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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 CO_2 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

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is to evaluate the impact of forest thinning on production of higher value timber products, and on the environmental balance.

2.. Materials and Methods

2.1Scope 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.

2.2Life 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

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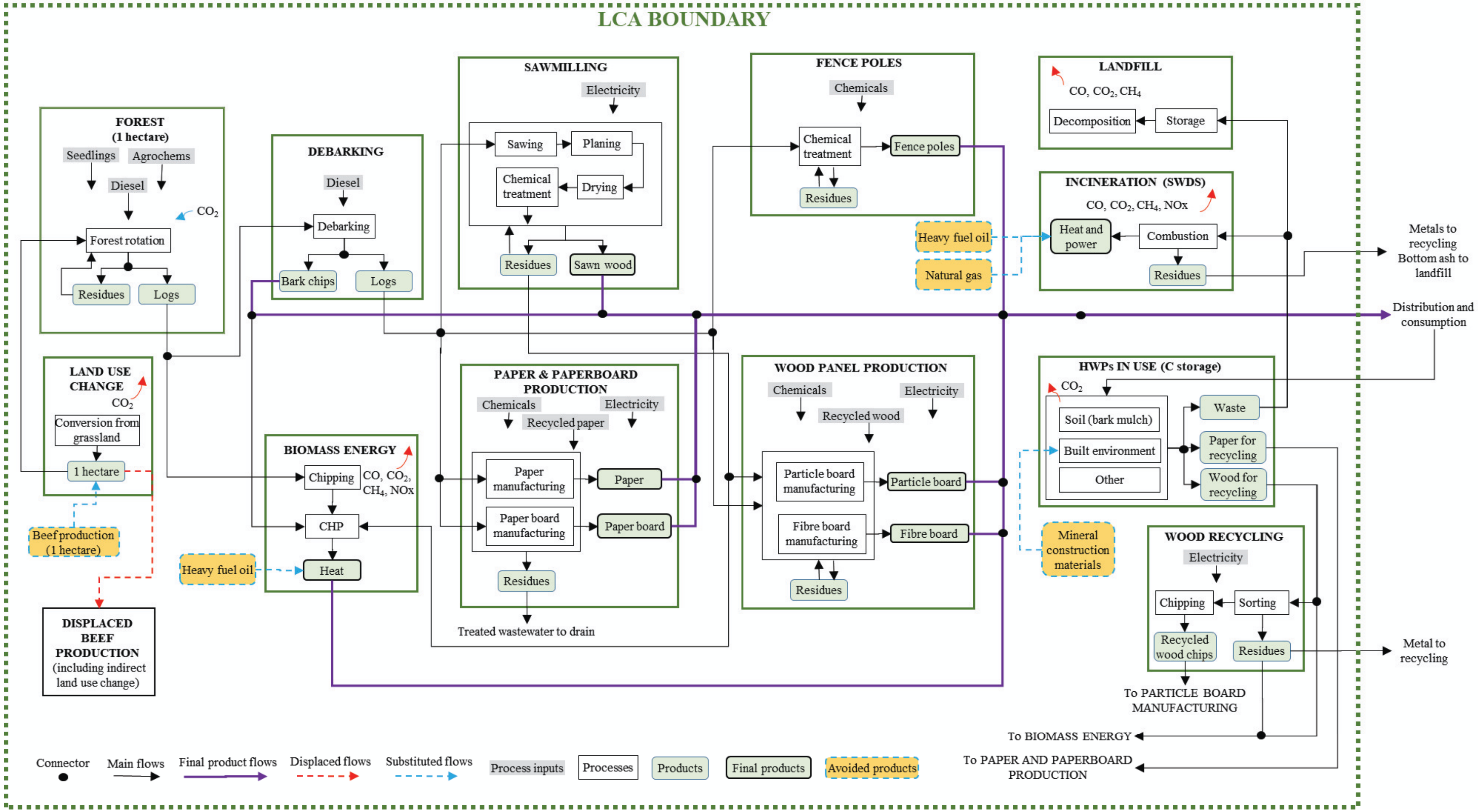

Figure 1. Main processes and inputs accounted for within expanded consequential life cycle assessment boundaries, including: storage of C in HWPs, recycling and disposal of HWPs; substitution of fossil fuels for energy production; substitution of mineral building materials.

