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Research paper

Understanding the timing and variation of greenhouse gas emissions of forest bioenergy systems

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ABSTRACT

Forest-based bioenergy plays an important role in climate mitigation for limiting global mean temperature increase to below 2 °C. The greenhouse gas (GHG) impact of three forest-based bioenergy systems from the USA, Canada and Spain supplying wood pellets for electricity in the UK were evaluated by conducting lifecycle assessments and forest carbon modelling of the three forest systems. Cumulative emissions were analysed by calculating the forest carbon stock change and net GHG emissions balance of the forest-based bioenergy electricity. The analysis considered both the replacement of the existing electricity mix with bioenergy electricity and forest management with and without bioenergy use. The supply chain emissions and forest carbon balances indicated that GHG emission reductions are possible. However, the cumulative net GHG balance at forest landscape scale revealed that the reduction potential is limited, potentially with no GHG reductions in fast growing forests with shorter rotations, while slow growing forest systems with longer rotations result in greater GHG reductions. This means that the maximum climate benefit is delivered at a different point in time for different forest systems. To evaluate the climate change mitigation potential of forest-based bioenergy it is therefore necessary to consider the management, utilisation and relevant counterfactual of the whole forest and its products. In terms of climate change mitigation potential and minimising possible negative impacts that would require multi-level governance.

1. Introduction

Cumulative greenhouse gas (GHG) emissions and emission budgets are central in the IPCC emission scenarios [1] and as part of the Paris Agreement many countries have adopted emission budgets as part of their national climate mitigation strategies [2]. Avoiding dangerous climate change requires actions to limit the cumulative quantity of long-lived GHG's, like CO_2, released to atmosphere over time to stay within the agreed emission budget [2]. This is not the same as reducing the amount of emissions for a particular year, nor as meeting long-term GHG reduction targets, which describe intermediate reduction rates and endpoints. The emission budget determines the pathway and if the pathway changes, e.g. the budget is exhausted faster or slower, the reduction rates and reduction targets change [3].

Negative emissions from forest-based bioenergy plays an important role in the IPCC's low emission scenarios. Bioenergy provides opportunities for atmospheric CO_2 removal through biomass growth.

Since the rate of CO_2 removal from the atmosphere by biomass/forest growth varies with time, the potential for a bioenergy system to contribute to GHG reductions against emission budgets also varies with time. This work aimed to establish how tree species, forest rotation period or management regime make a difference to that potential contribution. This information is important to verify the conditions under which forest biomass can contribute to GHG reductions and identify any constraints related to forest type, location or management regime, which may limit the utility of forest biomass in climate mitigation.

Frameworks which consider all biogenic carbon within plants to be carbon neutral [4–6] simplify implementation and are reasonably accurate for bioenergy systems where carbon sequestration and release are temporally close e.g. annual crops, but fail to capture the more complex carbon dynamics of forests. Additionally, accounting methods

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deliver varying results depending on the scope and boundaries of the investigated system [7–11]. Such discussions about and criticism of forest-based bioenergy systems and accounting frameworks show the importance of timing related to biogenic carbon emissions that are not necessarily compensated for by contemporaneous sequestration and the accumulation of carbon and emissions in forests, forest products or atmosphere [4,12,13]. The temporal framing of forest carbon stocks and flux differs between forest type and forest management as work by others has shown [14–22]. This creates additional variation and uncertainties when assessing carbon dynamics and the possible climate change mitigation potential of forest-based bioenergy.

The evaluation of emissions from forest-based bioenergy systems needs to consider the bioenergy feedstocks in the context of the whole forest product value chain, which relates back to setting the system boundaries. Biomass feedstocks can be procured either from purpose-grown plantations for bioenergy production, or from forests that are grown and managed for a wide range of products (lumber, panel, pulp). In the latter case, feedstocks are sourced from primary (thinning, harvest) and secondary (wood processing) residues or from low-quality roundwood with no other industrial use [23–25].

One of the most common ways to use forest residues as bioenergy feedstock is in form of wood pellets. Wood pellets are increasingly a globally traded commodity delivering energy often far away from their original point of production. The United Kingdom (UK) is currently the largest importer of wood pellets to produce large-scale electricity [26,27] and therefore has been used as the energy producer case study for this research.

This work aimed to evaluate the climate change mitigation utility and significance of variations of the net GHG balance across a range of forest types, locations, rotations and management regimes. This information is needed to inform policy and governance systems designed to deliver genuine GHG reductions. For this, three different supply chains based on different forest systems and regions were investigated: temperate forest in South East USA; temperate forest in Asturias, northern Spain; and boreal forest in Quebec, Canada. These forests provide different types of residual feedstocks (thinnings, degraded wood, harvest residues, processing residues) or purpose grown biomass, which is processed to wood pellets and used for electricity generation in the UK.

Additionally, different forest management options were considered, to investigate the effects of management changes on the forest carbon stocks and net GHG balance. While other research often considers just one forest region with changes in management for bioenergy feedstock sourcing [9,18–20,22,28–33], this research evaluates contrasting bioenergy supply chains that avoid product competition from different global regions and forest systems.

For each supply chain a suite of three assessment methods were applied:

1. Lifecycle assessment (LCA), to evaluate GHG emissions (including CO_2 and non-CO_2 emissions) of the supply chain processes and activities at each point of occurrence.
2. Forest carbon modelling, to assess the carbon balance of the forest stands, evaluating the amount and dynamics of the carbon sequestration and release in the forest system.
3. GHG balance assessment (incorporating LCA and carbon forest modelling in a cumulative emissions framing).

These facilitate evaluation of the climate change mitigation potential of the forest-based bioenergy electricity. Carbon stocks, fluxes and emissions of the whole forest system (including forest, products and bioenergy feedstocks) as well as supply chain emissions related to bioenergy at forest landscape scale were assessed. To assess the net GHG balance, the results were compared to reference scenarios, considering alternatives to the bioenergy electricity application by expanding the system boundaries to the whole forest-wood product-bioenergy system.

The combination of assessment methods is required to assess if forest-based bioenergy electricity can make a meaningful contribution to climate change mitigation by decarbonising the energy sector and supporting atmospheric CO_2 removal when considering the amount and timing of cumulative sequestration and emissions of forest-based bioenergy.

2. Methods and material

2.1. Supply chains and forest management

Three supply chains from three different forest regions providing wood pellets for bioenergy electricity in the UK were investigated. The forest regions analysed were: temperate forests in South East USA; temperate forests in Asturias, northern Spain; and boreal forests in Quebec, Canada. South East USA is currently the most common origin for wood pellets used for the UK's bioenergy electricity generation and one of the main supply chains of industrial wood pellets from softwood globally [34]. Canada is also an exporter to the UK, with pellets mostly originating from British Columbia [35]. The wood pellet production and export potential of Quebec is currently being explored [23]. Spain was selected to investigate a potential feedstock of fast growing biomass from a European origin with increasing relevance for the bioenergy sector [36] and to allow comparison of a much shorter rotation, purpose grown feedstocks.

The forest management regimes were not standardised for comparative purposes. Instead, the assessment was based on typical management regimes likely to be experienced in economically productive forests in each of the three region. Different forest management and procurement options were assessed to investigate the effects of management changes on the forest carbon and net GHG balance. Large-scale electricity generation in the UK was assumed for the final use of the wood pellets. Forest management practices were assumed to be compliant with UK sustainability standards and policies [5,37–39]. This requires no changes to forest management practices or land use that could cause negative/unsustainable environmental impacts to the forest system and so it was assumed that there was no land use change from the existing, sustainable forest cover.

The current level of bioenergy electricity production in the UK is 12.7 TWh, mainly generated in large-scale facilities [26], requiring about 7 Mt wood pellets per year. It was assumed that bioenergy electricity generation levels will not change significantly in the UK in the future [35,40–43] and so this was taken as the feedstock demand with full specifications and feedstock demand for the investigated supply chains provided in supplementary material A.1.

2.1.1. USA forest system and supply chain

The geographic region considered is Georgia, USA. Loblolly pine (*Pinus taeda*) plantations are grown under intensive management in a 25-year rotation. This is based on a typical management regime practiced in this region. At establishment, fertilisers and herbicides are applied. After 15 years, the forest is thinned and receives another fertiliser application. After 25 years, the forest is harvested with a clearcut. The main products are pulpwood at the 15-year thinning and final clearcut after 25 years, which also provides some lumber [44–46]. Biomass for energy is sourced from thinnings as small trees and as forest primary residues (branches and tops) and secondary residues (wood chips, shavings and sawdust) from wood processing. Therefore, two different forest management and procurement variants were investigated with different proportions of thinnings used for bioenergy. With the slowing growth of the pulp and paper industry, it is feasible that an increasing share of thinnings and pulpwood is freed up for other uses such as bioenergy (**Variant 1a** 50% and **Variant 1b** 100% of thinnings being used for wood pellets). The counterfactual is the supply chain with conventional forest products (pulp and paper, lumber), primary residues are left in the forest, sawmill residues are disposed at the sawmill dumpsite and there is no sourcing of bioenergy feedstocks.

2.1.2. Spanish forest system

The geographic region considered is Asturias, Spain. Eucalyptus (*Eucalyptus* L'Hér. 1789), a fast growing species, is grown in plantations with a rotation length of 32 years. This management system is typical for the region, currently supplying the pulp and paper industry, but with a trend to grow eucalyptus as a bioenergy feedstock instead [36]. At establishment, fertiliser and herbicide are applied. After 16 years, the trees are coppiced and the stand receives another fertiliser application. After 32 years the stand is harvested, all stumps are removed and the plantation is re-established [36,47]. Both cuts are used for bioenergy only. Two different management variants were investigated with different rates of residue removal: **Variant 2a**: no residues removed and **Variant 2b**: 50% of residues being removed for wood pellets. The counterfactual is a pulp and paper supply chain with no sourcing of bioenergy feedstocks and no removal of residues.

