Linking construction timber carbon storage with land use and forestry management practices

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Abstract. Consequential life cycle assessment was applied to forestry systems to evaluate the environmental balance of expanding forestry onto marginal agricultural land to supply more timber for the built environment, accounting for land use effects and product substitution. Forestry expansion to supply timber buildings could mitigate UK greenhouse gas (GHG) emissions by 2.4 Gg CO₂ eq. per ha of forest over 100 years, though net mitigation could be halved if beef production were displaced to Brazil. Forest thinning increases wood yields and percentage conversion of harvested wood to construction sawnwood, resulting in 5% greater net GHG mitigation compared with unthinned systems. Optimising the environmental sustainability of construction timber value chains in a circular, bio-based economy will require holistic accounting of land use (change), forestry management and complex flows of wood.

1. Introduction
Forests sequester and store carbon (C) from the air as they grow, and harvested wood products (HWPs) can continue to store carbon and/or displace fossil fuel (FF) combustion for energy generation or displace production of mineral construction materials, further mitigating GHG emissions. Life cycle assessment (LCA) studies have shown that timber use in buildings can reduce embodied GHG emissions due to displacement of mineral materials (Hafner and Schafer, 2017, Pajchrowski et. al., 2014) and the UK Committee on Climate Change (CCC) has recently recommended that by 2025 all new housing should be timber framed (CCC, 2019). The construction sector already accounts for 61% of UK timber consumption and there is no plan to address how an increased demand will be met. The UK imports 66% of consumed timber (98% of its sawn softwood) (TTF, 2017) and whilst UK (and global) timber consumption is rising (FAO, 2017), projected UK timber supply is in decline (FC, 2016). The UK is failing to achieve even half of its 20,000 ha/year planting target (CCC, 2018). Land for afforestation could be released through increased productivity of existing farmland and forests (CCC, 2018; Lamb et al., 2016) and reduced meat consumption. However, displacement of farming activities (e.g. beef production) could also lead to detrimental indirect land use change elsewhere (Searchinger et. al., 2018). In commercial plantations, young trees may be thinned; i.e. a proportion of trees removed in order to create more growing space for the remaining trees, with the aim of increasing the yield of usable timber over the life of the crop (FC, 2015). Thinning can improve stand quality and reduce the time taken for trees to reach valuable sawlog size (Hibberd, 1991), but incurs additional costs. Decisions on thinning depend on current and anticipated timber markets, stand quality, risk of wind damage and costs (FC, 2015). Logs are sorted into different product quality categories during harvesting, with the best logs ultimately ending up as higher value sawn products with longer product lives. Therefore, thinning could increase the size of the harvested wood product (HWP) carbon pool and potentially improve the overall environmental benefit delivered per hectare of managed forest. However, to our knowledge there have been no LCA studies quantifying the environmental impact of shifts in HWP value chains as a result of thinning.

The main study objective is to evaluate the environmental balance of expanding forestry onto marginal agricultural land in the UK to provide more timber for the built environment, accounting for land use effects and product substitution throughout extended wood value chains. A secondary objective...
is to evaluate the impact of forest thinning on production of higher value timber products, and on the environmental balance.

2. Materials and Methods

2.1 Scope and boundary definition
Given the significant GHG mitigation potential of wood use as construction material and for bioenergy through substitution of mineral building materials and FFs, respectively, as well as the potential impact of direct and indirect land use change (LUC), we applied a consequential LCA approach (Weidema, Ekvall, & Heijungs, 2009) (Figure 1) to evaluate environmental impact. The functional unit is the total production from the reference flow of one hectare of land in the UK, converted from grassland used for low intensity beef production, to forest land, planted with 100% Sitka spruce and managed under a clear-fell system on a 50-year rotation. A 100-year study period was used to account for two forest rotations. Expanded boundaries encompassed: (i) LUC due to afforestation, and displacement of extensive beef production; (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) biomass energy generation; (x) credits for avoided use of FFs (energy generation and construction materials); (xi) carbon storage (and ‘decay’) in HWPs and (xiii) recycling and disposal of ‘decayed’ HWPs. The production and transport of all material and energy inputs were accounted for, as were the construction or manufacture of infrastructure and capital equipment.

