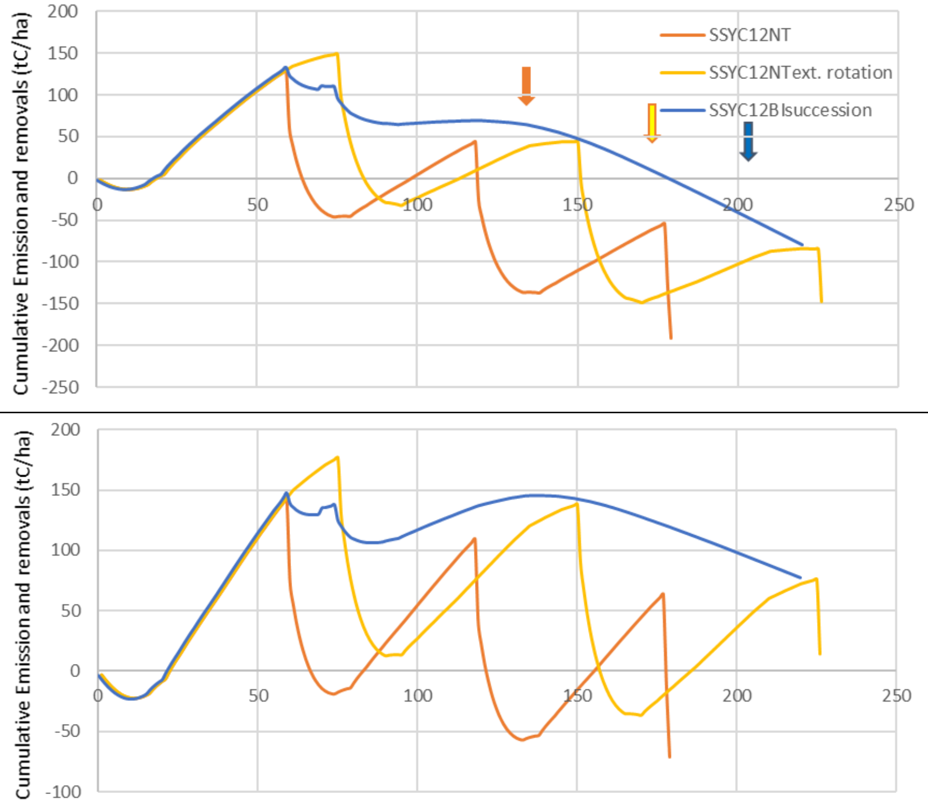

Figure 8 Cumulative emissions and removals for all pools under a constant emission factor (EF) (top panel) and an exponential decay (bottom panel) for different forest types over 3 successive rotations: Sitka source YC 12 "no-thin" with clearfell at commercial rotation age (SSYC12NT) or at MMAI (SSYCNText. rotation) and gradual succession to birch woodland (SSYC12BIsuccession).

The vertical arrows show where the corresponding forest type becomes a net emission.

In the constant EF scenario, extension of rotations to MMAI results in an additional accumulation of C in the biomass pools, greater HWP removals and product substitution (Figure 8), when compared to a commercial rotation. The analysis also suggests that the transition from a net remover to a net emitter is delayed by ca. 50 years by extending rotation age to MMAI for the yield classes analysed (Figure 8 top panel). The same trend could be observed for other yield classes but may display a different temporal dynamic (transition time from a source to emission would occur at different periods) and assumes a system boundary that does not import timber.

Although the gradual transition to birch woodland result in losses of carbon from biomass and dead organic matter (DOM), these emissions are lower than those associated with clearfelling pools (Figure 8). Transition to birch woodland results in the sustained removal for at least 75 years longer than the commercial rotation scenario (Figure 8).

The following silviculture options were considered for higher YC stands (i.e. ones not deemed appropriate for alternative land-use management based on the above-mentioned analysis, Figure 9):

- Extension of rotation age, but no examples were explored in addition to those presented in Figure 8 because the extension of rotation age will increase C capture for all YCs;
- Alternative forest management such as CCF or shelterwood systems (modelled as regular thinning interventions);
- Thin versus "no-thin" options.

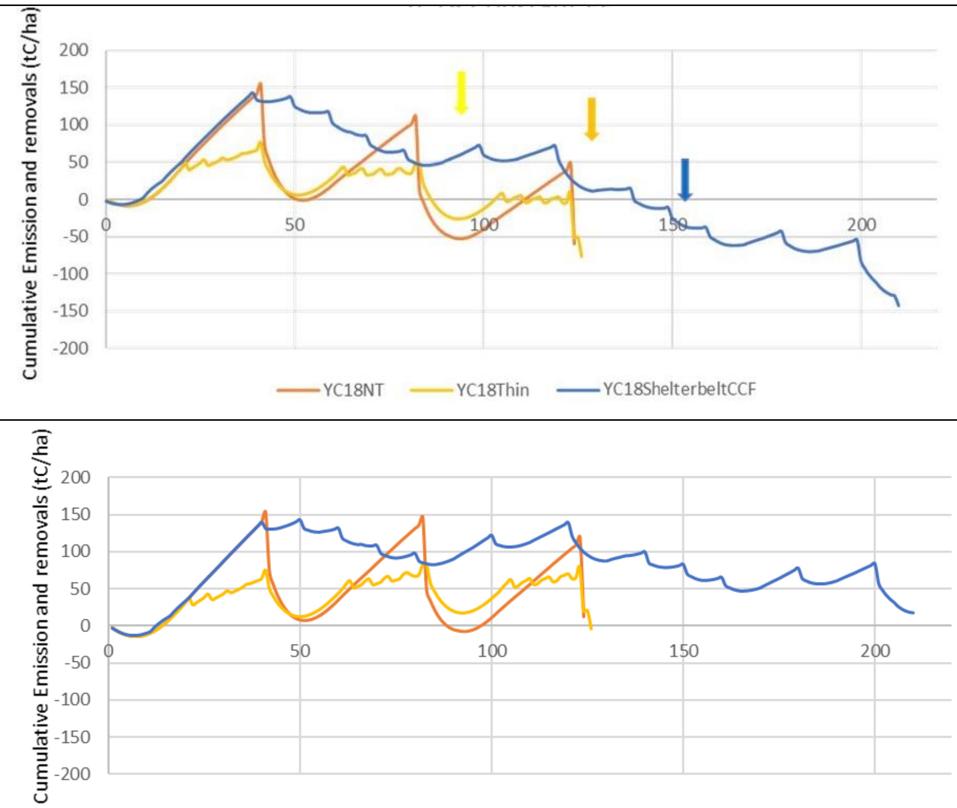

Figure 9 Cumulative emissions and removals for all pools under a constant emission factor (EF, top panel) and an exponential decay (bottom panel) for different peat forest types over 3 successive rotations: Sitka source YC 18 "no-thin" (YC18NT) and thin (YC18Thin) with clearfell at commercial rotation age and transformation to an irregular shelterbelt system (YCshelterbeltCCF).

The vertical arrows show where the corresponding forest type becomes a net emission.

There is a large reduction in total removals (incl. HWP and product substitution) when thinned stands are compared to "no-thin" stands (Figure 9). This is consistent with published research. The major reason associated with these differences is that more carbon is stored in the forest in the deadwood pool under a "no-thin" scenario, compared to the increased HWP pool in thinned stands, where the residence time of C in the is shorter than that of deadwood. It should be highlighted that only 43% sawlog is recovered for HWP and this decays nearly twice as fast as carbon in the deadwood pool. As a result, "no-thin" stands generally (and regardless of soil type) capture double the amount of carbon in the forest, HWP and product substitution pools, when compared to thinned stands.

The results suggest that the transition to net emissions under the constant peat EF assumption occurs one rotation later in unthinned stands than in thinned stands (Figure 9). The results also suggest that transition to shelterwood CCF will extend the period peatland forest remains a net remover for a further 30 years (Figure 9 top panel). All silvicultural options for high YC stands, under the exponential decay assumption, result in net removals for 3 rotations or more than 200 years in the case of CCF (Figure 9 lower panel). It is important to note however that this does not consider aspects such as site suitability, age class or landscape level interactions as described in the subsequent section, or indeed potential total impacts on HWP pools. As noted previously there is currently a lack of evidence and empirical data of steady state CCF stands in Ireland that could adequately inform the implementation of CCF on peatland forests on a large scale. Therefore, whilst CCF can have benefits in delivering on other objectives such as ecological and recreation, the benefits of CCF for climate mitigation are inconclusive. Refer to Appendix III for further details.

4.1.3 Landscape level interactions

Interpretation of the indicative impact at the stand level should be treated with caution due to interactions that occur at the landscape level. For example, extensions of rotations may result in large short-term increases in CO_2 removals and the level of harvest will decline. However, if harvest is not constrained there may be large emissions when forests get older and are harvested. This is well illustrated in a landscape scenario analysis where C capture is maximised using abovementioned silvicultural interventions, in particular extended rotations.

Figure 10 shows a comparison of the max C scenarios where rotations were extended with no harvest constraint (C-DT_nocap, top panel). Total removals for the entire Coillte managed forest estate increase to ca 3,500 Gg CO_2 per year by 2030, before reverting to an emitter of ca 2,000 Gg CO_2 per year over the medium and longer term. This is associated with a reduction in harvest and an increase in biomass increment as a result of extended rotations. However, the level of harvest increases rapidly after 2035 as forests meet the threshold clearfell age criteria, and the estate becomes a large emitter from 2040 to 2070. These fluctuating cycles between net removals and net emissions will continue until age class structure is normalised and stabilised in response to new silvicultural practices. An alternative would be to constrain the level of harvest so that timber demand is met but excess available timber is not harvested (see C-DT_cap, Figure 10 bottom panel). In this example, the GHG balance of the estate stabilises after the initial increase in removals. While this approach will maximise carbon storage in the short term, it will have a direct impact on the level of timber production, provision of sustainably certified timber to the Irish market and Coillte's potential to deliver on the other forest objectives. Furthermore, this scenario demonstrated that the Coillte estate would become an emitter in the order of ca 500 to 1,000 Gg CO_2 per year in the longer term. It also ignores the short-term risk associated with potential pests and diseases arising from an unmanaged forest and ignores the need to maintain a consistent supply of timber to the industry. Furthermore, it ignores that the importation of timber from potentially unsustainable sources may contribute to leakage effects at global level.