2.1.3. Canadian forest system

The geographic region considered is Quebec, Canada. The forest is a typical eastern boreal stand dominated by eastern balsam fir (*Abies balsamea* (L.) Mill) [48]. There is no site preparation and all trees regenerate naturally; still, this is a commercially managed forest grown for timber production. After 70 years, the forest is harvested with a clearcut. The main products from harvested softwoods are lumber and pulp, while hardwoods are used for pulp. Biomass for energy is sourced from harvest and processing residues, which do not compete with or displace fibre for other wood products.

A total area of about 20 million hectares of forest are currently affected by wildfire or insect epidemics in Canada [49]. Fibre quality of dead or dying trees can decrease rapidly due to the action of wood-rot fungi, and trees can no longer be processed into lumber or pulp [50]. When a large proportion of trees within a stand is degraded, harvesting of the stand becomes non-profitable even though it may still contain sound roundwood [23]. Degraded trees could serve as feedstock for bioenergy since the fibre quality requirements are less stringent than for lumber or pulp. As described by others [23,51], harvesting degraded trees for bioenergy could provide an economic opportunity and clear naturally disturbed forests to re-establish healthy stands. Since this represents a potentially significant biomass resource a supply chain variant has been included that assesses the carbon dynamics of a forest affected by a natural disturbance.

Two different management regimes were investigated for the Canadian forest system:

Variant 3a; an unaffected forest where harvest residues and processing residues are used for bioenergy with the counterfactual of conventional forest products only and no bioenergy

Variant 3b; an affected forest with sourcing of low-quality wood for bioenergy and sound wood to products. In this case, the counterfactual is not to harvest the forest at all but leave it untouched.

All supply chains had an increased removal rate of residues for bioenergy, which affects the forest carbon stocks. This was accounted for in the carbon model. Full details on forest management, yields, type and share of the different wood products and residues removal rates for the different variants and counterfactuals, are provided in Table 1 and the supplementary material A.2.

2.2. Lifecycle assessment

Attributional lifecycle assessment (LCA) was conducted with the goal of investigating the GHG emissions of the different supply chains from generating electricity in a power station with dedicated biomass boilers. The LCA followed the ISO Standard 14040:2006 and 14044:2006 [52,53] and calculations were done in SimaPro 8.3 using the Ecoinvent database and the IMPACT 2002 + V2.13 method [54]. Global warming potential (GWP) was selected as the impact category. The final unit of measurement was kilograms of CO_2 equivalent (eq) mass per MWh; this included CO_2 and non-CO_2 emissions. The functional unit was 1 MWh of generated electricity from wood pellets. A midpoint LCA approach was taken to facilitate comparison of supply chains and allow the LCA results to provide inputs to the cumulative emission assessment. Full details of the LCA methodology are provided in the supplementary material A.3, but the scope included: site preparation, forest establishment and management including fertiliser and herbicide application where relevant, harvest and feedstock handling, feedstock processing, transport and electricity generation (Fig. 1). It was assumed that the feedstock was collected at forest and processing sites, transported to a local pellet mill and processed into wood pellets. The pellets were transported to a regional port where they were loaded and shipped to the UK. At the UK port, the pellets were loaded onto trains and brought to a power station with dedicated biomass boilers where electricity was generated in a 650 MW biomass boiler unit.

The focus of the research was the climate change mitigation potential of forest-based bioenergy electricity assessing the cumulative emissions and net GHG balance. Therefore, upstream inputs and emissions related to forest establishment and management were included for bioenergy feedstocks and allocated by mass. Allocation by energy would have been appropriate if multiple energy products were investigated. Allocation by economic value would have resulted in a lower emissions to the pellets as under current market conditions as the value of residues is much lower compared to conventional wood products. The results would be sensitive to market forces but not consistent with the goal and scope focussing on the actual amount of carbon. Some methodologies suggest not allocating any upstream emissions to residual material [5,53,55]. Even though the main products are lumber and pulp, the calculations have been tailored to recognize that there is a demand for wood pellets from residues and therefore a proportion of upstream emissions based on mass should be allocated to residues.

Sensitivities related to emissions of supply chain activities were considered but not included in the discussion as detailed discussions on aspects like transport, processing, storage, energy conversion, carbon debt, allocation methods or system boundaries have already been reported by others [20,56–59] and are not the main focus of this work. The cumulative emissions assessment allowed evaluation of the sensitivity of the carbon balance to forest management and choice of reference cases. The full data inventory of the LCA is presented in the supplementary material A.4.

2.3. Forest carbon modelling at forest stand scale

The LCA system boundaries and allocation method capture the processes directly related to the wood pellet supply chain. The carbon model system boundaries are designed to capture comprehensively the forest product fractions and carbon dynamics, including living and dead biomass and wood products with stocks and fluxes of the different carbon pools, including those routed to bioenergy (Fig. 1). This is particularly relevant for the two North American forest systems, where bioenergy feedstocks are part of an array of products. In the forest carbon model the amount of carbon sequestered, stored and released in forest and products was assessed for each of the described forest systems and management variants using CO2FIX Version 3.2.0 [60,61]. This allowed the assessment of the carbon balance (stocks and fluxes) in the forest and wood products at forest stand scale. Data for the stem volume growth and tree compartment allocation was taken from Refs. [45,62–66] and is presented in detail in the supplementary material A.5. The carbon model included carbon stocks and fluxes for all living and dead biomass and forest soil carbon, typical for the selected tree species, geographic and climatic characteristics, management system and wood products considering decomposition of organic matter,

Table 1
Supply chain and forest management settings, biomass production and feedstock availability for supply chains USA, Spain and Canada (values calculated in CO2FIX and via bottom-up approach as detailed in supplement material A.1). All mass given as dry matter.

	Unit	USA			Spain			Canada		
Geographic coordinates (rounded)		33 N, 84 W			43 N, 6 W			50 N, 76 W		
Age at thinning/coppicing activities	y	15			16			n/a		
Age at final harvest activities	y	25			32			70		
Total biomass yield without foliage	t ha^{-1}	130			388			157		
Thinnings/coppicing	t ha^{-1}	23 (stems) + 5 (tops)			158 (stems) + 14 (tops)			n/a		
Stems (final harvest)		95			198			131		
Tops and branches (final harvest)		12			18			26		
		Counter factual	Variant 1a	Variant 1b	Counter factual	Variant 2a	Variant 2b	Counter factual	Variant 3a	Variant 3b
Utilisation of thinnings/coppicing	%	100% pulp	50% pulp 50% bioenergy (BE)	100% BE	100% pulp	100% BE	100% BE	n/a	n/a	n/a
Utilisation stems, final harvest	%	75% pulp 25% lumber	75% pulp 25% lumber	75% pulp 25% lumber	100% pulp	100% BE	100% BE	44% pulp 56% lumber (variant 3a) No harvest (variant 3b)	44% pulp 56% lumber	33% pulp 42% lumber 25% BE (low-quality wood)
Utilisation harvest residues, final harvest	%	100% on forest floor	50% on forest floor 50% BE	50% on forest floor 50% BE	100% on forest floor	100% on forest floor	50% on forest floor 50% BE	100% on forest floor	50% on forest floor 50% BE	50% on forest floor 50% BE
Utilisation sawmill residues	%	mill dumpsite	100% BE	100% BE	n/a	n/a	n/a	mill dumpsite	100% BE	100% BE
Total biomass available as BE feedstock per rotation	t ha^{-1}	n/a	34	50	n/a	306	333	n/a	33	64
Thinnings/coppicing/degraded wood	t ha^{-1}	n/a	12	28	n/a	136	148	n/a	0	36
Harvest residues, final harvest	t ha^{-1}	n/a	6	6	n/a	170	185	n/a	14	14
Sawmill residues	t ha^{-1}	n/a	16	16	n/a	0	0	n/a	19	14
Energy available per rotation (after losses)	MWh ha^{-1}	n/a	48	58	n/a	503	547	n/a	42	82
Area required per annum for generating 12.7 TWh electricity	ha	n/a	264,892	197,193	n/a	25,238	23,213	n/a	299,425	154,165

