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Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK

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ABSTRACT

Life cycle analysis is used to assess the energy requirements and greenhouse gas (GHG) emissions associated with extracting UK forest harvesting residues for use as a biomass resource. Three forest harvesting residues were examined (whole tree thinnings, roundwood and brash bales), and each have their own energy and emission profile. The whole forest rotation was examined, including original site establishment, forest road construction, biomass harvesting during thinning and final clear-fell events, chipping and transportation. Generally, higher yielding sites give lower GHG emissions per 'oven dried tonne' (ODT) forest residues, but GHG emissions 'per hectare' are higher as more biomass is extracted. Greater quantities of biomass, however, ultimately mean greater displacement of conventional fuels and therefore greater potential for GHG emission mitigation. Although forest road construction and site establishment are "one off" events they are highly energy-intensive operations associated with high diesel fuel consumption, when placed in context with the full forest rotation, however, their relative contributions to the overall energy requirements and GHG emissions are small. The lower bulk density of wood chips means that transportation energy requirements and GHG emissions are higher compared with roundwood logs and brash bales, suggesting that chipping should occur near the end-user of application.

1. Introduction

Biomass is identified as an important component of the future energy mix of the UK and, in 2007, the UK Biomass Strategy highlighted the significant contribution that forest resources could make to the total indigenous biomass supply [1]. Forest resources are comprised of residues from harvesting operations in commercial forests and from sawmills. In total, this could yield up to 3 million oven dried tonnes (ODT) of biomass per year [2]. Residues consist of small roundwood, branches, stem tips, whilst sawmills can produce co-products such as sawdust and slab wood. It is anticipated that the existing wood-using industries will make use of the readily available resources, such as small roundwood and sawdust, with the remainder being accessible to new woodfuel projects [2]. Currently, a large part of this remainder is left on the forest floor as it is more difficult and expensive to process than other potential fuel sources [3]. Small roundwood thinnings, if not economic to extract, are often left in the forest, though it is possible to obtain this material using existing, but not widely

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Abbreviations

CP	corsican pine
$CO_{2eq.}$	carbon dioxide equivalents
DF	douglas fir
GHG	greenhouse gas
JL	Japanese larch
l	litres
LP	lodgepole pine
MJ	megajoules
NS	Norway spruce
ODT	oven dried tonne
SP	scots pine
SS	sitka spruce
t	tonnes

available forest equipment. Stem tips and branches are removed by harvesting equipment in the forest and purposely left for use as 'brash mats' that protect the forest floor from damage by heavy passing machinery [4]. Though there are concerns about the long-term sustainability of removing large amounts of forest residues from forest sites [4–9], it is possible that a proportion of them could be extracted without adverse ecological impacts [10]. Such quantities would be site specific, and assessed using the Ecological Site Classification Decision Support System [11].

Biomass resources will need to demonstrate their greenhouse gas (GHG) emission saving credentials in order to benefit from financial incentives supporting low-carbon technologies in the UK [12]. In order to calculate GHG emission savings from using UK woody biomass for energy, it is important to develop strong life cycle-based knowledge of forest residue harvesting systems in the context of the full forest rotation. This has been explored further in a report entitled "Understanding the Carbon Footprint of Timber Transport in the United Kingdom" [13], which uses and expands on this original analysis. The report examines the impact of timber transportation within the context of the full supply chain of fuelwood and construction timber production, including the avoided emissions from conventional fossil fuels and construction materials. This study explains in detail assumptions of the forest road construction, and places the resulting energy requirement and emissions in context with the total energy balance and GHG emissions avoided during the removal of harvesting residues and thinnings from conventional clear-fell forests.

1.1. *Forest residues*

Plantation forestry is common practice in the UK, and tree crops are managed to maximise timber volume production, typically under a clear-fell regime [14]. About 60% of UK woodland is populated by conifers, particularly in the northern parts of the UK [15]. Harvesting residues include whole tree early thinnings, small roundwood, stem tips and branches. It is assumed that biomass, in itself, is carbon neutral, yet the GHG emissions from consumption of fossil fuels during harvesting and handling need to be taken into account [5]. Harvesting residues are considered to be 'co-products' from timber production and not 'wastes'. Therefore, the energy requirements and GHG emissions from original site establishment and forest road construction are allocated between each tonne of material produced on a given site, whereas the specific harvesting and transport components are allocated entirely to the respective forest product. The allocation of energy inputs and GHG emissions to these forest output categories will differ with Yield Class, species and residue types.

A number of energy and GHG emission studies of forest systems have been performed, though they differ in terms of system boundaries, functional units and country [16]. Before this study, and [13], the Biomass Environmental Assessment Tool version 2 (BEATv2) [17] provided the most recent published UK-based life cycle assessment (LCA) for harvesting forest residues from a forest system relevant to the UK [18]. By applying default parameters and removing the landfill reference system option, a total energy requirement of 694.5 MJ ODT^{-1} and total GHG emissions of 43.74 kg $CO_{2eq.}$ ODT^{-1} for average forest residues is estimated by BEATv2.

This analysis examines the regeneration of a forest stand from a previous clear-felling operation, harvesting of saw logs and small stemwood, and extraction of bales of branch wood to the roadside. It is assumed that the sites are accessible and conventional harvesting equipment can be used. It is also assumed that the site is not at particular risk of soil erosion. 'Whole tree harvesting' is defined as the removal of most branches and needles from a harvesting site in addition to the stemwood removed during conventional harvesting [19]. This is only performed for the first two early thinnings, when the trees have too small a diameter to be used for pulping. This also avoids compromising the principle of sustainable forest management due to excessive nutrient removal through whole tree removal for long periods of time, potentially having adverse effects on future rotations of tree growth [4]. When whole trees are removed, this is assumed to involve mechanical tree felling at the base, followed by the physical removal of the whole tree from the site to the roadside by forwarders. After the trees have reached over 7 cm diameter at breast height (DBH) trees are harvested as roundwood and this is when extraction for pulp production begins [2]. Harvesting roundwood requires the use of conventional harvester heads that cut and top the trees, leaving branches and stem tips on the forest floor [19]. The roundwood is then transferred to the roadside by forwarders. Stem tips and branches are also left onsite during the final clear-fell event. A separate pass is then required to harvest the stem tips and branches which are collected and extracted by a forwarder with a modified bundle head that compresses the residues into bundles (pers. com. I. Murgatroyd). Bundling produces cylindrically shaped bales of forest residues, and this gives logistic advantages for handling. Bundles are also said to reduce fungal degradation during storage [5]. Stem tip and branch harvesting can only occur when the site is cleared of trees and it is assumed that all previous deposits of stem tips and branches are short-lived and cannot be harvested [7]. Up to 70% of this brash can be collected [20].

1.2. *Sawmill co-products*

Unlike in BEATv2, sawmill co-products are not included in the present study, as there are some complicating LCA issues and current problems with clarity and consistency of essential data. Here, we consider that in biomass supply chains, sawmill residues and forest residues are best regarded as deriving from distinct, separate routes: as co-products of an industrial process (sawmilling) and as co-products of forest management and harvesting activities respectively. In LCA there is a requirement to provide an appropriate reference system for the alternative fate for the biomass if it were not being used to produce bioenergy. In BEATv2 it is assumed that the appropriate reference system for harvesting residues is natural decay on the forest floor if not removed from the site whereas sawmill residues, are assumed to be landfilled [17]. This reference system assumption for sawmilling residues is open to serious question as it is based on earlier work [17] and may be contradicted by current practice [21]. According to the Forest Statistics, 2008, about 83% of sawmill residues are sold to wood processing industries for manufacturing products such as medium density fibreboard and chipboard [15] and no sawmill residues are landfilled [23]. An LCA study including sawmill residues would therefore need to assess the environmental impacts of producing these products from alternative resources. In either case, sawmill residues are best regarded as co-products of saw logs and, in the present study these saw logs are allocated an appropriate burden of the site management energy requirements and GHG emissions.