2.2 Life cycle inventory
This study assesses a simplified timber value chain in which production of construction-grade sawn timber is maximised. Forest growth, decay and harvesting volumes were calculated using CBM-CFS3 carbon model (Kull et al., 2016), assuming ‘average’ soil type. We input to that model the best fit yield tables from Forest Yield (a PC-based yield model for forest management in Britain) (Matthews et al., 2016), specifying 100% Sitka spruce and yield class 18. The thinned scenario assumes a single thinning in year 21 of each rotation, with 36% of the ‘harvestable’ material (i.e. logs only, not branches, leaves or stumps) being removed for HWPs). How CBM-CFS3 implements a thinning disturbance is to reduce the biomass components and transferring carbon out of the ecosystem or to the dead organic matter as appropriate. Then the next increments are assigned to the reduced biomass so in effect the same gross volume is eventually achieved. Clear-fell harvest is implemented in year 50 (a conservative average for this species in UK conditions), followed by immediate replanting, to enable a second clear-fell in year 100. Non-merchantable biomass was assumed to be left to decay on site. The carbon modelling results provide the quantity and year of harvested timber as well as the net ecosystem C change over the 100 year period.

The quantity of harvested material was converted into a product breakout (at the forest gate) using operational data from the forest management company Gresham House (GH) for 2,000 ha of commercial Sitka spruce plantations across the UK (47% unthinned, 54% thinned) (Table 1). The GH data show that thinned forest stands had 26% higher merchantable volume by the time of the final harvest (excluding thinning harvests) compared with unthinned stands (Table 1). The thinned stands also had greater conversion of harvested trees to higher value log products (‘greens’) (64% vs 57% of logs), with fewer logs going to chip/fuel/pulpwood (15% vs 21%) (see Table 1 for product definitions). Downstream product breakouts were calculated from data provided by the sawmills of James Jones & Sons Ltd (JJ) and from UK timber-use statistics (Forestry Commission, 2017). Detailed material flow tables were produced, along with Sankey diagrams (an example is provided in Figure 2). Around 40% of main crop harvests end up in construction materials (carcassing and wood panels) for both unthinned and thinned systems. However, a greater proportion of carcassing materials is produced from the thinned system (17.9% vs 15.9%). Conversion of harvested carbon from CBM-CFS3 to merchantable volume was
Figure 1. Main processes and inputs accounted for within expanded consequential life cycle assessment boundaries, including: storage of C in HWPs, recycling and disposal of HWPs; substitution of fossil fuels for energy production; substitution of mineral building materials.
calculated assuming 49.95% C content of dry wood, and the wood density factor 1.08 m³/tonne assuming 47% moisture content.

**Table 1.** Product break out from Sitka spruce stands (main crop harvest), listed in order of value. ‘Red’ and ‘Green’ refer to a threshold of acceptable straightness, taper and knots in a log, with ‘Green’ being the higher quality. Source: GH. Thinnings data are not collected by GH so an equal split between ‘chip’, ‘fuel’ and ‘fence pole’ logs is assumed. Merchantable volume is per clear fell harvest.

| Log quality categories (from low to high, left to right) | Merchantable volume m³/ha |
|--------------------------------------------------------|---------------------------|
| Chip/Fuel/Pulp | Fence pole | Red | Bar/Pallet | Green | |
| **Unthinned (main crop)** | | | | | |
| 21% | 5% | 2% | 15% | 57% | 499 |
| **Thinned (main crop)** | | | | | |
| 15% | 4% | 2% | 15% | 64% | 630 |
| **‘Thinnings’** | | | | | |
| 67% | 33% | 0% | 0% | 0% | unknown |

**Figure 2.** Biogenic carbon material flow of main crop wood harvest (from an unthinned forest). Units are percentages of original harvest. (A rounding error is present in the harvesting total.)

... Table 2 summarises the main inputs and outputs along the value chain life cycle stages considered in the LCA. Input and output data were extracted from unit processes in Ecoinvent v.3.5, using OpenLCA v1.7.4 for all timber processing phases and scaled up in Microsoft Excel using the HWP material flow. Possible LUC consequences were modelled by accounting for displacement of beef previously produced on land areas converted to forest according to simple scenarios: intensification of existing UK beef production systems (Scenario 1), or expansion of beef production in Brazil, driving indirect deforestation (IPCC, 2006) (Scenario 2). Changes in direct emissions from beef rearing were also accounted for based on intensive UK and average Brazilian beef production footprints (Styles et al., 2018).