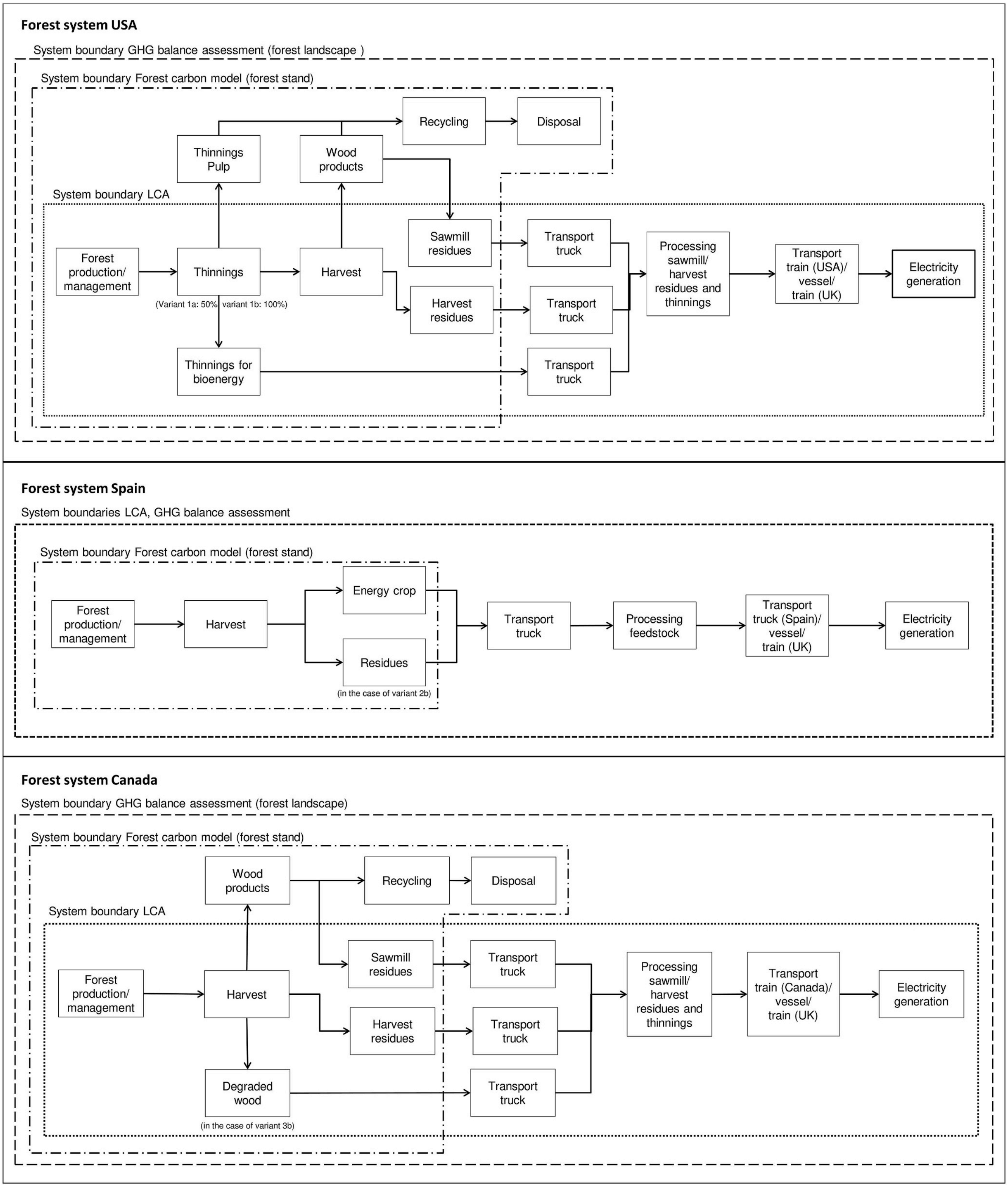


Fig. 1. System boundaries for LCA, carbon model and GHG balance assessment. Different system boundaries allow looking at different aspects of the bioenergy system (supply chain GHG emissions, forest carbon balance, net GHG balance). Forest system USA: variant 1a and 1b (variant 1b with larger amounts of thinnings for bioenergy); Forest system Spain: variant 2a and 2b (variant 2b with larger amounts of residue removal for bioenergy); Forest system Canada: variant 3a and 3b (degraded wood as feedstock for variant 3b, but not an existing forest product in variant 3a).

lifespan of products and final use and disposal. Wood products' main use was allocated according to the forest systems (e.g., pulp wood or lumber production) with bioenergy feedstock considered as part of the product basket. Default settings in CO2FIX were kept for decomposition, lifespan and final fate of the products to allow comparability and decrease sources of variation and uncertainty. The lifespan for biomass allocated to bioenergy was considered as one year with the final fate of combustion for electricity generation. It is possible that wood products are used for energy generation at their end of life (e.g. as mixed waste or separated wood waste). However, this amount of carbon removed from the system was not allocated to the bioenergy category as final location of disposal and type of disposal (potentially landfill or/and energy conversion) has a high level of uncertainty. The changes of carbon stock related to wood products at their end of life are therefore expressed as a decrease in carbon stock and not as emissions. Full details of the carbon model settings can be found in the supplementary material A.5-8.

The results present the carbon balance as CO_2eq mass per unit area on an annual basis over 200 years of a forest stand with trees of uniform age and the above described rotations.

Soil carbon stocks were included in the calculation. It was assumed that land use does not change (continuous forest). Forest soil carbon is complex but usually recovers after time when land use is not changed and the forest is re-established [67–69] and is not significantly affected when about 50% of residues are sustainably removed [69,70]. These parameters and the biomass allocation for wood products/bioenergy use were set in the CO2FIX model to calculate changes in the different carbon pools (forest, soil, products) with time.

2.4. GHG balance of forest landscapes

For assessing the GHG balance and cumulative emissions of forest-based bioenergy electricity, the Results from the LCA and forest carbon model were incorporated in a forest landscape consisting of forest stands of successive ages. While the carbon balance was modelled for a forest stand of uniform age with harvest and feedstock sourcing during the years of thinning/coppicing and harvesting activities, this would not provide any information on the carbon accumulated and GHGs emitted across a whole forest landscape providing bioenergy feedstock on a year-by-year basis. Attributing for the annual electricity generation of 12.7 TWh, it was assumed that each forest stand was sized at the required area to produce the annual amount of wood pellets to cover the UK's demand. This means that the forest landscape has constant boundaries as described by Cintas et al. [24] and is not expanding as every year one forest stand successively reaches maturity and is harvested. However, for the affected Canadian forest (variant 3b), the forest area needed to expand to provide sufficient feedstock once the affected forest was re-established to a healthy stand, since an unaffected stand provided a smaller amount of bioenergy feedstock.

In the case of forest management with thinning or coppicing activities, feedstock can be sourced from two stands annually; the stand with thinning/coppicing and final harvesting activities. These two stands were combined in terms of feedstock availability and the forest area required for wood pellet production was calculated correspondingly.

Based on the LCA and the forest carbon model, the GHG balance assessment provides the net carbon flux including the cumulative carbon sequestered in forest and products and the related cumulative carbon emission released from bioenergy electricity generation. The assessment of net carbon flux allowed identifying the point in time when more carbon was sequestered than released and vice versa. Once the GHG emissions from the supply chain were included in the net carbon flux, this effectively represents the GHG balance of the forest system with bioenergy.

The accounting started with the harvest of the first mature forest stand as this is the first time bioenergy can be generated. The time horizon for the GHG balance assessment was 100 years.

Following the counterfactuals of the supply chains describing what would have happened if no biomass was used for bioenergy [53,71,72], the results of the GHG balance were compared to two reference cases representing the alternative to generating bioenergy electricity from wood pellets. From this, the cumulative net GHG balance was calculated evaluating which system (forest-based bioenergy electricity or the references case) is more beneficial in terms of climate change mitigation over the investigated timeframe of 100 years. The value of the net GHG balance was calculated by subtracting the cumulative GHG balance of the reference case from the cumulative GHG balance of the forest system [24,28].

The following two reference cases were considered:

1) Energy generation: This reference case considers the UK grid electricity with an emission intensity of a CO_2eq mass of 392 kg MWh^{-1} [73]. The UK's grid electricity is a mix of fossil and renewable fuels with the largest shares of renewables from solar and wind [26]. It can be argued that bioenergy electricity is part of the mix but currently the fraction of wood pellet derived electricity is less than 4% of the total electricity generated. Existing emission reporting frameworks are inadequate to capture the full balance of international bioenergy supply chains as only territorial emissions of a country is accounted for and bioenergy is considered as carbon neutral. This means, a forest producing nation (e.g., USA, Spain, Canada) accounts for the sequestered carbon in forests and the carbon flux in the case of harvest, while the bioenergy electricity generating nation (e.g., UK) considers only supply chain GHGs released on their territory excluding the biogenic carbon release during the energy conversion process. For consistency and comparability with other work, the energy generation reference here is taken as the reported GHG intensity of the UK electricity mix, whilst noting that this is a slight underestimate since the small proportion of existing bioenergy from overseas imports is ignored. As this is a reference case being subtracted from the fully comprehensive accounting carried out in this work the net impact will be a very slight underestimation of the climate benefit of implementing bioenergy electricity compared to the existing electricity mix.

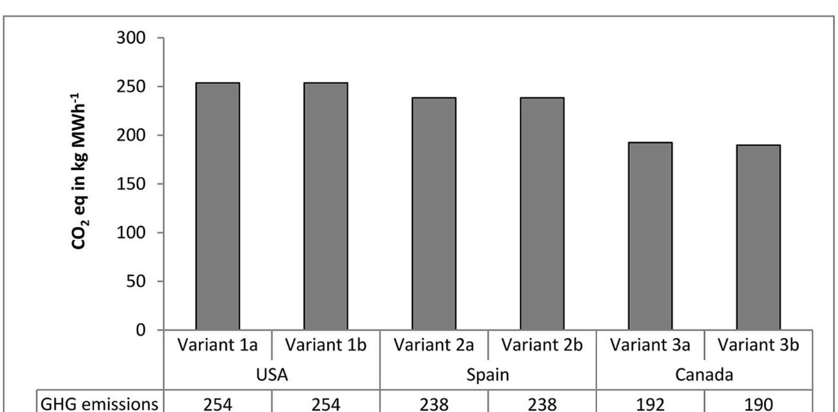


Fig. 2. Total supply chain emissions of the different forest supply chains and management variants using the LCA system boundaries as described in Fig. 1.

2) Forest production: This forest management reference case incorporates forest management for conventional products only with no bioenergy use (as described in the supply chain counterfactuals). The 12.7 TWh electricity still would need to be generated and come from other sources. For this case the UK electricity grid mix with an emission intensity of a CO_2eq mass of 392 kg MWh^{-1} [73] was considered.

