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Can temperate forests deliver both future wood demand and climate-change mitigation?

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Abstract

Global wood demand is projected to rise but supply capacity is questioned due to limited global forest resources. Furthermore, the lifecycle global warming potential (GWP) impact of additional wood supply and use is poorly understood. For the case of a temperate country, combining forest carbon modelling and life-cycle assessment we show that sustained afforestation to double forest area alongside enhanced productivity can meet lower-bound wood demand projections from 2058. Thus, temperate forestry value-chains can achieve a cumulative GWP benefit of up to 265 Tg CO_2-equivalent (CO_2e) by 2100 for each 100,000 ha (expanding to 200,000 ha through afforestation) of forest. Net GWP balance depends on which overseas forests supply domestic shortfalls, how wood is used, and rate of industrial decarbonisation. There is considerable but constrained potential for increased wood-use to deliver future climate-change mitigation, providing it is connected with a long-term planting strategy, enhanced tree productivity and efficient wood use.

Introduction

Global wood demand has been rising by 1.1% per annum over the last 20 years[1] and is projected to grow at even higher rates[2,3,4], due to population growth, economic growth[4] and the transition towards a net zero bioeconomy[5,6] as per the Paris Agreement[7]. However, high levels of uncertainty surrounding timber demand projections[5], and key knowledge gaps on the impact of timber demand on terrestrial carbon flux[8] and lifecycle greenhouse gas emissions[9,10,11] remain.

Integrated assessment models (IAM) are often used in global analyses of the environmental impact of major economic activities, to assist informed policy-making in the context of climate change[12,13,14]. However, IAM typically fail to account for the importance of region-specific management of existing forests and investment in managed forest, which could lead to underestimating forest carbon flows[8]. In contrast, forest land-sector focussed economic models (known as forest sector models, FSM[15,16]), such as Global Timber Model (GTM)[17], Global Biosphere Management Model (GLOBIOM)[18], and Global Forest Products Model (GFPM)[19], can incorporate heterogeneity in the forest resource base, as well as ecological constraints, management opportunities, product markets, and land use and management responses to market and environmental change[15,20]. FSM are typically used to project global wood demand under different economic and climate policy scenarios[3,5,6]. However, important local variations in tree species composition, growth rates and forest management practices within regions may not be captured[15], and these models rely on assumptions about future environmental, macroeconomic and specific forest market conditions[21]. Therefore, uncertainty remains about biophysical supply meeting projected demand[8], and with competing demands on land use there is a risk of 'over-stated reliance' on wood resources in net-zero decarbonisation plans[22].

Supplementing IAM with further analytical approaches is recommended[23] to increase resolution of analysis[24,25] and to reality-check scenarios[22]. Combining IAM and high-resolution forest carbon modelling, Blattert et al.[22] found disparity between IAM-projected demand for wood needed for achieving EU net zero greenhouse gas (GHG) emissions targets and available supply calculated using national-scale modelling. This disparity is an under-considered policy conundrum[22] and it raises the question addressed in the present study - what lifecycle global warming potential (GWP) consequences will result from increased wood demand: (i) being supplied via combinations of augmented (national) temperate forest value chains and overseas imports, and/or (ii) facing supply shortfalls, prolonging dependency on non-wood product alternatives via supply chain displacement?

Addressing this question requires a finer resolution of analysis than is possible using IAMs and is beyond the scope of FSM and forest growth models. Lifecycle assessment (LCA) offers a rigorous methodological framework[26] for analysing these carbon-critical[9,27] value chain impacts. There have been recent examples of LCA being integrated with IAMs for modelling low carbon power systems[28] and improving prospective product assessment[3,29]. LCA has also been integrated with forest growth modelling[30,31] to account for the GWP impact of expanded forestry value chains. These are advanced by the present study through integration of high-resolution forest carbon modelling and dynamic (accounting for system changes over time, such as industrial decarbonisation), consequential (capturing cause-and-effect relationships, such as indirect land-use change) LCA of forestry value chains, to calculate the terrestrial and harvested wood products (HWP) lifecycle GWP impact of (FSM-) projected increase in timber demand in temperate countries. We quantify the GWP impact across a plausible range of wood demand and production scenarios (defined below), elucidating possible climate-change mitigation trade-offs across increased wood-use and forestry expansion at national scale, and increased harvest rates from national or overseas forests.

Scenarios modelled

In order to provide new insights that have broad relevance, we analyse shifts in management strategy and expansion (afforestation) for a hypothetical, aspatial, temperate forest under two wood demand projections - 'low and 'high', defined as linear growth rates of 1.1% and 2.3% per annum respectively, from 2023, and equating to a demand increase of 30% and 62% by 2050, respectively (see Methods below). We assess a range of forest management strategies through which a country's existing forest and land resources could supply increased wood demand, including increasing the rate of production from existing forest resources, and expanding the area of productive forest.

As a reference scenario we use a 100,000 ha Sitka spruce forest managed on a clear-fell 50-year rotation (from planting to harvest) - in which there are 2,000 ha of forest in each year age-class. We model eight forest management and expansion scenario combinations, defined in Table 1. The management scenarios include 1) 'reference' rotation; 2) intensification of 'reference' production through a 10% 'shortened rotation' to 45 years, phased over a 50 year period (i.e. 10,000 ha are shortened to 45 years every 5 years to avoid 'shocks' to the ecosystem and to annual wood supply); 3) extensification of 'reference' production through a 10% 'extended rotation' to 55 years, over 50 years; and 4) replanting after 'reference' harvest with 'higher productivity' (25% increase in yield), faster-growing trees.

The expansion scenarios increase the area of each of these four (existing forest) management scenarios through afforestation, applying the same rotation length and productivity criteria (i.e. for the 'shortened rotation' scenario the new forest is harvested from year 45; and for the 'higher productivity' scenario the new forest is planted with trees of that higher productivity from year 1). Expansion is modelled at two different afforestation rates: 2000 ha/yr for 50 years, equating to a doubling of forest area; and 1000 ha/yr for 50 years equating to a 50% increase in forest area. Both afforestation rates are within current policies for low forest cover nations[32,33,34]. To test the sensitivity of the results to the duration of forest expansion (afforestation period) we also calculate the impact of shortening the duration from 50 to 35 years. These hypothetical land-use scenarios help reveal relationships between forestry value chains and climate mitigation that are relevant to temperate forest regions, whilst not being tied to the unique situation of a specific country (e.g. the scale, productivity and age classes of its forest resources).

We used the Carbon Budget Model for the Canadian Forestry Service (CBM-CFS3)[35] to model terrestrial carbon dynamics (forest carbon storage and emissions) and LCA to quantify GWP impact (measured in kg CO_2e) from forestry operations through wood processing and HWP-manufacturing to (cascading) product use(s), over a 100-year study period (GWP_{100}, referred to as GWP from now on). We account for upstream and direct processing emissions, HWP carbon storage, avoided emissions from product substitution, land use (and management) change and indirect land use change (caused by a change in imported HWP). More details are provided in Methods below.

Results

Supply-demand deficit

We find that in a temperate country context for the tested scenarios there is a large gap between realistic biophysical potential wood supply and a rate of increased wood demand at the high end of the range projected in previous studies. Even a doubling of temperate forest area is insufficient to consistently meet future demand during the study period. In all modelled scenarios there will be increased reliance on imports (indicated in red on Fig. 1) over the next 35-55 years, for both ‘low’ and ‘high’ wood demand projections. This is because changes to rotation length have minimal impact on wood supply – illustrated by the small shift in existing forest production rates from the ‘reference’ scenario line (Fig. 1 b,c,f,g); and contributions from afforestation or replanting with ‘higher productivity’ forest only materialise when trees reach harvest age.

‘Higher productivity’ existing forest supplies a 21% increase compared to ‘reference’ and is the only scenario in which existing forest, shown in dark blue, Fig. 1, provides a contribution to marginal demand (i.e. the difference between ‘projected demand’ and ‘reference’ lines) on average over the study period. With existing and new forest combined, ‘higher productivity’ supplies in aggregate, 57% and 93% more than ‘reference’ (baseline, no expansion) for ‘low-‘ and ‘high-expansion’, respectively. In contrast, the combined existing and new forest ‘reference-rotation’ supplies in aggregate, 25% and 51% more wood than ‘reference’ (baseline, no expansion) for ‘low-‘ and ‘high-expansion’, respectively.