1.3. *Site management*

Forest roads are required for forest access and are built purposely to do so. Very few LCA studies of forest residues however, include this aspect. The most detailed LCA examines the GHG emissions from forest road construction in Finland [22]. The construction of 'permanent forest' roads was identified as the highest source of GHG emissions for silvicultural and forest maintenance work on a per hectare basis, with a total emission of 3321 $kg\,CO_{2eq.}\,km\,road^{-1}$, and a road density of 1 $km\,ha^{-1}$. 'Permanent forest roads' are long-lasting features and, therefore, initial road construction events have to be allocated between each subsequent rotation to which the road provides a service. In the UK, forest rotations last between 40 and 60 years for conifers, whereas for broadleaves they are typically 80–100 years. Forest roads are maintained throughout this time. UK forest roads are classified into types A, B and C, though only types A and B are used for harvesting activities. Both roads have similar construction; the main difference is the frequency of use and, thus, the extent of resurfacing and maintenance required by each type. Type A roads are used as principal timber haulage routes and, are constructed to a high specification and in some cases, can be maintained up to five times a year. Type B roads are only used for timber haulage during specific operations and are typically only maintained before each harvesting event (pers. com. D. Killer, Forestry Commission Civil Engineering Dept.). Type C roads are not used for timber haulage [23]. Forest road construction in the UK will vary according to region and geology. For this, a single case study from Galloway, Dumfries, Scotland was used to assess how significant forest road construction and maintenance is in the context of the whole forest rotation, and the harvesting operations for extracting forest residues.

1.4. *Effect of residue removal*

Conventional plantation forestry practices have not been found to compromise long-term sustainability [19] however, increasing interest in whole tree harvesting, involving removal of brash, has lead to concerns of carbon loss and nutrient removal [4]. When biomass is utilised for energy, CO_2 is ultimately released faster through combustion compared to a longer process of decomposition [6]. The IPCC guidelines consider these processes over a 100 year cycle, and under this virtually all the biomass would have been converted to CO_2 via either the combustion or decomposition route and it is the long-term accumulation of CO_2 in the atmosphere that is crucial for the magnitude of the greenhouse gas effect and subsequent global climate change [6]. It has been suggested, however, that removing stem tips and branches from the forest floor may lead to a decreased flux of carbon into the forest litter and soil resulting in a reduction of the carbon storage in the forest soil [7]. In this study, changes in carbon fluxes have not been modelled due to a lack of data. Instead, a biomass removal rate is suggested so that it is possible that soil and above ground carbon stocks may be built up in parallel with sustainable harvesting for fuel production [10]. The removal rate parameters are applied to brash and roundwood, with values set for the former for ecological reasons and the latter for reasons of competition for a resource.

This study assesses the direct and indirect primary energy requirements (MJ) and GHG emissions for harvesting whole trees, roundwood and stem tips and branches for 8 different tree species growing in the UK: Corsican Pine (CP), Douglas Fir (DF), Japanese Larch (JL), Lodgepole Pine (LP), Norway Spruce (NS), Scots Pine (SP) and Sitka Spruce (SS).

2. Methods

Direct energy requirements are based on the energy content of the fuel consumed by machinery to carry out a given task and direct GHG emissions from fuel combustion. Direct energy requirements and GHG emissions also arise from the process of manufacturing products used on the forest site (such as fencing). Indirect energy requirements and GHG emissions for fossil fuels (primarily diesel fuel) represent the upstream events that provide the fuel to the consumer. These are UK-specific figures based on 'Methodology for Environmental Profiles of Construction Materials, Components and Buildings', produced by the Building Research Establishment (BRE) in 2000 [24], which provides total and upstream fuel emission factors for 1996. This is the same as earlier work [25]. BEATv2 is also used to calculate avoided GHG emissions from displaced fossil fuels. Energy requirements and GHG emissions for forest management supplies (such as agrochemicals, etc.), were also obtained from BEATv2. Value of Global Warming Potentials of each GHG are based on the latest IPCC guidelines, for carbon dioxide (1), methane (25) and nitrous oxide (298) [26]. The final unit of measurements are MJ or kg GHG gas per oven dried tonne (ODT) of wood chips. Equivalent figures for 'per green-tonne' and per 'MWh chip' are also provided to aid comparison with other studies. The systems boundaries used are similar to that other earlier work [27]. An MS Excel based 'Forest LCA tool' was developed, and this is summarised in Fig. 1.

2.1. Forestry operations

2.1.1. Site establishment

Site establishment includes basic land preparation and planting. Land preparation involves mounding, herbicide application operations and fence construction as described elsewhere [18]. Seedlings are planted at a density of 29 seedlings ha^{-1} by hand. For mounding, a 20-tonne Daewood Excavator was used with a diesel fuel consumption requirement of 18–20 l h^{-1} and a work rate of approximately 6.75 h ha^{-1} (Pers. com. Murgatroyd). A small amount of herbicide (0.06 kg active ingredient ha^{-1}) is then applied using a typical 75 kW tractor, consuming 24 l h^{-1} with a work rate of 1.2 h ha^{-1} [18]. Fencing requirements are based on [18] with a total primary energy requirement of 12,952 MJ ha^{-1} and GHG emissions of 538 kg $CO_{2eq.}$ ha^{-1}. Energy requirements and GHG emissions for the provision of seedlings are 39 MJ ha^{-1} and GHG emissions 1.8 kg $CO_{2eq.}$ ha^{-1} [18].

2.1.2. Forest road construction

The site operations, fuel consumption and material usage for the construction and maintenance of forest roads were recorded both onsite and from records by the South West Scotland Forestry Civil Engineering Department in Castle Douglas in 2008. This road is an overlay road construction, which involves spreading blasted rock on top of the soil, which is then covered with a layer of finer, crushed aggregate. Hence, forest road construction requires mining, crushing and hauling road aggregate to the construction site where it is spread, graded and rolled. Approximately 8800 t of blasted rock and 1200 t of crushed rock are spread per km road. Mining involves drilling into the rocky substrate using a drill rig and explosives are then used to blast the rocks apart. Approximately 0.3 kg of ammonium nitrate-base explosives are used per tonne of blasted rock. An excavator is used to load blasted rock into either a truck trailer or into the crusher. The aggregate is mined within 16 km of the forest road site. The road construction engineers discussed plans to use alternative aggregates such as clam shell waste. On arriving at the road site the aggregate is dumped and bulldozers are used to spread the pieces of rock so that they can be graded and then rolled. Road maintenance involves re-surfacing the roads with a layer of crushed aggregate at a rate of 1500 t km^{-1} road. The road is then graded and rolled. Type A roads are maintained every year and Type B are maintained before every harvesting event.