These reference cases are effectively expanding the system boundaries to describe cause and effect of the related forest and energy systems. Calculating the cumulative net GHG balance allows evaluation of the relative climate change mitigation impacts of: forest management with bioenergy electricity; or forest management with biomass use for other products (either leaving residues in the forest or disposing of processing residues (according to the supply chain counterfactuals) and UK grid electricity.

The calculations acknowledge that the emission intensity of the UK electricity will decrease to a CO_2eq mass of 2 kg MWh^{-1} by 2050 due to the legally binding UK Climate Change Act and set carbon budgets [74] and the reference case assumes that this would be achieved with wind, solar and nuclear, as described in the supplementary material A.9.

3. Results

The results are presented for each of the three different forest systems in the sections below:

- Section 3.1: LCA results of the three supply chains
- Section 3.2: Forest carbon modelling results of the three forest systems at forest stand scale
- Section 3.3: GHG balance results of the three forest systems at forest landscape scale

3.1. Lifecycle assessment

The results of the LCA (Figs. 2 and 3) present the GHG emissions related to supply chain processes and activities within the described system boundaries of growing and managing forest, wood pellet production, transport and generating electricity. The results do not include the biogenic carbon, which is dealt with in the forest carbon model, reported in section 3.2 and incorporated in the GHG balance results in section 3.3. .

Fig. 2 illustrates the supply chain emissions of the different variants of the three supply chains. The GHG emissions per unit of energy related to the USA (CO_2eq mass of 254 kg MWh^{-1}) and Spanish supply chains (CO_2eq mass of 238 kg MWh^{-1}) are similar while the Canadian supply chain (CO_2eq mass of 190 kg MWh^{-1} to 192 kg MWh^{-1}) emits about 20%–25% less GHGs. This is mainly due to natural regeneration of the forest and hydro electricity used for processing activities in the Canadian system. The considered changes in forest management do not significantly change the supply chain emissions per unit of energy as the same amount of pellets is required to produce the same amount of electricity. Emission figures are given only for years in which activities (and therefore emissions) occur. All other years incur zero emissions.

The GHG emission profiles in Fig. 3 a-c show that all three supply chains incur low or no emissions during establishment (year 0). Emissions during year 15 and 16 related to feedstocks from thinning and coppicing in the case of the USA and Spanish supply chains are caused by intermediate harvest activities and mid-rotation fertiliser application. The main share of GHG emissions occur at the stages of harvest, feedstock processing and transport; year 16 and 32 in the Spanish case and year 25 in the USA case. In the Canadian supply chains emissions occur in year 70 as this is the only time when any supply chain activities take place, because the forest reproduces naturally and no forest activities take place during growth.

Assessing supply chain emissions per unit of energy is most relevant for an electricity producer with the target of generating electricity with a low emission intensity. In this case, the Canadian supply chain offers lowest supply chain emissions. More detailed LCA results for the different supply chains are presented in the supplementary material A.10 - 12.

3.2. Forest carbon modelling at forest stand scale

For each forest system, its variants and the counterfactuals, the carbon stocks and fluxes were modelled. The carbon balance is presented as CO_2eq mass per unit area on an annual basis over 200 years (Fig. 4). This includes the carbon stock changes of the biomass in the forest (above- and belowground biomass, dead wood, litter, soil organic

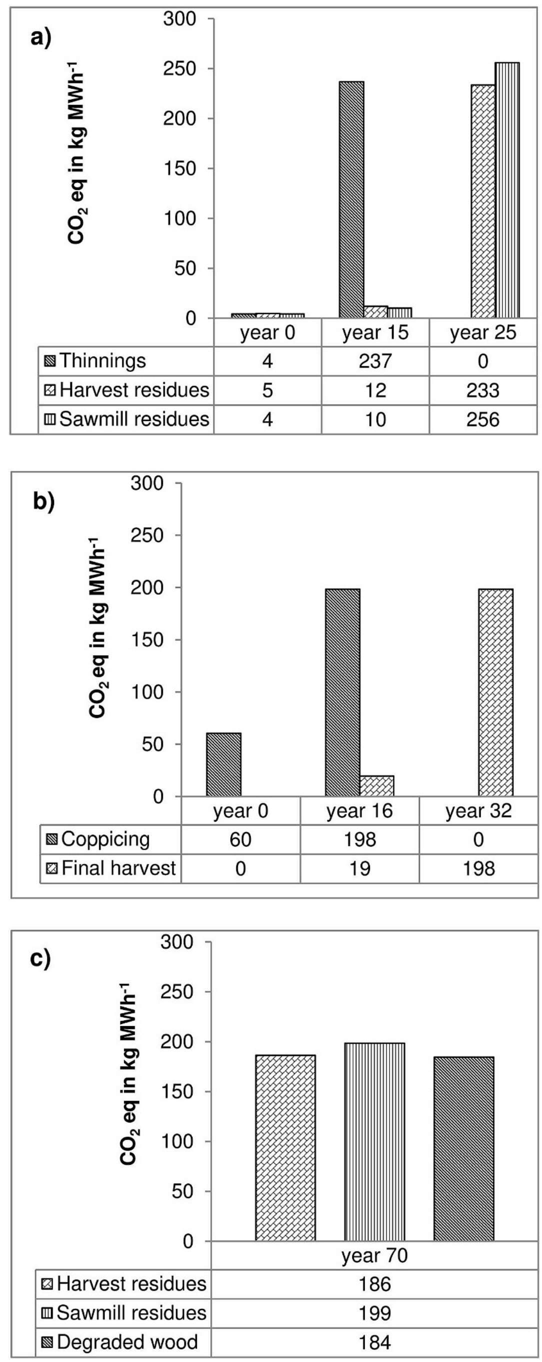


Fig. 3. Supply chain emissions of the different feedstocks for each supply chain in the year of activities and according to the LCA system boundaries. a) USA supply chain; b) Spanish supply chain; c) Canadian supply chain.

carbon), the carbon stock changes of wood products and the carbon stock changes of wood pellets for bioenergy. Wood pellets as part of the wood products are presented as separate category.

The USA forest system (Fig. 4 a, b) shows a steep increase in forest carbon stock with two peaks in the 25-year rotation: after 15 years before the stand is thinned and after 25 years before the stand is clearcut harvested. The CO_2 sequestered by trees is a CO_2eq mass of 218 t ha^{-1} after 15 years and 58 t ha^{-1} of it being removed during thinning. Between year 15 and 25 an additional CO_2eq mass of 64 t ha^{-1} is sequestered, which makes a CO_2eq mass of 224 t ha^{-1} at final harvest.

The Spanish forest system (Fig. 4 c, d) shows a very steep CO_2 sequestration rate, peaking every 16 years before the stand is coppiced or harvested. The CO_2 sequestered by the trees is a CO_2eq mass of 522 t ha^{-1} after 16 years and a CO_2eq mass of 542 t ha^{-1} after 36 years.

The Canadian forest system (Fig. 4 e, f) has a slower CO_2 sequestration rate compared to the other two systems and peaks after 70 years before the stand is harvested. At this time, the carbon stock is a CO_2eq mass of 287 t ha^{-1}.

For all three forest systems the trajectories do not start at zero, as the soil carbon and organic material on the forest floor are included in the analysis and presented as part of the forest carbon stock. However, no changes in soil carbon stock were assumed, as land use is not changing. Effectively, it has been assumed that the forest management techniques adopted (in particular the removal of residues) are not changing the long-term soil carbon content. This is consistent with the sustainable rate of residues removal assumed [75].

Variations in sequestration rates of the different forest systems are caused by geography, species and forest management regime, the rotation length and end-use of the wood. The USA forest completes almost three and the Spanish forest almost two rotations during one rotation of the Canadian forest. This means that the USA and Spanish forest system sequester much larger amounts of carbon over the same timeframe, than the Canadian system (Fig. 5).

The carbon release rate is affected by the type and lifespan of the wood products, e.g., paper, wood pellets have a shorter lifetime and therefore show a sharp decrease in the wood products trajectory in Fig. 4. A slow decrease indicates products with a longer lifetime (e.g., construction, furniture). In the two North American forest systems, the total system's carbon stock (including forest and wood product carbon pools) show a net increase from rotation to rotation because the carbon pool in wood products, constantly accumulates through products with a longer lifespan. In the case of the Spanish forest system, all biomass is used for bioenergy and the total carbon stock between successive rotations does not change.

The moment bioenergy electricity is generated all carbon stored in wood pellets is released to the atmosphere. This is shown in the significant reduction of carbon in the system at the point of harvest/bioenergy generation (see Fig. 4).