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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
	Chip/Fuel/Pulp	Fence pole	Red	Bar/Pallet	Green	m^3/ha
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

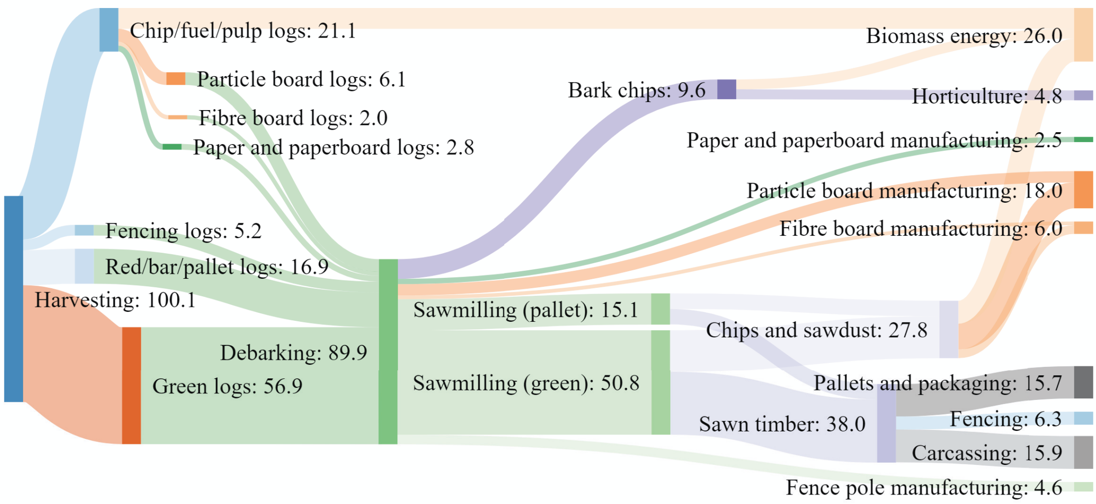

Figure 2. Biogenic carbon material flow of main crop wood harvest (from an unthinned forest). Units are percentages of original harvest. (A rounding error is present in the harvesting total.)

.... 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		Thinned		EFs		EF source
				In	Out	In	Out	FRDP	GWP	
Site establishment	Land		ha	1		1				
	15 tonne 360 Excavator	Expert estimate	hr	15		15		941	65	Ecoinvent
	Herbicide (glyphosphate)	Industry recommended	kg	1		1				Ecoinvent
Planting (1&2)	Tree seedlings	GH	Item(s)	50,000		50,000		1	0	Ecoinvent
	15 tonne 360 Excavator	GH	hrs	30		30		941	65	Ecoinvent
	Pesticides (acetamiprip)	Industry recommended	kg	2		2				Ecoinvent
Forest management	Harvester (diesel use)	GH	hrs	64		78		784	56	Ecoinvent
	Forwarder (diesel use)	GH	hrs	64		78		646	46	Ecoinvent
Forest growth	Net C sequestered	CBM-CFS3	kg C	222,077		206,928				IPCC 2006
	Harvested wood	CBM-CFS3, GH	m^3		1,321		1,426			IPCC 2006
Transport (forest to processor)	>32 t truck, EURO6	GH	t.km	2,823		3,046				Ecoinvent
Debarking	Harvested wood	CBM, GH	m^3	1,187		1,310				
	Diesel	Ecoinvent	MJ	1,395		1,543				
	lubricating oil	Ecoinvent	kg	1		1				
	bark chips	GH, FR CFs	kg		117,768		130,240	299	20	Ecoinvent
	Debarked wood	GH, FR CFs	m^3		1,060		1,169			
Sawing	Diesel (internal transport)	Ecoinvent	MJ	13,122		14,952				
	Electricity	Ecoinvent	kWh	8,775		9,999				
	Lubricating oil	Ecoinvent	kg	48		54				
	Debarked wood	GH, FR CFs	m^3	870		957				
	Sawnwood	JJ&S	m^3		502		572	363	25	Ecoinvent
	Sawmill residues	JJ&S	kg		170,307		192,502			