The ‘high expansion’ scenarios could produce sufficient wood to exceed ‘low’ projected demand increase in the longer term (from year 35-55 onwards, scenario dependent, indicated in pink, Fig. 1e-h). However, if projected wood demand increase is ‘high’, no scenarios will supply this (Fig. 1).

A supply deficit and reliance on imports is exacerbated if the duration of afforestation is shortened from 50 to 35 years, which leads to pronounced dips in future supply (indicated by the boundary between the pale and dark grey segments, Fig. 1). Committing to a minimum afforestation duration equal to the forest rotation length would help avoid major dips in future supply.

Next, we analyse the GWP impact of supplying projected wood demand via the domestic and import supply balances for each of the forest management scenarios portrayed in Fig. 1.

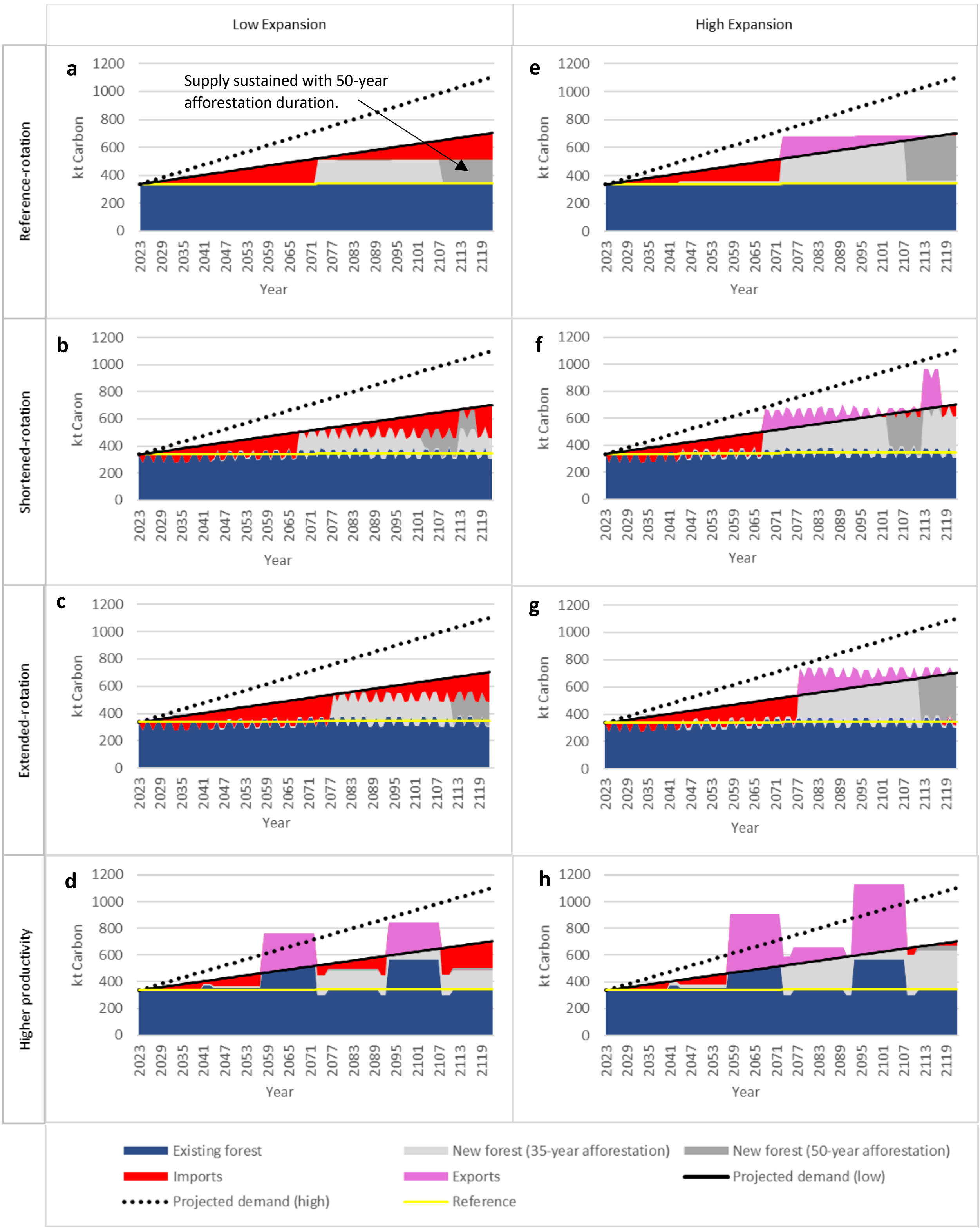

Fig. 1 Annual wood supply and demand for eight management and expansion scenarios for an existing 100,000 ha of temperate forest. In all forest management scenarios we balance projected demand with supply – by modifying imports (or exports) to make up any deficit (or surplus) in domestic (temperate forest) wood production. These scenarios comprise existing forest under four different management applications (1. 'reference-rotation' (a&e), 2. 'shortened-rotation' (b&f), 3. 'extended-rotation' (c&g) and 4. 'higher productivity' (d&h)). Detailed definitions are provided in Methods. Each existing forest management application is paired with two different expansion rates

– ‘low’ (a-d, 1000 ha/yr) and ‘high’ (e-h, 2000 ha/yr). In addition, the new forest is represented as two afforestation durations – 35 years (pale grey) and 50 years (years 36-50 shown in dark grey). Production from existing forest and new forest are plotted against a ‘reference’ scenario (business as usual management of existing forest i.e. reference-rotation with no expansion, yellow line) and two wood demand projections: ‘projected demand (low)’ (solid black line) and ‘projected demand (high)’ (dotted black line), representing 1.1% and 2.3% linear annual growth rates, respectively. The difference between ‘projected demand (low)’ and the combined existing plus new forest (with 50-year afforestation duration) supply, is calculated as ‘imports’ (red) or ‘exports’ (pink), depending on whether supply is lower than or exceeds (respectively) the ‘projected demand (low)’ curve. The 15-year ‘peaks’ in temperate production observed for ‘high productivity’ scenarios (d&h) result from a shift in rotation from 50 years to 35 years (exacerbated by a 50-year afforestation duration for a 35-year rotation forest), leading to 15-year periods when (existing forest and new forest) harvested area doubles. ‘Projected demand (high)’ is indicated by the black dotted line but demand-supply balances for ‘projected demand (high)’ are not illustrated here.