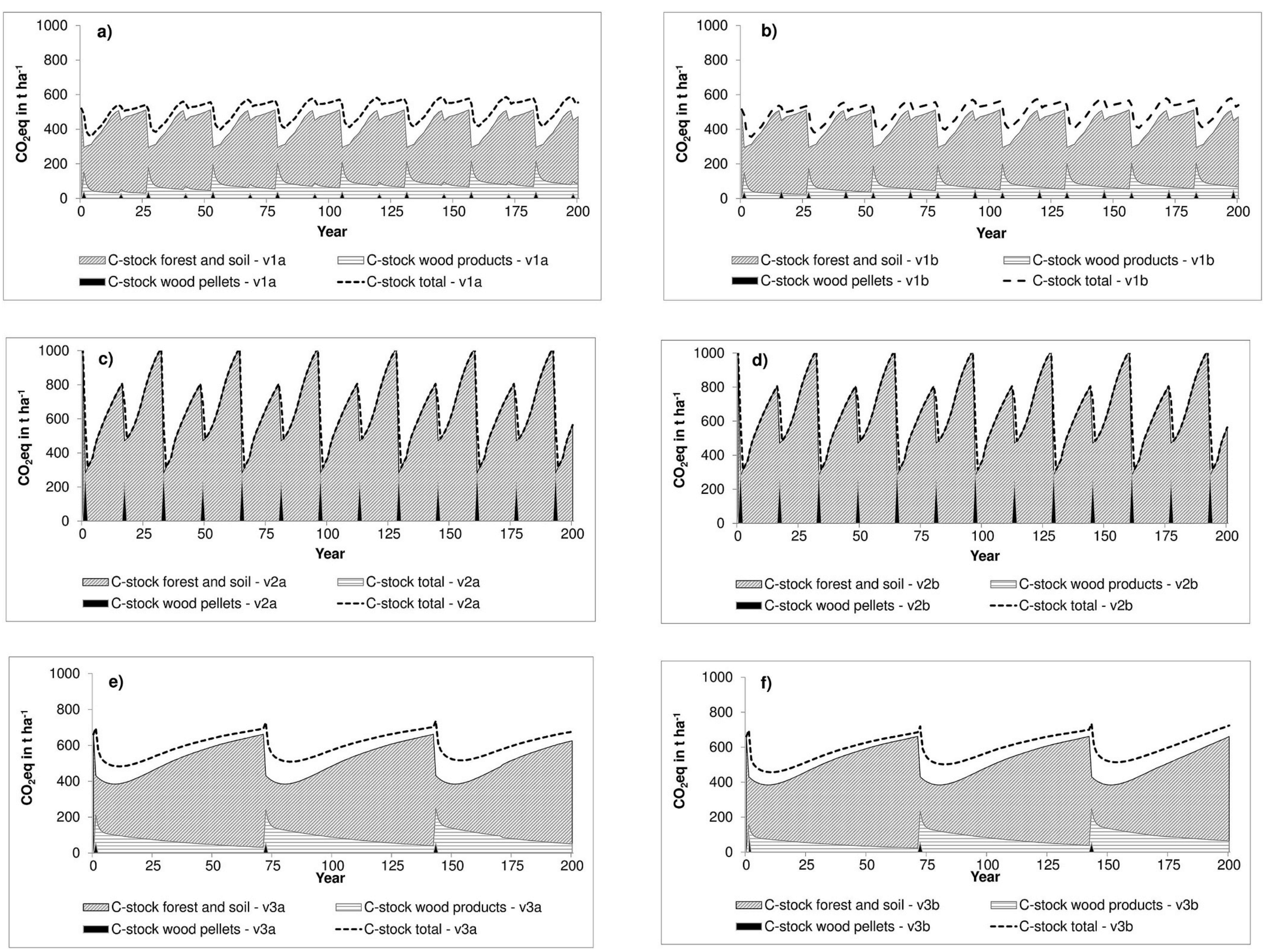


Fig. 4. Carbon stocks of forest, wood products and wood pellets of the three forest systems over 200 years as tonnes of CO2eq mass per hectare (a) variant 1a; (b) variant 1b; (c) variant 2a; (d) variant 2b; (e) variant 3a; (f) variant 3b).

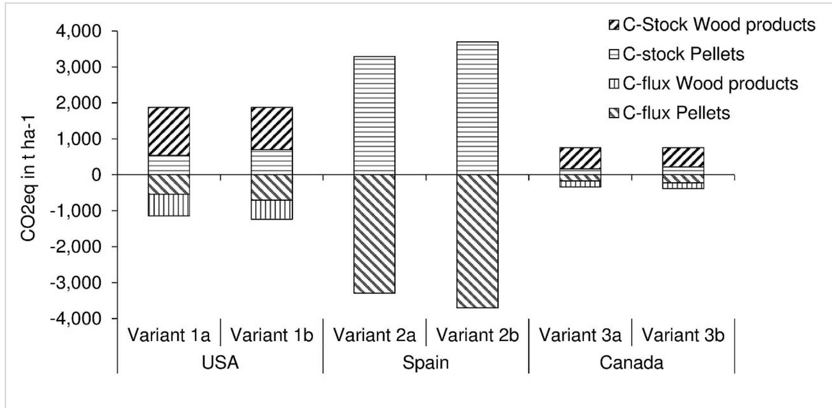


Fig. 5. Total carbon stock and flux for wood product (including pellets) for each variant.

3.3. GHG balance at forest landscape

As described in the method section, the carbon balance of all stands of a forest system were combined at forest landscape scale. While this provided cumulative carbon stocks and fluxes, the assessment focussed on the changes of carbon stocks evaluating sequestration and emissions of the forest-based bioenergy system identifying when the net carbon flux is positive or negative; respectively, more carbon is sequestered than released or vice versa. Adding the supply chain emissions to the net carbon flux gives the cumulative GHG balance of the forest-based bioenergy system. Additionally, the cumulative net GHG balance was calculated by comparing the forest-based bioenergy system to the reference cases: energy generation and forest production. In all cases, negative values present emissions and positive values present sequestration.

On landscape scale a forest systems' carbon stocks (forest and products) reaches a steady state, if there is no significant disturbance or radical change in management (Figs. 6–8, C-stock forest & products). This means even though there are carbon fluxes into (CO2 sequestration from atmosphere) and out of the forest (removal of biomass during harvest, disposal of wood products and decomposition), the forest system's carbon stock comes close to a steady state. This is the case of the investigated forest systems with accumulation of additional carbon in forest and products at a slow rate over the investigated time of 100 years. However, the focus of the assessment is on the emission impact and climate change mitigation potential of bioenergy; therefore, the net carbon flux expressing the amount of carbon sequestered and released is most relevant. In the case of forest-based bioenergy electricity, biomass for wood pellets is not just removed from the forest system as part of the carbon fluxes but it is converted to electricity, leading to an immediate release of biogenic carbon to the atmosphere. These emissions are showing in Figs. 6, 8 and 10 (Biogenic C-emissions BE) and are included in the trajectories showing the net carbon flux and GHG balances.

3.3.1. Net GHG balance: USA forest system

In the case of the USA forest system the cumulative net carbon flux, including sequestration and emissions (Fig. 6), has positive values in the first few years, as the cumulative carbon sequestration of the forest systems exceeds the cumulative emissions. However, after 2 years (variant 1a) and 4 years (variant 1b) the cumulative emissions from bioenergy electricity start to exceed the cumulative carbon sequestration of the rest of the forest system, leading to a negative net carbon flux. While the total carbon stock of the forest system is still very high, sequestration is taking place at a slower rate than the emissions related to bioenergy electricity generation.

Considering the cumulative net GHG balance when replacing the UK electricity mix (Fig. 7) with bioenergy electricity from the USA forest system, shows that the bioenergy option has lower emissions than the UK grid reference in the first few years. The net GHG balance has a negative value after four and six years (variant 1b and 1a respectively), which indicates that from this point the system's cumulative emissions

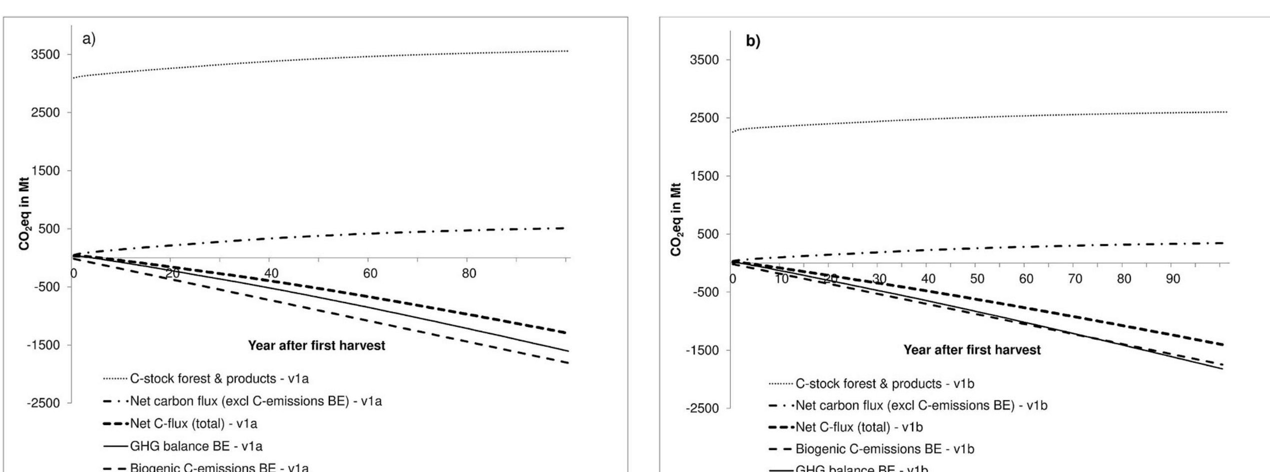


Fig. 6. Cumulative net carbon flux (sequestration minus emissions) and GHG balance for bioenergy (C-flux plus supply chain GHG emissions) at forest landscape scale for variant 1a (Fig. 6a) and variant 1b (Fig. 6b). Cumulative biogenic C-emissions from bioenergy illustrated separately (Biogenic C-emissions BE).

