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Wood pellets, what else? Greenhouse gas parity times of European electricity from wood pellets produced in the south-eastern United States using different softwood feedstocks

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Abstract

Several EU countries import wood pellets from the south-eastern United States. The imported wood pellets are (co-)fired in power plants with the aim of reducing overall greenhouse gas (GHG) emissions from electricity and meeting EU renewable energy targets. To assess whether GHG emissions are reduced and on what timescale, we construct the GHG balance of wood-pellet electricity. This GHG balance consists of supply chain and combustion GHG emissions, carbon sequestration during biomass growth and avoided GHG emissions through replacing fossil electricity. We investigate wood pellets from four softwood feedstock types: small roundwood, commercial thinnings, harvest residues and mill residues. Per feedstock, the GHG balance of wood-pellet electricity is compared against those of alternative scenarios. Alternative scenarios are combinations of alternative *fates* of the feedstock materials, such as in-forest decomposition, or the production of paper or wood panels like oriented strand board (OSB). Alternative scenario composition depends on feedstock type and local demand for this feedstock. Results indicate that the GHG balance of wood-pellet electricity equals that of alternative scenarios within 0–21 years (the GHG parity time), after which wood-pellet electricity has sustained climate benefits. Parity times increase by a maximum of 12 years when varying key variables (emissions associated with paper and panels, soil carbon increase via feedstock decomposition, wood-pellet electricity supply chain emissions) within maximum plausible ranges. Using commercial thinnings, harvest residues or mill residues as feedstock leads to the shortest GHG parity times (0–6 years) and fastest GHG benefits from wood-pellet electricity. We find shorter GHG parity times than previous studies, for we use a novel approach that differentiates feedstocks and considers alternative scenarios based on (combinations of) alternative *feedstock fates*, rather than on alternative land uses. This novel approach is relevant for bioenergy derived from low-value feedstocks.

Keywords: bioenergy, biomass, carbon, counterfactual, forest, GHG emission, parity time, payback time, US South

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Introduction

The EU aims to increase the share of renewable energy in its gross final energy consumption to 20% by the year 2020 to mitigate climate change and improve energy security of supply (EU directive 2009/28/EC). Wood pellets, a type of solid biofuel, form one such renewable and accounted for 0.47% of EU gross inland energy consumption in 2014 (Aebiom, 2015; Eurostat, 2016). The EU is the largest global producer, consumer and importer of wood pellets used for both electricity production

and for residential and district heating (Sikkema *et al.*, 2011; Lamers *et al.*, 2012; Goh *et al.*, 2013; Eurostat, 2015). The United Kingdom, the Netherlands, Belgium and Denmark have been the main importers of wood pellets from outside the EU that are used for (co-)firing in power plants to (partly) replace fossil fuels (Sikkema *et al.*, 2011; Lamers *et al.*, 2012, 2015; Goh *et al.*, 2013; Goetzl, 2015). These wood-pellet imports increased more than fourfold between 2009 and 2014 (Eurostat, 2015).

The United States is the largest global exporter of wood pellets (EIA, 2014). Production is largest in the US Southeast (US SE; as defined by Wear & Greis, 2012, see Fig. S1) and nearly all wood-pellet exports from the US

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SE go to the EU (Pinchot institute, 2013; Abt *et al.*, 2014; EIA, 2014). Primarily driven by EU demand (Abt *et al.*, 2014), US SE wood-pellet production and export have doubled since 2011 (Eurostat, 2015; Prestemon *et al.*, 2015), making the region one of the largest global wood-pellet suppliers to the EU (Hoefnagels *et al.*, 2014). Even so, the wood-pellet market is small relative to that of other forest products (e.g. saw timber or paper), with wood pellets having comprised <1% of total US forest products by weight and about 1% of total US forest products exports by value in 2014 (FAO, 2016).