2.1.3. Harvesting and forwarding

Energy requirements for harvesting operations were based on advice from Forestry Commission harvesting specialists. Diesel fuel consumption for felling is estimated at 1.2 l m^{3-1} biomass, forwarding 0.9 l m^{3-1}, and 2 l $bale^{-1}$ (approximately 0.7 kg m^{3-1}). Harvesting unit fuel consumption is, therefore, different for each forest residue type, based on the bulk density of the residue (see Table 1). The whole tree harvesting system involves tree felling and extraction from the forest floor using forwarders. Roundwood is harvested by conventional forest harvesters, during which the trees are cut and forwarded. Stem tips and branches are harvested together as compressed bundles which are harvested using bundle harvesters and then forwarded. It is assumed that each biomass type is stored at the roadside to allow for natural drying from 50% to about 30% moisture content.

2.1.4. Chipping

Chipping operations can either occur at the roadside or at the point of use. Chipping was based on a Heizohack drum chipper with a total working life of 3000 h. The diesel fuel

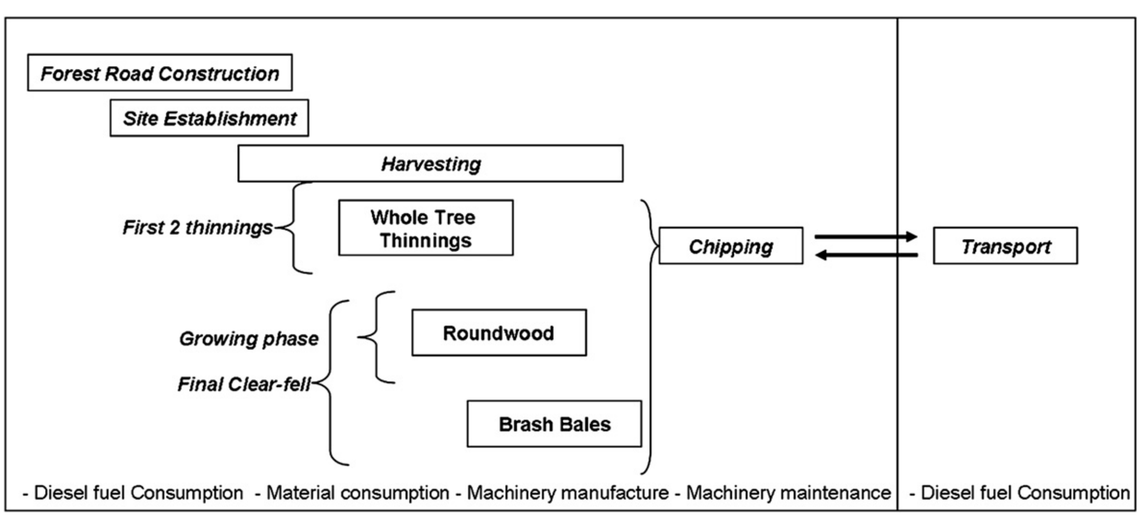

Fig. 1 – Systems boundaries of study.

Table 1 – Bulk densities assumed for each forest harvesting residue based on the specific density of Sitka Spruce as a general indicator of density (0.33 odt/m^3).

	Basic density (odt/m^3)	Solid: air 'stacked ratio'	Bulk density (odt/m^3)	Actual bulk density (tonnes/m^3)[b] at 50% m.c.	Actual bulk density (tonnes/m^3)[c] at 30% m.c.
Roundwood	0.33	0.65	0.215	0.429	0.306
Whole trees	0.33	0.6	0.198	0.396	0.283
Brash bales	0.33	0.7[a]	0.231	0.462	0.330
Wood chips	0.33	0.4	0.128	0.256	0.183

a Assume these are compressed bales.
b Assume these are harvested and forwarded at a moisture content of 50%.
c Assume the woody material is naturally dried to 30% moisture content.

consumption 1.85 l m$^{3-1}$ chipped biomass [28], again with the fuel consumption 'per ODT' varying with the bulk density of the material being chipped. It is assumed that the woody material is chipped at 30% moisture content. A lower heating value (LHV) of 12.1 GJ t^{-1}, or 3.4 MWh t^{-1} is assumed, based on the Milne equation, using average compositional data for coniferous wood available from the Phyllis Database [29].

2.2. *Allocation*

Two allocation procedures are examined here: allocation by mass and by price. The energy requirements and GHG emissions for the establishment, road construction and road maintenance events are allocated between each co-product removed from the site. The economic value of saw logs, pulpwood and biomass are based on a ratio of 4:2:1 [17]. Harvesting, processing and transportation events are allocated specifically to each co-product. Site establishment and road construction events are allocated between biomass and roundwood according to the extractable yield. Material left on the site is not accounted for.

2.3. *Yield and material losses*

The yield of each forest residue type for each tree species at various yield classes was obtained from the Forestry Commission BSORT model [30]. This provides yields in ODT ha^{-1} for all above and below ground biomass for forest stands over the full rotation, and includes removals at thinning events. The model is based on allometric equations that estimate crown biomass and woody root biomass for different tree species [31]. Estimating the percentage of total biomass that could be accessed was based on a series of coefficients which can be altered in the LCA model to suit different sites. It was assumed that 100% of the above ground biomass of whole trees can be made available for biomass, as there is no competing industry for this material. Whole tree thinnings are assumed to occur for the first 2 thinnings. As softwood roundwood is currently used by the pulp industry it is assumed that 15% could potentially be used as biomass. About 25% of stem tips and branches produced during the final clear-fell event are assumed to be able to be removed from the site and 100% of this is available for biomass. The sensitivity of the final GHG emissions for removal rates from 0% and 100% are tested, along with estimates for carbon removal rates, based on a carbon content of 50% for wood. Stem tip and branch deposits are assumed to be "short-lived" residues, therefore brash from previous thinning events are assumed to have degraded and are not available for collection [7]. Dry matter losses are included at every step of the LCA model. Losses of 2% are assumed for each of the storage, chipping and transportation events [32].

2.4. *Transport*

It is assumed that all transportation occurs in a large 44 gross vehicle weight (GVW) truck with total weight payload of 28.5 t and volume capacity of 70 m^3 [33]. In this case, the transport energy requirements and GHG emissions are different for various biomass types according to their bulk densities. It is estimated that, in most cases, the full truck payload cannot be achieved due to the low bulk density of the dried woodfuel (Table 2). This means that the truck payload is volume and not weight limited, resulting in a load factor less that 100% with subsequent effect on diesel fuel consumption and GHG emissions. It is assumed that the residues are transported

Table 2 – Details of payload capacity achieved in 44 GVW truck used to transport forest harvesting residues and chips. This is based on the specific density of Sitka Spruce as a general indicator of density (0.33 ODT/m^3).

	Payload achieved in truck (tonnes/delivery)	Diesel fuel consumption (litres/t-km)[a]
Roundwood	21.1	0.029
Whole trees	19.5	0.031
Brash bales	22.7	0.027
Wood chips	12.6	0.046

a Tonnes refer to actual tonnes transported, and diesel fuel consumption accounts for a round trip (outward and return) with an empty return journey.

Table 3 – Details of machinery used for the construction and maintenance of forest roads.