... The rate of ‘decay’ of the HWPs is calculated according to IPCC methods (IPCC, 2006). As products ‘decay’ from the HWP C pool, they are recycled or disposed of (by incineration or landfill) in proportions calculated from Defra, (2018) (using 2016 data), respectively. Note that almost 100% of paper and paperboard is recovered and 80% of wood products are recovered (16% to biomass energy). All ‘decay’ of tertiary products is assumed to be disposed of. Horticultural mulch is assumed to decay at a rate similar to composted municipal solid waste (Bruun et al., 2006) since no data could be found on the decay rate of tree bark. Wood fuel is not included in the HWP C pools owing to rapid oxidation.
All biogenic C emissions from oxidation of wood at ‘end of life’ is assumed to be zero (since the sequestration of this C is not accounted for in the net forest C sequestration).

... All burdens associated with production and transport of inputs, as well as for all timber processing phases, were extracted from Ecoinvent v.3.5 (Wernet et al., 2016) using OpenLCA v1.7.4. Emissions from landfill disposal were calculated according to the IPCC First Order Decay (FOD) method (IPCC, 2006). Fuel-to-energy conversions factors (for natural gas and wood chips) from Ecoinvent unit processes were used to calculate fossil fuel substitution by biomass energy and wood waste incineration. Substituted FF is assumed to be natural gas, given a trend towards greener energy production and given the substitution occurs 21 to 100 years in the future.

In the absence of high quality data on direct product substitution ratios, preliminary estimates of the burdens avoided through substitution of mineral construction materials were made by first translating the final mass of construction timber per ha (129 and 150 tonnes per ha (20% moisture), for unthinned and thinned forests, respectively) into an equivalent area of timber-framed wall using industry standard design (0.0175 m$^3$ of timber per 1 m$^2$ wall). 1 m$^2$ of timber frame wall was assumed to replace 1 m$^2$ of single skin, 140 mm concrete block and mortar wall (typical of a UK house). This enabled avoided burdens to be calculated, using emissions factors from Ecoinvent for the manufacture of concrete blocks, sand and cement, scaled to the quantity of materials used per 1 m$^2$ of concrete block and mortar wall. To estimate the area of forest required to supply a prescribed number of houses, data on the volume of timber contained in a typical timber framed house was used (6 m$^3$ in the timber frame) (Suttie et al., 2009).

Table 2. Inventory of key inputs and outputs for processes considered along the life cycle of forestry value chains derived from unthinned and thinned forest systems over 100 years. Emissions factors (EF) and their sources are indicated. FRDP is fossil resource depletion potential and GWP is global warming potential.

