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**Commercial afforestation can deliver effective climate change mitigation
under multiple decarbonisation pathways**

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Abstract

Afforestation is an important greenhouse gas (GHG) mitigation strategy but the efficacy of commercial forestry is disputed. Here, we calculate the potential GHG mitigation of a UK national planting strategy of 30,000 ha yr⁻¹ from 2020-2050, using dynamic life cycle assessment. What-if scenarios vary: conifer-broadleaf composition, harvesting, product breakouts, and decarbonisation of substituted energy and materials to estimate 100-year GHG mitigation. Here we find forest growth rate is the most important determinant of cumulative mitigation by 2120, irrespective of whether trees are harvested. A national planting strategy of commercial forest could mitigate 1.64 Pg CO₂e by 2120 (cumulative), compared with 0.54–1.72 Pg CO₂e for planting only conservation forests, depending on species composition. Even after heavy discounting of future product substitution credits based on industrial decarbonisation projections, GHG mitigation from harvested stands surpasses unharvested stands. Commercial afforestation can deliver effective GHG mitigation that is robust to future decarbonisation pathways and wood uses.

Introduction

Achieving the ambition of The Paris Agreement to limit global warming to 1.5 °C above pre-industrial levels requires rapid implementation of negative emissions technologies¹, in particular increasing forest carbon sinks². Afforestation on land spared from agriculture³ is proposed as an integral element of greenhouse gas (GHG) mitigation^{4,5}, but mitigation efficacy is highly context-specific and depends on, *inter alia*, climate, tree species, management, and product substitution. In tropical regions, fast growing commercial forests managed for wood production have been unfavourably compared to restoration of natural forest⁶ but these conclusions are not transferable to a temperate context. There remains a gap in evidence determining the most effective type of temperate forestry for achieving GHG mitigation. The role of sustainable wood harvesting is recognised in GHG mitigation strategies^{5,7,8} and could be enhanced through cascading use of wood⁹, but recent modelling indicates that future mitigation from product substitution will diminish owing to

decarbonisation of substituted materials and energy^{10,11}. In coniferous temperate forests, bioenergy harvest breakeven times can range from 30 to 70 years assuming coal is being replaced, depending on the scale of the assessment and whether the stands are damaged¹². Meanwhile, dynamic life cycle assessment (LCA) studies indicate that it can take up to 100 years for CO₂ released from current bioenergy generation to be fully compensated by forest regrowth^{13,14}.

To fully understand the role of new commercial forests in future GHG mitigation, there remains a need for coherent modelling of GHG mitigation across the four life cycle stages (production, use, cascading use and end-of life) of hierarchical wood value chains¹⁵ in the context of decarbonised material and energy systems⁴. We fill this gap through comparison of 100-yr mitigation achieved by newly planted commercial and conservation (i.e. unharvested) forests in the UK, a country with high afforestation potential^{3,16,17}. Although prioritising GHG mitigation in afforestation strategies will involve complex trade-offs with other ecosystem services^{18–21}, such as biodiversity conservation, the purpose of this paper is not to explore these. Rather, it aims to generate robust evidence on the efficacy of alternative afforestation options for the primary strategic aim of mitigating GHG emissions. We apply dynamic consequential LCA²² to 33 what-if scenarios representing a range of commercial Sitka spruce (*Picea sitchensis*) forests with different harvested wood product value chains, and conservation forests, across representative growth rates, and in the context of different decarbonisation pathways (Table 1).

Under typical conditions, one hectare of newly-planted commercial forest could achieve cumulative GHG mitigation of up to 2.27 Gg CO₂e ha⁻¹ within a core decarbonisation pathway projected for the UK⁴ by 2120 – up to 269% more mitigation than delivered by newly planted conservation forests, and 17% more than achieved by leaving a newly planted fast-growing conifer forest unharvested. Harvesting reduces long-term terrestrial carbon storage by 61%, but this is more than offset by harvested wood product (HWP) carbon storage, and concrete and energy substitution - even with near total decarbonisation of the energy sector within the 100 year study horizon. Projected wide

deployment of carbon capture and storage (CCS)⁴ contributes up to 45% of cumulative 100-year mitigation benefit, but also reduces the energy substitution credits realised by future wood energy. Consequently, the efficacy of mitigation is surprisingly similar between hierarchical and bioenergy uses of wood, and remarkably resilient to CCS deployment assumptions. To contextualise the results in a national planting strategy, we model the UK Committee on Climate Change recommended planting rate of 30,000 ha yr⁻¹ from 2020 to 2050. If this strategic target is met with commercial forests, it would cumulatively mitigate up to 1.64 Pg CO₂e emissions by 2120, compared with 0.54 Pg CO₂e for a semi-natural broadleaf conservation forest, or 1.09 Pg CO₂e for an equal planting rate of 15,000 ha yr⁻¹ of each forest type. For UK forests and projected decarbonisation pathways, large-scale commercial afforestation could contribute strongly to GHG mitigation targets.

Results

One hundred year snapshots following a single planting event: Terrestrial carbon sequestration in semi-natural broadleaf, mixed conifer-broadleaf and fast-growing conifer conservation forests planted in 2020 equates to cumulative mitigation by 2120 of 0.62 (0.41-0.82), 1.30 (0.94-1.64) and 1.94 (1.30-2.58) Gg CO₂e ha⁻¹, respectively (Fig. 1). Mitigation performance across these conservation forest types is proportionate to yields (Table 1). On average over 100 years, commercial Sitka spruce forests store 61% and 42% less terrestrial carbon than unharvested conifer and mixed conservation forests, respectively, but still 24% more than slow-growing semi-natural broadleaf forests (Fig. 1). However, in addition to terrestrial carbon storage, commercial forests realise ca. 1.7 Gg CO₂e ha⁻¹ mitigation by HWP carbon storage, fossil fuel substitution, BECCS and concrete substitution in the *Core* context, at average growth rates (Fig. 1). Relatively small processing emissions of 0.20 (*Bioenergy* prioritised wood use) to 0.28 Gg CO₂e ha⁻¹ (*Hierarchical* wood use) are based on the conservative assumption of a very gradual decline in the emission intensity of processing operations (Table 2 and Supplementary Data 1). Overall, one hectare of YC 18 commercial forest planted in 2020 will achieve cumulative GHG mitigation of between 2.0 and 2.27

Gg CO₂e by 2120, varying by less than 8% and 10% between wood use strategy and decarbonisation context, respectively. Yield variability extends the mitigation range to 1.36-2.96 Gg CO₂e ha⁻¹ by 2120. Thus, commercial Sitka spruce forests support between 3% (relative to 100% conifer) and 269% (relative to 100% broadleaf) more GHG mitigation than conservation forests over a 100-yr time horizon from establishment.