Operation	Description	Work rate	Fuel consumption
		h/km	l/h
Excavator	Used to load rock into truck or crusher	87.5	13.5
Haulage	Delivers rock to road site	175	13.75
Bulldozer	Spreads rock across road surface	87.5	7
Grader	Evens-out rock surfacing	6.25	10.5
Roller	Compacts top layer or rock surfacing	6.25	6.5
		h/tonne rock	l/tonne rock
Drilling	Drills rock surface to insert explosives	0.001	0.03
Crushing	Crushes rock	0.008	0.2
Loading	Loads rock into truck or crusher	0.008	0.2

50 km to the end-use consumer. Road transport primary energy requirements per tonne-km (t-km) at full capacity are based on the relationship between fuel consumption efficiency (litres km^{-1}), payload capacity (tonnes) and fuel consumption at various load capacities [33]. The load capacity is calculated based on the volume of the material being transported and the volume capacity of the truck [34].

2.5. *Forest machinery construction and maintenance*

The energy requirements and GHG emissions for construction of forest machinery were estimated using multipliers [35]. These were derived from Input-Output Analysis [36] of 51 different sectors of industries. This enables the multipliers to represent total primary energy inputs and total GHG emissions associated with the extended process chains involved in producing goods and services from original raw materials. The multipliers are expressed per unit of £value for relatively broad categories of products and services. Largely due to this, such multipliers are usually regarded as order-of-magnitude estimates of total primary energy requirements and total GHG emissions factors. This is normally adequate for their applications in situations where contributions within any given process or activity are relatively small compared to those from direct fuel combustion, etc. Hence, they are ideally suited to the evaluation of contribution from the manufacture and maintenance of machinery, equipment etc. Cost data for use with such multipliers were obtained from [37] and from Forestry Commission experts. The total working life for each machine was estimated at 10,000 hrs [38] and the total impacts for machine construction were allocated per hour of work. Maintenance requirements were based on 2.5% of the original machine construction requirement for maintenance per hour [17].

2.6. *Forest road density*

Forest road density for Dumfries and Galloway, and the other forest districts of the UK, was estimated using data from Forest Research GIS Division to provide figures for the length and density of road types A and B in each forest district. Data from Forest Enterprise was obtained for the areas of forestland in these areas, and together the information was used to calculate km ha^{-1} figures for road density.

3. Results

3.1. *Forest road construction energy and GHG emissions*

Forest road construction is a highly energy-intensive operation. Operations such as grading, rolling and hauling stone requires approximately 4.7 l diesel for 1 m of road. Table 3 provides the details for the equipment used and the fuel consumption per km road and Table 4 shows the breakdown of the energy requirements and GHG emissions for forest road construction. In total, road construction requires 404 GJ and emits 41 t $CO_{2eq.}$ km^{-1} road. Diesel fuel consumption and road aggregate production contribute equally to (each approximately 44%) of the total GHG emissions per km. Machinery manufacture accounts for 11% of total energy requirement and 13% of GHG emissions, whereas machinery maintenance makes a negligible contribution (0.2% of energy requirement and 0.3% GHG emissions).

Producing blasted rock requires 14 MJ and 2.2 kg $CO_{2eq.}$ t^{-1}, which includes initial rock drilling and the manufacture of explosives. Loading and crushing rock requires an extra 27.5 MJ and 1.9 kg $CO_{2eq.}$ t^{-1}. Blasting rock accounts for the majority of methane and nitrous oxide GHG emissions, which is due to the consumption of ammonium nitrate-based explosives.

Road maintenance events are less energy intensive due to the smaller quantities of aggregate used per km, and fewer machinery operations. To maintain 1 km of road requires 102 GJ and 9 t CO_{2eq}. Type A roads, however, receive maintenance once a year and Type B roads are maintained before each harvest. Therefore over the full forest rotation road maintenance requirements exceed that of the original road construction (Fig. 2). In the area studied the road density of Type A roads is 0.008 km ha^{-1} and B roads is 0.007 km ha^{-1} therefore over a 50-year forest rotation with six harvests, original road construction requires 120 MJ ha. a^{-1} and emits 8.0 kg CO_{2eq}. ha. a^{-1}, and road maintenance requires 1912.2 MJ ha. a^{-1} and emits 129.9 kg CO_{2eq}. ha. a^{-1}.

Across the forest districts in the UK, forest road density ranges between 0 km ha^{-1} (in Northants, New Forest and West Midlands) and 0.016 km ha^{-1} (in North West England) for Type A roads and 0.003 km ha^{-1} (in Lorne) and 0.024 km ha^{-1} (in Coed y Goroau) for Type B roads. Across districts, the average road density was 0.005 km ha^{-1} (Type A) and 0.011 km ha^{-1} (Type B).

Table 4 – Breakdown of energy requirement and GHG emissions from construction and maintenance of forest roads.

Stage	Energy requirement MJ/km	Emissions			
		kg CO_2/km	kg CH_4/km	kg N_2O /km	kg CO_2 eq./km
Road construction					
Diesel fuel					
Loading roadstone	48,867.96	3376.73	0.925	0.026	3407.59
Haulage	99,545.84	6878.53	1.883	0.053	6941.38
Spreading roadstone	25,338.94	1750.90	0.479	0.013	1766.90
Grading	2714.89	187.60	0.051	0.001	189.31
Rolling	1680.64	116.13	0.032	0.001	117.19
Material inputs					
Roadstone (blasted)	127,509.70	7605.12	32.075	39.175	20,081.00
Roadstone (crushed)	51,657.34	3416.85	5.226	5.369	5147.44
Machine manufacture					
Excavator	9003.75	668.96	0.982	0.039	705.21
Haulage	25,725.00	1911.31	2.806	0.112	2014.87
Bulldozer	9261.00	688.07	1.010	0.040	725.35
Grader	1194.38	88.74	0.130	0.005	93.55
Roller	422.63	31.40	0.046	0.002	33.10
Machine maintenance					
Excavator	180.08	13.38	0.020	0.001	14.10
Haulage	514.50	38.23	0.056	0.002	40.30
Bulldozer	185.22	13.76	0.020	0.001	14.51
Grader	23.89	1.77	0.003	0.000	1.87
Roller	8.45	0.63	0.001	0.000	0.66
Total	403,834.19	26,788.09	45.745	44.841	41,294.33
Road maintenance					
Diesel fuel					
Loading roadstone	7330.19	506.51	0.139	0.004	511.14
Haulage	14,931.88	1031.78	0.282	0.008	1041.21
Spreading roadstone	3800.84	262.63	0.072	0.002	265.03
Grading	2714.89	187.60	0.051	0.001	189.31
Rolling	1680.64	116.13	0.032	0.001	117.19
Material inputs					
Roadstone (crushed)	62,942.74	4158.50	6.502	6.710	6320.71
Machine manufacture					
Excavator	1350.56	100.34	0.147	0.006	105.78
Haulage	3858.75	286.70	0.421	0.017	302.23
Bulldozer	1389.15	103.21	0.152	0.006	108.80
Grader	1194.38	88.74	0.130	0.005	93.55
Roller	422.63	31.40	0.046	0.002	33.10
Machine maintenance					
Excavator	27.01	2.01	0.003	0.000	2.12
Haulage	77.18	5.73	0.008	0.000	6.04
Bulldozer	27.78	2.06	0.003	0.000	2.18
Grader	23.89	1.77	0.003	0.000	1.87
Roller	8.45	0.63	0.001	0.000	0.66
Total	101,780.95	6885.75	7.992	6.763	9100.92

The total energy requirement and GHG emissions for site establishment is 20.8 GJ ha^{-1} and 1.1 t CO_{2eq}. ha^{-1}. Details are summarised in Table 4 and the relative contributions are illustrated in Fig. 2.