| Process stage | Input/output/process | Activity | data source | Units | Unthinned In | Unthinned Out | Thinned In | Thinned Out | EFs | EF source |
|---------------|----------------------|----------|-------------|-------|--------------|--------------|------------|------------|-----|-----------|
| Site establishment | Land | ha | Expert estimate | 1 | 1 | | | | FRDP | IPCC 2006 |
| | Excavator (diesel use) | GH | Industry recommended | 30 | 78 | 784 | 56 | Ecoinvent |
| | Herbicide (glyphosphate) | kg | Industry recommended | 1 | 1 | 941 | 65 | Ecoinvent |
| | Planting (1&2) | GH | Industry recommended | 50,000 | 50,000 | 1 | 0 | Ecoinvent |
| | Forest management | GH | Industry recommended | 2 | 2 | 646 | 46 | Ecoinvent |
| | Harvester (diesel use) | GH | Industry recommended | 64 | 78 | 784 | 56 | Ecoinvent |
| | Forwarder (diesel use) | GH | Industry recommended | 64 | 78 | 646 | 46 | Ecoinvent |
| | Forest growth | Harvested wood | CBM-CFS3, GH | m$^3$ | 1,321 | 1,426 | IPCC 2006 |
| | | Sawmill residues | CBM-CFS3, GH | kg | 222,077 | 206,928 | IPCC 2006 |
| | Transport (forest to processor) | >32 t truck, EURO6 | t.km | 2,823 | 3,046 | Ecoinvent |
| | Debarking | Harvested wood | CBM, GH | m$^3$ | 1,187 | 1,310 | IPCC 2006 |
| | | Lubricating oil | CBM, GH | kg | 1,595 | 1,543 | IPCC 2006 |
| | | bark chips | CBM, GH | kg | 1,768 | 1,060 | IPCC 2006 |
| | | Debarked wood | CBM, GH | m$^3$ | 1,768 | 1,060 | IPCC 2006 |
| | Sawing | Diesel (internal transport) | Ecoinvent | MJ | 13,122 | 14,952 | IPCC 2006 |
| | | Electricity | Ecoinvent | kWh | 8,775 | 9,999 | IPCC 2006 |
| | | Lubricating oil | Ecoinvent | kg | 48 | 54 | IPCC 2006 |
| | | Debarked wood | CBM-CFS3, GH | kg | 1,730 | 1,730 | IPCC 2006 |
| | | Sawmill residues | IH&S | kg | 170,307 | 192,502 | IPCC 2006 |
| Process stage | Input/output/process Activity | data source | Units | In | Out | Thinned | EFs | EF source |
|---------------|------------------------------|-------------|-------|----|-----|---------|-----|----------|
|                 | Drying (of sawn timber) | | | | | | | |
|                 | Electricity Sawnwood | Ecoinvent | kWh | 8,384 | 502 | 9,553 | 572 | Ecoinvent |
|                 | Sawnwood - dried (u=20%) | | | | | | | |
|                 | EFs | | | | | | | |
|                 | FRDP | | | | | | | |
|                 | GWP | | | | | | | |
|                 | Planing | | | | | | | |
|                 | Electricity Sawnwood (carcassing) dried (u=20%) | | | | | | | |
|                 | EFs | | | | | | | |
|                 | FRDP | | | | | | | |
|                 | GWP | | | | | | | |
|                 | Sawnwood (carcassing) planed | | | | | | | |
|                 | Sawmill residues | | | | | | | |
|                 | Chemical treatment | | | | | | | |
|                 | Electricity | | | | | | | |
|                 | Wood preservative Sawnwood (fencing) dried (u=20%) | | | | | | | |
|                 | EFs | | | | | | | |
|                 | FRDP | | | | | | | |
|                 | GWP | | | | | | | |
|                 | Debarked wood (fence poles) preserved wood | | | | | | | |
|                 | Sawmill residues | | | | | | | |
|                 | Particle board production | | | | | | | |
|                 | Electricity | | | | | | | |
|                 | Heat | | | | | | | |
|                 | Resin | | | | | | | |
|                 | Debarked wood (chip) | | | | | | | |
|                 | Sawmill residues | | | | | | | |
|                 | Recycled wood | | | | | | | |
|                 | Particle board | | | | | | | |
|                 | Fibre board production | | | | | | | |
|                 | Electricity | | | | | | | |
|                 | Heat | | | | | | | |
|                 | Debarred wood (chip) | | | | | | | |
|                 | Sawmill residues | | | | | | | |
|                 | Fibre board | | | | | | | |
|                 | Woodchip production (for biomass energy) | | | | | | | |
|                 | Electricity | | | | | | | |
|                 | Lubricating oil | | | | | | | |
|                 | Harvested wood - 'fuel' | | | | | | | |
|                 | Recycled wood - 'biomass' | | | | | | | |
|                 | Wood chips | | | | | | | |
|                 | Biomass energy | | | | | | | |
|                 | Electricity | | | | | | | |
|                 | Wood chips | | | | | | | |
|                 | Bark chips | | | | | | | |
|                 | Sawmill residues | | | | | | | |
|                 | Heat | | | | | | | |
|                 | Graphics paper production | | | | | | | |
|                 | Electricity | | | | | | | |
|                 | Debarked wood - 'pulp' | | | | | | | |
|                 | Paper, newsprint, virgin | | | | | | | |
|                 | Graphics paper production (recycled) | | | | | | | |
|                 | Electricity | | | | | | | |
|                 | Recycled paper | | | | | | | |
|                 | Paper, newsprint, recycled | | | | | | | |
|                 | Paperboard production | | | | | | | |
|                 | Electricity | | | | | | | |
|                 | Debarked wood - 'pulp' | | | | | | | |
|                 | Board box | | | | | | | |
|                 | HWP in use | | | | | | | |
|                 | Landfill | | | | | | | |
|                 | Waste wood | | | | | | | |
|                 | Waste paper | | | | | | | |
|                 | Incineration | | | | | | | |
|                 | Waste wood | | | | | | | |
|                 | Waste paper | | | | | | | |
### Process stage