Process stage	Input/output/process	Activity data source	Units	Unthinned		Thinned		EFs		EF source
				In	Out	In	Out	FRDP	GWP	
Drying (of sawn timber)	Electricity	Ecoinvent	kWh	8,384		9,553				
	Sawnwood	JJ&S	m^3	502		572				
	Sawnwood - dried (u=20%)	Assume no loss in volume during drying	m^3		502		572	403	29	Ecoinvent
Planing	Electricity	Ecoinvent	kWh	4,353		4,960				
	Sawnwood (carcassing) dried (u=20%)	JJ&S	m^3	502		572				
	Sawnwood (carcassing) planed	Vol loss accounted for in 'sawing'	m^3		502		572	469	35	Ecoinvent
	Sawmill residues	JJ&S	kg		170,307		192,502			
Chemical treatment	Electricity	Ecoinvent	kWh	46		54				
	Wood preservative	Ecoinvent	kg	64,953		75,122				
	Sawnwood (fencing) dried (u=20%)	JJ&S	kg	37,452		41,711				
	Debarked wood (fence poles)	GH,FR CFs	kg	27,501		31,331				
	Preserved wood	No vol. change	kg		64,953		75,122	0	0	Ecoinvent
Particle board production	Electricity	Ecoinvent	kWh	39,415		44,232				
	Heat	Ecoinvent	MJ	462,488		519,008				
	Resin	Ecoinvent	kg	19,329		21,691				
	Debarked wood (chip)	GH	kg	66,805		60,263				
	Sawmill residues	JJ&S	kg	153,277		173,252				
	Recycled wood	FC report	kg	261,906		303,546				
	Particle board	FR CFs	m^3		390		438	4,716	262	Ecoinvent
Fibre board production	Electricity	Ecoinvent	kWh	1		1				
	Heat	Ecoinvent	MJ	1		1				
	Debarked wood (chip)	GH, FR CFs	kg	22,268		20,088				
	Sawmill residues	JJ&S	kg	51,092		57,751				
	Fibre board	JJ&S, GH, FR CFs	m^3		53		56	1,064	98	Ecoinvent
Woodchip production (for biomass energy)	Electricity	Ecoinvent	kWh	2,118		1,955				
	Lubricating oil	Ecoinvent	kg	0		0				
	Harvested wood - 'fuel'	GH	kg	65,717		56,825				
	Recycled wood - 'biomass'	FC	kg	70,188		81,579				
	Wood chips	GH	kg, dry		135,904		138,404	0	0	Ecoinvent
Biomass energy	Electricity	Ecoinvent	kWh	19,061			21,293			Ecoinvent
	Wood chips	GH	Kg, dry	135,904		138,404				Conversion biogenic C to CO_2 eq
	Bark chips	GH, FR CFs	kg	31		34				
	Sawmill residues	JJ&S	kg	136		154				
	Heat	Ecoinvent	MJ		1,946,830		1,982,642	0	0	Ecoinvent
Graphics paper production	Electricity	Ecoinvent	kWh	16,421		11,673				
	Debarked wood - 'pulp'	FR CF	m^3	16		12				
	Paper, newsprint, virgin	FR CF	kg		5,815		4,133	16	1	Ecoinvent
Graphics paper production (recycled)	Electricity	Ecoinvent	kWh	8,529		4,044				
	Recycled paper	GH, FR CFs	kg	5,330		2,521				
	Paper, newsprint, recycled	Mass equal to recycled paper	kg		5,330		2,521	12	1	Ecoinvent
Paperboard production	Electricity	Ecoinvent	kWh	804		576				
	Debarked wood - 'pulp'	GH, FR CFs	GH	16		12				
	Board box	GH, FR CFs	kg		11,472		8,218	11	1	Ecoinvent
HWP in use	C accumulated in HWP	IPCC	kg C	568,622		618,548				IPCC 2006
Landfill	Waste wood	FC, Defra, IPCC	kg	2,100		2,434				IPCC, 2006
	Waste paper	FC, Defra, IPCC	kg	4,502		654				IPCC, 2006
Incineration	Waste wood	FC, Defra, IPCC	kg	55,343		64,140				
	Waste paper	FC, Defra, IPCC	kg	1		0				Conversion

Process stage	Input/output/process	Activity data source	Units	Unthinned		Thinned		EFs		EF source
				In	Out	In	Out	FRDP	GWP	
	Electricity	Ecoinvent	kWh		157,729		182,799			of biogenic
	Heat	Ecoinvent	MJ		21,370		24,767			C to CO_2eq
Avoided construction materials	140 mm concrete block and mortar wall replaced by timber frame wall	Industry standard	m^2	18,461		21,444		236	37	Ecoinvent
Avoided FFs	Avoided natural gas (hp)	Ecoinvent	m^3	77,593		82,540				Ecoinvent
Avoided beef production	Low intensity beef production, UK	Styles et. al., 2018	kg	18,315		18,315			33	Nguyen et al., 2010
	Sc1 - high intensity production, UK	Styles et. al., 2018	kg	18,315		-			22	Nguyen et al., 2010
	Sc2 – avge. intensity production, Brazil)	Styles et. al., 2018	kg	18,315		1			47	Nguyen et al., 2010
	Sc2 - iLUC (rainforest to grassland, Brazil)	Styles et. al., 2018	ha	1					723,259	IPCC, 2006

2.3Impact assessment and interpretation

Two environmental impact categories were considered in this study: global warming potential (GWP), expressed as kg CO_2 eq; fossil resource depletion potential (FRDP), expressed in MJ. Summary results are presented in the main body of the paper.

3.. Results and discussion

Afforestation of 1 ha of grass land to produce timber for construction offers significant CO_2 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 CO_2 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).

	Scenario 1		Scenario 2	
Impact category	Unthinned	Thinned	Unthinned	Thinned
FRDP (TJ eq.)	-4.28	-4.88	-4.28	-4.88
GWP (Gg CO_2 eq.)	-2.30	-2.41	-1.12	-1.22

3.1Abatement 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 CO_2 eq (over 100 years) due to displacement of mineral construction materials.