There are several concerns regarding the sustainability of electricity production from wood pellets, including biodiversity loss, soil degradation and climate change (e.g. Lamers *et al.*, 2013b; Pinchot Institute for Conversation, 2013; Thiffault *et al.*, 2015; Olesen *et al.*, 2016). This study considers the climate change impact of wood-pellet electricity. This impact is usually assessed by constructing the greenhouse gas (GHG) balance of wood-pellet electricity, and then determining the (time to) GHG emission savings (i.e. GHG benefits) compared to a reference system or scenario. Standardized guidelines for GHG accounting currently do not exist (Buchholz *et al.*, 2015; Galik & Abt, 2015). However, there is wide agreement that regardless of the GHG accounting method applied, larger and faster GHG emission savings (GHG benefits) from wood-pellet electricity are achieved:

- when replacing higher GHG-intensity fossil fuels (e.g. Cherubini *et al.*, 2009; Walker *et al.*, 2010; Colnes *et al.*, 2012; Zanchi *et al.*, 2012; Jonker *et al.*, 2013; Lamers & Junginger, 2013a),
- when forest productivity is high; productivity depends on climate, soil and other biophysical site characteristics, as well as tree species and forest management (e.g. Marland & Schlamadinger, 1997; Cherubini *et al.*, 2011; Zanchi *et al.*, 2012; Jonker *et al.*, 2013; Lamers & Junginger, 2013a),
- when GHG emissions along the wood-pellet supply chain are low; emissions depend on forest management, transport and processing (e.g. Schlamadinger & Marland, 1996a; Magelli *et al.*, 2009; Sikkema *et al.*, 2010; Mitchell *et al.*, 2012; Jonker *et al.*, 2013).

Greenhouse gas footprinting studies that use a life-cycle assessment approach (in which forest carbon sequestration is accounted for by considering biogenic emissions carbon neutral) show that European electricity generated using softwood wood pellets from the US SE causes 50–75% less GHG emissions than fossil-fuel-derived grid electricity (Dwivedi *et al.*, 2011, 2014a; personal communication G.-J. Jonker, October 23, 2015). Other studies point out that GHG benefits of wood-

pellet electricity are often not immediate but depend on the following: (1) the time lag between GHG emission (harvesting of forest biomass and burning of resulting biofuels) and GHG sequestration during forest regrowth (Zanchi *et al.*, 2010; McKechnie *et al.*, 2011; Lamers & Junginger, 2013a); (2) the potential (in)direct GHG emissions or sequestration from the conversion of a previous land- or forest use to production forests (Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009; Berndes *et al.*, 2013; Lamers & Junginger, 2013a; Wang *et al.*, 2015); and (3) whether or not the GHG balance of wood-pellet electricity is compared against a (dynamic) *counterfactual scenario*, in which forestland or pellet feedstock is used differently and electricity is produced from fossil sources (Schlamadinger & Marland, 1996b; Mitchell *et al.*, 2012; Lamers & Junginger, 2013a; Lamers *et al.*, 2014; Stephenson & MacKay, 2014; Buchholz *et al.*, 2014).

The first two effects can lead to initial GHG emissions and an initial dip in the GHG balance of forest bioenergy that is ambiguously referred to (Matthews *et al.*, 2014) as the *carbon debt* (Zanchi *et al.*, 2010; reviewed by Lamers & Junginger, 2013a). Carbon debt payback times (i.e. the time until forest regrowth and avoided fossil GHG emissions compensate the carbon debt) have been estimated to be 1–27 years for Dutch electricity from US SE wood pellets (Jonker *et al.*, 2013). The third consideration has led to the calculation of so-called *GHG (or carbon-) parity times*: the time to the point at which wood-pellet electricity (usually with higher initial emissions) and the counterfactual have the same cumulative net GHG emissions (explained in detail by Mitchell *et al.*, 2012; Lamers & Junginger, 2013a). Beyond the GHG parity time, wood-pellet electricity leads to GHG emission savings compared to the counterfactual. For European electricity from US SE wood pellets, estimated GHG parity times range 2–80 years (in most cases: 20–50), when compared to commonly used counterfactuals of continued forest growth or natural regrowth after one harvest (Colnes *et al.*, 2012; Jonker *et al.*, 2013).