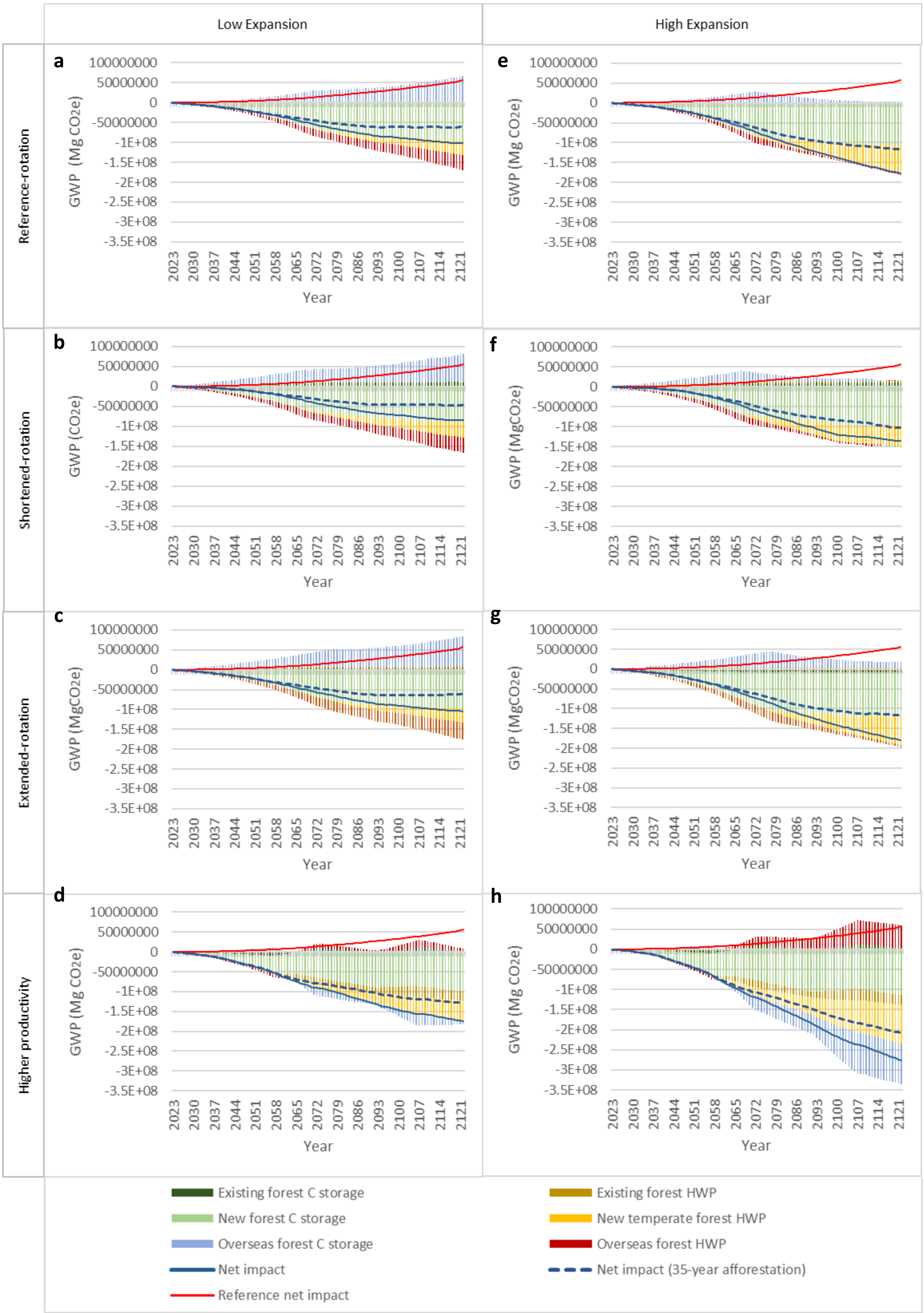

Fig. 2 Cumulative marginal GWP effects, relative to a 2023 baseline, of eight management and expansion scenarios for an existing 100,000 ha of temperate forest under ‘low’ projected demand

(see Fig. 1 or Table 1 for definitions of scenarios), plotted against a reference-rotation with no expansion (i.e. continuation of business as usual – red line). ‘Low’ and ‘high expansion’ mean temperate forest expands linearly by 1% and 2%per year, respectively. All results relating to new forest shown in Fig. 2 are for an afforestation duration of 50 years, unless otherwise indicated. As a sensitivity analysis ‘net impact (35-year afforestation)’ is calculated and plotted to show the GWP impact of shortening the afforestation duration to 35 years (blue dashed line), for each scenario. All results relate to marginal changes in carbon (C) storage and product substitution “credits” from the 2023 baseline for the focal country in which the temperate forest is located. ‘Existing forest C storage’ relates to change in terrestrial C storage (i.e. net forest CO_2 flux) caused by shifting management of the existing 100,000 ha ‘reference’ forest (to shortened-rotation, lengthened-rotation or increased productivity). ‘Overseas forest C storage’ is the change in terrestrial C storage in non-temperate forests in other countries due to increased or decreased harvesting (i.e. increased imports or exports to the temperate country) in order to meet projected demand –described further in Methods. ‘Existing forest HWP’ is the change in C storage plus product substitution ‘avoided emissions’ associated with increased/decreased harvesting arising from shifting management of the existing 100,000 ha ‘reference’ forest (to shortened-rotation, lengthened-rotation or increased productivity). ‘New forest HWP’ is the change in C storage & product substitution arising from harvest of new temperate forest planted nationally. ‘Overseas forest HWP’ is the change in C storage & product substitution associated with the change in imported/exported harvested wood products required to balance supply with demand in the focal country.

Low wood demand projection

Without modified forest management or expansion (‘reference’, red line, Fig. 2), cumulative net GWP impact will remain positive and increase steadily over time (i.e. wood demand will increase cumulative net GHG emissions). This is because static domestic wood production leads to rising annual imports (in line with demand), resulting in overseas forest C storage losses that exceed GWP “credits” derived from carbon (C) storage and product substitution by overseas forest HWP for scenarios modelled in this study (see below, ‘Relative impacts of marginal imports’). In other words, terrestrial carbon (C) losses from forest degradation caused by increases in HWP imports are not fully compensated by the associated HWP C storage and product substitution benefits.

‘Low expansion’ can deliver cumulative GWP mitigation of -174 Tg CO_2e over 100 years with the ‘higher productivity’ scenario (Fig. 2d). Only ‘higher productivity’ achieves mitigation via enhanced overseas forest carbon storage (i.e. terrestrial C gain, blue bars, Fig. 2d&h) – a result of domestic supply exceeding projected demand on average. The varied rotation scenarios (Fig. 2a to c) provide much lower cumulative GWP mitigation of -84, -102 and -104 Tg CO_2e for ’shortened-rotation’, ‘reference-rotation’ and ‘extended-rotation’, respectively. Furthermore, annual GWP mitigation is only sustained for the whole study period with a 50-year afforestation duration. Shortening the afforestation duration to 35 years for ‘low expansion’ scenarios reduces cumulative mitigation by 27-46% (equating to 39-46 Tg CO_2e), scenario dependent, and for all scenarios except ‘higher productivity’ the value-chain even becomes a net CO_2e emitter during the final three years of the study period (indicated by the rising trajectory of cumulative net GWP impact from year 2119, dotted line, Fig. 2 a-c).

‘High expansion’ scenarios deliver 59-73% more cumulative GWP mitigation than ‘low expansion’ (Fig. 2e,f,g&h) due to the impact of greater ‘new forest’ C sequestration and ‘new forest HWP’ GWP benefits, combined with lower dependency on imports. ‘Increased productivity’ (Fig. 2h) again delivers the most notable cumulative GWP mitigation, at -277 Tg CO_2e over 100 years (54-104% more than the varied rotation scenarios). Cumulative GWP mitigation delivered by the varied rotation scenarios remains relatively close when expansion is ‘high’, at -136, -177 & -180 Tg CO_2e for ‘shortened-rotation’, ‘reference-rotation’ and ‘extended-rotation’, respectively. Shortening the afforestation duration from 50 to 35 years for ‘high expansion’ scenarios reduces cumulative GWP mitigation by 25-36% (equating to 34-70 Tg CO_2e), scenario dependent. Although net GWP mitigation is sustained during the study period, it diminishes under the shortened afforestation duration scenarios, as indicated by the levelling out of cumulative net GWP mitigation (dashed lines, Fig. 2e-h).

If projected demand is ‘low,’ all management scenarios with ‘high expansion’ can support net cumulative GWP mitigation, and this mitigation can be doubled by ‘increased productivity’. Varied rotation management scenarios have more limited effect, confirming that expansion of productive forestry and yield enhancement are the most important forest-related strategies to maximise climate change mitigation.