3.2. *Available biomass and yield class*

Fig. 3 compares the yield of each harvesting residue and compares the total amount of available biomass for each tree species at yield class 14, as estimated by the BSORT model. Out of all species and yield classes DF has the greatest yield of biomass fuel per hectare and rotation (saw logs, roundwood, whole trees, stem tips and branches combined). This species also reaches the highest yield class (24) in the BSORT model. Over all yield classes, the average utilisable biomass yield from forestlands is 72.5 ODT ha. $rotation^{-1}$ (standard deviation $\pm$ 19 ODT ha. $rotation^{-1}$), and 1.5 ODT ha. a^{-1} (standard deviation $\pm$ 0.5 ODT ha. $rotation^{-1}$), ranging between

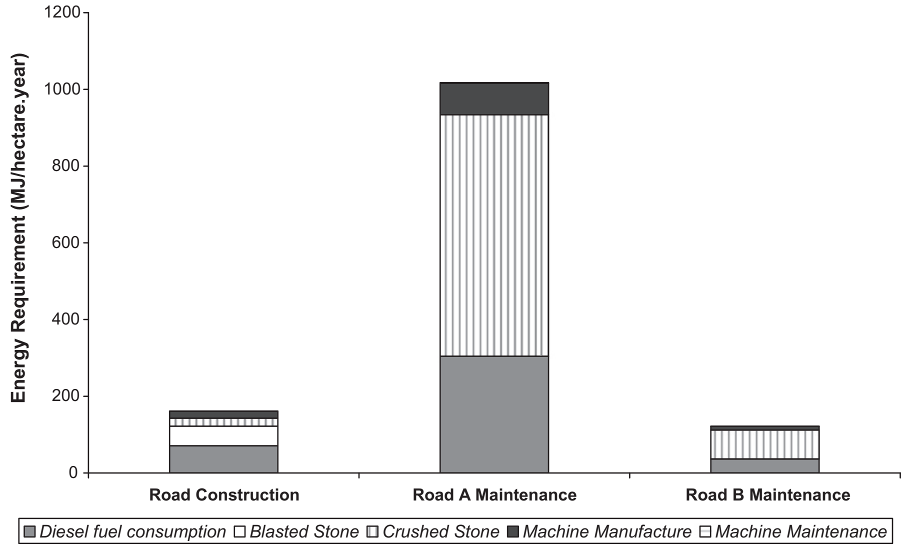

Fig. 2 – Total annual energy requirement per hectare for forest road construction and maintenance over a 50-year rotation with six harvesting events. Assumes a road density of 0.008 km ha^{-1} for Type A roads and 0.007 km ha^{-1} for Type B roads.

3 ODT ha. a^{-1} for DF, yield class 24, and 0.6 ODT ha. a^{-1} for LP yield class 4.

There is a strong positive relationship between yield class and biomass yield for all species, as shown in Fig. 4. Whole trees are available in the early stages of the rotation and roundwood is available from year 30–45 onward and at the clear-fell event. Stem tip and branch bundles, and roundwood are only available during the final clear-fell event.

The highest yielding forest residue type is whole tree thinnings, yielding between 50 (NS) and 70 (DF) ODT ha. $rotation^{-1}$, and it is assumed that 100% of this is available for bioenergy uses. Over the whole rotation, the extractable yield of roundwood exceeds that of stem tips and branches (between 39 (NS) and 66 ODT ha. $rotation^{-1}$ (DF)), though it is assumed that 85% of this potential yield is sent to the pulp market, leaving an obtainable biomass yield of

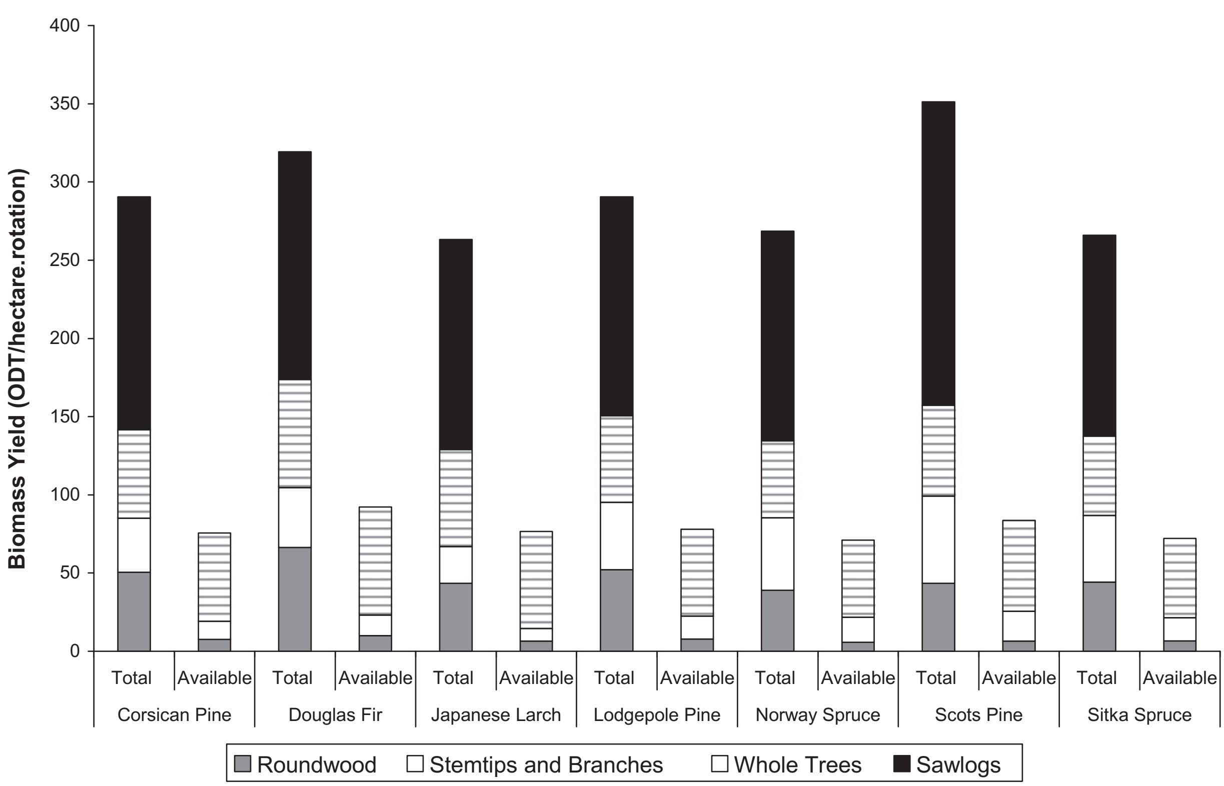

Fig. 3 – Breakdown of yields of forest harvesting residues, roundwood and saw logs from a range of tree species (at yield class 14 for comparison). Potential available and extractable biomass yields are shown.

between 6 and 10 ODT ha. rotation^{-1}. Stem tip and branches from the final clear-fell event yield between 23 (JL) and 56 (SP) ODT ha. rotation^{-1}, though after considering that only 25% can be removed from the forest floor for sustainability purposes the extractable biomass yields range between 8 and 19 ODT ha. rotation^{-1}, and it is assumed that all of this is available for bioenergy. In total between 49 (LP 4) and 115 (NS 22) ODT of stem tips and branches are produced by the forest during all thinning events of one rotation, but between 15 (31%) and 65 (57%) ODT rotation^{-1} of this is assumed to be left on the forest floor for sustainability reasons. In total, whole trees represent between 69% and 81%, stem tip and branch bundles between 14% and 23%, and roundwood between 8% and 11% of the total obtainable biomass from forest harvesting residues.