The choice of counterfactual greatly influences the GHG benefits of wood-pellet electricity (Jonker *et al.*, 2013; Lamers & Junginger, 2013a; Lamers *et al.*, 2014; Stephenson & MacKay, 2014). So far however, the counterfactuals for wood-pellet electricity considered in previous studies have been limited and can be improved in three ways. First, earlier work on counterfactuals has focused on alternative land or forest uses (Colnes *et al.*, 2012; Mitchell *et al.*, 2012; Jonker *et al.*, 2013; Lamers & Junginger, 2013a; Lamers *et al.*, 2014). However, decisions on land- or forest use are more often driven by saw timber and paper markets (Wear & Greis, 2013; Forest2market, 2016) or external pressures like urbanization (Wear & Greis, 2013) than

by wood-pellet markets. Instead of alternative land-use, counterfactuals for wood-pellet electricity should therefore focus on alternative fates of wood-pellet feedstock material. That is, what would have happened to the feedstock material had it not been used to produce wood pellets. Examples include the production of other products or in-forest decomposition of feedstock material (similar to counterfactuals by Stephenson & MacKay, 2014).

Second, the exact type of wood-pellet *feedstock* likely affects its alternative-fate counterfactual. Counterfactuals should therefore be determined per feedstock type. This approach enables more accurate parity time calculation as well as intercomparison of GHG benefits of wood-pellet electricity from different feedstocks. Wood-pellet feedstock types derived from softwood plantations in the US SE generally include (saw) mill residues, small roundwood (including pulpwood traditionally used for the pulp and paper industry), forest thinnings and harvest residues (Lamers & Junginger, 2013a; Dwivedi *et al.*, 2014a; Dwivedi & Khanna, 2014; Stephenson & MacKay, 2014; Buchholz & Gunn, 2015; Dwivedi & Khanna, 2015). Previous work on the effect of feedstock type on GHG emissions has been limited to show that using harvest residues as wood-pellet feedstock leads to largest GHG benefits while assuming that residues would otherwise decompose or be burnt (e.g. McKechnie *et al.*, 2011; Zanchi *et al.*, 2012; Bernier & Paré, 2013; Lamers & Junginger, 2013a; Lamers *et al.*, 2014; NRDC, 2015).

Third, multiple counterfactuals, that is, multiple alternative fates, for each wood-pellet feedstock type are feasible (e.g. some material is used in the paper industry, whereas the remainder decays on site). To our knowledge, there has been no attempt to create a mix of counterfactuals and analyse its effect on GHG benefits of wood-pellet electricity or forest bioenergy in general.

In this study, we calculate GHG parity times of wood-pellet electricity from different feedstocks originating from existing US SE softwood plantations, to determine whether and when GHG benefits of wood-pellet electricity occur. We use a new approach that for *each feedstock* compares the GHG balance of wood-pellet electricity against alternative scenarios that are *combinations* of individual *feedstock fate-based counterfactuals*. Alternative scenario composition is also made to depend on demand for the different feedstock materials for production of alternative products. Our research focuses on pellets from softwood plantations, as more than 60% of US SE wood pellets are produced from softwood material (Forest2Market, 2016), and softwood plantations form 19% of US SE total forest cover (Wear & Greis, 2013).

Materials and methods

The GHG balance of forest bioenergy is often assessed using a forest carbon accounting model like GORCAM (Schlamadinger & Marland, 1996b; Jonker *et al.*, 2013), LANDCARB (Harmon, 2012; Mitchell *et al.*, 2012) or FOR-CARB2 (Heath *et al.*, 2010). However, the exact calculations behind these models are often not transparent and/or US SE-specific parameterizations are not available. We therefore calculated GHG parity times with a set of equations tailored for comparing wood-pellet electricity to alternative scenarios, and parametrized for the US SE (Table S1). Before discussing these calculations in detail, we first define different wood-pellet feedstock types. We then describe feedstock production, wood-pellet electricity and individual counterfactuals and their combination into alternative scenarios (Fig. 1). Then lastly, we set out our GHG accounting assumptions and explain our calculations and sensitivity analyses.