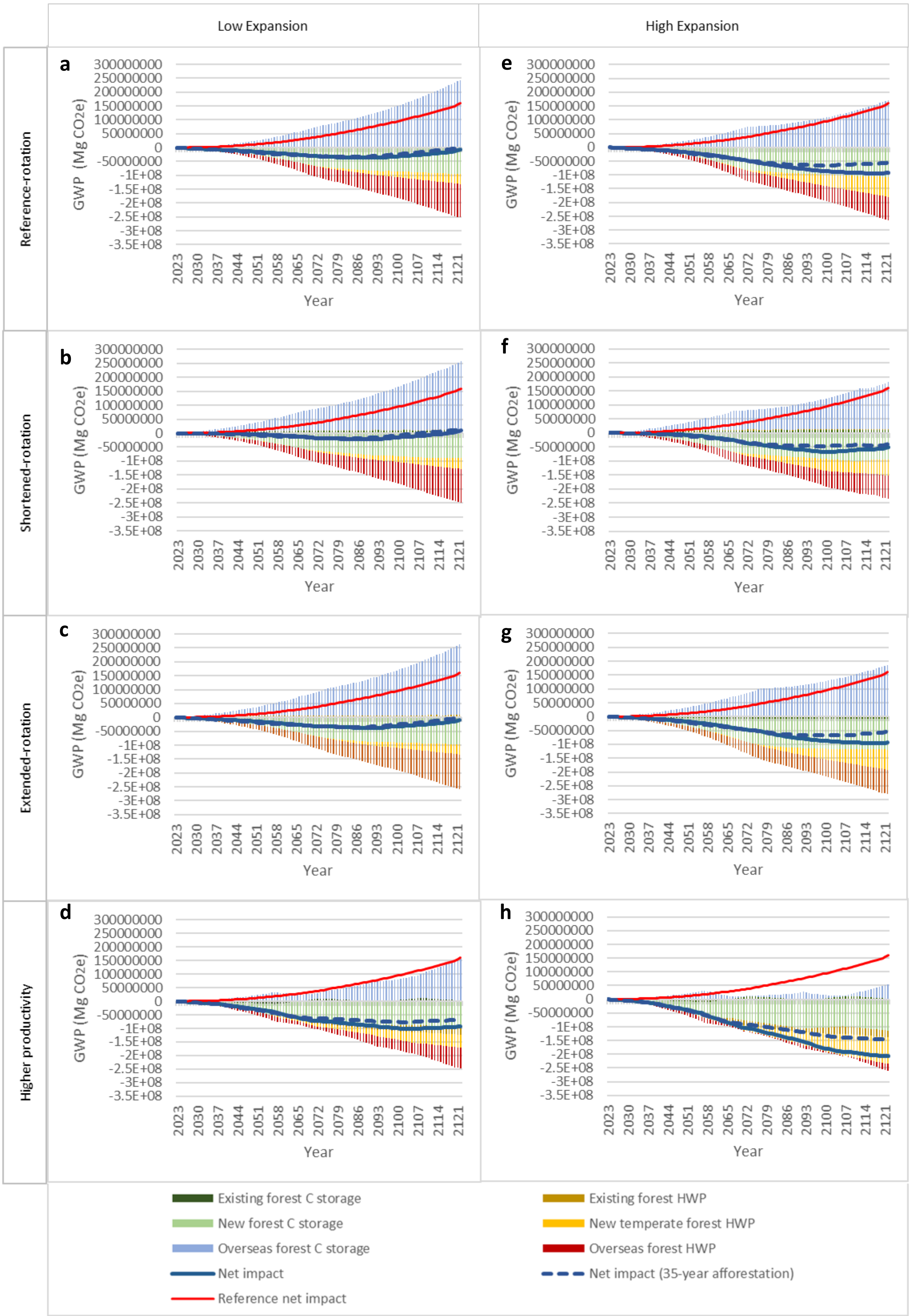

Fig. 3 Cumulative marginal GWP effects, relative to a 2023 baseline, of eight management and expansion scenarios for an existing 100,000 ha of temperate forest under 'high' projected demand (see Fig. 1 or Table 1 for definitions of scenarios), plotted against a reference-rotation with no

expansion (i.e. continuation of business as usual – red line). ‘Low’ and ‘high expansion’ mean temperate forest expands linearly by 1% and 2% per year, respectively. All results relating to new forest shown in Fig. 2 are for an afforestation duration of 50 years, unless otherwise indicated. As a sensitivity analysis ‘net impact (35-year afforestation)’ is calculated and plotted to show the GWP impact of shortening the afforestation duration to 35 years (blue dashed line), for each scenario. All results relate to marginal changes in carbon (C) storage and product substitution “credits” from the 2023 baseline for the focal country in which the temperate forest is located. ‘Existing forest C storage’ relates to change in terrestrial C storage (i.e. net forest CO_2 flux) caused by shifting management of the existing 100,000 ha ‘reference’ forest (to shortened-rotation, lengthened-rotation or increased productivity). ‘Overseas forest C storage’ is the change in terrestrial C storage in non-temperate forests in other countries due to increased or decreased harvesting (i.e. increased imports or exports to the temperate country) in order to meet projected demand –described further in Methods. ‘Existing forest HWP’ is the change in C storage plus product substitution ‘avoided emissions’ associated with increased/decreased harvesting arising from shifting management of the existing 100,000 ha ‘reference’ forest (to shortened-rotation, lengthened-rotation or increased productivity). ‘New forest HWP’ is the change in C storage & product substitution arising from harvest of new temperate forest planted nationally. ‘Overseas forest HWP’ is the change in C storage & product substitution associated with the change in imported/exported harvested wood products required to balance supply with demand in the focal country.

High wood demand projection

When projected wood demand is ‘high’, results become dominated by the impacts of marginal imports (Fig. 3, blue and red bars), which are highly dependent on the balance between overseas forest C storage (CO_2e losses) and C storage and production substitution “credits” attributable to ‘overseas forest HWP’. Despite this, all but one of the modelled scenarios results in cumulative net GWP mitigation by the end of the study period (Fig. 3a-g). Only ‘shortened-rotation, low expansion’ (Fig. 3b) leads to cumulative net GWP impact exceeding zero in the final few years of the study period. However, across every scenario, cumulative GWP mitigation at the end of the study period is 70-95 Tg CO_2e less than in the respective ‘low projected demand’ scenario (Fig. 2). Additionally, although cumulative GWP mitigation is sustained for all but one scenario, the value-chain becomes a net CO_2e emitter from 2107 onwards in the varied rotation, low expansion scenarios, as indicated by the upward trajectory of net GWP impact (blue line).

Relative impacts of marginal imports

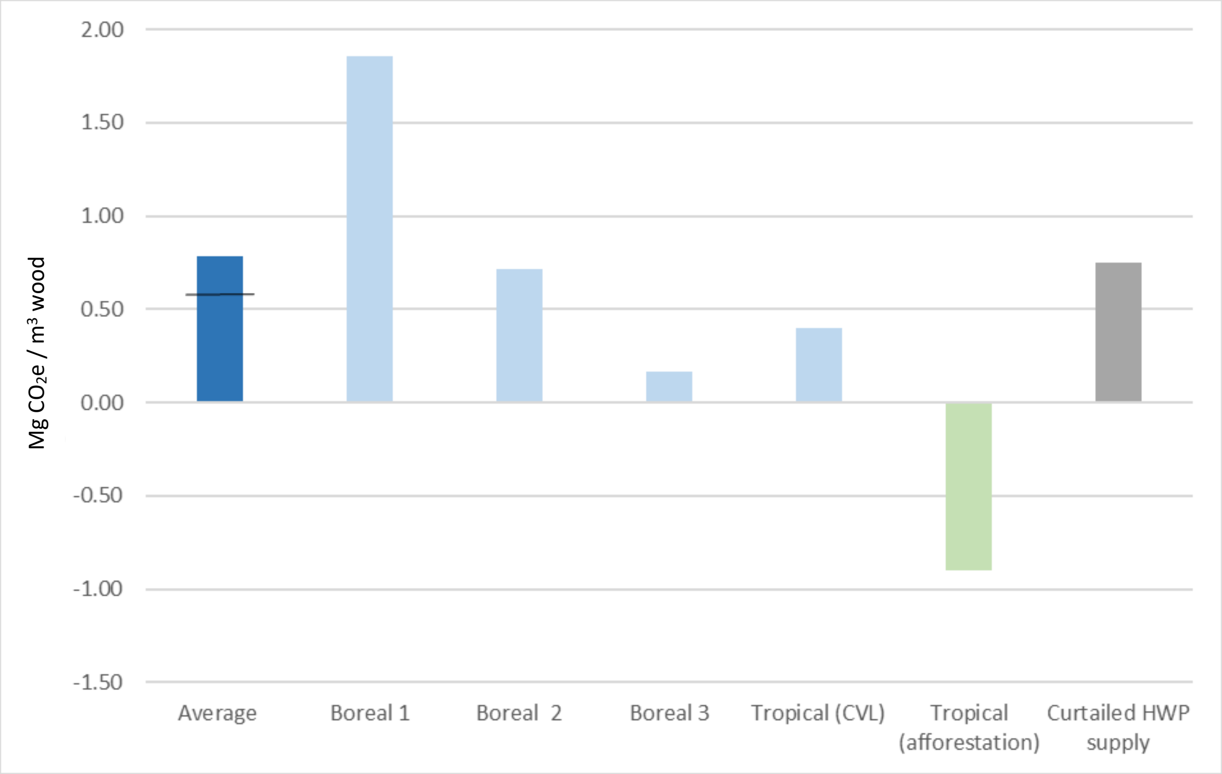

Fig. 4. 'Overseas forest C storage' GWP impact expressed per m^3 of marginal imported wood supply. Five forestry scenarios are considered: 'Boreal (1)' is shortening rotation of old-growth boreal forest from 128 years to 68 years; 'boreal (2)' is shortening rotation from 128 years to 68 years and harvesting stumps and residues; and 'boreal (3)' is harvesting stumps and residues (from a boreal forest already managed on a 68-year rotation). 'Tropical (CVL)' is the CO_2e cost of continuing conventional logging instead of shifting to reduced impact logging in tropical moist forest. 'Average' is the average (net forest CO_2e flux) of the preceding four scenarios – this is used to calculate 'overseas forest C storage' impact in Fig. 2 & 3. The black line shows the possible shift in 'average' if 'tropical (afforestation)' is included in the average calculation. 'Curtailed HWP supply' is the GWP impact per m^3 of marginal wood not supplied (i.e. the CO_2 equivalent emissions due to consumption of non-wood product substitutes, in this case concrete and fossil fuels). Details of modelled scenarios are in Methods.