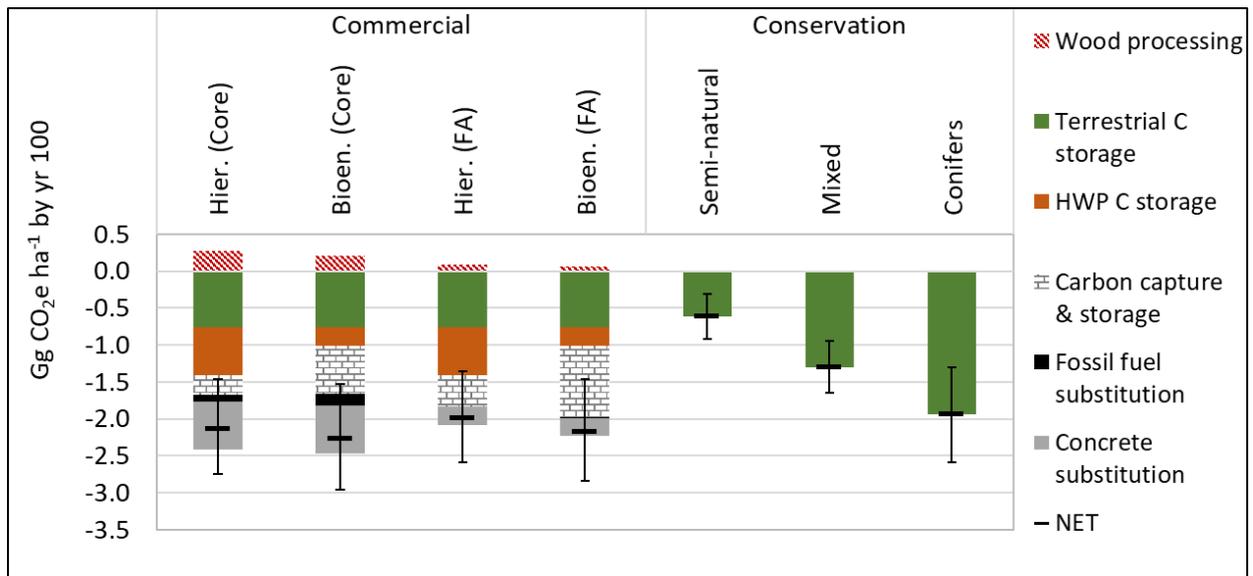


Figure 1 – Contribution of major processes to cumulative GHG fluxes from one hectare of afforested land (planted in 2020) by year 100, for commercial and conservation forests. Default yield class 18 (m³ ha⁻¹ yr⁻¹) for the commercial and unharvested conifer conservation forests, 4 for the semi-natural broadleaf conservation forest and 11 for the mixed conifer-broadleaf conservation forest. Error bars represent full yield ranges presented in Table 1. Commercial forest results are presented for *Core* and *Further Ambition* (FA) decarbonisation contexts, and for *Hierarchical* (Hier.) and *Bioenergy* (Bioen.) wood use strategies, with differing mitigation contributions from concrete and fossil fuel substitution and carbon storage in harvested wood products (HWP) or long term geological stores via carbon capture & storage.

National planting programme

In our scenario of a commercial forest planting programme involving 30,000 ha planted every year from 2020 until 2050 (Fig. 2), only 15% of the 100-year mitigation will be achieved by 2050. A 30-year commercial forest planting strategy could achieve cumulative net mitigation of up to 1.64 Pg CO₂e at default yield (Fig. 2), with a range across yields and scenarios of 1.13 to 2.0 Pg CO₂e for YC 14 *Hierarchical* (*Further Ambition*) and YC22 *Bioenergy* (*Core*), respectively (shown in S3 & S4). This

compares with mitigation of between 0.54, 1.15 or 1.72 Pg CO₂e from equal planting of semi-natural, 50:50 conifer-broadleaf mixed or unharvested conifer forests, respectively (Fig. 2), at default yields (Table 1). A mixed planting strategy of 15,000 ha per year each of commercial forest (YC 18) and semi-natural broadleaf forest (YC 4) could achieve 1.09 Pg CO₂e mitigation, 34% lower than commercial forestry alone. For commercial forests established after 2040, cumulative mitigation from regrowth and downstream mitigation does not catch up with cumulative mitigation achieved by unharvested conifer conservation forests by 2120, so that the latter forest type outperforms commercial forests for the 30-yr planting programme – despite commercial forests achieving more mitigation across two full rotations (Fig. 1). However, mitigation trajectories (Fig. 2) and 100-yr mitigation performance (Fig. 1) indicate that commercial forests would achieve considerably more mitigation than conifer conservation forests beyond our 2120 cut-off. Basing the national forest planting programme entirely on a *Bioenergy* wood use strategy would achieve annual mitigation of 20.2 Tg CO₂e by 2050 from YC 18 Sitka spruce, under a *Further Ambition* context (S4), equating to 24% of projected gross anthropogenic GHG emissions in the UK if net zero targets are achieved⁴. Establishing 30,000 ha yr⁻¹ of commercial forests could directly supply 3.88 or 14.2 TWh yr⁻¹ electricity from thinnings plus first-harvest biomass, from 2070 onwards, based on *Hierarchical* (S3) or *Bioenergy* (S4) wood use strategies, respectively (end-of-life use of construction wood for bioenergy generates a further 20-43% electricity over the following 50 years – S3 & S4).