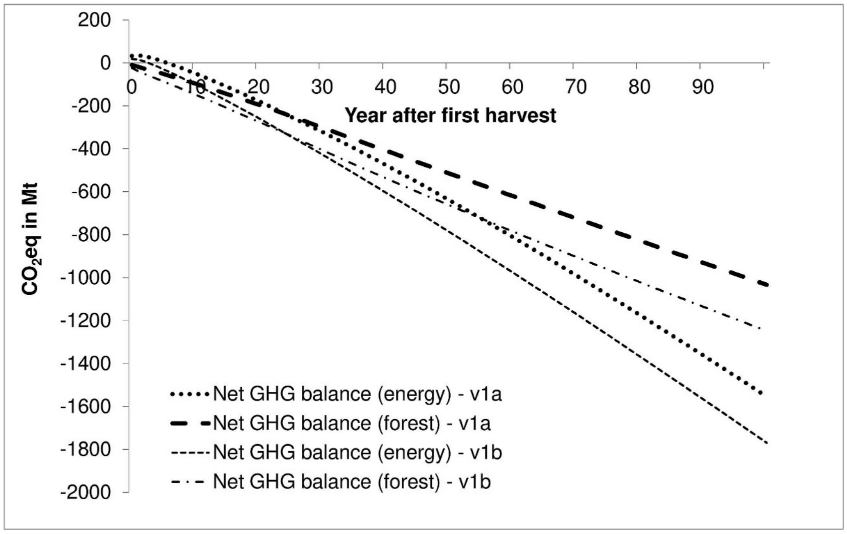


Fig. 7. Net GHG balance for variant 1a and 1b for energy generation (net GHG balance (energy)) and forest production (Net GHG balance (forest)) references. Negative values mean GHG emissions exceed carbon sequestration.

exceed the cumulative carbon sequestration.

In the case of the forest production reference, (Fig. 7), the net GHG balance has negative values from the first year, hence, the forest system without bioenergy and use of alternative fuels equal to the UK grid emission intensity, releases less GHGs to the atmosphere than the bioenergy option.

However, comparing the two net GHG balances after 25 years the net GHG balance of the forest production reference exceeds the net GHG balance of the energy generation reference (for variants 1a and 1b), which means the system boundaries for the forest reference become more favourable from this point. Nevertheless, the net GHG balance of the forest production reference has negative values throughout, which indicates that the system is releasing more GHGs than it sequestering carbon. This is because carbon sequestration has plateaued because the growth rate of the forest landscape has plateaued under this forest management regime. With this, the bioenergy system is resulting in higher levels of GHG emissions than the reference case.

3.3.2. Net GHG balance: Spanish forest system

Similar to the USA forest system, the Spanish forest system's carbon stock has reached a plateau (Fig. 8). The carbon sequestration rate is very low and is exceeded by the cumulative emissions from bioenergy electricity from the start, which means the system sequesters less carbon than it releases. This is expressed in the negative values of the net carbon flux. For both variants, the results are very similar as only the amount of residue removal varies (variant 2a: no removal, variant 2b: 50% removal).

Replacing the UK electricity mix with bioenergy electricity from the Spanish forest system (Fig. 9), shows that the bioenergy options do not achieve GHG savings compared to the UK grid option and forest system without bioenergy, as the net GHG balances are negative from the start; hence, the system's emissions are higher than the carbon sequestration.

Similar to the USA forest system, for a few years the forest production reference is less beneficial than the energy generation reference However, after 8 years the forest reference becomes more beneficial than the electricity generation option. As in the USA case, this shows that accounting for the whole system instead of just the energy generation indicates that less GHGs are released to the atmosphere.

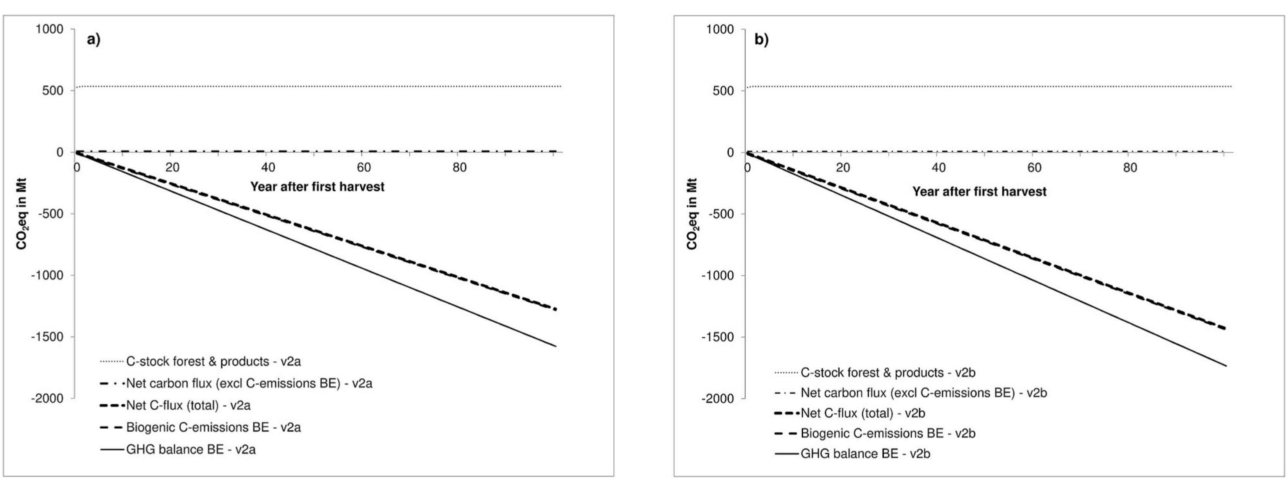


Fig. 8. Cumulative net carbon flux (sequestration minus emissions) and GHG balance for bioenergy (C-flux plus supply chain GHG emissions) at forest landscape scale for variant 2a (Fig. 8a) and variant 2b (Fig. 8b). Cumulative biogenic C-emissions from bioenergy illustrated separately (Biogenic C-emissions BE).

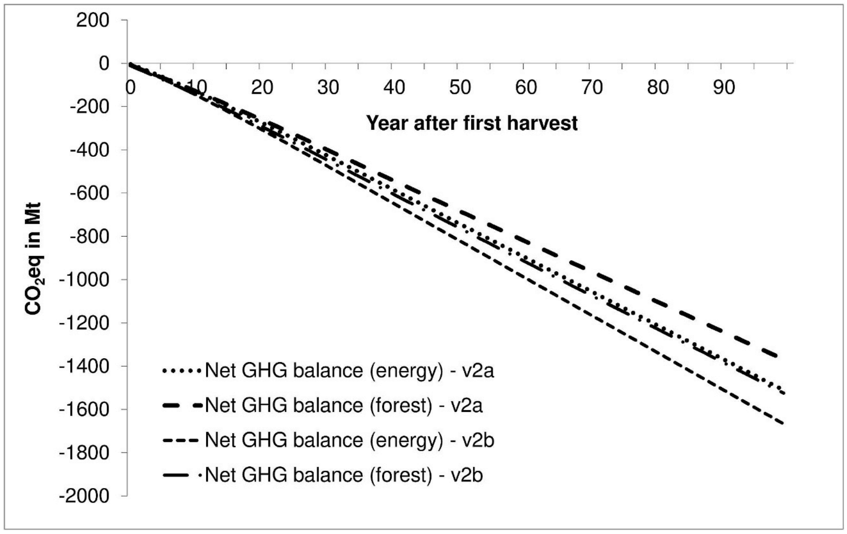


Fig. 9. Net GHG balance for variant 2a and 2b for energy generation (net GHG balance (energy)) and forest production (Net GHG balance (forest)) references. Negative values mean GHG emissions exceed carbon sequestration.

3.3.3. Net GHG balance: Canadian forest system

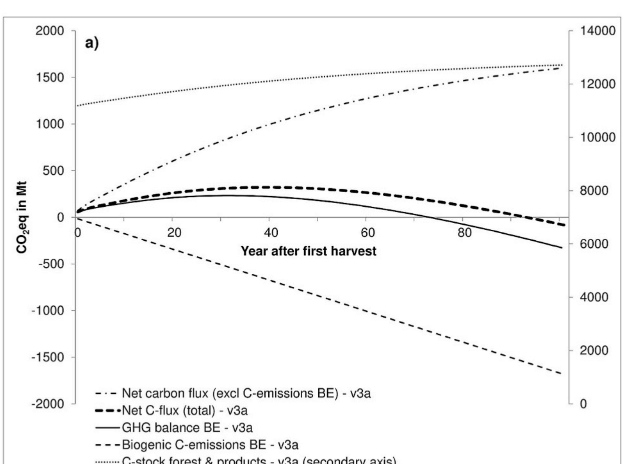
Compared to the USA and Spanish forest system, for the Canadian forest system variant 3a the carbon sequestration exceeds the emissions (Fig. 10a). For 72 years the forest system has a positive net carbon flux but after 72 years the cumulative carbon release starts to exceed the amount of carbon sequestered by the forest. The continuous accumulation of carbon in the system can be explained by the long rotation time, which means large amounts of wood products with a long lifespan are produced, keeping carbon locked in for a longer time.

Variant 3b draws a different picture (Fig. 10b). The cumulative carbon sequestration of the forest systems exceeds the cumulative emission from bioenergy electricity throughout the assessed timeframe of 100 years. This is caused by the long rotation time but also by the extension of the forest area once the disturbed forest has been harvested as it is presumed that an undisturbed forest regrows with a lower feedstock availability for bioenergy but more conventional wood products (lumber and pulp). Hence, more area per unit of energy is required once an affected forest is re-established as a healthy stand. Once all the disturbed areas have been harvested and regenerated after 70 years, the sequestration rate will start to slow down (similar to variant 3a). However, the sequestered amount of carbon is larger than the cumulative emission released from bioenergy, leading to a positive net carbon flux. This shows that bioenergy only contributes to net carbon savings if the carbon sequestration rate can be maintained at a high level throughout the forest and electricity production lifetime and in variant 3b, this happens by expanding the land area, which cannot expanded forever.