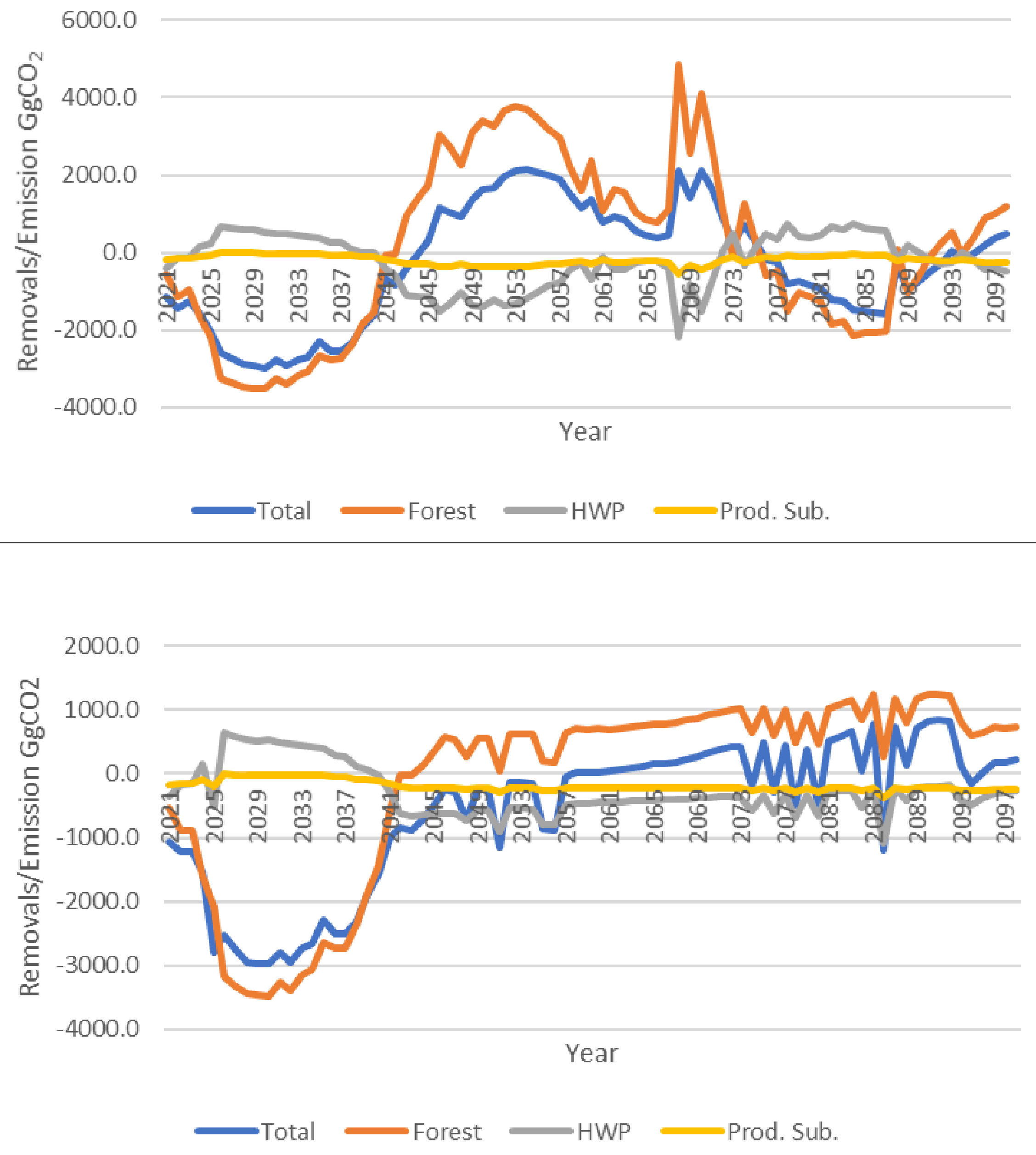

Figure 10 Annual CO_2 emissions (positive values) and removals (negative values) of the Coillte estate under alternative management scenarios, in particular, where rotations are extended to MMAI without harvest constraint (C-CT_nocap, top panel) and with harvest constraint (C-DT_cap bottom panel).

CO_2 emissions and removals for the total, forest (incl. organic soils), HWP and Product substitution pools are expressed in Gg CO2 (1Mt=1000Gg).

The scenarios presented above are not intended to be prescriptions for future management, but rather illustrations of interactions that occur at the landscape level, which are not evident when only stand level assessments are evaluated and analysed. These specific scenarios are designed purely to understand the dynamics associated with a carbon/climate mitigation perspective and do not consider the multiple objectives/ecosystem services that need to be balanced across the estate.

Another example of landscape level interactions is the implementation of "no-thin" silviculture at the landscape level, which suggests that the impact of no-thinning versus a business-as-usual scenario is quite small, despite the observed large stand level difference. This is because more harvest volume will originate from clearfells to compensate for no harvest from thinning. This has a negative feedback influence because of age class shifts and increased emissions from clearfelling.

Implementation of transition to birch woodland using the approach outlined in section 4.1.2, which assumes a slow transition over time (Figure 8) could be difficult to implement at scale and/or may not be economically feasible. An alternative is to replace low yielding conifer stands with native woodlands immediately after clearfelling instead of a gradual conversion to native woodland. The landscape level climate mitigation impacts of diversification using the species replacement approach at clearfell is likely to be negligible, however further research in this area is required.

4.1.4 Bog restoration

Rewetting peatland forests to facilitate bog restoration is suggested by some to be a positive climate mitigation action. Although CO_2 eq emissions from rewetted deforested organic soils are lower than those from drained forest soils[36,37], the overall ecosystem and landscape effect is often not considered. Contrary to suggestions in the IPCC GHG guidelines and other publications, it may take a long time for rewetting emission reductions to be realised[33]. A chronosequence study on rewetted blanket peatlands in the west of Ireland show no change in net GHG emissions from rewetted forested peats after 8 to 10 years[38]. There are also suggestions that rewetting peatland in boreal and temperate forests result in additional global warming due to the increase in methane emissions, deforestation emissions and the lower uptake of CO_2 by forests at the landscape scale[39]. Interestingly, the study by Ojanen and Minkkinen was the only one where deforestation emissions associated with peatland restoration were considered.

In order to investigate the potential impact of rewetting on the overall ecosystem balances, sensitivity analyses were carried out at the landscape level based on deforestation and bog restoration of 8,000 ha of low YC conifer crops on blanket peat sites. In this example (taken from the New Forestry Model scenario), bog restoration of 8,000 ha was assumed to take place over 50 years, starting at 212 ha per year in 2021 and decreasing to 21 ha per year by 2070. The sensitivity analyses considered a low impact and high impact scenario:

- Low impact rewetting scenario: assumed an emission reduction of 1.21 t CO_2eq per ha per year based on modified data presented by Wilson et al[37] Deforestation emissions were assumed to be high by only selecting low YC conifer stands at rotation age.
- High impact rewetting scenario: assumed that restored peatlands have the same EF (as above) but include additional biomass removals, resulting in a net removal of 0.5 tCO_2 per ha per year[40] after 10 years. The removal value for peatlands is based on eddy covariance studies

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[36] IPCC 2014. 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands. In: Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., TroxleR, T.G. (ed.). IPCC, Switzerland.

[37] Wilson et al., 2016. Greenhouse gas emission factors associated with rewetting of organic soils. Mires and Peat, 17(Article 4):1-28.

[38] Rigney, C., Wilson, D., Renou-Wilson, F., Müller, C., Moser, G. and Byrne, K.A. 2018. Greenhouse gas emissions from two rewetted peatlands previously managed for forestry. ***Mires and Peat,*** 21(24), 1-21.

[39] Ojanen, P., & Minkkinen, K. 2020. Rewetting offers rapid climate benefits for tropical and agricultural peatlands but not for forestry-drained peatlands. Global Biogeochemical Cycles, 34, https://doi.org/10.1029/2019GB006503https://doi.org/10.1029/2019GB006503

[40] Sottocornola, M and Kiely, G. 2010.Energy fluxes and evaporation mechanisms in an Atlantic blanket bog in south-western Ireland. Water Resour. Res: 46 DO - 10.1029/2010WR009078

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on undisturbed peatlands. Deforestation emissions were assumed to be lower by randomly selecting all age classes of low YC conifer stands.