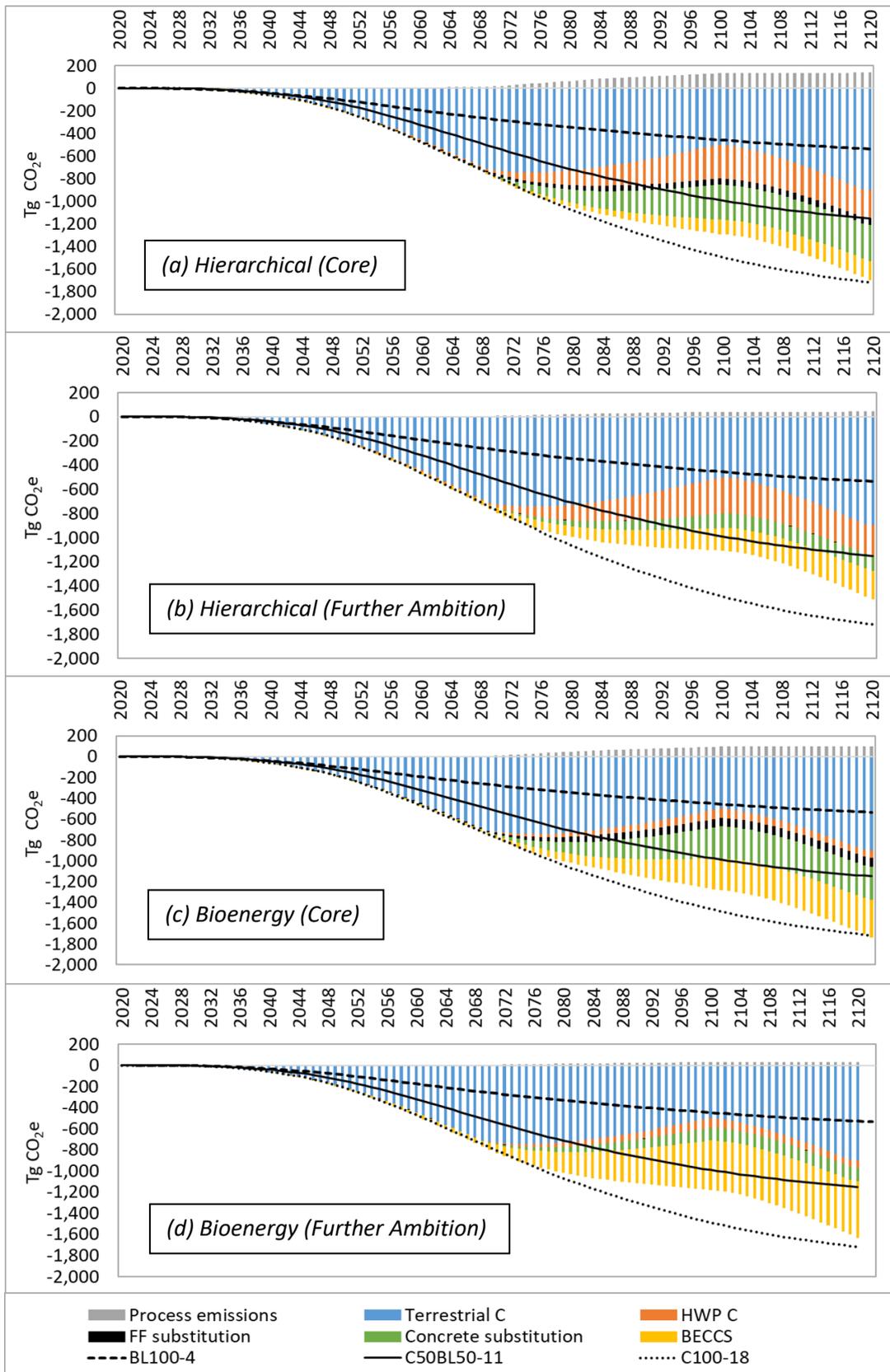


Figure 2 – Cumulative CO₂e mitigation over a 100-year period for commercial forests planted at a rate of 30,000 ha yr⁻¹ from 2020 to 2050, with a *Hierarchical* wood use strategy (a & b) or a *Bioenergy* wood use strategy (c & d), under *Core* (a & c) or *Further Ambition* (b & d) decarbonisation contexts. Commercial Sitka spruce forests are modelled based on default yield class 18. Contributing factors are shown as stacked bars: process emissions, terrestrial forest carbon storage, harvested wood product (HWP) carbon storage, fossil fuel

(FF) substitution (negligible in the *Further Ambition* context), concrete substitution and bioenergy carbon capture and storage (BECCS). Also shown (lines) are cumulative CO_{2e} mitigation trends for conservation forests planted at the same rate, ranging from semi-natural 100% broadleaf (YC 4), through a 50:50 mixed conifer:broadleaf forest (YC 11) to an unharvested 100% conifer forest (YC 18). These lines represent terrestrial forest carbon storage only, and the C100-18 forest provides a direct comparison of cumulative mitigation that could be achieved by YC 18 conifers if they are not harvested.

Wood use and decarbonisation scenarios

For a national planting programme of 30,000 ha yr⁻¹, more rapid decarbonisation of the wider economy represented in the *Further Ambition (vs Core)* context could reduce cumulative national mitigation achieved by *Hierarchical* or *Bioenergy* wood use in 2120 by 5% or 2%, respectively (Fig. 2). Meanwhile, a *Bioenergy* wood use strategy rather than *Hierarchical* wood use strategy could increase cumulative GHG mitigation achieved in 2120 by 5% (*Core* context) to 8% (*Further Ambition* context) (Fig. 2). In the *Further Ambition* context, future process emissions and fossil fuel substitution credits are minor, concrete substitution credits are diminished relative to the *Core* context, and mitigation by BECCS becomes prominent through time (Fig. 2). In fact, BECCS accounts for 33% of cumulative mitigation by 2120 in the *Bioenergy* wood use strategy, whilst HWP carbon storage accounts for just 5% of cumulative mitigation (Fig. 2), reflecting the fact that 65% of harvested biomass immediately goes to bioelectricity generation (Table 1). Respective figures for the *Hierarchical* wood use strategy are 16% and 17% for BECCS and HWP carbon storage (Fig. 1). HWP carbon storage of 69 (53-85) Tg C by 2120 in the *Hierarchical* value chains (Supplementary Data 1) is likely to increase further following subsequent harvests and cascading use of the circa 140 Tg of wood dry matter remaining within the built environment at the end of the studied time horizon. In both *Bioenergy* and *Hierarchical* scenarios, the BECCS pool will also continue to grow as biomass and cascaded products reach their final use.

Sensitivity analysis

In the national planting program with *Hierarchical* wood use, product substitution (concrete) accounts for 0.12-0.32 Pg CO₂ (8-20%) of cumulative GHG mitigation by 2120 for *Core* and *Further Ambition* contexts (YC18), respectively. Reducing product substitution by 50% would reduce

cumulative GHG mitigation by 5% or 11% for *Core* or *Further Ambition* contexts, respectively (Supplementary Data 5). Counter-intuitively, concrete substitution makes a greater relative contribution to GHG mitigation in the *Further Ambition* context than the *Core* context, because net mitigation is lower and concrete decarbonisation lags energy decarbonisation under the *Further Ambition* decarbonisation pathway. Alternatively, introducing glulam production (substituting structural steel) alongside development of fibres to substitute oil-derived textile fibres could increase cumulative GHG mitigation achieved in 2120 by 10% or 7% for a national planting program in a *Core* or *Further Ambition* context, respectively (Supplementary Data 5). Potentially, viscose fibre could substitute cotton fibre instead of synthetic fibres, in which case one ha of cotton production could be avoided for every ha of commercial forest planted – which could lead to significant further afforestation and associated GHG mitigation overseas (beyond the scope of this study to quantify). In the pessimistic event of no deployment of CCS technology during the 100-year study time horizon, 100-yr mitigation achieved by a commercial forest planting strategy in the UK would be reduced by just 8% (*Core*) or 6% (*Further Ambition*) for *Bioenergy* wood use (Supplementary Data 7) and 6% (*Core*) or 4% (*Further Ambition*) for *Hierarchical* wood use (Supplementary Data 6), respectively. In the absence of CCS, energy and concrete substitution credits are larger than in the base case, counteracting the effects of reduced BECCS and thus reducing the sensitivity of net GHG mitigation to CCS deployment. Across all these alternative product substitutions, commercial forestry remains an effective GHG mitigation strategy, still achieving up to 162% more GHG mitigation than semi-natural conservation forestry in the worst case scenario of reduced concrete substitution.