| Activity data source | Units | Unthinned | Thinned | EFs | EF source |
|----------------------|-------|-----------|---------|-----|-----------|
| **Electricity**      |       |           |         |     |           |
|                     |       | In 157,729 | Out 21,370 | FRDP | GWP       |
| **Heat**             |       | In 182,799 | Out 24,767 |     |           |
| Avoided construction materials | 140 mm concrete block and mortar wall replaced by timber frame wall |             |         |     |           |
| Avoided FFs          |       | Industry standard | Ecoinvent |     |           |
| Avoided beef production | Low intensity beef production, UK |         |     |       |
|                       | Sc1 - high intensity production, UK |         |     |       |
|                       | Sc2 - average intensity production, Brazil |         |     |       |
|                       | Sc2 - iLUC (rainforest to grassland, Brazil) |         |     |       |

### Inputs/Outputs/Process

| FRDP (TJ eq.) | GWP (Gg CO₂ eq.) |
|---------------|------------------|
| Unthinned     | Thinned          |
| Unthinned     | Thinned          |
| -4.28         | -4.88            |
| -2.30         | -2.41            |

### Impact assessment and interpretation

Two environmental impact categories were considered in this study: global warming potential (GWP), expressed as kg CO₂ eq; fossil resource depletion potential (FRDP), expressed in MJ. Summary results are presented in the main body of the paper.

### Results and discussion

Afforestation of 1 ha of grassland to produce timber for construction offers significant CO₂ mitigation potential, for both unthinned and thinned forest management scenarios, with FF displacement of 4.3 TJ and 4.9 TJ, and GWP mitigation of 2.3 and 2.4 Gg CO₂ eq, respectively (Table 3) over 100 years. Thinning increases GWP mitigation by 5% and FRDP mitigation by 14% over 100 years (for scenario 1). Although unthinned forests achieve higher net forest C sequestration over this timescale, this is more than offset by the higher quantity of harvested timber produced in thinned systems, and improved conversion to sawnwood – which results in higher accumulation of C in HWP and greater emission avoidance via fossil fuel and mineral construction material substitution (Figure 3). When comparing scenarios 1 and 2, the burdens associated with displacement of beef production vary significantly (Table 3). The displacement of beef to intensive UK systems achieves further GWP savings via reduced emissions intensity of production, whereas displacement to average intensity production in Brazil increases GWP, mainly due to indirect land use change (deforestation) (Table 3 and Figure 3).

### Table 3. Mitigation of fossil resource depletion potential and global warming potential achieved by converting 1 ha of beef production land to timber production forest, over 100 yrs. Displacing beef production to intensified UK production (Sc1) and Brazil on land converted from rainforest (Sc2).

| Impact category | Scenario 1 | Scenario 2 |
|-----------------|------------|------------|
|                 | Unthinned  | Thinned    | Unthinned  | Thinned    |
| FRDP (TJ eq.)   | -4.28      | -4.88      | -4.28      | -4.88      |
| GWP (Gg CO₂ eq.)| -2.30      | -2.41      | -1.12      | -1.22      |

### 3.1 Abatement potential - Construction use

Timber use in construction has significant abatement potential through both long-term storage of C in the HWP C pool and also displacement of mineral construction materials (Table 4). Thinning produces 16% more wood product for carcassing use (e.g. timber-frame walls) than unthinned systems per ha of forest. If used as external-wall timber framing, this additional 16% increases GHG mitigation by 110,176 kg CO₂ eq (over 100 years) due to displacement of mineral construction materials.
Table 4. Avoided CO₂ eq. emissions and FF depletion from displacement of mineral construction materials by sawn timber (used in external timber frame wall, replacing concrete block and mortar wall) from 1 ha of afforested land over 100 years.