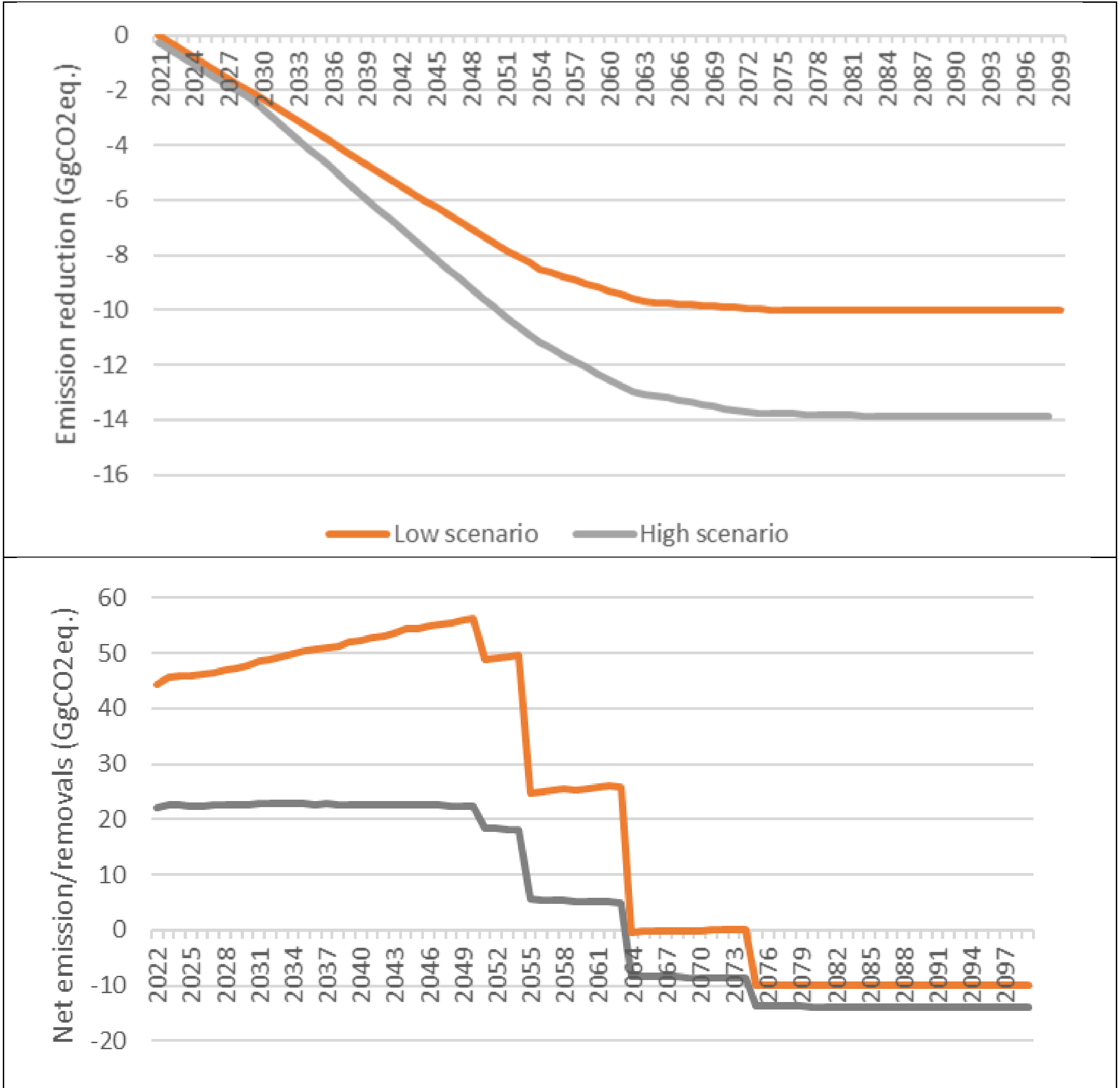

Figure 11 Impact of rewetting 8,000 ha of peatland forest for bog restoration, excluding deforestation emissions (top panel) and including deforestation emissions (bottom panel), assuming a low and high impact scenario for CO_2 equivalents (CH_4, N_20 and CO_2) emission reductions are considered as removals (negative values)

The results show that the reduction in emission associated with rewetting 8,000 ha of drained organic soils has a very small climate change mitigation advantage, peaking at -8 to -14 $GgCO_2$ eq. per year by 2070 (top panel Figure 11). However, when deforestation emissions are included (bottom panel, Figure 11) rewetting for bog restoration results in emissions 2 to 5 times larger than the emission reductions associated with soils. These results suggest that rewetting will have negative climate change impact in the short-term due to deforestation. Although there are small emission reductions in the long term, these have a small impact on the overall emission/removal profile. These results are based on the CO_2 equivalence principle and not the Global Warming Potential (GWP) calculation consistent with the study presented by Ojanen and Minkkinen[39]. If the scenario profiles are based on GWP, then there is no climate change mitigation benefit over the entire time series. This is due to the larger warming potential of methane, which is the dominant GHG form associated with rewetted organic soils.

Rewetting of drained organic forested peatland soils, while offering no short-term climate change mitigation benefit, does provide benefit in the longer term. However, it is important to note that the research related to rewetting forested peatlands in Irish (or temperate) conditions is limited both in terms of time and space. Consequently as new research and findings emerge, it is likely that these will further inform our decisions relating to the redesign prescriptions applied in low productive peatland forests. It is important to note that there are also ecological benefits and ecosystem services associated with redesign and rewetting prescriptions. Climate change mitigation action should be directed toward changes in management of high YC stands (extended rotations) and a move to low impact management or redesign of low productive stands, in order to reduce disturbance emissions in low YC sites. These strategies will delay the tipping point, where peatland forest become a net emission.

4.2 Carbon Decision Tree

A carbon decision tree (Figure 12) was developed based on the analysis presented in section 4.1. This work provided guidance on:

- How soils should be classified based on different emission factors (section 4.1.1);
- The YC thresholds applied for each soil type where redesign options (i.e. conversion to semi-natural woodland (SNW), and rewetting should be considered (section 4.1.1 and 4.1.2);
- The YC threshold for different soil types where changes in conifer stand management, such as thinning vs no-thinning or extension of rotation, should be considered (section 4.1.2).

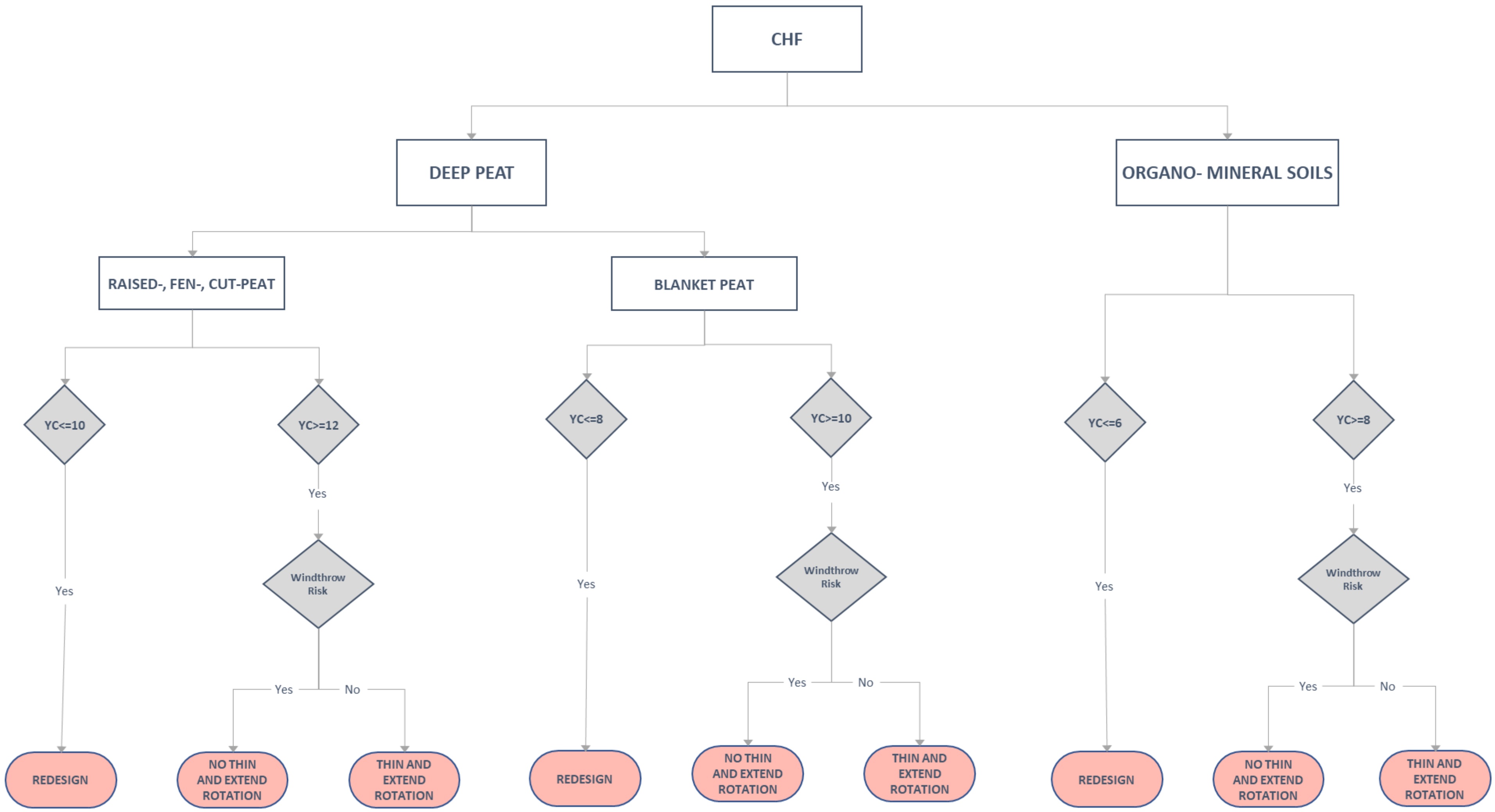

Figure 12 Carbon Decision Tree for Coniferous High Forest (CHF) on forested peatlands

The redesign option is implemented if the YC is below a defined YC threshold for each soil type (Figure 12). If the YC is above the threshold, then silvicultural options are based on suitability for thinning or no-thinning using windthrow risk as a key decision criterion. Sites with high windthrow risk are not considered for thinning (Figure 12).

4.2.1 Implementation of the C decision tree

The C decision tree is used by Remsoft to optimize for maximum carbon capture. It should be highlighted that there are multiple objectives that Remsoft optimises before the C decision tree is implemented. These include net present value (NPV), nature objectives, recreation objectives and environmental constraints. In the absence of any other objectives or constraints, the direct implementation of the C decision tree will result in the profile presented in Figure 10 in section 4.1.3

It is important to note that some of the C decision tree objectives include biodiversity measures that result in some additional emission (e.g. rewetting) in the short-term.

4.3 Carbon Profiles

4.3.1 Calibration of scenarios

One of the main challenges of using a combined Remsoft/CBM modelling framework is matching the amount of harvesting, due to the different levels of generalisation, different sampling stratification and different growth models used by the two models (see Table 1, section 3.3.1). This analysis calibrated the Remsoft based harvest to an accuracy of 92 to 96 % with the CBM harvest. In most cases the level of harvest was overestimated by 8-14%. This would result in an overestimation of emissions.

There have been technical improvements to the CBM model as part of the development of the New Forestry Model. An iterative development process of the new Remsoft translator resulted in an improved method for the calibration of the harvest with the reported accuracy and bias in Table 6. The reasons for this include:

- Better definition of clearfell ages for species strata, which results in a marked influence on growth increment and C removals;
- Less reallocation of scheduled harvest volume to other species strata, such as broadleaves, to make up required level of harvest defined by Remsoft.