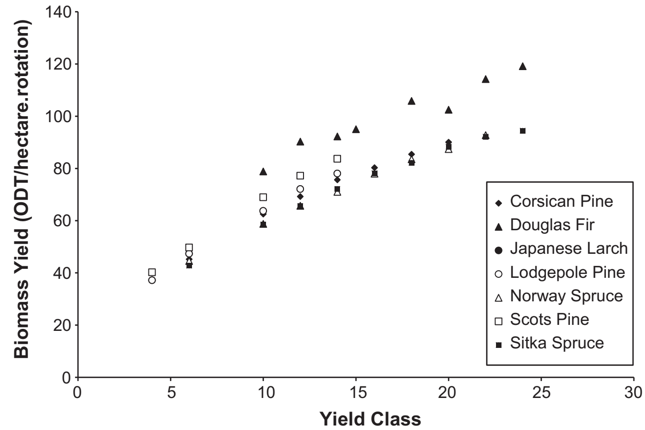

Fig. 4 – Relationship between yield class and biomass yield for 7 softwood tree species.

3.3. *Effect of allocation procedure*

The energy requirements and GHG emission for fuel and material consumption were allocated between biomass, pulpwood and saw logs by two methods: by price and by mass. Only site establishment and road construction events are allocated between biomass and roundwood according to the extractable yield on a mass basis. Material left on the site is not accounted for. When allocated by mass, biomass receives a greater allocation of onsite energy requirements and GHG emissions compared to allocation by price. For both allocation procedures, it can be seen that, as the yield class increases, the overall allocation to biomass decreases. Harvesting fuel consumption and machine requirements remain constant on a per-ODT-basis, explaining the asymptotic nature of Fig. 5.

3.4. *Harvesting and processing*

Fig. 6 compares the GHG emissions from harvesting and chipping of each type of forest harvesting residue, comparing diesel fuel consumption, machinery manufacture and maintenance. Onsite and offsite chipping are also compared. Harvesting whole tree thinnings and roundwood both require passes of both a harvester and forwarder. Therefore, these have higher overall GHG emissions for harvesting compared to brash bundles which are harvested using a single pass machine. Overall, the energy requirements and GHG emissions for harvesting and chipping one ODT of whole trees, before transporting, are 1177 MJ and 85 kg $CO_{2eq.}$, roundwood 1082 MJ and 77 kg $CO_{2eq.}$, and brash bales 740 MJ and 52 kg CO_{2eq}. Transporting wood chips for 50 km requires 73.80 MJ t^{-1} and emits 5.15 kg $CO_{2eq.}$ t^{-1}, compared to 46.26 MJ t^{-1} and 3.23 kg $CO_{2eq.}$ t^{-1} for roundwood and whole trees, and 53.23 MJ t^{-1} and 3.71 kg $CO_{2eq.}$ t^{-1} for brash bales. Therefore, when forest residues are chipped onsite the overall GHG emissions are higher, mainly due to higher GHG emissions from transporting chips compared to logs or composite brash bales (Fig. 6).

3.5. *Brash removal rate*

Fig. 7 shows the effect of the brash removal rate per hectare on overall GHG emissions per hectare. The carbon removal rate was based on a typical carbon content of 50% for wood. The overall GHG emissions are negative, mainly due to the avoided GHG emissions from displacing conventional fossil fuels (in this case coal). When the carbon losses due to residue removal are taken into account this effect is reduced slightly but there are still net $CO_{2eq.}$ savings from removing brash after fossil fuel displacement is taken into account. As the brash removal rate increases, greater biomass yields per hectare mean that greater harvesting GHG emissions are incurred, but also greater fossil fuel displacement is possible. On a per-ODT-basis, between extracting 0% and 100% brash from the site, the GHG emissions increase by a total of 0.47 kg $CO_{2eq.}$ ODT^{-1} for both allocation by price and mass, where a greater percentage of the original site establishment and forest road construction is allocated to the brash.

3.6. *Whole life cycle breakdown*

On a ‘per-ODT’ basis the energy requirements and GHG emissions for harvesting, chipping and transporting will be the same for each species. The energy requirements and GHG emissions from site establishment and road construction

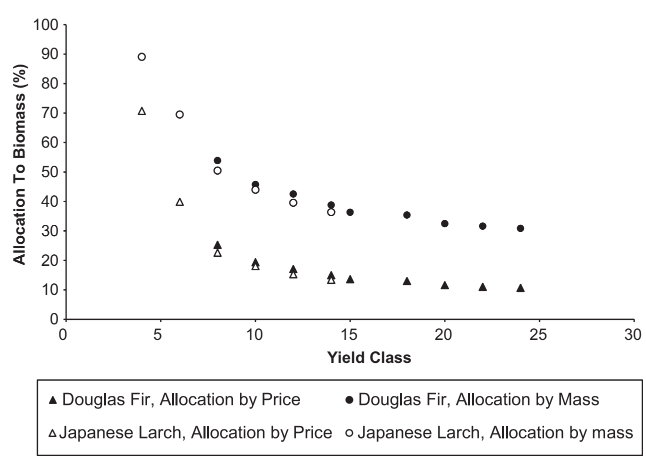

Fig. 5 – Proportion of site inputs and energy consumption allocated to biomass, comparing allocation by price and by mass. Shows the highest (Douglas Fir) and lowest (Japanese Larch) yielding species in this study.

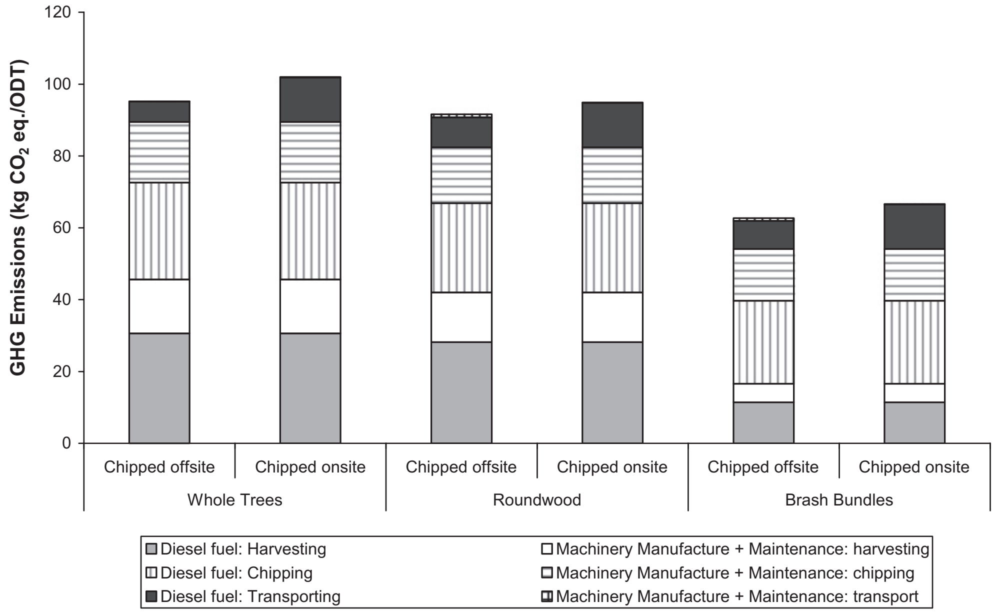

Fig. 6 – Total GHG emissions from harvesting and processing whole tree thinnings, roundwood and brash comparing onsite and offsite chipping. Shows relative contribution of each stage to the overall GHG emissions per ODT of procured biomass.

however, are shared between all products of the forest and, therefore, will depend on the overall yield from the site and the allocation procedure applied. With species with low yields (e.g. JL, 4) the contribution of shared impacts is greater, and the overall GHG emissions per ODT of biomass are higher (Fig. 8). As mentioned beforehand, when allocated by mass, biomass receives a greater allocation of onsite energy requirements and GHG emissions, compared to by allocation by price, but the difference between the two allocation methods is generally small (Fig. 5).