The range of possible non-temperate forest sources that are likely to be needed to meet shortfall in domestic wood supply in a temperate country versus projected increased future demand, have potentially substantial, though very different, GWP implications. CO_2e emissions associated with an increase in overseas wood supply could potentially exceed the GWP impact of the alternative, prolonged use of non-wood product and fuel alternatives (when accounting for optimistic, progressive industrial decarbonisation during the study period) (Fig. 4).

Of the scenarios considered in this study, the existing forest source for increasing imported wood supply with the lowest GWP-impact is extraction of stumps and harvesting residues in boreal systems that are already managed at moderate harvest intensity (68-year rotation), at 0.17 Mg CO_2e per m^3 wood (Fig. 4). However, given the limited range of HWPs this lower quality wood is suited to, additional wood sources would also be required. Reducing harvest rotation in old-growth boreal forest (i.e. from 128 years to 68 years) results in the highest GWP per m^3 wood, at 1.85 Mg CO_2e per m^3. In contrast, increasing supply from tropical afforestation can offer net C sequestration benefits, of -0.9 Mg CO_2e per m^3 wood. When tropical afforestation is included in calculation of the 'average' impact of sources of marginal wood imports, the GWP impact drops from 0.78 (the value used to calculate 'marginal import/export forest' for modelled scenarios in Fig. 2 and 3) to 0.45 Mg CO_2e (indicated by the black line, Fig. 4). Notably, the value switches from being higher than 'avoided HWP-use' (i.e. the impact of continuing to use non-HWP alternatives) to lower. This would result in marginal imports deriving a net GWP "credit" per m^3, instead of a net GWP burden per m^3 as considered in Fig. 2 & 3. These results illustrate the particular sensitivity of the net balance between (average) net forest CO_2e emissions and HWP GWP "credits" associated with increased harvest demand to a range of counterfactual assumptions across entire value chains (full life cycle perspective). Thus, small changes in (counterfactual) assumptions may propagate to large net changes in net balance, and thus fundamentally alter conclusions of studies evaluating forest management and harvest strategies[3]. Therefore, studies with unclear or truncated boundaries could easily derive misleading results through systematic bias in the calculation of this balance.

Discussion

Although options for increasing wood supply before 2050 in most temperate countries are clearly limited, action started now and sustained to increase forest area and productivity could close the long-term supply-demand gap within the lower range of demand projections. However, the upper range of future demand projections cannot be met by temperate forests, implying a possible need to moderate prospective wood demand and use as the bioeconomy expands[36]. A focus on reducing process losses[5], and maximising value in cascading and circular value chains[37] could regulate demand[9,36], whilst also achieving considerable HWP C storage and product substitution credits[6,9].

There is an important need to relate bioeconomy (industrial) expansion back to feedstock availability to avoid unrealistic expectation on supply, especially for forestry, owing to the time needed to grow trees. Therefore, integrated assessment and modelling used in the context of climate change mitigation should consider forestry (land use) and wood value chains as a policy package: importantly, linking increased harvesting to forest expansion and improved productivity to secure future wood supply and decarbonisation. Increased wood demand is known to stimulate productive forest expansion[38] due to market influences and timber price elasticity[39]. However, if expansion is inhibited, e.g. via absent supporting policy or restrictive land use policy, thereby limiting supply, then harvest leakage will occur[17,20, 40], i.e. harvesting will increase elsewhere to compensate. Ignoring market influences and response of supply to demand in climate change mitigation studies[3] could lead to wood- and land-use conclusions that hinder net-zero efforts. Restricting wood-use would delay bioeconomy growth and global decarbonisation[41], yet increasing wood-use without expanding forest resources and enhancing productivity could lead to net CO_2e emissions.

When projected demand is supplied via augmented (national) temperate forest value chains and overseas imports this will lead to net GWP benefits. In all the scenarios modelled here, net cumulative CO_2e emissions remain below zero. However, when projected demand is high, net annual CO_2e emissions ultimately occur after 2107. Therefore, limiting wood demand through improved value-chain efficiencies is also an important strategy to prevent undermining net climate-change mitigation benefits of future wood use, whilst also sustaining growth of the bioeconomy[9,36]. It is clear that increased wood use is not, in itself, a climate-change solution[42], unless afforestation, increasing forest productivity under sustainable forest management, and mitigating demand increases through enhanced circularity and cascading of wood use are also integrated into the strategy[9,36].

The relative GWP impact of prolonging dependency on non-wood product alternatives via supply chain displacement versus supplying increased wood demand depends on the source of wood.

Reliance on wood imports to deliver increasing domestic demand and territorial net-zero targets risks undermining global (overseas) climate-change mitigation efforts. The range of GWP burdens associated with wood imports to temperate regions considered in this study provide a conservative bounding of impact. The net GWP balance between overseas forest C storage loss and GWP credits associated with HWP use is very sensitive, and can tip from net mitigation to a net CO_2e source (Fig. 4), depending on where the wood is sourced from (the age, management history and growth rate of forests) and how it is used. Given this sensitive balance and the dominant impact it has on overall GWP results, it is imperative that forestry studies evaluating climate mitigation should transparently consider a comprehensive range of land use (change) scenarios as well as full downstream wood use consequences. Notably, IAM do not include cascading uses of wood[23,43] which may tip the implied balance to a net emission, and thus steer inferred climate action away from additional wood use.

There is potential to expand wood supply in tropical areas in a manner that increases terrestrial C storage[44,45,46,47], which therefore implies GWP mitigation associated with imports from these areas. However, in a world where all countries are likely to be increasing demand for wood simultaneously[5], and given an absence of control over land management in other countries[48,49,50], relying on this possibility would be naive, and comes with numerous socio-economic[51] and biodiversity conservation[20] caveats. The average GWP burden attributed to wood imports in this study is conservative, supporting robust conclusions.

There are important product substitution GWP benefits of using wood (e.g. in construction), and C stored in HWP can provide a C sink[27,52]. Bioenergy with carbon capture and storage (BECCS) also has promise for further enhancing the C sink[53,54,55]. Based on conservative assumptions around GWP impacts of imported wood and GWP credits from future wood use, new results presented here demonstrate potential for considerable, yet constrained, expansion of wood-use in the bioeconomies of temperate regions to drive overall climate-change mitigation. To achieve this potential, national net-zero policies must connect climate-change mitigation in wood-using sectors with wood supply (expansion) in the land sector, and prospective demand may need to be moderated via support for cascading and circular use of wood[9]. There is an urgent need for more integrated evidence that incorporates holistic assessment of prospective forestry value chains alongside landscape dynamics (including forest management and expansion), at both national and global scales.

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Methodology (Online)

Scope of LCA

The boundary of the LCA is represented in Fig. 5. A more detailed diagram is included in Supplementary Information.