Table 6: CBM calibration

	Business As Usual Model	New Forestry Model
Accuracy (r^2)	0.96***	0.92**
Bias %	-3.5 ns	-5.3ns

Statistical parameters were deemed significant at p<0.01***, p<0.05** and P<0.01*, ns is not significant

4.3.2 Business As Usual scenario

The system boundary for this scenario included:

- HWP inflows are estimated based on new Coillte data not EUROSTAT national data;
- Product substitution;
- Deforestation is not included in the business-as-usual scenario as this is currently not a land/forest management approach employed operationally. Furthermore, it is expected that any deforestation will be mitigated through land acquisitions and replacement planting ;

The business-as-usual model demonstrates that there is a steady decline in removals and a transition to net emissions by 2045 (Figure 13). Emissions then continue to increase to ca. 1,000 Gg CO_2 per year by the end of the century.

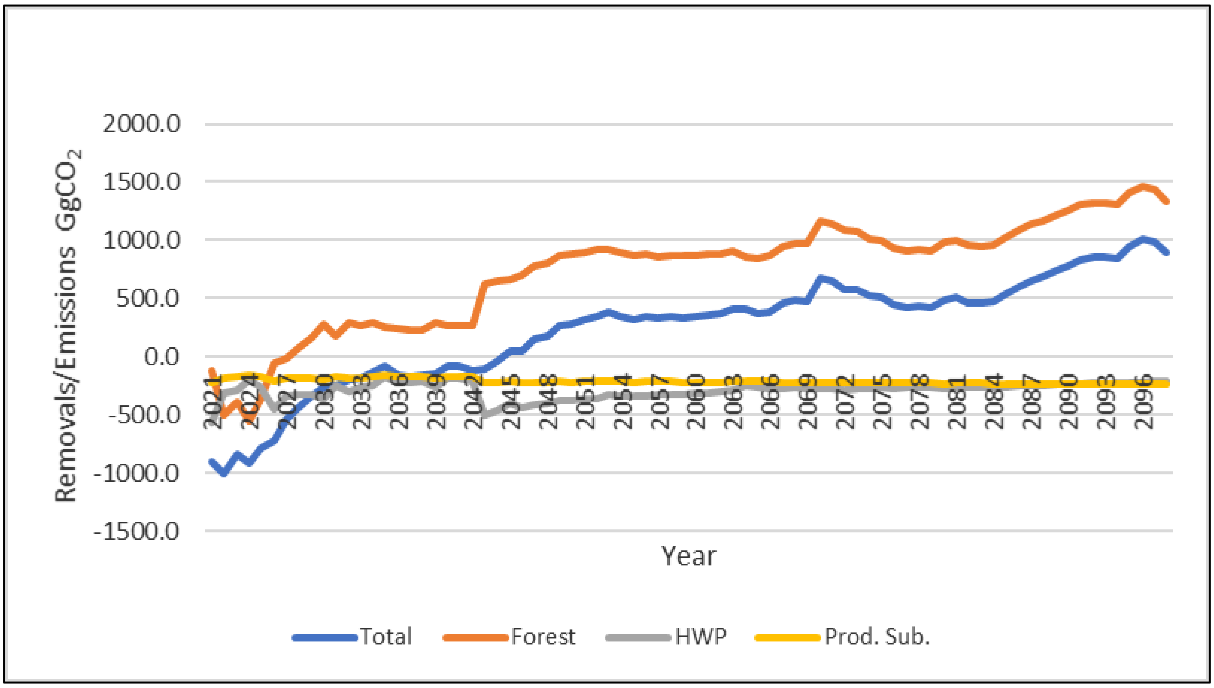

Figure 13 GHG profile of the business-as-usual scenario.

The forest pools and emissions from organic soils are the major drivers influencing the observed transition from net removals to net emissions and continued increase emissions after 2046 (Figure 13). These are associated with:

- A gradual increase in harvest which is reflected by shifts in age-class distributions
- Broadleaves are included in the framework assuming no management at all. This has adverse GHG balance impacts. Analysis of broadleaf profiles show that the broadleaf CO_2 removals decline from -836 Gg CO_2 in 2021 to -168 Gg CO_2 by 2100. This is associated with a 5-fold decline in biomass increment as broadleaf forests get older.
- Ongoing emissions from peat soils (ca. 1,000 Gg per year, see Appendix II) and additional disturbance emissions when peatland forests are clearfelled result in peatland forests eventually becoming a net emitter under the business-as-usual scenario (see Section 4.1.1).

Product substitution has a small impact on the overall GHG balance, removing ca 200 Gg CO_2 per year. HWP removals are slightly higher at ca 300 Gg CO_2 per year. Both the HWP and product substitution removals increase as the level of harvest increases (Figure 13).

4.3.3 New Forestry Model

The GHG profile for the New Forestry Model projection also shows an initial net removal in 2021 (Figure 14). The observed total removals from 2021 to 2030 (Figure 14) are much lower than the expected increase in removal as seen in the Max C decision tree profiles (see Figure 10). This is because the implementation of the C decision tree requires the balancing of all of the other objectives across the estate to produce a fully balanced land-use model. This means that the recommended climate mitigation measures (section 4.2), such as extended rotations ages, are not fully implemented because of the requirement to balance the other ecosystem services, such forests for wood, forests for people, and forests for nature in the delivery of the multiple objectives of forestry. As a result, initial removals for the New Forestry Model scenario (Figure 14) are much smaller than what would be expected when compared to the maximum potential C capture (Figure 10). This is because the max C scenario ignores the short-term risk associated with potential pests and diseases arising from an unmanaged forest and ignores the need to maintain a consistent supply of timber to the industry. Furthermore, the importation of timber from potentially unsustainable sources may contribute to leakage effects at global level.

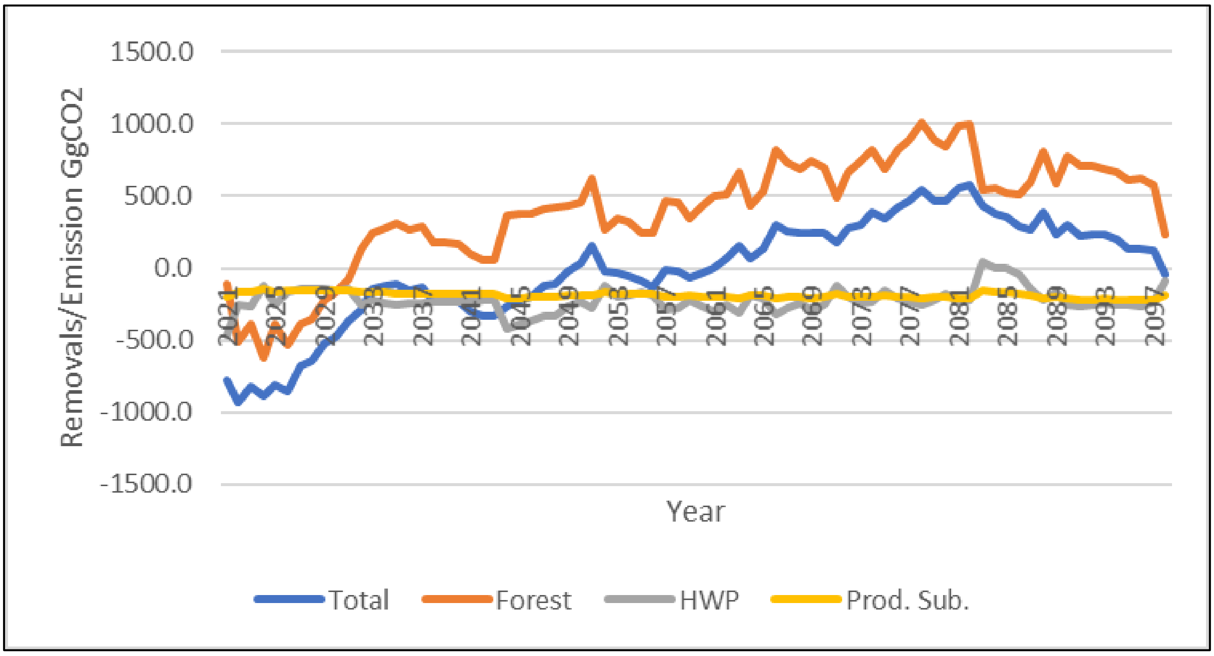

Figure 14 GHG profile of the New Forestry Model forecast.

The observed trends in the New Forestry Model profile can be linked to:

- The level of harvest. A gradual increase in harvest which is reflected by shifts in age-class distributions but a more moderate increase when compared to the BAU scenario;
- The fluctuation in harvest appears to drive the interannual variations in overall removals but this does not explain the overall declining trend in removals and a transition to net emissions by 2050. It appears that weighted rotation age is relatively constant but there is a shift in age class structure towards more stands between 0 and 20 years old for the period 2056-2080. This corresponds with a decline in growth increment for this period (Figure 15). Forest growth increment increases again after 2080 as forest get older (mid rotation);
- Rewetting and conversion to peatland restoration provide negative short-term and small long-term mitigation benefits (see section 4.1.4);

- From 2045 to 2080, there is an increase in the proportion of harvest from thinnings (20%), compared to periods before and after this period (13-14%).