Wood-pellet feedstock definition

A softwood plantation yields several products; most valuable are saw logs [diameter at breast height (DBH) of >35 cm] and chip-n-saw wood (DBH of 25–35 cm; SC forestry commission, 2015). These two categories were lumped here as saw wood, which is sawn into lumber at a (chip-n-) sawmill and it is too expensive for use as wood-pellet feedstock (Dwivedi *et al.*, 2014b), except for the (chip-n-) saw mill's residues. We defined the following wood-pellet feedstocks derived from softwood plantations, in consultation with various local scientists and wood-pellet stakeholders [personal communication, K. Kline, A. Taylor, B. Abt, D. Hazel, K. Abt (US SE based forest/bioenergy scientists), B. Wigley, R. Miner (US National Council for Air and Stream Improvement), M. Jostrom, B. Emory (repr. largest US SE corporate foresters) and Parrish, B. (repr. a pellet mill), April 7–December 15, 2015; Enviva, 2015], and in line with previous studies (Dwivedi *et al.*, 2014a; Stephenson & MacKay, 2014; Buchholz & Gunn, 2015; Dwivedi & Khanna, 2015; NRDC, 2015):

- *Small roundwood*: wood harvested at final cut, including stemwood (10–25 cm DBH), larger tops and limbs (10–25 cm diameter) and stemwood >25 cm DBH that is damaged or otherwise unsuitable for saw wood. The category includes pulpwood (i.e. wood that is traditionally used in the pulp and paper industry).
- *Commercial thinnings*: wood that is harvested during mid-rotation plantation thinning and is merchantable (usually as pulpwood). Pre-commercial thinning (at an earlier stage of rotation) is not commonly practiced in the US SE (B. Parrish, personal communication, June 17, 2015) and was excluded.
- *Collectible harvest residues*: woody material left behind after the final cut that is still economically collectible (typically 70% of total harvest residues, Dwivedi *et al.*, 2014a; leaving 30% required for ecological services, Daioglou *et al.*, 2015). The category includes wood of <10 cm diameter, coarse

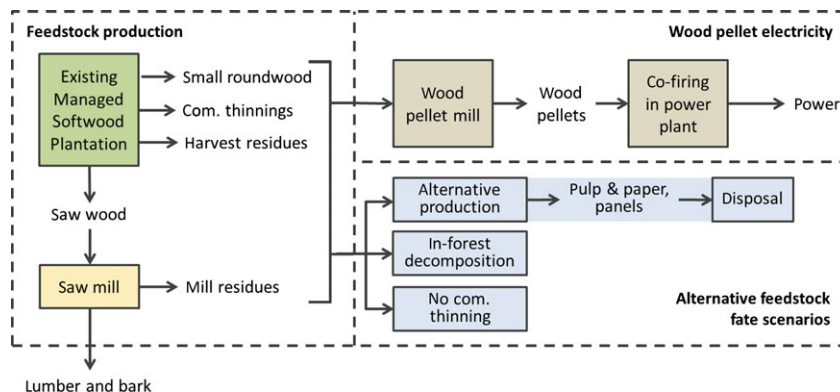


Fig. 1 Overview of feedstock production (on the left), wood-pellet electricity production (top right) and alternative scenarios (bottom right). Alternative scenarios consist of multiple individual feedstock-fate-based counterfactuals (shaded areas in the bottom right section). After feedstock material is produced, it either goes to wood-pellet electricity or the alternative scenario. All definitions are explained in detail in the main text. Note that in contrast to life-cycle assessment, the compared systems yield different products here: power vs. paper and panels (e.g. OSB). Avoided GHG emissions of these products were included in our analysis.

woody debris and in-wood chips (i.e. chipped harvest residues).

- *Saw mill residues*: woody material that is a co-product of sawing saw logs and chip-n-saw wood into lumber, that is, clean wood chips including chips from chip-n-saw wood (67%), wood shavings (15%) and sawdust (18%; Aebiom, 2013).