Discussion

New evidence presented in this paper emphasises the efficacy of commercial forestry for GHG mitigation, and its resilience to future decarbonisation pathways and wood uses, highlighting the effective and reliable contribution that commercial forestry could make towards the Paris Agreement¹ even with projected decarbonisation of marginal materials and energy that are likely to

be substituted by harvested wood products in the future. These results counter the conclusions of recent studies questioning the climate credentials of commercial forestry^{6,10,45}. Our study demonstrates the importance of considering multiple stages of hierarchical wood use, considering, *inter alia*, consistent time-dependent substitution factors and CCS deployment based on published projections^{4,29}. However, we do find that at equivalent growth rates, commercial forests lag unharvested conservation forests in cumulative GHG mitigation until just before the second harvest cycle (90 years after establishment for typical UK forests).

The magnitude of GHG mitigation achieved by commercial forestry is remarkably resilient to the uses of wood and wider decarbonisation pathways over a 100-year timeframe. Indeed, across all the variables considered, it is clear that tree growth rates have the greatest influence on GHG mitigation, in line with previous studies focussed primarily on terrestrial carbon storage by forests^{46,47}. In this study, the vast majority of product substitution credits attributable to new forest planting are heavily discounted because they arise over 50 years into the future (after first main harvest) when decarbonisation projections indicate much lower emission intensities for substituted energy and materials (Supplementary Data 1). Had current substitution credits been applied throughout, the GHG mitigation achieved by commercial forests would have been considerably greater, and more sensitive to variations in wood use^{15,44,48}. Nonetheless, it remains clear that hierarchical use of timber relies on proven technologies to deliver the majority of 100-year mitigation via HWP carbon storage and displacement of mineral construction materials which are unlikely to fully decarbonise for many decades^{4,9} (Table 2), maintaining effective mitigation 100 years after first plantings (Fig. 2). Demand for wood is expected to grow as the circular bio-economy expands and new products are developed (e.g. engineered and modified timber construction products, silvi-chemicals, textiles and biocomposites)^{47,4}. Our results show that commercial forests could supply a large share of these future demands whilst delivering comparable or more long-term GHG mitigation compared with conservation forests.

Somewhat surprisingly, both *Hierarchical* and *Bioenergy* value chain GHG mitigation was robust to assumptions about CCS deployment. BECCS features prominently in many climate stabilisation scenarios^{1,4,5} but depends on commercially unproven technology⁵¹. Conservatively, our *Core* decarbonisation pathway involves widespread deployment of BECCS only after 2085, whilst our *Further Ambition* pathway assumes widespread deployment from 2050 (Table 2) – though with limited effects until the first main harvests from 2070 onwards (Fig. 2). Most climate change mitigation projections indicate a substantial role for dispatchable bioenergy (with CCS) at least up to the end of this century^{4,5,17,52}. Global requirements for primary energy from biomass to meet Paris Agreement goals range from circa 100 to 400 EJ yr⁻¹, and BECCS is expected to play an important role in achieving net zero carbon emissions^{5,51–53}. Associated global land requirements have been estimated at between 3 and 7 million km², with possible negative side effects for biodiversity and food security^{5,52,54}. The UK Climate Change Committee recommends installing circa 67 TWh of BECCS electricity generation by 2050⁵⁵. Based on our *Bioenergy* value chain, over 7 million ha of land would need to be afforested by 2070 in order to fully meet BECCS ambitions exclusively with forest harvests (excluding high-quality sawn wood) – requiring a rate of planting 4.6 times higher, and continuing 20 years longer, than the 30,000 ha yr⁻¹ over 30 years considered in our study based on UK Committee on Climate Change recommendations⁴. Although a large area, this would bring total UK forest cover to around 42%, close to the European average of 40%⁵⁶. Whilst purpose-grown bioenergy crops could deliver more rapid fossil fuel substitution using less land⁵⁵, commercial forests combine the provision of high-quality materials into the circular economy with the delivery of multiple ecosystem services^{5,20}, including medium-term climate regulation by terrestrial C storage⁵⁷ and HWP C storage in the decades before BECCS is anticipated to become widely deployed^{4,53} (Table 2). Unlike many purpose-grown bioenergy crops, Sitka spruce can also produce reliable growth on marginal land that could be spared from extensive livestock production in the UK³.

Commercial afforestation can deliver significantly greater GHG mitigation than semi-natural afforestation largely due to the higher growth rate of conifers. Commercial investment in afforestation is based on the expectation of timber harvest and, to match current timber markets in the UK and the benefit of earlier harvest of faster-growing tree species, this generally leads to the planting of conifer rather than broadleaved species. Thus, faster growing commercial forests deliver more, and longer-term, GHG mitigation than slower growing semi-natural forests. Depending on future decarbonisation and technology contexts, market demand and environmental risks, high yielding conifer forests could be harvested⁵⁸ for hierarchical wood use or for bioenergy (with CCS), or left in the ground to maximise terrestrial C storage. The latter option can be chosen late in the forestry cycle in response to relevant market, environmental and/or policy signals. Commercial forestry therefore provides a robust strategy for GHG mitigation across a wide range of future contexts, at least in temperate zones, and merits a prominent role in climate policies, including nationally determined contributions under the Paris Agreement, and the forthcoming EU Forest Strategy⁵⁸.

Our results pertain to regions with commercial forest rotations of 50 years (or less). In regions (e.g. boreal) with slower tree growth rates and longer forestry cycles, leaving wood unharvested could be a better mitigation option over the next century^{18,58,5}. We applied a 100-year cut-off to our analysis to maintain a realistic time horizon for climate policy decision-making, and to avoid deeply uncertain marginal technologies beyond this time horizon. A longer time horizon is likely to favour harvested commercial forests owing to saturating carbon sequestration in conservation forests (Fig. 2). There is some uncertainty about whether old forests may in fact continue to act as significant carbon sinks^{19,59,60}. Unexpected losses from pests, pathogens, fires, windthrow and drought-caused mortality pose an increasing risk to GHG mitigation from affected areas, but such losses are not likely to affect commercial forests more than conservation forests. In fact, active management and

periodic harvesting of commercial forests can reduce fire risks^{61,62} and safeguard carbon stocks within harvested wood products whilst climate change increases environmental risks to old forests.