When examining the whole life cycle breakdown for an 'average ODT of forest harvesting residues' with economic allocation, between the highest and lowest yielding species, site establishment accounts for between 0.8% and 7.8% and road construction between 0.1% and 1.1% of the total GHG emissions, respectively. The majority of the GHG emissions are associated with harvesting (46.3–41.7%) and chipping (41.6–38.8%), and a small part transport (11.2–10.6%). When examining the sources of GHG emissions in terms fuel, site inputs or machinery use, the same effect of the allocation procedure can be seen, however, diesel fuel is always by far the most significant source, accounting for over 50% of GHG emissions. Machine manufacture accounts for between of 27.2% and 31% of GHG emissions, and maintenance between 0.6% and 1%. The contribution from 'site inputs', which refers to fencing, herbicides and road surfacing aggregate, is most

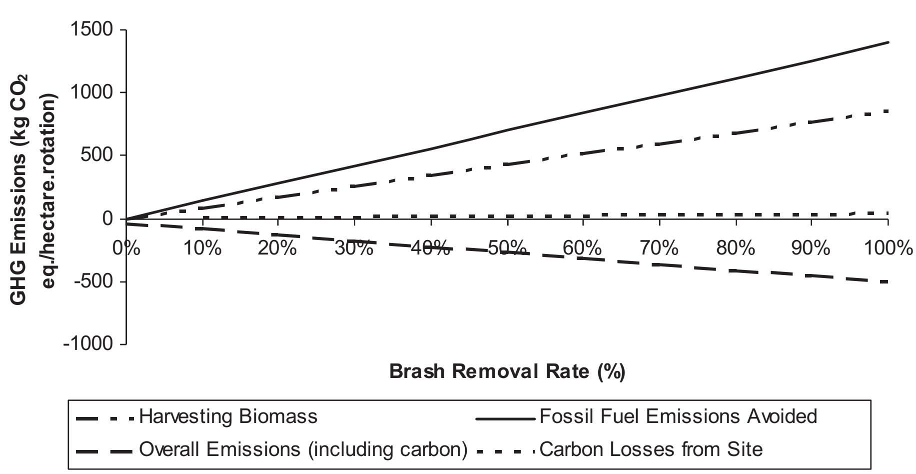

Fig. 7 – Effect of brash removal rate on overall GHG emissions per hectare. Includes GHG emissions from site management, harvesting, and examines the potential for GHG emission displacement from displacing coal with biomass. The example given is Sitka Spruce (Y.C. 10). The avoided GHG emissions are calculated assuming the application in which biomass is combusted gives a similar conversion efficiency to heat or power generation as does coal.

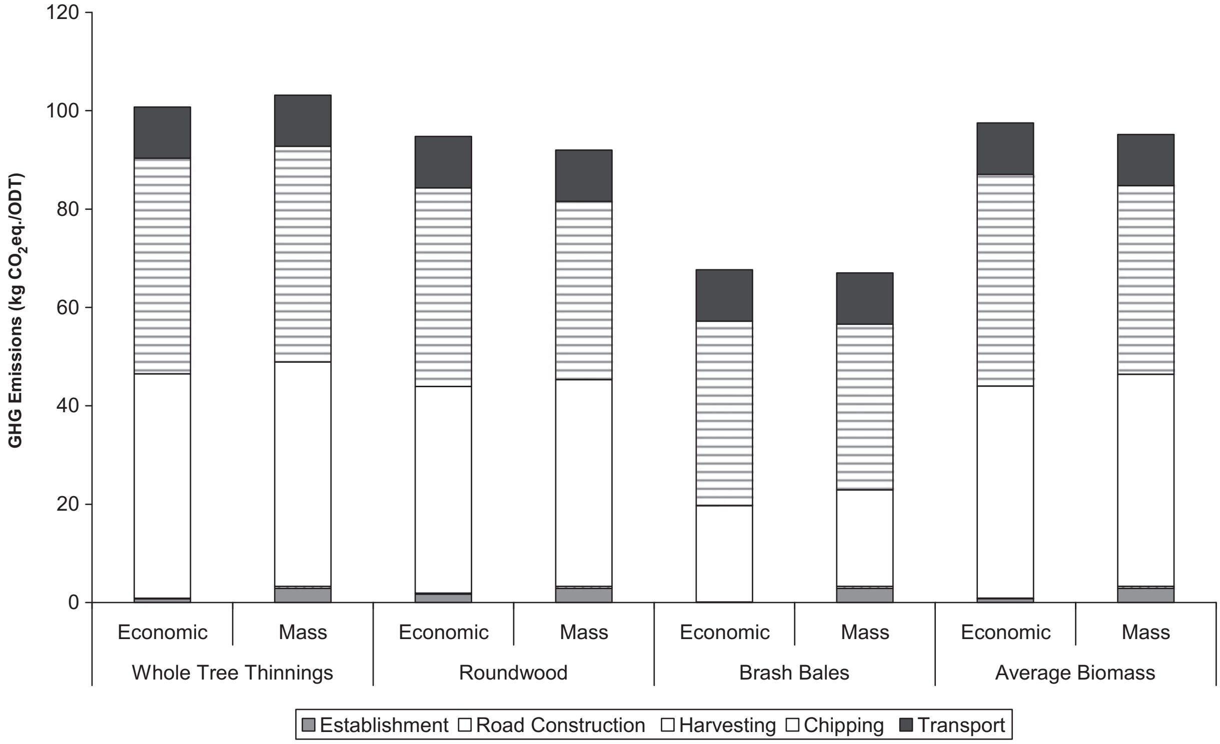

Fig. 8 – Breakdown of the contribution of each phase in the forest life cycle to the overall GHG emissions resulting from the establishment, harvesting, processing and transport of one ODT of wood chips from various forest harvesting residues. Compares high (Douglas Fir, yield class 24) and low yielding species (Japanese Larch, yield class 4).

effected by yield, ranging between 0.5 and 8.5%. Overall, roundwood has a greater allocation of GHG emissions from shared operations when allocated both by price (due to the higher price associated with roundwood), and by mass (due to lower yield of available roundwood for biomass), but this is overwhelmed by the larger diesel fuel requirement for harvesting, chipping and transporting whole trees due to their low bulk density.