We account for terrestrial (soil and biomass) carbon (C) storage, harvested wood product (HWP) C storage, substitution of materials and fossil fuels, and long-term sequestration of biogenic C via future deployment of Bioenergy with carbon capture and storage (BECCS), over a 100-year period (using the same assumptions as Forster et al.[27] and summarised here). Expanded LCA boundaries (Fig. 5) encompassed: (i) forest management change (due to shifts in rotation and/or productivity (ii) land use change due to temperate afforestation on spared agricultural grassland; (iii) forest establishment; (iv) forest growth; (v) forestry operations; (vi) debarking; (vii) sawmilling (including drying, plaining and chemical treatment); (viii) wood panel production; (ix) paper and paperboard production; (x) bioenergy generation, including BECCS; (xi) credits for avoided use of fossil fuels (substituted energy generation and mineral construction material production); (xii) C storage in HWPs related to 'decay' (retiral) functions[37], and (xiii) recycling and disposal of retired HWPs, including via (x). The production and transport of all material and energy inputs were accounted for, as were the construction or manufacture of infrastructure and capital equipment. Full life cycle inventories are provided in Supplementary Data 1, with an example table for the Hierarchical wood use value chain in Supplementary Table 1. Material flows were derived using UK data from a combination of forest C modelling[35], harvest data from over 2,000 ha of commercially managed forests, data form a commercial sawmill that maximises sawn-wood output[56], national recycling data[57] and timber-use statistics[58] – elaborated in Supplementary Data 1. Given the focus of this paper on GHG mitigation, only the global warming potential (GWP_{100}) impact category was evaluated, expressed as kg carbon dioxide equivalent (CO_2e) emissions.

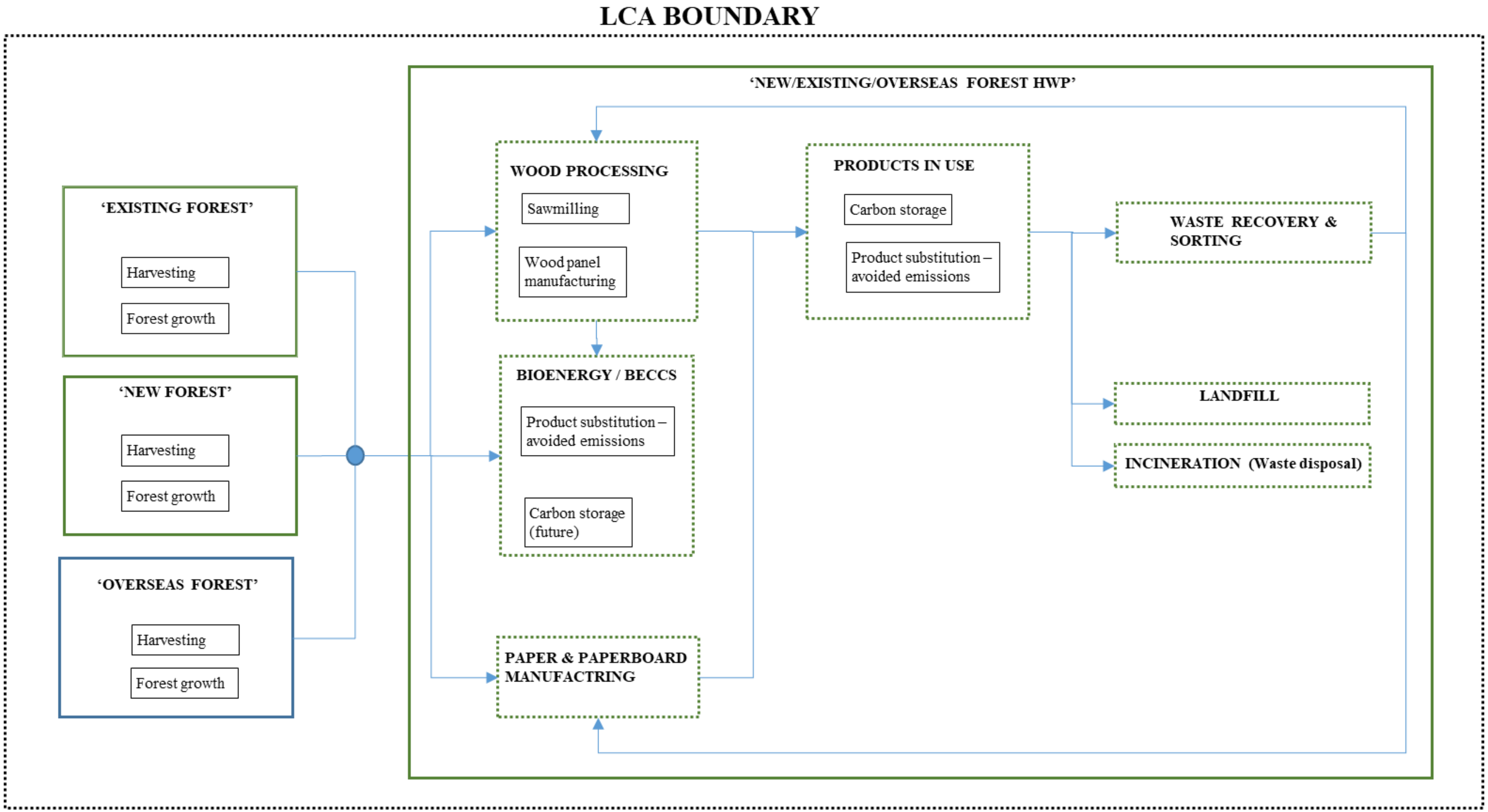

Fig. 5 Life cycle assessment system boundary. We calculate the global warming potential (GWP) impact of forestry value chain (system) changes from year 0 baseline 'business as usual' (BAU) due to shifts in temperate forest management and area to meet projected wood demand increases. 'Overseas' land-use change refers to changes to harvest intensity from tropical and boreal forests assumed to make up marginal demand shortfalls from temperate forests.

BECCS is bioenergy with carbon capture and storage. See Fig. 1 and Table 1 for further details of modelled scenarios. A more comprehensive LCA boundary diagram is provided in Supplementary Fig. 1.

We assess the GWP impact of the following forest management, wood demand and supply variations for a temperate country, relative to business-as-usual management of existing forest in the baseline year of 2023:

- changes to existing forest management and expansion of forest area
    - Increased or reduced rotation length in existing forest
    - Increased growth rate of existing forest
    - Afforestation – temperate forest expansion (at a fixed rate of 2000 ha per year), with a varying proportion of (i) new commercial (conifer) forest subsequently harvested for wood production to (ii) new forest of broadleaved tree species characteristic of semi-natural forests, left unharvested throughout the study period). Management of new forest is the same as existing forest
- an increase in imports required to meet shortfall in the within-country wood production relative to annual demand, through different options to intensify or expand production in various forest types in other exporting countries:
    - Old-growth boreal forest (shortening rotation only)
    - Old-growth boreal forest (shortening rotation, with thinning and removal of tree harvest residues)
    - Tropical forest (continuation of more intensive conventional logging of natural forest rather than shifting to reduced impact logging)
    - Afforestation with new plantations in a tropical country
- continued reliance on fossil fuel-derived materials – if marginal wood demand is not supplied.

Full definitions of the scenarios modelled are provided in Table 1.

Forest growth model

Forest C modelling is performed using the Carbon Budget Model for the Canadian Forestry Service CBM-CFS3[35]. Note we do not model forest losses due to, e.g., pests, disease, wind and fire. Neither do we model forest albedo effects on global warming or the effects of climate change (i.e. warming) on forest growth. Whilst these are important factors that affect the climate change mitigation efficacy of forests[59-64] the risks are highly uncertain and would apply similarly across the study scenarios so would not be expected to significantly alter the study findings.

Further key methodology assumptions are described below.

Assumptions:

Forest management

The study 'reference' is a 100,000 ha 'normal' forest (i.e. comprising an even distribution of annual age classes) of Sitka spruce, yield class (YC) 18, managed with a 50-year clear-fell rotation, with thinning in year 21 (all representative of current forest management of temperate oceanic environments such as those in UK and other countries within its region). All alternative management scenarios modelled start with these 'reference' conditions in year 0 of the study period, which is 2023.

The study explores the GWP impact of altering forest rotation length, increasing tree growth rate and expanding forest area. We quantify the GWP impact of modifying forest management (from the reference) in combination with options for expanding forest area. The full range of management and expansion (afforestation) options that are assessed in this study are presented in Table 1.