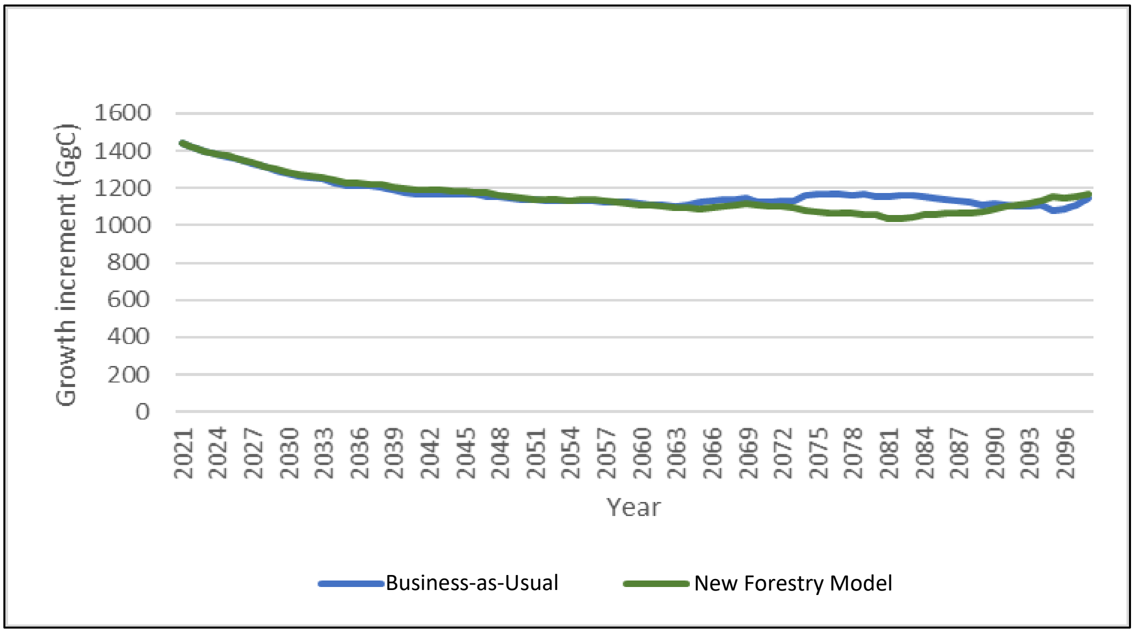

Figure 15 Growth increment in the business-as-usual and New Forestry Model scenarios

4.3.4 Comparison of the GHG profile for the New Forestry Model scenario

The business-as-usual scenario is used as a baseline, against which the delta GHG emissions/reductions or additional removals implemented in the New Forestry Model scenario can be measured (Figure 16). This gives an indication of the benefit of the additional climate change mitigation measures implemented as a result of the New Forestry Model.

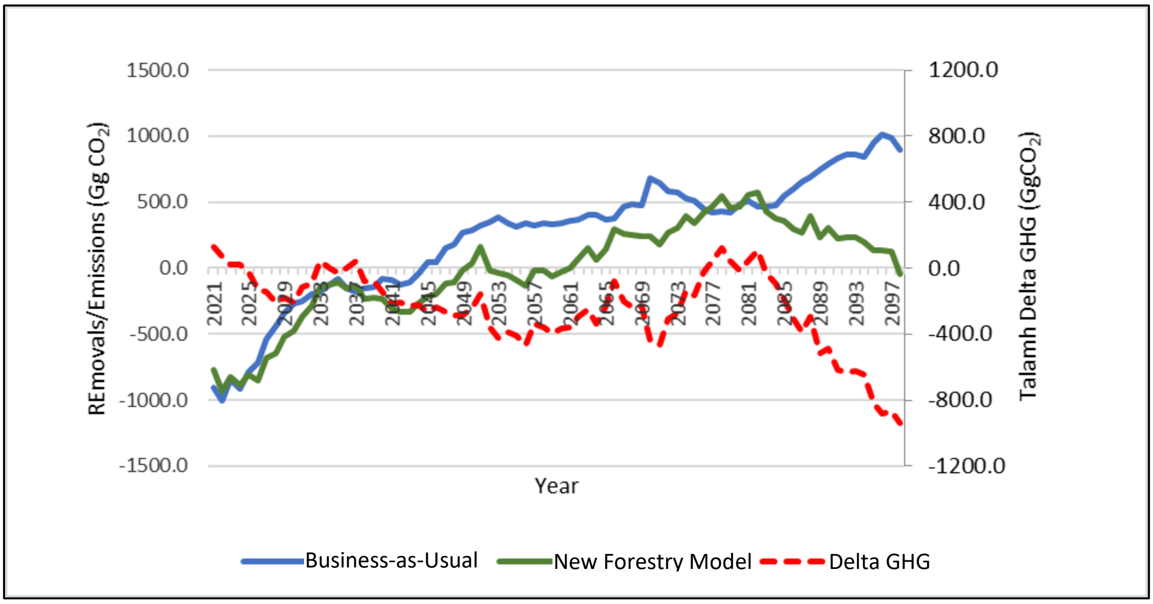

Figure 16 GHG profiles for the business-as-usual scenario and New Forestry Model scenarios (left Y axis) and the delta GHG savings/losses if the New Forestry Model is implemented (right Y axis, relative to the business-as-usual scenario).

Comparison of the business-as-usual and the New Forestry Model profiles suggest three distinct periods with different trends (Figure 16 and Table 7). For the period 2026-2030, the New Forestry

Model scenario results in larger removals than in the business-as-usual scenario - a difference of ca. -863 GgCO_2 (Table 7) due to a lower level of harvest and extended rotations. For the period 2031 to 2080, there are more emissions in the business-as-usual scenario compared to those in the New Forestry Model scenario, due to a higher level of harvest, a higher proportion of harvest from thinnings and shorter rotation lengths (Table 7). For the period 2080-2100, both scenarios result in net emissions, but the New Forestry Model scenario transitions to net removals by 2098. The overall emission reduction of -8,161 Gg CO_2 over this period (Table 7, Figure 16) is due to a sustained period of increased growth increment (Figure 16) and a lower level of harvest (Figure 15).

The total GHG saving associated with the implementation of the New Forestry Model management approach is a reduction of 19,464 Gg CO_2 emissions over the next 80 or so years (Table 7). The total carbon removals from the New Forest Model for the period 2022 to 2050 is 10,477 Gg CO_2, or an increase in removals of 3,687 Gg CO_2 over the same period when compared to the business-as-usual scenario.

Table 7: The delta GHG savings if the New Forestry Model is implemented, for three periods. Negative values represent increased removals or decreased emissions relative to the business-as-usual scenario.

Period	Delta Gg CO_2	Reason/driver
2026-2030	-863	Lower harvest level in New Forestry Model scenario
2031-2080	-10,440	Lower harvest level and less harvest from thinnings in the New Forestry Model scenario
2081-2100	-8,161	Increased growth increment as a result of longer rotations and reduced level of harvest in New Forestry Model scenario
Total (2026-2100)	-19,464	
2022-2050	*-3,687*	

4.4 Drivers and interactions contributing to increased C capture

In order to understand the drivers for the increased carbon capture in forest, HWP and product substitution pools, principal component analysis (PCA) was carried out. Key findings from the PCA include:

- Overall C and forest C capture increases as a result of an increase in biomass increment as harvest decreases and rotation age increases;
- HWP and product substitution increases as harvest increases, particularly for sawlog, but this has a small overall impact on total C capture. It also ignores the short-term risk associated with potential pests and diseases arising from an unmanaged forest and ignores the need to maintain a consistent supply of timber to the industry. Furthermore, the importation of timber from potentially unsustainable sources may contribute to leakage effects at global level
- Scenarios within the defined boundary used which cluster towards higher overall C capture have lower levels of harvest, increased rotation ages and lower C capture in the HWP and product substitution pools.

4.5 Long term emissions

It is important to note that both the business-as-usual and the New Forestry Model scenario generally show long-term increasing emissions (Figure 16). This appears to be associated with two major factors;

no management of the broadleaf estate and an increasing net emission from peatland forests under the BAU scenario.

4.5.1 Broadleaves stands

There are opportunities to improve our carbon profile through more active management of the broadleaf estate. Management of broadleaf forests are currently primarily for nature and recreational objectives. Under current practices, the broadleaf component of the Coillte estate results in a 5-fold reduction of carbon capture in the broadleaf strata due to the lack of regeneration and the increasing age-class of this stratum. If the age class structure of the broadleaf estate were to be managed to maximise productivity, this could result in a potential capture of 836 Gg CO_2 per year. The long-term net balance would depend on the extent of management for timber production and wood flows into the HWP pools, however any management of the broadleaf estate would also need to consider impact on ecological objectives.

4.5.2 Peatland emissions

There is a continuation of emissions from peatland forests and a reduction in the forest net removals for low productive peatland forests under clearfell and replant management. The low productive conifer forest has been converted to broadleaf forest in the New Forestry Model scenario; however, the GHG mitigation potential is minimal because transitions were implemented after clearfelling of conifer stands, with high disturbance and peat emission levels. However, this assessment has demonstrated that active management of productive peatland forests for wood results in these forests remaining a net carbon remover over three rotations.

4.6 Forest management in the New Forestry Model

The Climate Action Plan does not consider any forest management related actions, but the New Forestry Model now provides some insight to how forest management may contribute towards the national climate change mitigation effort.

In order to make a significant contribution towards meeting the EU LULUCF target and the EU burden sharing agreement, silvicultural and land-management prescriptions will be required to turn the observed increasing emission trend into a decreasing one and/or increasing removals. The max C scenario shows that the potential is great, exceeding 3,000 Gg per year in the short-term (Figure 10), before then reverting to an emitter of ca 2,000 Gg CO_2 per year over the medium and longer term. This represents a common climate change mitigation dilemma however, as short-term mitigation actions could impact directly on the supply of certified timber to the market and could potentially have significant, direct impacts on the forest sector and timber processing industry and may require the import of unsustainable timber. Furthermore, the importation of timber from potentially unsustainable sources may contribute to leakage effects at global level, i.e. the shift in carbon emissions from one country to another. The mitigation measures must therefore be balanced with other objectives such as biodiversity, recreation, species diversification and a sustainable supply of certified timber.

Even where the C decision tree is constrained and balanced by multiple forest objectives in the New Forestry Model, this results in an increase in removals of 863 GgCO_2 for the period 2026 to 2030 when compared to the business-as-usual scenario. The mitigation action due to the implementation of the New Forestry Model has even greater medium- to long-term impacts than the business-as-usual scenario (Table 7) and a positive climate change impact from 2021 to 2100 due to a reduction in emissions (Figure 16).

Other measures to improve climate mitigation potential require further consideration and analysis, such as the sustainable management of the broadleaf woodlands to enhance their climate mitigate potential and the evaluation of low impact silvicultural systems for peatland forests.

5. Conclusion

This report documents the analyses carried out to model the carbon profile associated with the Coillte managed forest estate in the business-as-usual and the New Forestry Model scenario. The results outlined in this report are based on research analyses conducted both at stand and landscape level, to understand the impact of a range of climate mitigation options that could be applied to specific site and stand types, and across the estate to reduce emissions and increase removals.