Whilst results in this paper demonstrate the comparatively high long-term GHG mitigation efficacy of commercial forests compared with unharvested conservation forests, it is imperative to note that commercial and conservation forests deliver different suites of important ecosystem services and should be considered complementary and not conflicting land uses⁵. Rather than limiting the area of commercial forests in favour of semi-natural forests⁶, more emphasis should be placed on rapid deployment of both forest types, and on the cascading use of harvested wood to derive maximum economic and mitigation value. Although our modelled commercial forestry system is 100% Sitka spruce, single species forests are not the only commercial option, and there is increasing support for mixed-species conifer forests (or conifer-broadleaf mixtures), under sustainable forest management to deliver both a high yield of wood products and other ecosystem services^{20,63}. Diversification of commercial forestry could also enhance resilience to pests, diseases and climate change effects^{64,65,66}. Nabuurs et al.⁸ argue for policy changes to encourage such “climate-smart forestry”, claiming it could deliver an extra 441 Mt CO₂e yr⁻¹ mitigation across Europe by 2050. National afforestation strategies should promote a portfolio of commercial, conservation and agroforestry systems tailored to local conditions and adapted to climate change^{5,67}, in order to deliver the range of ecosystem services required by society, in addition to GHG mitigation⁶⁸. To achieve this there is a strong case to increase the 30,000 ha yr⁻¹ UK afforestation area target of the Committee on Climate Change, which is very modest in the context of international ambitions for increased tree canopy cover, such as the 0.9 billion hectares identified by Bastin et al.⁶⁹, or indeed the EU Forest Strategy objective to plant 3 billion trees by 2030⁵⁸. Successful forest policy will also need to integrate social outcomes, and engage local stakeholders in strategic planning⁶³.

We conclude that fast growing tree species should be a major component of national afforestation strategies in order to achieve ambitious GHG mitigation targets. Commercial investment will favour

such high production forests of species that produce timber matching market demand. The GHG mitigation potential of commercial forestry is robust against future decarbonisation scenarios, and will continue to deliver mitigation well beyond the 100-yr time frame considered in this study, when conservation systems have reached their peak capacity. Furthermore, commercial forestry can deliver similar long-term mitigation when wood is used in either hierarchical or bioenergy value chains, potentially contributing to future circular bioeconomy, energy security and carbon removal objectives as required at the time of harvest. However, it takes time to establish large areas of new forest. In addition to the time-lag between forest establishment and GHG mitigation, especially pronounced when considering mitigation from commercial forest hierarchical value chains, there is a time lag in implementation of national afforestation policies owing to constrained planting rates⁷¹. Whilst sustainable intensification³ and curtailed demand for livestock products^{5,31,53} are projected to free up substantial land for afforestation in the UK and elsewhere over coming decades, our results reveal the urgency of commencing a programme of large-scale tree planting if afforestation is to significantly contribute to Paris Agreement targets for the second half of this century^{1,71}.

Methods (1560 text only; tables 517; table/figure headings 323)

Aim & scenarios

This study seeks to determine the most effective afforestation strategy for achieving climate change mitigation in a temperate region. Specifically, it aims to generate new evidence on the comparative long-term (100 year) GHG mitigation efficacy resulting from the establishment of commercial forests and conservation forests on grassland in the UK (baseline). We modelled 33 scenarios representing common temperate commercial and conservation forestry typologies, tree growth rates ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$: “yield class”) and HWP value chains (Table 1). Rationale for scenario development commensurate with study objectives and conclusions is fully elaborated in S1, and summarised below.

Table 1 – Evaluated forest value chain scenarios, comprising commercial and conservation forests with a mix of conifer and broadleaf species. Harvested wood product (HWP) carbon storage, and greenhouse gas emission displacement via product substitution, depend on choice of *Hierarchical* or *Bioenergy* wood use strategies, and the degree of decarbonisation in the wider economy – defined by UK Committee on Climate Change “*Core*” and “*Further Ambition*” pathways (see Table 2, S1 and Supplementary Data 1).

Forest value chain scenario	Species mix ²³	Yield class ²⁴ (m ³ ha ⁻¹ yr ⁻¹ growth)	Harvested thinnings, 1 st use	Main harvest, 1 st use	HWP 2 nd & 3 rd uses	Decarbonisation context
Commercial forest- <i>Hierarchical</i> (<i>Core</i>)	100% Sitka spruce (<i>Picea sitchensis</i>)	Default 18 ^{24,25}	30% boards,	18% carcassing,	44% boards,	<i>Core</i> (see Table 2)
Commercial forest- <i>Hierarchical</i> (<i>Further Ambition</i>)		Range 12-24	33% short-lived products, 37% electricity	23% boards, 33% short-lived products, 17% electricity, 7% heat	25% electricity, 14% incineration, 1% landfill, 2% paper production, 14% mulch	
Commercial forest- <i>Bioenergy</i> (<i>Core</i>)	100% Sitka spruce (<i>Picea sitchensis</i>)	Default 18 ^{24,25}	100% electricity	18% carcassing,	48% electricity,	<i>Core</i> (see Table 2)
Commercial forest- <i>Bioenergy</i> (<i>Further Ambition</i>)		Range 12-24		17% short-lived products, 65% electricity	19% incineration, 1% landfill, 32% mulch	
Semi-natural broadleaf conservation forest	40% silver birch (<i>Betula pendula</i>), 40% rowan (<i>Sorbus aucuparia</i>), 20% pedunculated oak (<i>Quercus robur</i>)	Default 4 ^{24,26} Range 2-6	NA	NA	NA	
Mixed conservation forest	10-30% Sitka spruce, 10-30% Corsican pine (<i>Pinus nigra</i> ssp. <i>Laricio</i>), 5-15% Douglas fir (<i>Pseudotsuga menziesii</i>), 10-30% silver birch, 10-30% rowan, 5-15% pedunculated oak	Default 11 ^{24,26} Range 7.5-14.5	NA	NA	NA	
Unharvested conifer	40% Sitka spruce, 40% Corsican	Default 18 ^{24,25}	NA	NA	NA	

conservation forest	pine, 20% Douglas fir	Range 12-24
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Commercial forestry was based on conifer (Sitka spruce) forests, with a conservative default yield class (YC) of $18 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (range 12-24)²⁴, with intermediate forest thinning in year 21 of each rotation when 36% of the harvestable material is removed in HWP. Clear-fell harvest is implemented in year 50 (a conservative average for this species in UK conditions), followed by immediate replanting, enabling a second clear-fell in year 100. Non-merchantable biomass was assumed to be left to decay on site. Two predominant types of wood value chain were modelled, representing different wood use strategies: (i) a *Hierarchical* wood use strategy, with wood flow based on UK statistics and data from mills that maximise the value of wood products, and embodying the waste hierarchy²⁷ (Fig. 3), i.e. wood is subject to cascading use via a prioritised order: durable wood product manufacturing, extending service life times, re-use, recycling, bioenergy generation, and disposal²⁸; (ii) a *Bioenergy* wood use strategy, in which high-value sawn wood is used in the construction sector (as in the Hierarchical wood use strategy), but all other wood, and end-of-life construction wood, is used for electricity generation to contribute to bioenergy targets⁴. Dynamic assessment of incurred and avoided emissions during future wood harvest and processing operations, construction material and fossil fuel substitution, and bioenergy carbon capture & storage (BECCS) deployment, was applied based on decadal progression of *marginal* technologies in line with two sets of projections made by the UK Committee on Climate Change: “*Core*” and “*Further Ambition*” pathways⁴ – detailed in Table 2. These pathways involve differing rates of fossil fuel replacement by low carbon and renewable technologies, and differing rates of carbon capture and storage (CCS) implementation across industry sectors, representing different future contexts in which forestry value chains could exist. Note that fossil fuels remain the marginal source of dispatchable energy generation well into the future, especially for industrial heat, despite renewable

energy technologies predominating²⁹. Very few studies to date consider the timing of GHG emissions⁶³ and avoided GHG emissions in this way.