Altering rotation length:

Since the ‘reference’ forest is already managed close to the optimal (commercial) rotation length for typical temperate plantations, large shifts are unlikely. Therefore, we model shortening and extending rotation length by 10% from the reference scenario, implementing this shift gradually over a 50-year period (i.e. 10% of the forest area is transitioned every 5 years) so as to limit the rate of change to annual harvest volumes (which would be constrained by wood value chain and market capacity) and forest C dynamics.

Increasing productivity:

Harvested trees (at 50 years) are replanted with YC24 Sitka spruce, managed on a 35-year rotation. This equates to a 25% increase in productivity such as could be possible with an enhanced breeding program[65], from 17.2 to 21.5 m^3/ha/yr.

Afforestation

There is a physical limit to the land available for expansion of forest area through afforestation in temperate countries, and its implementation is further constrained by multiple social, economic and political factors: the timber market, jurisdictional regulation and policy[36].

We assume that commercial plantation afforestation is part of a comprehensive strategy to achieve fixed targets for increase in total forest area (as is the case for national policies in many temperate countries, such as the UK[32,33]. However, such policies in temperate countries typically do not specify the types of forest planted. While commercial wood production interests and rapid achievement of ‘net zero’ targets favour fast-growing conifers[27], biodiversity conservation and delivery of other cultural and regulatory ecosystem services may favour establishment of unharvested forests comprising broadleaved tree species typical of semi-natural forests. Therefore, we calculate the consequential impact of varying the proportion (high and low) of commercial conifer to broadleaved species in the afforestation strategy. The ‘high’ afforestation strategy equates to a doubling of the area over 50 years of commercial conifer plantation (with wood harvested at the end of the rotation) and the ‘low’ strategy equates to a 50% increase of commercial conifer plantation area over 50 years, with the balance of the total afforestation area comprising broadleaved species. In relation to the reference forest area, this translates to commercial conifer plantation afforestation rates of 2000 ha/yr and 1000 ha/yr, respectively. In the ‘low’ strategy we calculate the impact of the marginal increase (1000 ha/yr) in broadleaf forest area comprising a mixture of sycamore, silver birch, oak and rowan, with an average growth rate of YC6, that is unharvested during the study period, a typical scenario for the low-productivity land most available for large-scale afforestation (in the UK).

To assess the impact of afforestation duration at these planting rates, on both wood supply and GWP impact, we also model a shorter afforestation duration of 35 years for each afforestation strategy, applying the same annual planting rates of 2000 ha/yr and 1000 ha/yr (so the total new forest area planted is 30% lower than for the standard 50-year afforestation strategies). The full range of management and expansion (afforestation) options that are assessed in this study are presented in Table 1.

Projected wood demand

We use the FAO definition for industrial round wood (IRW)[66], which is all round wood except wood fuel. It includes sawlogs, veneer logs, pulpwood and other IRW and, in the case of trade, chips and particles and wood residues. The majority of IRW production is traded in the form of HWPs[67], i.e. IRW that has already been processed (normally in the production country), such as sawnwood, wood-based panels, and paper and paperboard. Therefore, in the present study we use the term 'wood' to inclusively refer to IRW and/or HWP, unless differentiation is important for clarity.

Low demand projection is based on historic global wood production rates[67], which are similar to rates in Europe, both at 1.1% average linear growth per annum over the last 20 years. We assume that future demand growth continues at this linear rate.

We decouple a higher projected demand increase from historic trends to account for growth of the bioeconomy and turn to IAM and FSM projected demand in published studies. However, there is great uncertainty surrounding projected demand for IRW because like it depends on social, political, economic and environmental systems that are 'non-stationary', with correlations between variables changing over time[68]. It is therefore unsurprising that previous studies have reported a wide range of rates of predicted increase in future demand for IRW and typically limit the study period to 30- to 40-year timeframes, rarely projecting far beyond 2050[2,3,4,5,22]. This means that the extended projection of published growth rates to 2122, applied in the high-demand scenario in the present study, is very uncertain.

Increased global IRW demand projections by FAO (using The Global Forest Products Model) range between 27% and 44% for 2020-2050, depending on efficiency of residue use (70% and 30%, respectively); and a further increase of up to 14% is possible if trends for timber construction and man-made cellulosic fibres (MMCF) in textile production increase[5], equating to a possible 58% rise globally between 2020? and 2050, or 1.9%? per year on average.

There is, however, significant regional variation in projected change in demand[2,3,4,5,22], with the greatest increases predicted in Eastern Asia where it is predicted to expand its leading role, consuming 41% of the world´s primary processed wood products" in 2050. This is an increase in demand of 56% between 2020-2050, equating to linear demand growth of 1.9% between 2020-2050. Coupled with the further potential 14% demand linked to trends for timber construction and MMCF, the average annual demand increases to 2.3% per annum. Other studies project wider variations still. Demand by East Asia and Pacific has been projected to rise by between 2%[2] and 4.4% per annum to 2050[3] for sawnwood and wood panels combined (total IRW demand, not separately reported, can be interpreted to rise at a similar rate since demand for paper and paperboard – the other major traded HWP group – has similar growth projections). Meanwhile, Europe and Central Asia has relatively lower projected sawnwood demand increases of 0.5%[2] to 0.6%[3] per annum to 2050. National-scale projection for Finland, Sweden, Norway and the temperate region of Germany (Bavaria), project demand increases of 34% (Sweden) to 40% (Norway) between 2020 and 2050 (interpreting growth curves)[22]. Notably, these countries are important timber production regions, together contributing 29% of Europe's IRW production[67]; and they already have high wood consumption per capita, relative to (low production) countries such as the UK, Ireland and the Netherlands[69] so the potential for percentage demand increase may be tempered by this.

To account for the wide range of published projections and the great uncertainty of these projections we selected two contrasting scenarios for the rate of increase in future demand for IRW representative of the lower and higher estimates in the range of previous studies, respectively. This is important to assess the sensitivity of net value chain GWP impact to this variation in future demand. We selected annual linear growth of 1.1% to represent a 'low' demand projection scenario.

It matches historic growth in timber consumption globally and in Europe, according to FAOSTAT[67]. It also closely matches historic growth in the UK, a temperate developed country with moderate[69] per capita timber consumption, over that last 20 years. It equates to a 30% demand increase by 2050, or a 85% increase by 2100. For the 'high' demand projection we use 2.3% annual growth, which equates to a 62% demand increase by 2050, or a 177% increase by 2100, which is the highest case regional scenario (for Eastern Asia) derived from FAO modelling. However, at a country level, demand increase could potentially be even higher as there is likely to be further variation within regions.

Harvested wood products impact

We assume a 'hierarchical' value chain breakout for wood flows that remains constant throughout the study period. The assumptions and methodology for calculating the GWP impact of processing and use of HWP under this hierarchical value chain are taken from Forster et al.[27] (Supplementary Data 1), including the decarbonisation projections and product substitution effects. The current study advances the work by Forster et al.[27] by calculating the GWP impact of dynamic annual harvests from both existing and new forest. A HWP GWP impact calculation module (Supplementary Data 2) was developed (from Supplementary Data 1) for this purpose and used in the present study.

The same GWP impact calculation methodology is applied to all HWP, including marginal imports and exports. The volume of marginal imports (or exports) is calculated as the difference between projected demand and supply from commercial plantations within the temperate country (illustrated in Fig. 1).

Marginal imports Forest impact

We assume marginal imports (i.e. import differences vis-a-vis the 2023 baseline year) are supplied from non-temperate forests in order to gauge the range and scale of potential consequential impact if temperate regions cannot increase production sufficiently to meet their own projected demand. For this we have treated boreal forests as a different category from temperate forests, which is particularly appropriate as a major component of wood demand in temperate countries is softwood from conifer trees, and boreal forests represent a major source of this softwood in global trade[5].

This calculation has high uncertainty for multiple reasons:

- future product breakout (wood use) is uncertain, i.e. how wood will be used in the future due to developments in technology and the bioeconomy[37]
- product breakout from different forest types and regions varies greatly, due to variation in productivity, wood properties and quality, and local uses
- there is a wide range of options for increasing harvest volumes across regions (e.g shortening rotations[70] or increasing productivity[71])
- there is great complexity and challenge in accurately modelling C fluxes in different forest management scenarios, and in many cases there are limited available data.

We therefore take a simplified approach to modelling the GWP impact from fluxes in forest C stocks (forest C) of marginal imports, with the intention of estimating the potential scale of impact, rather than attempting a precise dynamic representation of impact.