Wood-pellet feedstock production

We estimated biomass growth (Fig. S2) and associated carbon sequestration (Table S1) of medium- to highly intensively managed softwood plantations using the Carbon OnLine Estimator (COLE; NCASI, 2016). COLE uses empirical data from the US Forest Service's Forest Analysis & Inventory data base (FIA, 2016) and estimates stored carbon in live tree biomass, among other ecosystem carbon pools (which are fairly constant on both landscape and plot level; Smith *et al.*, 2006; NCASI, 2016; for details see Table S1). Based on COLE and a plantation rotation period of 25 years (Markewitz, 2006; Colnes *et al.*, 2012; Jonker *et al.*, 2013; Dwivedi *et al.*, 2014b; Dwivedi & Khanna, 2014; Dwivedi & Khanna, 2015; Table S1), plantation yield was estimated at 197 dry tonne tree biomass per hectare after 25 years, including thinnings [in line with Dwivedi *et al.*, 2011, 2014a; Dwivedi & Khanna, 2015; Jonker *et al.*, 2013 (140–232.5 dtonne ha⁻¹ 25 yr⁻¹ at medium-high intensity management)]. Plantation thinning was included by harvesting one-third of live tree biomass 15 years after planting (based on Markewitz, 2006; Jonker *et al.*, 2013). We estimated that the *enhanced* growth of the remaining trees after thinning compensates for 50% of the biomass taken out during thinning (for details, see Table S1; Fig. S2). This estimate is conservative, as some studies indicate near 100% compensation (e.g. Gonzalez-Benecke *et al.*, 2010, 2011; Jonker *et al.*, 2013). Mass fractions of the different products originating from softwood plantations (saw wood, small roundwood, etc. – at medium- to high-intensity forest management) and saw mills (lumber, residues and bark) were estimated from literature (Table S2).

Greenhouse gas emissions of medium- to high-intensity forest management (including site preparation, planting, fertilizer and herbicide use, and thinning) and harvesting were obtained from literature (Table S1). Emissions were allocated to the different forest products, according to their mass [or equivalently: embodied carbon – as all feedstocks were assumed to have the same moisture- and carbon contents (0.5 and 0.25, respectively), Table S1]. Similarly, sawmill GHG emissions were mass-allocated over different sawmill products, including mill residues. No forest management GHG emissions were allocated to non-collectible harvest residues (twigs, needles; 3.7% of total live tree biomass produced).

Wood-pellet electricity

Getting electricity from wood-pellet feedstock requires transport of feedstock and pellets (truck, train, transatlantic shipping), pelletizing, handling and combustion, which lead to GHG emissions in the form of biogenic CO₂, fossil CO₂, CH₄ and N₂O emissions. These supply chain emissions were assumed to be equal for all feedstocks and were based on literature (Table S1). It was assumed that wood-pellet feedstock material is dried at the pellet mill using heat from burning biomass (Magelli *et al.*, 2009; Sikkema *et al.*, 2010; Dwivedi *et al.*, 2011, 2014a; McKechnie *et al.*, 2011; Jonker *et al.*, 2013); in this study: bark (in case of commercial thinnings and small roundwood, which are debarked at the pellet mill) and/or part of the feedstock material itself (Table S1). Feedstock and pellet material that is lost along the supply chain is assumed to decompose quickly (Table S1). Based on this set of assumptions and parameterization, overall supply chain efficiency (including losses) was 2.56 tonne of wet feedstock per tonne pellets combusted (Table S1), in line with Dwivedi *et al.* (2011) (2.32) and Jonker *et al.* (2013) (2.65).

Wood-pellet electricity was assumed to replace EU fossil grid electricity (JRC, 2014), thereby avoiding emissions from fossil grid electricity. Since wood pellets from all feedstocks are dried to the same moisture level, they have the same energy

density and lead to the same (gross) avoided emissions per tonne of pellets combusted.

Counterfactuals and alternative scenarios

If wood-pellet feedstock is not used to produce wood pellets, there are three main *counterfactuals* in the US SE (personal communication, B. Abt, K. Abt, D. Hazel, M. Jostrom, R. Miner, A. Taylor, B. Wigley, May 28–December 15, 2015): (1) wood-pellet feedstock is used for alternative products, that is, pulp and paper and panels (including feedstock use for process heat), (2) wood-pellet feedstock remains in the forest and decomposes, and (3) (for the commercial thinnings feedstock category specifically) softwood plantations are *not* thinned in the first place.