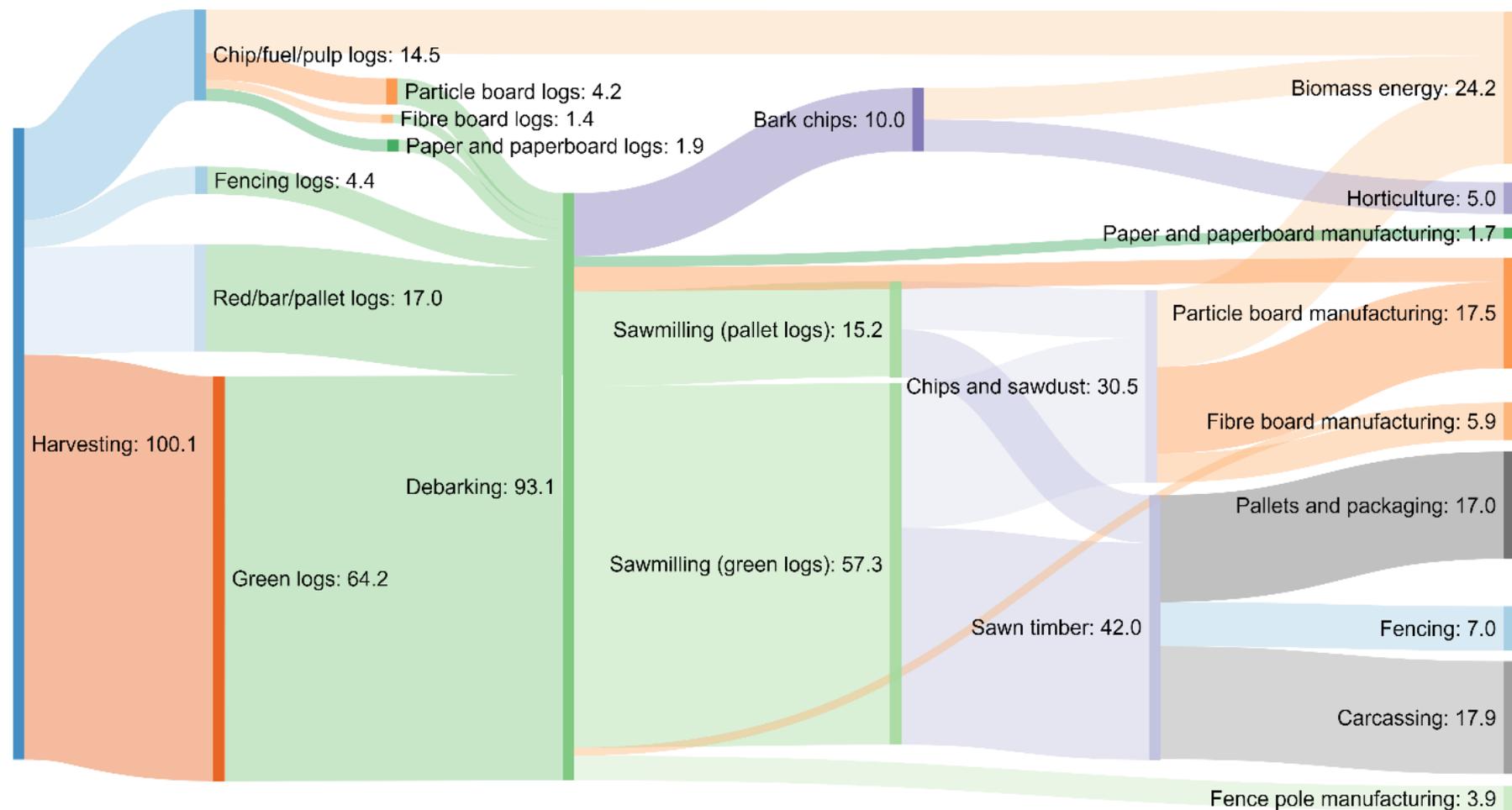


Figure 3 - Biogenic carbon material flow from wood harvest going to *Hierarchical* use. Units are percentages of original harvest calculated in the CBM model³⁰. ‘Red’ and ‘Green’ refer to a quality threshold of acceptable straightness, taper and knots in a log accepted by sawmills, with ‘Green’ being the higher quality. Carcassing refers to construction grade sawn wood. Data sources include wood harvest volumes from the CBM-CFS3 model, saw-mill product breakouts, UK statistics on wood waste and harvested wood product decay functions, elaborated in relevant sections of Methods and in S1.

Forests may be established for varying conservation objectives, from habitat provisioning to terrestrial carbon storage^{5,7}. We represented a diverse range of possible conservation (unharvested) forest types based on different ratios of conifer (Sitka spruce, Corsican pine, Douglas fir) to broadleaf (silver birch, rowan, oak) trees (Table 1). The 100%-conifer conservation forest (YC 18) represents carbon sequestration prioritisation and provides an unharvested comparator for the equal-YC commercial forests. Meanwhile, the semi-natural 100%-broadleaf forest represents prioritisation of habitat provisioning, and delivers much lower rates of carbon sequestration owing to slow growth (YC 4) – representative of broadleaf forests grown on lower grade land in UK²⁴. Among a range of intermediate conservation forests, the default conservation comparator, delivering a mix of carbon sequestration and habitat provisioning, was a 50:50 conifer:broadleaf mix with YC 11. Yield classes for 100% Sitka spruce (18) and 100% broadleaved (4) are for the same site conditions.

Scenarios were analysed at two scales: 1 ha planted in 2020, and a national scenario of 30,000 ha yr⁻¹ planted from 2020 to 2050 as per UK climate recommendations^{4,17} on 900,000 ha of lower-quality grassland that could be taken out of livestock production through intensification³ and/or reduced market demand for livestock products^{4,31}. We assume that social and political change will lead to sufficient land being available, therefore, avoided GHG emissions from reduced livestock production or additional emissions from livestock production displacement are not considered. Analyses were cut off at 2120 in both scenarios, representing a maximum time horizon for climate policy. Climate change impacts on forest productivity were not included due to the already high complexity of the scenarios.