When replacing the UK electricity mix (energy generation reference) with bioenergy, variant 3a and 3b achieve GHG savings. For variant 3a, the net GHG balance (Fig. 11) indicates that the system has a higher carbon sequestration than emission release for the first 80 years. However, after 80 years emissions exceed sequestration. Compared to this, the net GHG balance for variant 3b has positive values throughout the evaluated timeframe.

In the case of the forest production reference, the net GHG balance for variant 3a has negative values from the start. This means, replacing the forest system without bioenergy with forest-based bioenergy electricity leads to a higher cumulative GHG release than sequestration and a significant loss of carbon from the system.

Compared to all other variants, variant 3b presents the only case where the cumulative net GHG balance of the forest production reference has positive values. This means a larger amount of carbon is sequestered than released. With this, variant 3b is the only of the six variants that achieves an atmospheric carbon removal from a forest



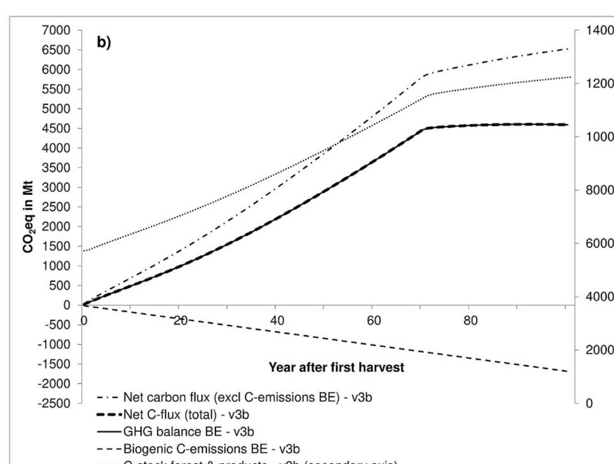


Fig. 10. Cumulative net carbon flux (sequestration minus emissions) and GHG balance for bioenergy (C-flux plus supply chain GHG emissions) at forest landscape scale for variant 3a (Fig. 10a) and variant 3b (Fig. 10b). Cumulative biogenic C-emissions from bioenergy illustrated separately (Biogenic C-emissions BE).

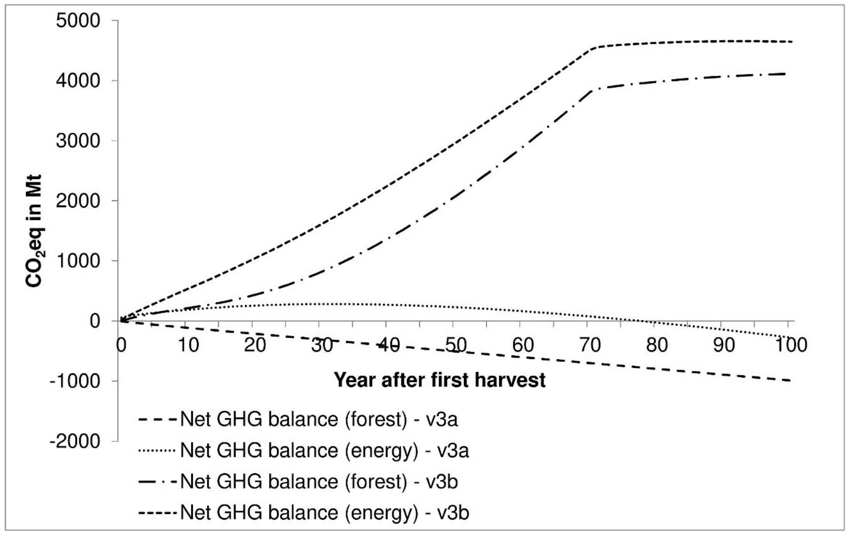


Fig. 11. Net GHG balance for variant 2a and 2b for energy generation (net GHG balance (energy)) and forest production (Net GHG balance (forest)) references. Negative values mean GHG emissions exceed carbon sequestration.

producer and energy generator perspective.

3.3.4. Comparison of net GHG balances

Fig. 12 shows the net GHG balances for the two different reference cases. As already shown above, apart from variants 3 all other systems eventually have higher cumulative emissions than carbon sequestration. Depending on the reference cases, the outcome of the net carbon balance is different. In the case of the energy generation reference, for variant 3a sequestration exceeds emissions for 80 years (for variants 1 this is only the case for the first few years) and is after variant 3b the most favourable option in terms of climate change mitigation during this period. After 80 years, variant 3a also becomes negative and does not offer any further GHG savings, but still offers lower net emissions than variants 1 and 2.

For the forest production reference, no variants, apart from 3b, deliver any GHG savings, as cumulative emission release is higher than carbon sequestration. However, just comparing the variants against each other variant 1a has the lowest GHG impact for the first 40 years (Fig. 12b). After that point, the GHG performance of variant 3a becomes more favourable.

4. Discussion

Bioenergy has to offer GHG reductions to be a valid option for supporting climate change targets. Many accounting frameworks consider bioenergy as carbon neutral, including accounting for supply chain emissions only but not for the carbon sequestered and released back to the atmosphere during growth and energy conversion respectively [5,6]. The results presented here, show that the release of biogenic carbon can play a significant role, in particular for forest-based bioenergy as carbon release and sequestration are not contemporaneous. Applying a suite of different methods that build up on each other, and with these expanding the system boundaries, showed that the release of biogenic carbon and the timeframe of sequestration and release has a significant impact on the GHG performance of forest-based bioenergy.

The results of the LCA for the different supply chains range between a CO_2eq mass of 184 kg MWh^{-1} and 270 kg MWh^{-1}. Within the set system boundaries, the LCA suggests that bioenergy electricity is less carbon intensive than the grid mix [76] in the UK, considering a CO_2eq mass of 392 kg MWh^{-1} grid emission intensity. With this, the investigated supply chains could deliver about 31%–53% GHG reductions. This is significantly less than others have found [17,19,24,29,30,56,58], with some cases over 90% reduction, as it still

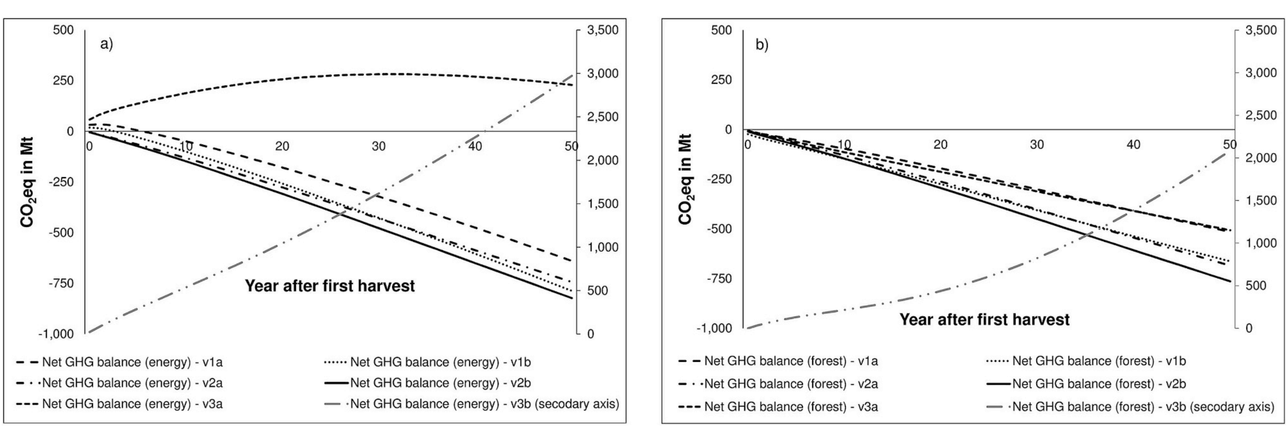


Fig. 12. Comparison of the net carbon balances of the different variants. All variants over a snapshot of 50 years. a) Net GHG balance for energy generation reference; b) net GHG balances for forest production reference.

is common to use traditional fossil fuels reference cases with high emission intensities. Since 1990, the electricity sector in many countries has achieved significant emission reductions. Considering the availability and scale of low emission technologies on one side and continuously high if not increasing global emissions on the other side, a comparison of bioenergy electricity to fossil fuels could provide misleading results in terms of the real emission reduction potential.

Forest-based bioenergy with carbon capture and storage (BECCS) and afforestation play an essential role in the IPCC's low emission scenarios [1]. Within these concepts, the system boundaries of forest-based bioenergy need to expand to the forest and other products to capture the dynamics of the carbon balance related to the forest and products. However, forest carbon models are terrestrial models treating bioenergy feedstocks as every other wood product and do not capture the released carbon accumulating in the atmosphere. The results of the carbon model emphasises that forests' growth rates, carbon stocks, carbon fluxes and bioenergy feedstock supply depend on natural conditions like tree species and climate as well as forest management and procurement. This is relevant as wood pellets at final application are normally a mix of feedstocks from different regions, management and procurement systems. This research investigated different forest region and typical management practices, with high potential of supplying feedstock for bioenergy electricity, with each forest system resulting in different carbon balances. Forest systems in temperate regions that have shorter rotations sequester high amounts of carbon during the more rapid growth at early ages, but this carbon is also released more quickly as products have a shorter lifespan. The investigated boreal forests are growing more slowly but due to longer rotations a larger share of products have a long lifespan leading to higher and carbon stocks embedded in products in the long term.