Table 5 summarises the total energy requirements and GHG emissions for producing one ODT and one MWh of each forest harvesting residue in the form of chips. The example given in Table 5 is for Sitka Spruce, yield class 20. One tonne (at 30% moisture content) of 'average forest residues' has a net calorific value of 12.1 GJ t^{-1}, or 3.36 MWh t^{-1}, and can displace approximately 0.5 t coal (assuming 25.2 GJ t^{-1}) and 0.3 t natural gas (assuming 35.7 GJ t^{-1} [39]), with relative energy savings of 96% and 97%, and GHG emission savings of 96% and 94% (assuming same percentage conversion efficiency to energy). When this is placed in context with the current estimated forest-based biomass resource potential for the UK

Table 5 – Summary of energy requirements and GHG emissions for establishing, harvesting, chipping and transporting each forest harvesting residue on a per ODT and per MWh-basis, assuming an energy content of 12.1 GJ/tonne, or 3.36 MWh/tonne and a moisture content of 30% wood chips. Methane and nitrous oxide emissions from biomass combustion have been included. This assumes that the application in which biomass is combusted gives the same conversion efficiency to heat or power as does coal or natural gas.

Summary		Primary Energy Requirement	Carbon Dioxide Emissions	Methane Emissions	Nitrous Oxide Emissions	Greenhouse Gas Emissions
Biomass	Units	MJ	kg CO_2	kg CH_4	kg N_2O	kg $CO_{2eq.}$
Whole tree thinnings	Per ODT	1343.72	94.34	0.058	0.002	96.43
	Per MWh	399.78	28.07	0.017	0.001	28.69
Roundwood	Per ODT	1276.19	89.12	0.054	0.002	91.07
	Per MWh	379.69	26.52	0.016	0.001	27.09
Brash bales	Per ODT	892.68	62.65	0.036	0.001	63.95
	Per MWh	265.59	18.64	0.011	0.000	19.03
Average forest harvesting residues	Per ODT	1272.43	89.31	0.055	0.002	91.27
	Per MWh	378.58	26.57	0.016	0.001	27.15
Coal	Per MWh	3646.80	306.61	0.940	0.027	338.12
Natural gas	Per MWh	3996.00	193.97	0.403	0.000	204.16

(1309 ODT yr^{-1} roundwood and 440 ODT yr^{-1} branches and stem tips per year [2]), forest biomass has the potential to displace 840 t coal or 593 t natural gas, saving 1840 and 1053 t of $CO_{2eq.}$ yr^{-1} in the UK, respectively. The additional 1 million ODT yr^{-1} forest biomass could save a further 1,045,177 and 659,034 t $CO_{2eq.}$ yr^{-1} if used to displace coal or natural gas, respectively.

4. Discussion

Forest road construction is a highly energy and GHG emissions-intensive operation, requiring large amounts of aggregate per km and a high degree of maintenance. The process is also associated with high diesel fuel consumption (approximately 4.7 l m^{-1}). When placed in context with the actual road density of forest roads (less than 0.01 km ha^{-1}) and the whole rotation and total yield of biomass, the overall impacts from road construction are smaller than those for site establishment, harvesting, chipping and transport. The site establishment phase is still, however, very small, contributing between 0.8% and 7.8% to the total GHG emissions, depending on the biomass yield over the rotation.

The overall energy requirement and GHG emissions from forest roads will depend on the maintenance frequency assumed, and how these emissions are shared between each ha of forest and its products [13]. After performing the original analysis, it was discovered that forest roads are sometimes constructed with a purposely ‘sacrificial’ layer that is allowed to gradually erode over time.. Maintenance events for these types of road involve re-grading without re-applying aggregate, and this method of maintenance would have a smaller energy and GHG emissions impact than observed in this study. The Type A road density examined in this study was 0.008 km ha^{-1} which is higher than the average in the UK (0.005 km ha^{-1}). For Type B roads, however, the density was lower than average (0.007 km ha^{-1} compared to the average of 0.011 km ha^{-1}). The frequency of road maintenance events will, however, vary across forest districts, depending on frequency of use, intensity of use, and original road construction. At least, road maintenance events required for forest harvesting should be taken into account in a forest residue LCA.

Generally, it was found that higher yielding sites give lower overall energy requirements and GHG emissions on a per-ODT-basis compared to lower yielding sites. With higher yielding sites, there is a greater share of the original site establishment and road construction events between each tonne of forest material leaving the site. This is true for both allocation procedures, though the difference between them is small. When examining energy requirements and GHG emissions on a per hectare basis, harvesting and chipping larger quantities of biomass on more productive sites requires a greater overall diesel fuel requirement and therefore overall management GHG emissions are higher on the per hectare basis. The same conclusion can be made when extracting brash, as extracting larger amounts has a negligible effect on the increased allocation from site establishment or road construction phases, but has overall higher GHG emissions per hectare if more biomass is extracted. Greater quantities of biomass however, ultimately mean greater displacement of conventional fuels, and therefore greater potential for global climate change mitigation. This effect is seen to overcome soil carbon losses contained within the residues (Fig. 7). The study assumes that stem tips and branch residues created during thinning events are not extracted from the site, and are thus left on the forest floor. This results in brash deposits of between 15 and 65 ODT ha. $rotation^{-1}$ compared to a removal rate of 8 and 19 ODT ha. $rotation^{-1}$. It is assumed that carbon losses from the forest soil are directly related to the carbon contained within the extracted material

The largest and most significant energy use and GHG emissions occur from diesel consumption during the harvesting and chipping phases, and in smaller part, transportation. On a per-ODT-basis, the energy requirement and GHG emissions from transporting wood chips are greater than for logs, whole trees and brash bales. This is due to the relatively low bulk density of wood chips meaning that less can be transported in a single load. There is also a possibility that chippers at central processing sites will be more efficient that those used for mobile chipping; consequently offsite chipping, close to the consumer, would have even more favourable energy and GHG emission balances. Chipping is an effective way to increase material heterogeneity and handle-ability compared to logs and bales, yet storability is negatively affected by chipping [40], as well as providing more opportunities for material losses to occur throughout the supply chain. Once chipped, biomass should be used within 14 days, as chips are more susceptible to fungal attack, which can lead high dry matter losses, risk of spontaneous ignition, and health risks [5,41]. Otherwise, the wood chips would require ventilated storage which would not only be costly but lead to greater GHG emissions from fuel consumption for ventilator fans and, it has been suggested, that methane GHG emissions may be released from the anaerobic regions of the slowly composting wood chip stack [42]. If biomass is not used within this 2 week window, the best option is to leave the material at the roadside [43], where it will retain its fuel quality and incur a lower dry matter loss [41]. Storage at the roadside also promotes natural drying so that, when transportation eventually occurs, it contains less water [44]. In general, the largest possible trucks should be used for transporting low bulk density biomass [44].

The results from this study can be used to predict the GHG mitigation potential from using all available harvesting residues from commercial conifer forests in the UK, as described by [2], to displace fossil fuels for heat or electricity production. Applying the results from this study, the current estimated conifer forest-based biomass resource has the potential to reduce UK GHG emissions by 1,047,017 or 595,973 t $CO_{2eq.}$ yr^{-1} if used to displace coal or natural gas, respectively. The study could be replicated to encompass broadleaved species under a clear-fell management, though a different approach would be required as no hardwood roundwood is utilised for pulp, and the economic value of saw logs will range between species. BSORT can produce yield figures for oak, beech, poplar and sycamore grown in commercial plantations but another yield model would be required to study other forestry harvesting systems, such as continuous cover and shelterwood silvicultural systems, which would require motormanual harvesting operations [45]. There is also a significant amount of biomass potentially available in neglected broadleaved forests [46]. In order to assess the GHG balance of harvesting these residues, however, the LCA would require different systems boundaries, time scales, as well as different machinery and deal with different terrain with varying sustainability impacts of residue removal.

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