We calculate the GWP (forest C) impact of the following four selected forest management change scenarios in tonnes of CO_2e per marginal m^3 of harvested wood. Boreal scenarios (1,2,& 3) account for changes to above- and belowground C. Tropical scenario accounts for change to aboveground C only.

Boreal (1) – boreal, managed on 128-year rotation with no thinning changed to a 68-year rotation with no thinning and no removal of harvesting residues[70])

Boreal (2) – boreal, managed on 128-year rotation with no thinning changed to a 68-year rotation with moderate thinning and removal of harvesting stumps and residues for processing[70])

Boreal (3) – boreal, managed on 68-year rotation with moderate thinning changed by introduction of removal of harvesting stumps and residues[70])

Tropical – continuation of more intensive conventional logging practice in natural tropical forest, instead of changing to low impact logging[72]. This scenario will maintain a higher rate of supply of tropical hardwood, which has limited potential to substitute for softwood in major markets (assuming historic wood-use trends), but is included in our study as an "outgroup" comparator for the scenarios of intensification of boreal forest harvesting.

To avoid complex temporal C dynamics caused by transitioning from one forest management regime to another, we assume an instant shift from steady state in the initial system to steady state in the new (higher supply) system. We calculate the change in average C stocks and average annual volume of harvested wood for each scenario. Whilst this doesn't capture important temporal C dynamics, it indicates the potential scale of impact of sourcing marginal IRW from different forest resources and highlights areas where further study is important. See Supplementary Data 3 for calculations.

We equate the change in average C stocks to a per m^3 of marginal harvested wood, for each of the four scenarios above (Boreal 1,2&3, and Tropical) and then calculate the 'Average' forest impact of each of these scenarios (their sum, divided by four) – this average value is used to calculate 'Marginal import/export forest' in Figu. 2 and 3 in the Results. We scale up the 'Average' GWP impact of 'Marginal imports/exports forest' from tonnes of C (as CO_2e) per m^3 of marginal harvested wood to the calculated m^3 of marginal imports/exports for each modelled scenario to quantify their respective GWP impacts.

Note that we apply the same product breakout assumptions used for the temperate plantations for these four different sources of imported wood, i.e. we do not account for variation in product breakout data for wood from difference sources. This could lead to underestimation of the area of forest required to supply marginal HWP imports – particularly for Boreal (3) where the additional wood removed is not logs but lower quality stumps and residues.

Tropical afforestation

Afforestation is linked to increased timber demand[73], so whilst detrimental GWP impacts of increasing harvesting from existing systems are possible, increased demand could also trigger beneficial GWP impact from afforestation (beyond temperate regions). Significant opportunities in the tropics, due to large areas of underutilized land and high potential tree growth rates[71], mean tropical afforestation can make a meaningful contribution to IRW supply within the study period, although the high growth rate tree species matched to most tropical environments (such as *Eucalyptus* spp.) produce hardwood with predominantly different uses and markets than temperate or boreal softwood, but still with an important role in large-volume global wood markets. We therefore estimate the possible impact of afforestation at a scale to deliver the average marginal import volume(s) over the study period. The modelled scenario involves land use change from tropical wet grassland3[2] to eucalyptus plantation managed on a 10-year rotation[75] clear-fell harvest with mean annual increment (MAI) 35 m^3/ha/yr[75]. While reported lower MAI could be used[76,77], we made our selection as it provides a conservative estimate of the potential GWP impacts of tropical afforestation (i.e. land use change) since the area of forest required to supply demand is relatively low (given the high MAI and therefore high wood supply rate, and low C storage per ha) and because we account only for CO_2 sequestration into aboveground C stocks, not belowground stocks.

We calculate the GWP (net CO_2e sequestration) impact of tropical afforestation in tonnes of CO_2e per m^3/yr of harvested wood and the associated land footprint to facilitate direct comparison with the range of intensified forest management scenarios described above. See Supplementary Data 3 for calculations.

Marginal wood demand not met

The impact of marginal IRW demand not being met is calculated as a loss of the avoided emissions impact of the marginal imported HWP i.e. consequential CO_2e emissions from increased use of concrete and prolonged reliance on fossil fuels.

It is calculated as an average impact per $1m^3$/yr over 100 years, to account for the effects of decarbonisation over the study period. See Supplementary Data 3 for calculations.

Table 1 – Part (a) defines the existing forest management options modelled in the study using the forest growth model, CBM-CFS3. Part (b) defines forest expansion options modelled in the study using the forest growth model. Part (c) defines the combinations of existing forest management and expansion options modelled and assessed using LCA in this study. ‘higher productivity’ refers to replanting with faster-growing trees for the next rotation after harvested at 50 years (then managed on a 35-year rotation thereafter). Afforestation (expansion) is modelled with options on afforestation rate and period.

Scenario description	**Scenario name**	**Yield Class (YC)**	**Harvest**	**Rotation length**	**Afforestation rate**	**Afforestation duration**
(a) Existing forest						
‘Reference’	Rotation_50_50	18	Clear fell, with thinning in year 21	50 years	n/a	n/a
Shortened rotation	Rotation_50_45	18	Clear fell, with thinning in year 21	Shift from 50 years to 45 years (gradual over 50-year period)	n/a	n/a
Extended rotation	Rotation_50_55	18	Clear fell, with thinning in year 21	Shift from 50 years to 55 years (gradual over 50-year period)	n/a	n/a
Higher productivity	Rotation_50_35	18, 24 after replanting	Clear fell, with thinning in year 21 (YC 18) or year 18 (YC24)	50 years then 35 years after replanting	n/a	n/a
(b) Forest expansion						
‘Reference’-rotation – with expansion options	Expansion_50	18	Clear fell, thinning in year 21	50 years	1,000 ha/yr	35 years
						50 years
					2,000 ha/yr	35 years
						50 years
Shortened rotation – with expansion options	Expansion_45	18	Clear fell, thinning in year 21	45 years	1,000 ha/yr	35 years
						50 years
					2,000 ha/yr	35 years
						50 years
Extended rotation – with expansion options	Expansion_55	18	Clear fell, thinning in year 21	55 years	1,000 ha/yr	35 years
						50 years
					2,000 ha/yr	35 years
						50 years
Higher productivity – with expansion options	Expansion_35	24	Clear fell, thinning in year 18	35 years	1,000 ha/yr	35 years
						50 years
					2,000 ha/yr	35 years

						50 years
Broadleaf – with expansion options	Expansion_BL	6	Unharvested - mixed broadleaf, (BL)	n/a	1000 ha/yr	35 years
						50 years

Table 2 - Scenario combinations include the reference forest (with no afforestation), and the four (including reference) temperate forest management scenarios with afforestation options, under both high and low timber demand projection scenarios. *excluded from this table to maintain clarity of presentation, the 1000 ha/yr afforestation rate scenarios also include 'Expansion_BL', i.e. 1000 ha/yr of mixed broadleaf afforestation (See Table 1). **low afforestation rate scenarios also present net results for 50-year afforestation to show the comparative impact of shortening the duration of the afforestation period.

Scenario combinations analysed						
Scenario description	**Existing forest**	**Forest expansion**			**Wood demand projection**	
		Management	**Afforestation duration**	**Afforestation rate**		
Reference	Rotation_50_50	n/a	n/a	n/a	Low	High
Reference-rotation, high expansion	Rotation_50_50	Expansion_50	50 years	1000 ha/yr*		
				2000 ha/yr		
Reference-rotation, low expansion**			35 years	1000 ha/yr*		
				2000 ha/yr		
Shortened-rotation, high expansion	Rotation_50_45	Expansion_45	50 years	1000 ha/yr*		
				2000 ha/yr		
Shortened-rotation, low expansion**			35 years	1000 ha/yr*		
				2000 ha/yr		
Extended-rotation, high expansion	Rotation_50_55	Expansion_55	50 years	1000 ha/yr*		
				2000 ha/yr		
Extended-rotation, low expansion**			35 years	1000 ha/yr*		
				2000 ha/yr		
Higher productivity, high expansion	Rotation_50_35	Expansion_35	50 years	1000 ha/yr*		
				2000 ha/yr		
Higher productivity, low expansion**			35 years	1000 ha/yr*		
				2000 ha/yr		