In the alternative products counterfactual wood-pellet feedstock material is used to produce the following alternative products (on landscape scale, on average): 80% pulp and paper, 19% oriented strand board (OSB) and 1% other wood panels like medium density fibreboard (MDF) (based on Matthews *et al.*, 2014), including biomass for process heat. The counterfactual includes the GHG emissions of production and disposal of these alternative products, as well as avoided GHG emissions of the alternative products (Table S1). Avoided emissions were based on what the (wood-based) alternative products replace and consist of the GHG emissions associated with the replaced products (recycled paper, blockwork external wall cladding, plasterboard partition wall, see Table S1 note ab; based on Matthews *et al.*, 2015). The alternative products' use phase (between production and disposal) does not lead to significant GHG emissions and was excluded (in line with Matthews *et al.*, 2015). Disposal is assumed to occur via incineration (or quick decomposition of uncollected waste), incineration with electricity production or landfilling (based on Smith *et al.*, 2006). Disposal patterns were based on Smith *et al.* (2006; see Table S3) and are specific to US SE softwood pulpwood products. As landfilled material decomposes, it releases CO₂ and CH₄. Landfill decomposition was modelled as exponential decay. Part of the produced CH₄ is flared or is used for electricity production (Table S1). Pulp and paper products can also be recycled. Carbon then remains embedded in products for a longer time – effectively delaying final disposal; this was investigated in the sensitivity analysis.

Based on previous studies (Naesset, 1999; Palosuo *et al.*, 2001; Liski *et al.*, 2002; Palviainen *et al.*, 2004; Zanchi *et al.*, 2012; Russell *et al.*, 2014), the in-forest decomposition counterfactual was modelled as exponential decay with the majority of carbon in the feedstock being released as CO₂, part as CH₄ and part of the carbon being stored in the soil (Table S1).

In the third counterfactual, plantations are not thinned, which means that the commercial thinnings are not produced and any (avoided/reduced) GHG emissions associated with their use no longer exist. Not thinning was therefore considered to cause zero GHG emissions. Not thinning *does* result in lower plantation management GHG emissions (Table S1) and larger landscape wide carbon stocks (Fig. S2). However, these effects reduce the GHG emissions of this counterfactual by less than 1% compared to wood-pellet electricity (based on default

parameterization, see Table S1) and were excluded from the analysis.

Which counterfactual is relevant for which feedstock and to what extent is a hypothetical matter that likely varies over time and space and is subject to large uncertainty. Therefore, we investigated a wide range of combinations of these counterfactuals into *alternative scenarios* for each feedstock type (Fig. 2). Alternative scenario composition was determined in consultation and conversation with local experts (personal communication, B. Abt & D. Hazel, K. Abt, M. Jostrom, A. Taylor, B. Wigley & R. Miner, May 28–December 15, 2015). Scenario composition was based on feedstock properties. For example, only a limited share of harvest residues can be used for alternative products, mill residues tend to be fully allocated in the market and decomposition of commercial thinnings is infrequent because economic use is what makes them 'commercial'. Alternative scenario composition was also made to be dependent on the demand for alternative products (pulp and paper, panels). Higher demand means that in the absence of wood-pellet production, less feedstock is left to decompose and more is used to produce alternative products (K. Abt, personal communication, November, 23, 2015; Stephenson & MacKay, 2014; p. 11). In this study, demand for feedstock material to produce alternative products was considered at three levels: low, US SE average or high. Feedstock properties and levels of demand were translated to fractions that each counterfactual contributes to the alternative scenarios of each feedstock (see Fig. 2).

GHG accounting assumptions

Three main assumptions underly our approach. First, biogenic CO₂ emissions were considered equal to non-biogenic CO₂

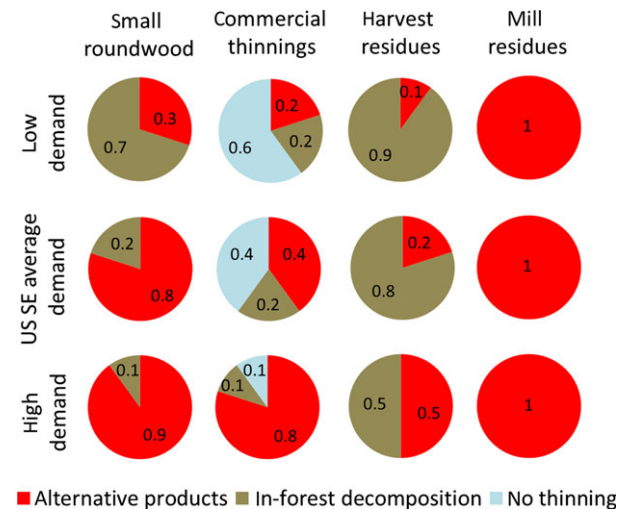


Fig. 2 Alternative scenario composition from individual counterfactuals. Each pie diagram represents one alternative scenario. The fractions that the counterfactuals of alternative products (f_{APi}), in-forest decomposition (f_{DCi}) and no thinning (f_{NTi}) contribute to each alternative scenario are indicated. Scenario composition depends on feedstock type and the demand for feedstock for alternative products.