Table 2 – Characterisation of marginal incurred or substituted processes accounted for in dynamic life cycle assessment of forestry value chains, evolving through five time periods over the time horizon considered. Marginal energy sources and technology deployment reflect *Core* and *Further Ambition* decarbonisation pathways projected by the UK Committee on Climate Change⁴, long-term marginal electricity supply mixes proposed for life cycle assessment modelling³², and a road map for decarbonisation of the UK cement industry³³.

Pathway	Energy source or technology	Time period				
		2020-2029	2030-2039	2040-2049	2050-2085	2085-2120
Core						
	Marginal industrial heating fuel	Coal	Coal	Coal	90% coal, 10% biomass	15% hydrogen, 85% biomass
	Marginal electricity generation	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas
	CCS deployment on biomass & fossil fuel electricity (%)	0%	10%	20%	50%	100%
	CCS deployment on biomass & fossil fuel heat (%)	0%	0%	0%	0%	45%
	CCS deployment on calcination in cement production (%)	NA (no sawn wood production, therefore no concrete substitution)			0%	10%
	CCS deployment on wood panel production emissions - heat plus ammonia/resin production (%)	0%	0%	0%	0%	45%
	HGV electrification/hydrogen fuel (%)	0%	0%	0%	13%	100%
Further Ambition						
	Marginal industrial heating fuel	Coal	Coal	40% coal, 60% biomass	15% coal, 85% biomass	15% hydrogen, 85% biomass
	Marginal electricity generation	Natural gas	Natural gas	Natural gas	Solar PV	Solar PV
	CCS deployment on biomass & fossil fuel electricity (%)	0%	50%	100%	100%	100%
	CCS deployment on biomass & fossil fuel heat (%)	0%	0%	45%	90%	100%
	CCS deployment on calcination in cement production (%)	NA (no sawn wood production, therefore no concrete substitution)			90%	100%
	CCS deployment on wood panel production emissions - heat plus ammonia/resin production (%)	0%	0%	45%	90%	100%
	HGV electrification/hydrogen fuel (%)	0%	0%	45%	90%	100%

Life cycle assessment goal & scope

We applied dynamic consequential LCA²² to evaluate the GHG emissions balance of afforesting one hectare of grassland in the UK, accounting for terrestrial (soil and biomass) carbon storage, HWP carbon storage, substitution of materials and fossil fuels, and long-term sequestration of biogenic carbon via future deployment of BECCS, over a 100-year period. Expanded LCA boundaries (Fig. 4) encompassed: (i) land use change due to afforestation on spared agricultural grassland; (ii) forest establishment; (iii) forest growth; (iv) forestry operations; (v) debarking; (vi) sawmilling (including drying, planing and chemical treatment); (vii) wood panel production; (viii) paper and paperboard production; (ix) bioenergy generation, including BECCS; (x) credits for avoided use of fossil fuels (substituted energy generation and mineral construction material production); (xi) carbon storage in HWPs related to 'decay' (retiral) functions³⁷, and (xii) recycling and disposal of retired HWPs, including via (ix). 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 2 & Supplementary Data 3, with an example for the *Hierarchical* wood use value chain in Supplementary Table 1 (S1). Material flows were derived using UK data from a combination of forest carbon modelling³⁴, harvest data from over 2,000 ha of commercially managed forests, data from a commercial sawmill that maximises sawn-wood output, national recycling data³⁵ and timber-use statistics³⁶ – elaborated in S1. Given the focus of this paper on GHG mitigation, only the global warming potential (GWP₁₀₀) impact category was evaluated, expressed as kg CO₂e. We discuss limitations later.

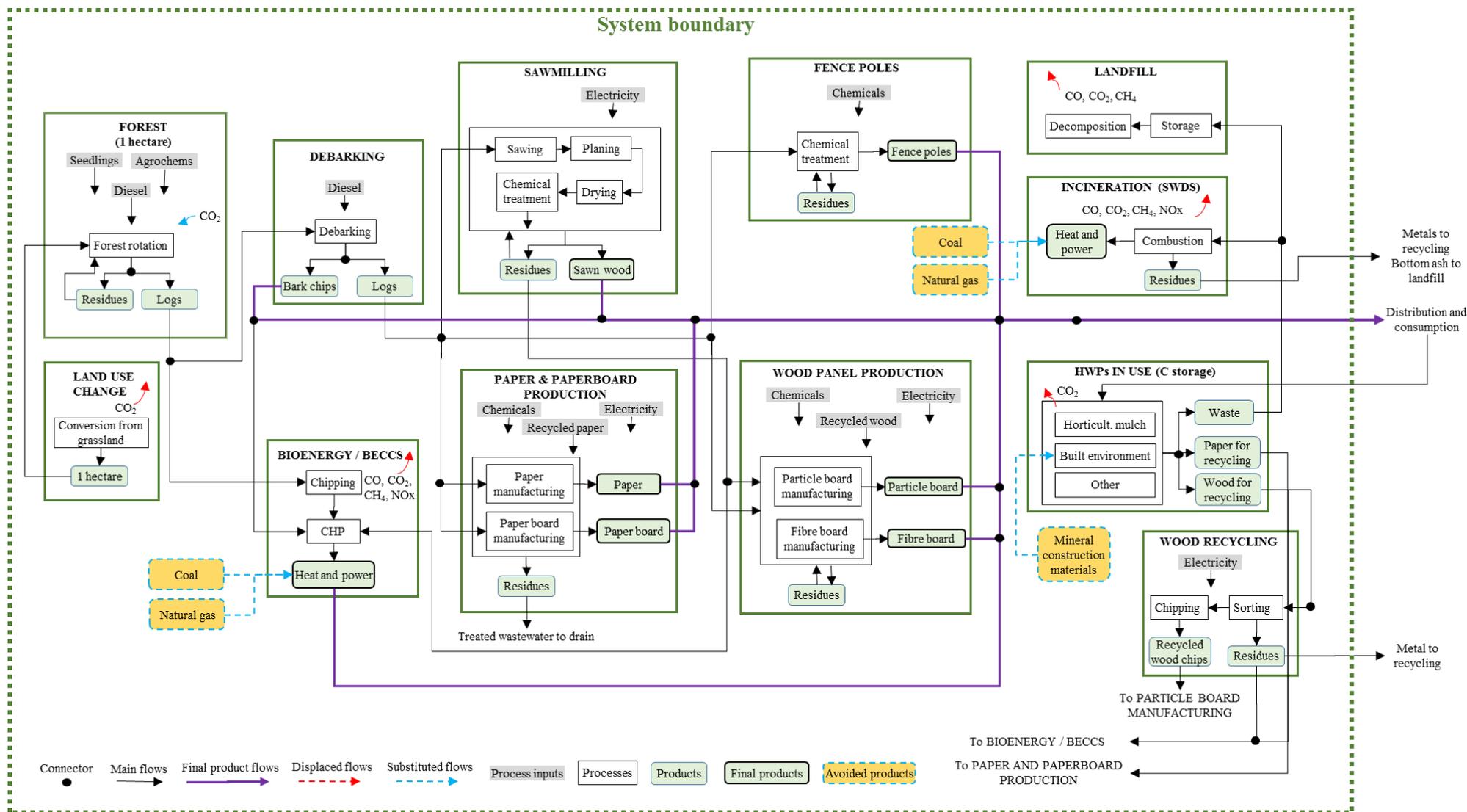


Figure 4 – Main processes and inputs accounted for during primary, secondary and end-of-life uses of harvested wood products (HWP) within consequential life cycle assessment boundaries. Main processes arise during each stage of the value chain, including: forest establishment (and associated land use change from grassland); wood processing (debarking, milling, wood panel and paper production from primary and secondary wood flows); storage of carbon in HWP (primary and secondary wood

products); recycling and disposal of HWP (primary and secondary wood products), including incineration (with energy recovery) and landfill; bioenergy generation (with bioenergy carbon capture & storage (BECCS) in later years); substitution of fossil fuels for energy generation; substitution of mineral construction materials.