The New Forestry Model scenario is estimated to represent an emission reduction of ca. 19 Mt CO_2 over the period 2021 to 2100, with a small reduction in emissions of 0.8 MtCO_2 up to 2030. It is important to note that the implementation of these mitigation options and the carbon objectives were incorporated into the New Forestry Model, which balances forests for people, nature, climate and wood. As outlined previously, to achieve this balanced model some of the climate mitigation measures were not fully implemented within the modelling framework. The aim of the New Forestry Model was to balance forests for climate with the other objectives, that includes forests for wood and the regular supply of certified timber, forests for people, and forests for nature. Whilst there is an opportunity to achieve more short-term carbon savings, this would likely result in direct impact and trade-offs with the other objectives and ignores the need to maintain a consistent supply of timber to the industry. Furthermore, the importation of timber from potentially unsustainable sources may contribute to leakage effects at global level.

The work that has been undertaken to date has advanced the knowledge and understanding associated with land- and silvicultural management of the Coillte estate. Furthermore, a sophisticated modelling framework was developed to analyse the carbon profile of the managed forest estate, which could be used to further investigate and assess scenarios as new data and knowledge become available.

Finally, it must be acknowledged that there are still large gaps in the understanding of GHG dynamics in the forest sector system boundary. In particular, the quantification of the contributions of peatland soil emissions and product substitution is still evolving. The impact of extreme events and climate change on forests to capture C in the future is also very uncertain. In addition to these model and scenario uncertainties, there will also be operational challenges associated with the timing and extent of the implementation that may reduce or enhance further climate mitigation options in the New Forestry Model.

Appendix I: Set up of CBM

There are 21 C pools in CBM, but these match the 5 basic IPCC forest C pools (Table A). The ecosystem process events are simulated as C transfers between C pools on an annual time step (Figure I).

Table A: IPCC and CBM C pools

IPCC Carbon Pools	Pool Names in CBM-CFS3
Living Biomass	
Above-ground biomass	Merchantable stemwood
	Other (sub-merchantable stemwood, tops, branches, stumps, non-merchantable trees)
Below-ground biomass	Foliage
	Coarse roots
	Fine roots
Dead Organic matter (DOM)	
Deadwood	Above-ground fast
	Below-ground fast
	Medium
	Softwood stem snag
	Softwood branch snag
	Hardwood stem snag
	Hardwood branch snag
Litter	Above-ground very fast
	Above-ground slow
Soil organic matter	Below-ground very fast
	Below-ground slow
	Black carbon
	Peat

Carbon taken up by biomass (net growth) is determined by the volume increment curves and biomass conversion equations for each species cohort in CBM. FERS has already developed 11 species cohort biomass and growth models, representing all Irish forest species (5 productivity classes for spruce, 2 for pine, a mixed conifer, other conifer, conifer broadleaf and 2 broadleaf cohorts). After growth and harvest is simulated, some of the biomass C is transferred to the dead organic matter (DOM) pool due to mortality and turn over (Figure I).

CBM simulates mortality and litter fall to represent transfers of C from biomass to other DOM pools resulting from tree, foliage, branch, and root mortality (Kurz et al., 2009[11]). Species specific turnover rates and transfer rates between DOM pools were specified in the AIDB (Kull et al., 2016[21]), based on previous work conducted by FERS Ltd. Inputs into, and emissions from, the DOM pool generally increases as mortality or harvests increases. Decomposition of C in DOM pools were modelled using a temperature-dependent decay rate function (Kurz et al., 2009[11]). This is the only climate dependent relationship used in CBM. The annual mean temperature for all regions in Ireland is set to 7.5 deg C in the AIDB database of the CBM. For a full description of the CBM model and its application under Irish condition, please refer to the NFAP[41].

Disturbance (harvest etc.) impacts are defined using a matrix that describes the proportion of C transferred between pools, as fluxes to the atmosphere, and as transfers to the DOM pools or the timber sector. These are specific transfers between C pools for each disturbance type were defined in the AIDB. Harvested timber (products), less harvest residue was then allocated to a separate HWP model (see Figure I).

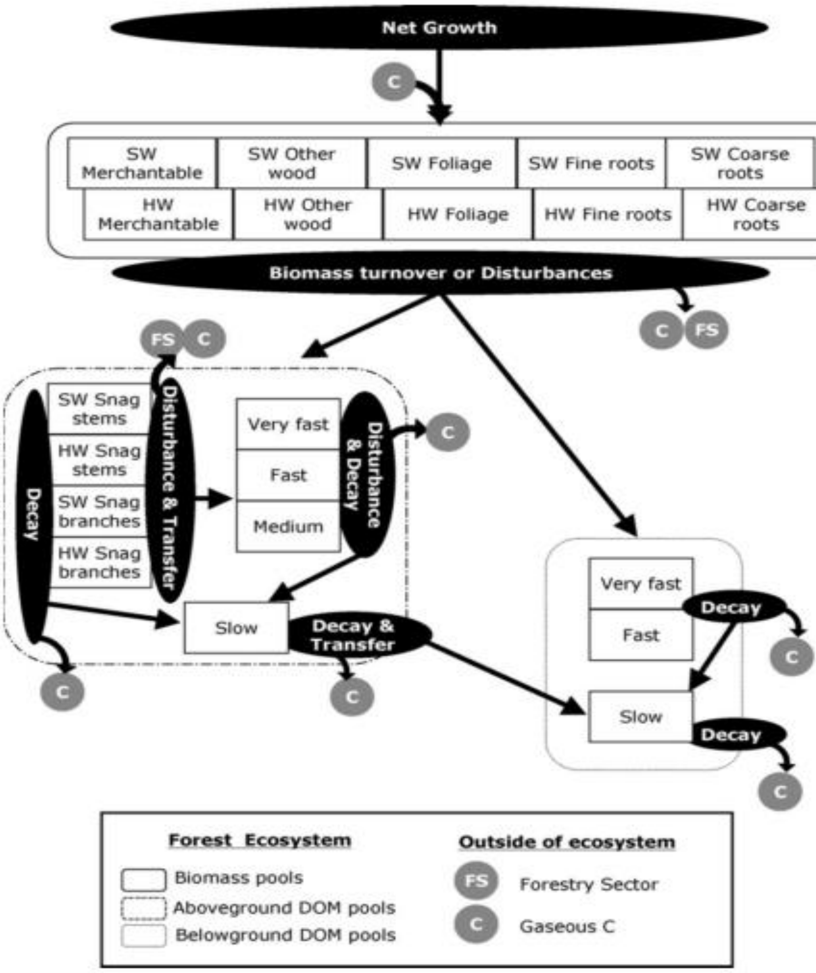

Figure I: A schematic summary of how annual processes and C transfers between pools are simulated in CFS-CBM model (taken directly from Kurz et al., 200911). Note that forestry sector (FS) products (i.e. harvests) are allocated to the HWP model (Figure 1).

[41] NFAP, 2020. Ireland's national forest accounting plan submission under the EU LULUCF regulation. https://www.gov.ie/en/publication/0ad4b-lulucf/

Forest stands were categorised by species cohorts and productivity strata. These strata have defined yield curves and silvicultural systems. The state of the forest (i.e. the age class structure and area breakdown of species cohorts) with defined management types and soil types for the Coillte estate was be defined using NFI data.

Scheduling the timing of timber harvests for each species and management type is controlled by a Remsoft transcript file for calibration and simulation of harvest.

The current estate age class distribution

The initial state of the existing Coillte estate (i.e. the age class and standing volume for species cohorts and productivity classes was derived from the 2017 NFI. The characterisation of specified species cohorts was required because of existing models developed for NFI data. The method also uses site index rather than yield class because this is more accurately derived from NFI plot data. The forest areas were scaled up to be equivalent to that reported in the Coillte Resource statistics (401 kha April 2020).

Scheduling harvest

Silvicultural assumptions used to facilitate scheduling of the harvest during simulations were based on the Remsoft transcript data provided by Coillte. These assumptions define the median clearfell ages for each species/productivity and management stratum. The amount of timber to be harvested (target harvest) for each management scenario and species was specified for each time step based on the thin and clearfell volumes for each stratum at each time step. All clearfelled forests are assumed to be replanted after 2 years unless a transition to another species or deforestation disturbance is specified in the transcript files.

The calibration of the target harvest was done in an iterative manner:

a. The thinning and clearfell harvests for each forest stratum was derived from the Remsoft transcript (2021-2100).
b. The resulting simulated harvest was compared to the target harvest. If a harvest volume value for each forest type and time step was not within 95% of the target value, the difference in volume was re-assigned to Conifer mix and conifer broadleaf mix types or to other site index categories:
    - Spruce13-16 re-assigned to OC;
    - Spruce17-20 re-assigned to Cmix and Cbmix;
    - Spruce24-30 re-assigned to Spruce20-24.
c. The harvest schedule was re-run and step b was repeated. Additional harvest were re-allocated:
    - OC re-assigned to FGB;
    - Cmix re-assigned to Cbmix;
    - Cbmix or any remaining additional harvest requirement re-assigned to SGB
d. Re-assignment of harvest to other categories were done until the simulated annual thin and clearfell harvests (i.e. calibrated harvest) for each forest category was within a threshold (95% for New Forestry Model) of the target harvest.
e. The final CBM harvest was then used to adjust the assortment outputs used in the HWP scripts.