On forest stand scale, carbon stocks are increasing and decreasing depending on the stage of forest management and product use. In the case of a healthy forest, with no significant changes in management and procurement, a single stand would develop a similar carbon balance from rotation to rotation. The carbon removed from the forest (in form of any wood products) would recover to previous levels in the next rotation and with wood products storing the sequestered carbon over their lifespan the overall carbon balance could increase over time. This is also the case for the investigated forests, which would suggest that carbon removed from the system would be re-sequestered at some point.

However, results change when the system boundaries are expanded to the forest landscape and include supply chain emissions. A landscape approach is often taken to argue the carbon benefits of bioenergy as part of a wider forest system [18,19,21,24,77]. However, on landscape scale the carbon stock as well as the net carbon flux reach a plateau. Focussing on bioenergy it is most relevant how much and when carbon is sequestered and emissions are released. While results for the USA and Canadian forest systems show carbon benefits at forest stand scale, at landscape scale only the Canadian variants delivered significantly higher cumulative sequestration rates than cumulative release. In contrast, the USA and Spanish variants with shorter rotations sequester large amounts of carbon, but release this more quickly as wood products have a shorter lifespan. In these cases, the level of emissions is higher than carbon sequestration, the carbon balance decreases steadily, leading to a loss of carbon from the forest system (including wood products). This point is reached very early in fast-growing systems with mostly short-lived products (or no other products than bioenergy feedstock), but takes much longer in slow-growing forest systems that generate a large share of long-lived wood products.

There is a large body of research assessing the carbon debt of forest-based bioenergy, which shows long payback periods when whole trees or large proportions of the forest biomass are utilised for bioenergy [18–21,30,78,79]. This raises the question if a cumulative emission focus is more plausible in terms of carbon than approaching forest-based bioenergy from a carbon debt and repayment perspective. The here presented analysis also shows that the use of whole trees can provide carbon benefits if it is part of stand management that triggers the establishment of a healthy stand and in conjunction of sourcing long-lived wood products and expanding the forest area as in variant 3b.

The assessment of the net GHG balance shows how reference cases (energy generation and forest production) with potentially different commercial and climate change objectives provide different results. This is supported by findings of others [18–20,22,24,31,59,78,79] that the change of reference cases can lead to very different results in terms of GHG performance of bioenergy systems. For a bioenergy electricity producing nation the main target might be replacing emission intensive fuels with a lower emission fuel, like wood pellets. From this perspective, bioenergy delivers limited emission reductions in the USA variants but not in the Spanish cases as the only wood product is pellets and no other products that could store some of the carbon during their lifespan. In the Canadian cases, emissions are not just lower compared to the UK's grid emission intensity but the forest system with bioenergy offers an atmospheric carbon removal due to the carbon benefits of the wider forest system.

From the perspective of a forest growing nation, the focus might be on maximising revenues from the forest sector or possibly maximising forest carbon stocks and carbon sequestration. From this perspective, the integration of bioenergy appears not beneficial for the USA and Spanish systems compared to conventional supply chains. As the net carbon fluxes of bioenergy shows, these systems are releasing a higher amount of emissions than sequestering carbon with a more unfavourable GHG performance in the medium and long-term compared to the non-bioenergy option. For the Canadian system, the results change significantly between the electricity generation and the forest production references. Results show that forest-based bioenergy can actually diminish some of the positive carbon benefits of forest management for conventional wood products and potential carbon benefits can be turned into a negative impact with the change of the reference case. From a perspective of decarbonising electricity using Canadian wood pellet for bioenergy electricity in the UK could create emission saving. Including the wider forest system in the assessment, which is an extension of the system boundaries, it is more favourable to leave residues in the forest or disturbed forests untouched and the UK would generate electricity from other low-carbon fuels.

With most of the exanimated options having higher cumulative emissions than sequestration raises the question of whether bioenergy electricity in this form can support climate change mitigation targets. BECCS might therefore be considered a necessary focus to achieve decarbonisation from forest systems, although viable engineering configurations of such systems need to be considered that include the energy demand of carbon separation technologies [80–82]. Moreover, BECCS could lead to an increasing demand of wood pellets with possible knock-on effects on forest management and feedstock procurement (e.g. increased allocation of wood to pellets or expansion of forest area) and possible technology lock-ins. This would affect the cumulative net GHG balance and change the system boundaries if there was a displacement of wood for other product. The only option of the investigated variants that can deliver an atmospheric carbon removal without additional technologies like CCS [83,84] is utilising naturally disturbed forests and re-establishing healthy forest instead, in combination with long rotation periods and expanding the forest area (latter could lead to a competition for land use). Still, this variant has a less favourable GHG performance compared the reference case.

Utilising disturbed forests becomes even more relevant when considering aspects beyond carbon, e.g. reduction of wild fire risk and spread of pests, income generation and diversification of the forest sector. By providing an outlet for unutilised surplus such as degraded or low-value trees within an existing forest industry, can contribute to forest restoration, preservation and climate change mitigation. If in that case bioenergy is supporting the overall economics of a forest, there might be cases where it tips the balance between bioenergy being unprofitable and profitable. The other variants show that a managed forest that is sequestering carbon in trees for conventional products and not energy and is profitable should just do conventional wood production. However, the question then would be if bioenergy could provide an additional income stream that makes the maintenance of the forest more viable. This is also relevant for forest systems with decreasing demands for specific wood types like pulpwood from thinnings.

This all shows the complexity of the topic: results for different stakeholders and objectives can have different outcomes and accounting frameworks and national emission reporting struggle to capture cross-sectoral and international supply chains and impacts. Additionally, methodological approaches add to the challenge of variations and uncertainties of result. There is a large body of research giving different results for the GHG performance of bioenergy electricity. On LCA level results often depend on biomass procurement, inputs, technology, application and practices leading to variations, making results case- and context-specific [11,20,57,58]. So does this work; for example, the Canadian forest system in this research has up to about 25% fewer emissions than the USA and Spanish forest system due to hydro-based electricity for processing and less input of agrichemicals. These are well-understood variables, which can be context specifically captured and accounted for. However, the difference in conclusion between the forest stand and landscape scale shows how the expansion of the system boundaries, which directly relates to assumption of displacement and counterfactuals, increases the level of uncertainty. Moreover, the investigated forest systems did not consider any significant changes in forest management, displacement of biomass, area expansion (apart from variant 3b) or change of land use, but other research has shown that this could be sources of uncertainties [9,10,20,24,29,58,79]. Applying two different, very specific, reference systems shows already changes to the results. If variants or assumptions would change and additional factors are considered, it would have been likely that results show even more variation.

Additionally, the carbon models like CO2FIX make specific assumptions regarding forest growth, decay rates, product lifespan and disposal and these values are limited by their underlying knowledge and data [4]. Variation in data, the framing and definition of the system and the limitations of knowledge, data and models make the results very context specific. This raises the question about the scale and method of the assessment. In relation to the global emission budget, this would probably require modelling at global level, which bears even higher levels of uncertainty and error margins. Nonetheless, this does not indicate the results are only valid for these specific cases of forest-based bioenergy electricity. What the results show is that bioenergy can only contribute to climate change mitigation if the sequestration rate of the biomass is high. That requires a product basket that is locking up the carbon, that feedstock sourcing happens early in the rotation or that at least some of the released carbon is either directly or indirectly captured, stored and/or used. National policy strategies and incentives consider bioenergy in the context of decarbonising the energy sector; the analysis showed that this could give an incomplete picture and possibly not capture the actual GHG performance as forest-based bioenergy is part of wider forest system.

5. Conclusion

With the urgent need to decarbonise the energy sector and to stay within the global emission budgets, bioenergy electricity needs to deliver GHG savings. The results show that forest-based bioenergy electricity can provide emissions savings, nevertheless, the presented results are context and objective specific and appropriate consideration and calculations are essential before drawing conclusions about other systems. In particular, evaluation of agri-residue, purpose grown energy crops and afforested systems would require new calculations, as would the replacement of fossil fuels for transport and heating. The results are then highly dependent on the method of assessment, system boundaries and the reference system that is replaced. However, methods like LCA, supply chain assessment and forest carbon modelling alone, do not capture the full carbon impact of systems like forests that provide several products and services. An electricity generator who sources pellets has no control over the final use of the other forest products and services, including what a forest grower does with the bioenergy feedstocks when not used for pellets. This means that governance and regulations are required at forest landscape level and the forest carbon is accounted for by including wider impacts and counterfactuals. The challenge is that a forest is multi-functional and under certain conditions, e.g. a natural disturbance, it is plausible to utilise biomass for energy even if it results in a carbon loss at the point in time but has wider sustainability benefits beyond carbon (e.g., reduced risk of disturbance, increased, re-forestation of a health stand, additional income). A solution could be that forest growers maintain a carbon account of their forest that is required at point of sale for renewable energy to prove its carbon sequestration or carbon stocks and emissions. This would require a multi-level governance framework that monitors the trail and appropriate counterfactuals of the forest/product carbon at system level considering the multi-functional (including services), multi-sectoral and international dimension of forests and bioenergy beyond energy and carbon. This would also mean that the categorisation of residues/wastes in terms of accounting and counterfactuals is likely to be particularly significant.

Declarations of interest

As Patricia Thornley, a co-author on this paper, is the Editor of Biomass and Bioenergy, she was blinded to this paper during review, and the paper was independently handled by Jon Paul McAlmont and Ralph Overend as editors.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2018.12.019.

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