|                  | GWP (kg CO₂ eq) | FF depletion (MJ eq) |
|------------------|-----------------|----------------------|
|                  | unthinned       | thinned              | unthinned       | thinned |
|                  | 681,807         | 791,983              | 4,365,022       | 5,070,383 |

... To build 100,000 new houses in the next 20 years (as projected for Wales: Welsh Government, 2018) using timber-frame construction would require 10,424 (unthinned) to 8,974 (thinned) ha of forest to supply the timber frames (not including supply of sawn timber required for roof and floor structures, and assuming forests are already established and ready to be harvested to meet demand). This would achieve 1.4 Tg CO₂ eq avoided emissions for mineral building material substitution. In addition, the forest supplying these houses (and their extended value chains) over a 20-year period could provide GWP benefits of -4.3 Tg CO₂ eq, and FRDP benefits of -8,753 TJ (for thinned systems).

3.2 Conclusions

Expanding forestry onto marginal agricultural land with the aim of providing more timber for the built environment will provide significant environmental benefits, in particular mitigation of GHG emissions and fossil resource depletion. Mitigation is primarily driven by C sequestration in growing trees, storage of C in the HWP C pool and the substitution of FF and mineral construction materials. However, this mitigation could be significantly reduced at the global level if agricultural production is displaced internationally, causing “carbon leakage”. In particular, displacement of beef production to Brazil could drive indirect deforestation, which could offset 50% of the UK GHG mitigation effect. However, there is significant scope for forestry expansion to be accommodated by, or even to drive, “sustainable intensification” of existing land-use systems within the UK, further enhancing net mitigation potential.

... This study highlighted the considerable potential to increase the resource efficiency of UK forestry, and to reduce the 98% import dependency for sawn-timber construction products. Currently, only around 40% of harvested timber ends up in buildings under best-case assumptions (16% carcassing plus 24% wood panels for unthinned systems; and 18% carcassing plus 23% wood panels for thinned systems). Thinning of forest systems improves resource-use efficiency by increasing productivity and timber quality, which reduces the area of land required to supply a given volume of sawn timber to the construction sector by 16%. This could be increased further by improvement of forestry management and processing efficiency, e.g. by greater use of thinning, which is currently carried out in only approximately half of commercial forests in UK. Resource efficiency could also be enhanced through increased recycling of wood products, with 80% (not including paper and paperboard) currently recovered (16% for biomass energy generation; 64% for non-energy uses) (Defra, 2018).

... Further work will be carried out to elaborate impacts of: (i) alternative land-use change scenarios; (ii) alternative forest management systems; (iii) UK-specific substitution factors for displacing mineral construction materials; (iv) alternative FF substitution scenarios in a future energy mix; and (v) alternative study periods.
Figure 3. Life cycle assessment results for unthinned and thinned forest management systems (for scenario 1, displacement of beef to high intensity production, UK). Results expressed for (a) fossil resource depletion potential (TJ eq) and (b) global warming potential (Gg CO₂ eq).
References

[1] Bruun S, Hansen, T L, Christensen T H, Magid J, Jensen L S 2006 Application of processed organic municipal solid waste on agricultural land - a scenario analysis Environmental Modelling and Assessment 11 pp 251-265

[2] Cameron A D 2002 Importance of early selective thinning in the development of long-term stand stability and log quality: a review. Forestry 71 1

[3] Castellani S, Sala V, Schau S, Secchi E, and Zampori M 2018 Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment method - New models and differences with ILCD (Ispra: European Commission) https://doi.org/10.2760/671368

[4] Committee on Climate Change 2018 Land use: Reducing emissions and preparing for climate change. Committee on Climate Change (London: Committee on Climate Change copyright) Retrieved from https://www.theccc.org.uk/publication/land-use-reducing-emissions-and-preparing-for-climate-change/

[5] Defra 2018 UK Statistics on waste datasets (UK: Defra copyright) Retrieved from https://www.gov.uk/government/statistical-data-sets/env23-uk-waste-data-and-management