Appendix II: Detailed emissions profiles

Business As Usual Scenario

Year	NEE	Organic soils		Forest	HWP	Prod.sub.	Total
	GgCO2	GgCO2-CO2	Gg CO2-CH4/N20	GgCO2	GgCO2	GgCO2	GgCO2
2021	-1250.7	966.6	170.7	-113.4	-571.3	-219.9	-904.6
2022	-1640.9	960.2	170.7	-510.0	-317.9	-177.5	-1005.4
2023	-1513.4	954.0	170.7	-388.7	-280.0	-171.9	-840.6
2024	-1676.8	948.0	170.7	-558.2	-197.1	-158.2	-913.5
2025	-1452.3	924.0	170.7	-357.7	-258.2	-169.5	-785.3
2026	-1153.2	927.7	170.7	-54.8	-457.5	-205.2	-717.5
2027	-1108.3	923.3	170.7	-14.3	-337.7	-185.9	-537.9
2028	-1016.8	919.1	170.7	73.0	-325.0	-184.8	-436.8
2029	-922.5	915.1	170.7	163.4	-319.9	-185.0	-341.5
2030	-791.2	904.3	170.7	283.8	-357.8	-192.7	-266.8
2031	-893.9	901.4	170.7	178.2	-253.9	-175.7	-251.4
2032	-776.7	898.7	170.7	292.7	-302.9	-185.1	-195.3
2033	-806.0	896.0	170.7	260.6	-264.6	-179.3	-183.3
2034	-771.1	893.6	170.7	293.1	-244.6	-176.7	-128.1
2035	-803.6	882.4	170.7	249.5	-164.7	-163.4	-78.7
2036	-806.4	881.1	170.7	245.4	-227.0	-174.8	-156.4
2037	-829.7	880.8	170.7	221.9	-222.6	-174.7	-175.4
2038	-823.1	879.5	170.7	227.0	-210.6	-173.3	-156.8
2039	-752.1	878.3	170.7	296.9	-254.5	-181.6	-139.2
2040	-767.1	868.8	170.7	272.3	-186.6	-170.5	-84.7
2041	-772.3	868.3	170.7	266.7	-182.9	-170.4	-86.6
2042	-775.6	867.9	170.7	263.0	-211.8	-176.0	-124.8
2043	-418.2	867.5	170.7	620.0	-499.1	-226.9	-106.0
2044	-388.3	867.1	170.7	649.5	-471.1	-223.7	-45.3
2045	-371.7	862.6	170.7	661.6	-403.6	-213.6	44.5
2046	-334.7	862.5	170.7	698.5	-435.4	-220.5	42.7
2047	-247.6	862.5	170.7	785.6	-417.7	-218.9	149.0
2048	-230.7	862.4	170.7	802.4	-404.4	-218.0	180.0
2049	-167.8	862.3	170.7	865.2	-381.4	-215.3	268.5
2050	-152.5	861.5	170.7	879.6	-380.6	-216.5	282.6
2051	-137.1	861.4	170.7	895.0	-361.1	-214.4	319.5
2052	-111.0	861.4	170.7	921.1	-360.3	-215.5	345.4
2053	-109.7	861.4	170.7	922.4	-324.8	-210.5	387.1
2054	-137.0	861.4	170.7	895.0	-343.1	-214.8	337.1
2055	-155.3	861.2	170.7	876.6	-343.8	-216.1	316.7
2056	-145.1	861.2	170.7	886.7	-334.0	-215.6	337.1
2057	-173.5	861.1	170.7	858.3	-319.9	-214.3	324.1
2058	-158.3	861.1	170.7	873.5	-320.7	-215.5	337.3
2059	-156.2	861.1	170.7	875.6	-326.7	-217.6	331.3
2060	-158.8	860.9	170.7	872.8	-318.0	-217.2	337.5
2061	-146.9	860.9	170.7	884.7	-307.8	-216.5	360.3
2062	-148.9	860.9	170.7	882.7	-298.5	-216.0	368.2
2063	-120.4	860.9	170.7	911.2	-289.0	-215.3	406.9
2064	-172.8	860.9	170.7	858.7	-245.9	-208.8	404.0
2065	-183.8	860.7	170.7	847.6	-264.7	-212.9	370.1
2066	-167.2	860.7	170.7	864.2	-271.2	-214.9	378.1
2067	-81.0	860.7	170.7	950.4	-272.8	-216.1	461.5
2068	-62.9	860.7	170.7	968.6	-266.2	-215.9	486.5
2069	-64.0	860.7	170.7	967.4	-277.0	-218.7	471.7
2070	139.0	860.7	170.7	1170.3	-268.9	-218.2	683.2
2071	106.4	860.7	170.7	1137.8	-272.2	-219.7	645.9
2072	52.5	860.7	170.7	1083.9	-281.0	-222.2	580.7
2073	44.0	860.7	170.7	1075.4	-276.0	-222.3	577.1
2074	-16.9	860.7	170.7	1014.5	-268.4	-221.9	524.2
2075	-38.5	860.7	170.7	992.9	-263.0	-221.9	507.9
2076	-91.1	860.7	170.7	940.3	-272.4	-224.5	443.5
2077	-125.9	860.7	170.7	905.5	-262.5	-223.7	419.3
2078	-111.8	860.7	170.7	919.5	-264.5	-224.9	430.1
2079	-127.7	860.7	170.7	903.7	-259.5	-225.0	419.2
2080	-42.3	860.7	170.7	989.1	-276.0	-228.8	484.3
2081	-26.9	860.7	170.7	1004.5	-265.4	-227.9	511.1
2082	-76.2	860.7	170.7	955.1	-261.8	-228.2	465.2
2083	-85.6	860.7	170.7	945.8	-255.0	-227.9	462.9
2084	-65.7	860.7	170.7	965.7	-261.1	-229.8	474.8
2085	-3.8	860.7	170.7	1027.5	-255.6	-229.8	542.1
2086	53.7	860.7	170.7	1085.0	-252.1	-230.0	602.9
2087	106.6	860.7	170.7	1137.9	-249.3	-230.4	658.2
2088	129.2	860.7	170.7	1160.6	-243.2	-230.2	687.1
2089	182.0	860.7	170.7	1213.4	-239.6	-230.5	743.3
2090	225.7	860.7	170.7	1257.1	-240.8	-231.5	784.8
2091	277.3	860.7	170.7	1308.7	-239.3	-232.1	837.3
2092	283.7	860.7	170.7	1315.1	-222.1	-229.9	863.1
2093	293.5	860.7	170.7	1324.8	-232.4	-232.5	860.0
2094	272.5	860.7	170.7	1303.9	-225.7	-232.1	846.1
2095	377.8	860.7	170.7	1409.2	-224.7	-232.8	951.7
2096	435.7	860.7	170.7	1467.0	-218.1	-232.4	1016.5
2097	404.7	860.7	170.7	1436.1	-213.9	-232.4	989.7
2098	304.7	860.7	170.7	1336.1	-209.3	-232.4	894.4

New Forestry Model Scenario

Year	NEE	Organic soils		Forest	HWP	Prod.sub.	Total
	GgCO2	GgCO2-CO2	Gg CO2-CH4/N20	GgCO2	GgCO2	GgCO2	GgCO2
2021	-1245.0	966.6	170.7	-107.7	-464.3	-201.083	-773.1
2022	-1636.9	960.2	170.7	-506.1	-257.8	-166.5	-930.3
2023	-1516.6	954.0	170.7	-391.9	-261.9	-167.992	-821.8
2024	-1737.5	948.0	170.7	-618.9	-125.2	-144.84	-888.9
2025	-1483.0	924.0	170.7	-388.3	-251.7	-167.235	-807.3
2026	-1632.6	927.7	170.7	-534.2	-162.1	-152.277	-848.6
2027	-1476.4	923.3	170.7	-382.4	-145.8	-149.841	-678.1
2028	-1447.2	919.1	170.7	-357.4	-139.7	-149.133	-646.3
2029	-1311.9	915.1	170.7	-226.1	-143.1	-150.046	-519.2
2030	-1241.6	904.3	170.7	-166.6	-152.9	-152.116	-471.6
2031	-1146.3	901.4	170.7	-74.2	-143.2	-150.801	-368.2
2032	-937.6	898.7	170.7	131.8	-250.2	-169.863	-288.3
2033	-820.2	896.0	170.7	246.5	-223.1	-165.886	-142.5
2034	-781.4	893.6	170.7	282.9	-239.5	-169.425	-126.1
2035	-741.3	882.4	170.7	311.8	-250.1	-172.002	-110.3
2036	-783.5	881.1	170.7	268.2	-248.7	-172.536	-153.0
2037	-766.8	879.8	170.7	283.7	-244.7	-172.606	-133.7
2038	-874.7	878.6	170.7	174.5	-237.1	-172.038	-234.6
2039	-868.3	877.6	170.7	179.9	-229.4	-171.43	-221.0
2040	-869.9	868.2	170.7	168.9	-226.9	-171.691	-229.6
2041	-939.7	867.9	170.7	98.8	-227.8	-172.561	-301.5
2042	-979.0	867.6	170.7	59.3	-222.9	-172.411	-335.9
2043	-981.6	867.4	170.7	56.5	-218.3	-172.334	-334.2
2044	-671.5	867.2	170.7	366.3	-424.1	-209.013	-266.8
2045	-657.8	864.1	170.7	377.0	-389.9	-204.488	-217.4
2046	-660.2	864.1	170.7	374.6	-367.6	-201.944	-195.0
2047	-622.3	864.0	170.7	412.4	-334.5	-197.422	-119.5
2048	-608.6	864.0	170.7	426.1	-333.4	-198.359	-105.6
2049	-596.4	864.0	170.7	438.3	-268.0	-188.075	-17.8
2050	-578.6	864.0	170.7	456.1	-236.7	-183.487	36.0
2051	-412.1	864.0	170.7	622.5	-272.8	-190.588	159.2
2052	-763.7	864.0	170.7	270.9	-122.1	-165.143	-16.3
2053	-688.5	863.9	170.7	346.2	-203.3	-179.706	-36.9
2054	-715.7	863.9	170.7	318.9	-192.8	-178.533	-52.4
2055	-786.0	863.8	170.7	248.5	-165.0	-174.268	-90.8
2056	-793.7	863.8	170.7	240.7	-192.0	-179.523	-130.8
2057	-568.7	863.8	170.7	465.7	-283.4	-196.126	-13.8
2058	-582.6	863.8	170.7	451.9	-276.9	-195.967	-21.0
2059	-686.6	863.8	170.7	347.9	-226.0	-188.001	-66.1
2060	-598.9	863.8	170.7	435.6	-266.7	-195.88	-27.0
2061	-536.5	863.8	170.7	498.0	-296.0	-201.911	0.1
2062	-518.2	863.8	170.7	516.2	-250.1	-194.898	71.3
2063	-370.4	863.8	170.7	664.0	-305.3	-205.402	153.4
2064	-603.3	863.8	170.7	431.1	-182.6	-184.997	63.5
2065	-496.7	863.8	170.7	537.7	-208.3	-190.106	139.3
2066	-209.6	863.8	170.7	824.9	-317.5	-209.905	297.5
2067	-298.5	863.8	170.7	735.9	-274.1	-203.422	258.4
2068	-341.9	863.8	170.7	692.5	-244.3	-199.16	249.1
2069	-289.7	863.8	170.7	744.7	-292.5	-208.433	243.8
2070	-330.4	863.8	170.7	704.1	-256.4	-203.146	244.5
2071	-547.7	863.8	170.7	486.7	-126.4	-181.294	179.0
2072	-372.3	863.8	170.7	662.2	-195.4	-193.771	273.0
2073	-288.2	863.8	170.7	746.2	-241.8	-202.557	301.8
2074	-216.1	863.8	170.7	818.3	-227.3	-200.871	390.1
2075	-347.1	863.8	170.7	687.4	-153.8	-188.791	344.8
2076	-210.4	863.8	170.7	824.0	-205.9	-198.421	419.7
2077	-141.1	863.8	170.7	893.4	-227.4	-202.897	463.0
2078	-20.5	863.8	170.7	1014.0	-255.7	-208.635	549.7
2079	-148.2	863.8	170.7	886.2	-221.4	-203.542	461.2
2080	-188.5	863.8	170.7	846.0	-180.2	-197.099	468.7
2081	-41.2	863.8	170.7	993.3	-231.8	-206.754	554.7
2082	-31.6	863.8	170.7	1002.9	-223.2	-206.057	573.6
2083	-488.9	863.8	170.7	545.5	46.7	-159.628	432.6
2084	-484.3	863.8	170.7	550.2	-2.9	-168.065	379.2
2085	-509.3	863.8	170.7	525.1	-0.6	-167.62	356.9
2086	-526.8	863.8	170.7	507.7	-41.7	-174.761	291.2
2087	-435.3	863.8	170.7	599.2	-139.2	-191.893	268.1
2088	-219.0	863.8	170.7	815.4	-216.1	-205.831	393.4
2089	-442.6	863.8	170.7	591.9	-165.6	-197.729	228.6
2090	-260.9	863.8	170.7	773.5	-258.5	-214.553	300.4
2091	-325.0	863.8	170.7	709.4	-268.1	-217.144	224.1
2092	-324.9	863.8	170.7	709.5	-258.2	-216.351	235.0
2093	-343.9	863.8	170.7	690.6	-239.5	-214.009	237.0
2094	-364.3	863.8	170.7	670.2	-254.8	-217.511	197.9
2095	-427.5	863.8	170.7	607.0	-252.2	-217.954	136.8
2096	-414.8	863.8	170.7	619.7	-261.6	-220.497	137.5
2097	-457.9	863.8	170.7	576.6	-235.3	-216.835	124.4
2098	-801.3	863.8	170.7	233.2	-83.3	-191.096	-41.2