Terrestrial carbon

Forest growth, decay and harvest volumes were calculated using the Carbon Budget Model for the Canadian Forest Sector (CBM-CFS3)³⁴, because it complies with the Intergovernmental Panel on Climate Change guidance³⁷, was developed for similar climate conditions to the UK, and provides default volume to biomass equations for Sitka spruce and Douglas fir (which are native to Canada), and genus equations for the other species in this study. It was parameterised using best-fit yield tables from Forest Yield, the standard yield model for forest management in the UK²⁴. For conservation forests, aggregate group YCs were calculated based on weighted mean YCs for the species mixes described in Table 1. CBM-CFS3 outputs include annual soil and biomass carbon stocks and flows of carbon in harvested timber. Harvested carbon from CBM-CFS3 was converted to merchantable volume based on a 49.95% carbon content in wood dry matter³⁸. Detailed material flows are presented in Supplementary Data 2 and Fig. 3 for the *Hierarchical* wood use strategy, and in Supplementary Data 3 for the *Bioenergy* wood use strategy.

Process emissions and carbon storage

All emissions associated with the production and transport of forestry inputs and all primary and secondary wood processing phases were extracted from Ecoinvent v.3.5³⁹ using OpenLCA v1.7.4 and scaled in Microsoft Excel using the HWP material flow (Supplementary Data 2 & Supplementary Data 3). Emissions from landfill disposal were calculated according to the IPCC First Order Decay (FOD) method³⁷. Retirement rates of HWP were calculated according to IPCC methods⁴⁰, with modified decay factors⁴¹. As products retire from the HWP carbon pool, they are recycled or disposed of (by incineration or landfill) in proportions calculated according to UK recycling statistics³⁵ (Fig. 3). Retired tertiary products (i.e. products that have already been recycled once) are conservatively assumed to be disposed of. Horticultural mulch is assumed to decay at a rate similar to composted municipal solid waste⁴². Wood fuel is not included in the HWP carbon pools owing to rapid oxidation; return of this biogenic carbon to the atmosphere from the forest ecosystem is represented in the

deficit between ecosystem carbon loss at the point of harvest, HWP carbon storage gain, and loss from recycled materials.

Substitution credits

Fuel-to-energy conversion factors (for coal, natural gas and wood chips) were taken from Ecoinvent unit processes³⁹ to calculate fossil fuel substitution by dedicated biomass energy generation and incineration with energy recovery for wood waste. Emission avoidance through substitution of mineral construction materials was estimated by translating the final mass of construction timber (150 tonnes at 20% moisture per ha thinned forest) into an area of timber-framed wall using industry standard design: 0.0175 m³ of timber per 1 m² wall (BRE IMPACT database⁴³ accessed via eToolLCD[®] software – Supplementary Table 1). 1 m² of timber frame wall replaces 1 m² of single skin, 140 mm concrete block and mortar (sand:cement ratio 10:3) wall with 10-mm jointing in typical UK house construction. Avoided emissions were then calculated using emission factors from Ecoinvent for the manufacture of concrete blocks, sand and cement. Projected decarbonisation of the cement sector is represented in *Core* and *Further Ambition* contexts (Table 2). Assumptions about substitution are elaborated in S1, and reflect marginal changes associated with additional wood supply (e.g. an increase in timber frame construction, hence substitution of mineral construction materials). CCS deployment is gradually increased on a decadal basis, at a faster rate for the *Further Ambition* context, and applied equally to marginal (substituted) fossil fuel and wood electricity generation (Table 2 and S1).

Sensitivity analysis

Recent papers have highlighted the uncertain assumptions inherent in wood product substitution estimates^{15,44}. This study presents a methodological approach that addresses key limitations by considering different value chains and dynamic product counterfactuals under different decarbonisation pathways. To further explore the complexity and uncertainty of future wood value chains, we modelled alternative product substitution assumptions to assess the sensitivity of model

results to product substitution. Details of these are provided in S1 and Supplementary Data 5, summarised in Table 3. We also modelled an alternative decarbonisation scenario in which there is no deployment of CCS during the study time frame (Supplementary Data 6 and Supplementary Data 7), to evaluate the dependency of results on this technology.

Table 3 – Summary of product substitution sensitivity tests (Alternative scenarios) performed on main results (Base case scenario). “Carcassing” refers to sawn structural timber.

	Base case scenario		Alternative scenario	
Sensitivity test	Product	Substituted product	Product	Substituted product
Reduced substitution	Carcassing (100% product substitution)	Concrete	Carcassing (50% product substitution, 50% no substitution)	Concrete
Increased substitution	Pallets and packaging Wood panels	None None	Glulam beam Viscose fibre	Structural steel beam Fibres from oil derivatives (PET, recycled PET, polyamides) ⁶⁹
Zero CCS deployment	BECCS Carcassing Wood panels (with CCS)	Fossil fuels (with CCS) Concrete (with CCS) None	Bioenergy (no CCS) Carcassing Wood panels (no CCS)	Fossil fuels (no CCS) Concrete (no CCS) None

Data availability

The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information and data files: S1 for elaboration of scenarios and assumptions, Supplementary Data 1 for projected energy and product emission intensities, Supplementary Data 2 & Supplementary Data 3 for *Hierarchical* and *Bioenergy* wood use strategies, respectively, Supplementary Data 4 for graphs, Supplementary Data 5 for sensitivity analyses on substitution

effects, Supplementary Data 6 & Supplementary Data 7 for full *Hierarchical* and *Bioenergy* inventory results, respectively, without future deployment of carbon capture & storage (sensitivity analyses). Background data were generated using the publicly-available CBM-CFS3 model and extracted from the Ecoinvent v.3.5 database. All subsequent calculations were undertaken using standard MS Excel functions.

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Author Contributions

EF undertook data collection and analysis, and drafted the manuscript. DS and JH informed study design and edited the manuscript. CD assisted with CBM and wood product modelling and edited the manuscript.

Competing Interests statement

The authors declare no competing interests.

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