Table 4. Avoided CO_2 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 CO_2 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 CO_2 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 CO_2 eq, and FRDP benefits of -8,753 TJ (for thinned systems).

3.2Conclusions

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.

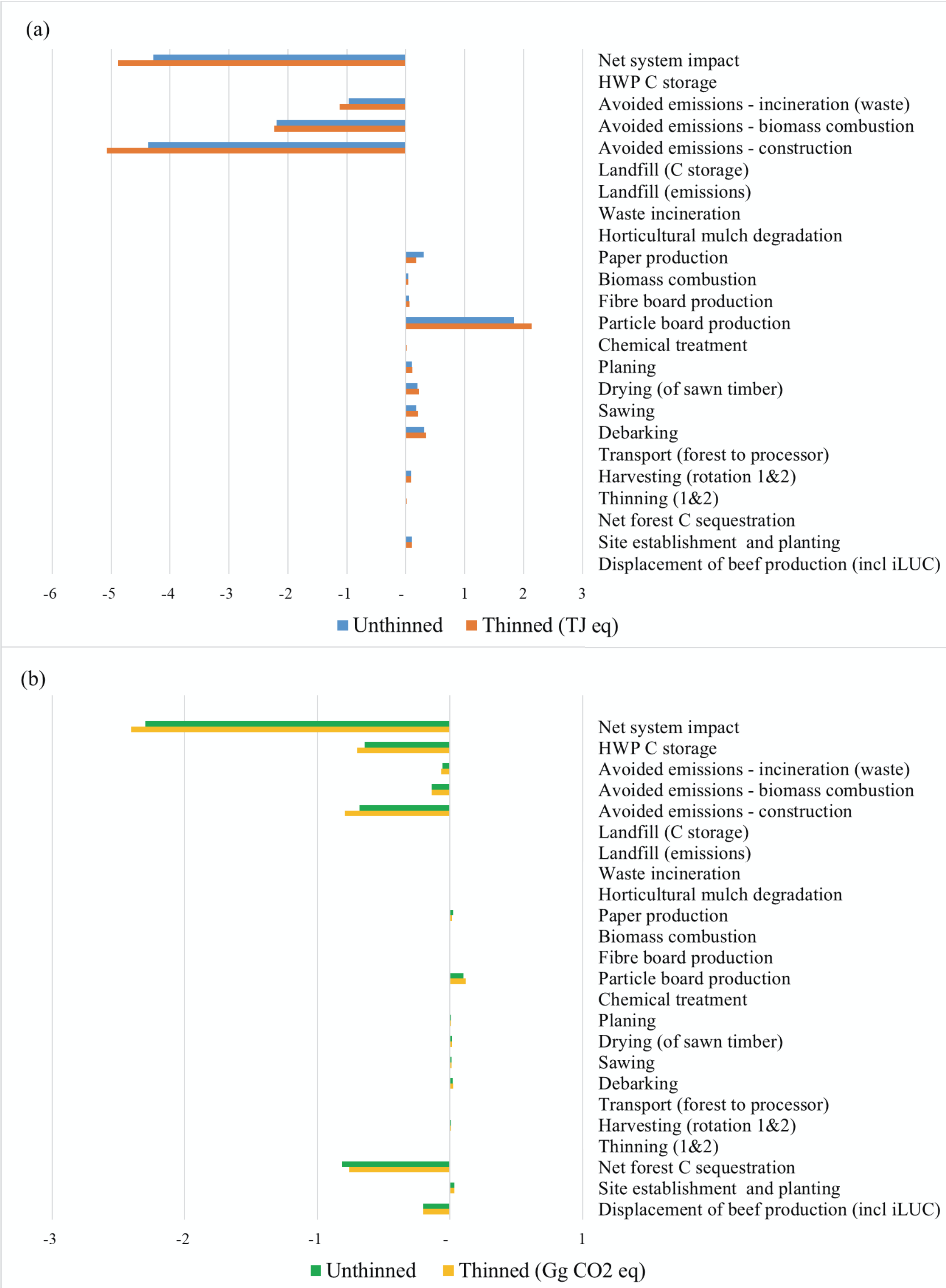

Figure 3. Life cycle assessment results for unthinned and thinned forest management systems (for scenario 1, displacement of beef to high intensity production, UK). Results expressed for (a) fossil resource depletion potential (TJ eq) and (b) global warming potential (Gg CO_2 eq).

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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] .... FAO 2017 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 Forestry Statistics. (IFOS-Statistics, Forest Research: Edinburgh) Retrieved from https://www.forestresearch.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

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012142 doi:10.1088/1755-1315/323/1/012142

[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