Appendix III Literature review of mitigation potential of CCF management

Forest managers and policy makers are now considering alternative management, such as continuous cover forest (CCF) options, to provide climate change resilience and better support for the ecosystem services that forests provide, including biodiversity protection, clean water, erosion control and carbon sequestration (Spiecker et al. 2004[42]). There has been a long-term debate on comparisons of productivity of CCF and plantation forestry, but only a few attempts to analyse rigorously and analytically the various aspects of CCF relative to even-aged forests (Kuuluvainen 2012[43]). Assessment of timber production in even aged versus CCF stands suggest that biomass growth is higher in even aged clear fell plantations than CCF systems (Table B). There are limited comparative studies which include forest HWP and product substitution C sequestration pathways (Table B). These studies report conflicting results due to different system boundaries and assumptions used. For, example, Lundmark et al (2016) report a slightly lower C sequestration in CCF and compared to plantation forestry when forest, HWP and product substitution is included in the system boundary. However, when transport and manufacturing emissions are also included in the system boundary, CCF has a higher C sequestration potential when compared to plantation forestry (Pukkala, 2014[44]; 2016[45]).

Only one study in Finland was based on experimental data, which found that forest sequestration was slightly lower in even-aged stands, compared to CCF stands (Table B). Out of the 11 studies identified, 6 reported a slightly to significantly lower potential C sequestration potential under CCF management.

There are few stands under CCF management in Ireland (Vítková et al., 2013[46]). The majority of these stands are transforming to CCF and have only been under CCF management for less than 15 years. It is likely that the C sequestration potential of stands undergoing transformation using selective thinning methods would not diverge much from even aged clear-felled systems until CCF transformation is complete and conventional stands have been clear-felled. Evidence from work in the UK shows that productivity in transforming stands actually decreases during the transformation process due to higher proportional removal of larger trees, relative to conventional rotation forestry (Poore, Selectfor pers com). Although it is obvious that harvest emissions are lower in CCF, the productivity of stand at steady state (i.e. when transformed to diverse structure and species) is not clear.

The key challenges are:

- Robust growth models need to be developed for CCF. To date there are a limited number of single tree models that can do that and these are confined to continental Europe. These models have not been calibrated for UK or Irish conditions.
- The is limited CCF data to calibrate the required models. One cannot evaluate carbon flows without a reliable growth model.
- The effect of CCF vs conventional rotation forestry of C balance is unclear and this varies depending on the system boundary used for the evaluation (Table B).

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[42] Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J.P., Sterba H, von Teuffel K (2004) Norway spruce conversion: options and consequences. European Forest Institute, Research report 18. Brill Academic Publishers, Leiden

[43] Kuuluvainen T, Tahvonen O, Aakala T (2012) Even-aged and uneven-aged forest management in boreal Fennoscandia: a review. Ambio 41:720–737

[44] Pukkala, T. (2014). Does biofuel harvesting and continuous cover management increase carbon sequestration? Economics 43: 41–50.

[45] Pukkala, T. (2016) Which type of forest management provides most ecosystem services? Forest Ecosystems, 3: 1-9.

[46] Vítková, L., Ní Dhubháin, A., Ó'Tuama, P., Purser, P. (2013) The practice of continuous cover forestry in Ireland. Irish Forestry 70: 141-156.

Table B: Summary of a literature review of comparison between conventional clearfell and replant management (i.e. even-aged stands) and uneven-aged stands (or stands under CCF management).

Author	System boundary	Approach	Finding
Nilsen and Strand. (2013)[47]	Forest C pools	Experimental site data	Long-term (81 years) C sequestration is slightly higher in an even-aged, compared to an uneven-aged stand.
Lundmark et al., 2016[48]	Forest C pools, HWP and product substitution and manufacture, transport emissions	Stand models	C sequestration potential slightly higher in clear-felled plantation compared to CCF stands aver 300 years
Pukkala, 2014 and Pukkala, T. (2016)	Forest pools, HWP, product substitution, manufacture and transport emissions	Stand models	Higher sequestration potential in CCF stands compared to even aged stands due to lower transport and manufacture emissions, but no real difference in forest, HWP and Product substitution C sequestration potential.
Bragg, D. C., Guldin, J. M. (2010)[49]	Forest pools excluding soils	Stand models initiated with experimental site data	A 50 % higher C sequestration in even-aged stands compared to un-ever-aged stands after a 100-year simulation
Parajul and Chang (2012)[50]	Forest pools	Stand models	No clear C sequestration advantage of uneven age management.
Vauhkonen et al., (2019)[51]	Biomass pools only	Landscape model	Higher biomass stocks in even age stands transitioned to CCF
Hynynen et al., (2019)[52]	Timber volume and volume growth	Landscape model with optimisation for NPV	Lower growth in uneven-aged stands compared to even aged stands. By inference, the biomass C increment is lower in uneven-aged stands. Effect of clearfell harvest not considered.
Eggers et al. (2020)[53]	Timber volume, harvest and growth	Landscape model	Lower growth in CCF stands compared to even aged stand Norway spruce. By inference, the biomass C increment is lower in uneven aged stands. Slightly higher growing stock in CCF stand after 100 years.
Peura et al. (2018)[54]	Forest pools only	Stand models	Higher C sequestration in CCF compared to rotation forests
Díaz-Yáñez et al. (2019)[55]	Forest and HWP (excl. product substitution)	Landscape model	Higher C sequestration in CCF compared to rotation forests
Seidl et al. (2008)56	Forest pools	Stand models	Conversion form even aged rotation forest to CCF increase C sequestration

[47] Nilsen, P., Strand, L. U. (2013). Carbon stores and luxes in even- and uneven-aged Norway spruce stands. Silva Fennica vol. 47 no. 4 article id 1024. 15 p.
[48] Lundmark T., Bergh, J., Nordin, A., Fahlvik, N., Poudel, B.C. (2016) Comparison of carbon balances between continuous-cover and clear-cut forestry in Sweden Ambio 2016, 45(Suppl. 2):S203–S213.
[49] Bragg, D. C., Guldin, J. M. (2010) Estimating Long-Term Carbon Sequestration Patterns in Even- and Uneven-Aged Southern Pine Stands. USDA Forest Service Proceedings RMRS-P-61.
[50] Parajuli, R., Chang, J. (2012) Carbon sequestration and uneven-aged management of loblolly pine stands in the Southern USA: A joint optimization approach. Forest Policy and Economics Volume 22, 65-71.
[51] Vauhkonen, J.; Packalen, T. (2019) Shifting from even-aged management to less intensive forestry in varying proportions of forest land in Finland: impacts on carbon storage, harvest removals, and harvesting costs. Eur J Forest Res , 138, 219–238.
[52] Hynynen, J.; Eerikäinen, K.; Mäkinen, H.; Valkonen, S. (2019) Growth response to cuttings in Norway spruce stands under even-aged and uneven-aged management. Forest Ecology and Management, 437, 314–323.
[53] Eggers, J.; Räty, M.; Öhman, K.; Snäll, T. How Well Do Stakeholder-Defined Forest Management Scenarios Balance Economic and Ecological Forest Values? Forests 2020, 11, 86.
[54] Peura, M., Burgas,D., Eyvindson, K., Repo, A., Mönkkönen, M. (2018) Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia Biological Conservation217, 104-112
[55] Díaz-Yáñez, O., Pukkala, T., Packalen, P., Peltola, H. (2019). Multifunctional comparison of different management strategies in boreal forests. Forestry; 93, 84–95, doi:10.1093/forestry/cpz053
[56] Seidl, R., Rammer, W., Lasch, P., Badeck, F-W., Lexer, M.J. (2008) Does Conversion of Even-Aged, Secondary Coniferous Forests Affect Carbon Sequestration? A Simulation Study under Changing Environmental Conditions. Silva Fennica 42(3) 369-386.