[6] FAOSTAT – Forestry database. Retrieved from http://www.fao.org/forestry/statistics/80938/en/http://www.fao.org/forestry/statistics/80938/en/

[7] Forestry Commission 2003 National Inventory of Woodland Trees. (UK: Crown copyright) ISBN 0 85538 602 9

[8] Forestry Commission 2015 Thinning control, Forestry Commission, Field Guide (Edinburgh: Crown copyright) pp 57 ISBN: 978-0-85538-930-7

[9] Forestry Commission 2016 National Forest Inventory Interim report. 25-year forecast of softwood timber availability (Edinburgh: Forest Research)

[10] Forestry Commission 2017 Forest Statistics. (IFOS-Statistics, Forest Research: Edinburgh) Retrieved from https://www.forestrystatistics.gov.uk/tools-and-resources/statistics/forestry-statistics/forestry-statistics-2017/

[11] Hafner A and Schafer S 2017 Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level Journal of Cleaner Production 167 pp 630-642

[12] Hibberd B G (Ed.) 1991 Forestry Commission Handbook 6 — Forestry Practice (11th edition) (HMSO: London)

[13] IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use. Geneva. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

[14] IPCC 2018 IPCC Special Report, Global warming of 1.5°C, Summary for policy makers ISBN 978-92-9169-151-7

[15] Kull S J, Rampley GJ, Morken S, Metsaranta J, Neilson E T and Kurz WA 2016 Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) version 1.2: user’s guide. (Edmonton, AB: Nat. Resour. Can., Can. For. Serv., North. For. Cent)

[16] Lamb A, Green R, Bateman I, Broadmeadow M, Bruce T, Burney J and Balmford A 2016 The potential for land sparing to offset greenhouse gas emissions from agriculture Nature Climate Change 6 5 pp 488–492. https://doi.org/10.1038/NCLIMATE2910

[17] Matthews R W, Jenkins T A R, Mackie E D and Dick E C 2016. Forest Yield: A handbook on forest growth and yield tables for British forestry (Edinburgh: Forestry Commission) 92 pp

[18] Nguyen T L T, Hermansen J E, and Mogensen L 2010 Environmental consequences of different beef production systems in the EU Journal of Cleaner Production 18 8 pp 756–766. https://doi.org/10.1016/j.jclepro.2009.12.023

[19] Pajchrowski G, NoskowiakA, Lewandowska A and Strykowski W 2014 Wood as a building material in the light of environmental assessment of full life cycle of four buildings Construction and Building Materials 52 pp 428-436
[20]. Rollinson T J D 1985 Windthrow and price and main thinning practice factors. Brit. Timber. A4 (October) pp 22-24.
[21]. Searchinger T D, Wirsenius S, Beringe, T, and Dumas P 2018 Assessing the efficiency of changes in land use for mitigating climate change Nature 564 7735 pp 249–253. https://doi.org/10.1038/s41586-018-0757-z
[22]. Styles D, Gonzalez-Mejia A, Moorby J, Foskolos A, and Gibbons J 2018 Climate mitigation by dairy intensification depends on intensive use of spared grassland Global Change Biology 24 2 pp 681–693. https://doi.org/10.1111/gcb.13868
[23]. Suttie E, Taylor G, Livesey K and Tickell F 2009. Potential of forest products and substitution for fossil fuels to contribute to mitigation Combating Climate Change - a role for UK forests eds Read D, et al. (Edinburgh: The Stationary Office) pp 119–138
[24]. TTF 2017 Statistical Review 2017 (UK: Timber Trade Federation) Retrieved from https://ttf.co.uk/download/ttf-statistical-review-2017/
[25]. Weidema B P, Ekvall T, and Heijungs R 2009 Guidelines for application of deepened and broadened LCA. Aalborg. Retrieved from https://pdfs.semanticscholar.org/8be5/9252f6790328a6360d506df522de78bbce4c.pdf
[26]. Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, and Weidema B 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment 21 9 pp 1218–30. https://doi.org/10.1007/s11367-016-1087-8
[27]. Welsh Government 2018 Estimates of housing need in Wales at a national and regional level (2018-based) Retrieved from https://gov.wales/statistics-and-research/housing-need-and-demand/?lang=en