emissions, and carbon sequestration during growth was explicitly modelled. Second, the time lag between GHG emission and sequestration was accounted for by applying a landscape-level approach, in which temporal dynamics of individual forest plots are averaged out geographically across all plots in the landscape (see Jonker *et al.*, 2013; Lamers & Junginger, 2013a). This results in constant annual carbon sequestration and GHG emission associated with (constant) wood-pellet feedstock production. Third, potential GHG emissions caused by the conversion of a previous land- or forest use to a softwood plantation were not included, as only existing plantations were considered (see section 'Discussion').

GHG parity time calculations

Greenhouse gas parity times were determined as the number of years it takes until the initial lower GHG balance of wood-pellet electricity (Eqn 1a) becomes equal to or larger than that of the alternative scenario (Eqn 2a). GHG balances were determined in time steps of 1 year by calculating *cumulative* GHG emissions and sequestration associated with a *constant* feedstock use of one tonne per year (for either wood-pellet electricity or the alternative scenario). GHG emissions are negative on the GHG balance, whereas sequestration and avoided emissions are positive. The equations are the same for all feedstocks. Parameter values can be found in Table S1.

Equation (1a) describes the GHG balance of wood-pellet electricity (B_{WP}). It consists of a constant feedstock production and use (u) over time (t) to produce wood-pellet electricity. Furthermore, it consists of GHG sequestration (SQ), various GHG emissions (e) including biogenic CO₂ emissions, and avoided GHG emissions (ae) associated with wood-pellet electricity. GHG sequestration and (avoided) emissions are expressed per tonne pellets and are therefore divided by the feedstock-to-wood-pellet conversion efficiency (H_{WP}).

$$B_{WP}(t) = u \cdot t \cdot \left(\frac{SQ - e_{MH} - e_{TH} - e_{SM} - e_{PM} - e_{PP} - e_{LO} + ae}{H_{WP}} \right) \quad (1a)$$

$B_{WP}(t)$ = cumulative GHG balance of wood-pellet electricity over time (kg CO₂-eq.); u = constant feedstock use (1 tonne feedstock yr⁻¹); t = time (years); SQ = carbon sequestration (kg CO₂-eq. · tonne pellets⁻¹); e = GHG emissions (kg CO₂-eq. · tonne pellets⁻¹); Subscripts: MH = plantation management and harvesting, TH = thinning, SM = sawmill, PM = pellet mill (incl. biogenic CO₂ emission from drying), pp = power plant (incl. biogenic CO₂ emissions from combustion), LO = transport losses (incl. biogenic CO₂ emission from lost biomass); ae = avoided GHG emissions of wood-pellet electricity (kg CO₂-eq. · pellets⁻¹); H_{WP} = overall conversion efficiency (tonne feedstock-tonne pellets⁻¹)

Equation (1b) describes the avoided GHG emissions of wood-pellet electricity (ae) with a pellet-to-electricity conversion efficiency η . Avoided emissions arise through replacing fossil-fuel-based electricity and avoiding its emissions (EF).

$$ae = \eta \cdot EF \quad (1b)$$

η = wood pellet to electricity conversion efficiency (MWh · tonne pellets⁻¹); EF = GHG emission factor of EU fossil grid electricity (kg CO₂-eq. · MWh⁻¹).

Equation (2a) describes the GHG balance (B) of alternative scenarios (i). In the first term, feedstock is produced at a constant rate, in the same way as in Eqn (1a). In the next three terms, feedstock is divided over the three counterfactuals (alternative products, in-forest decomposition and not thinning) according to the alternative scenario-specific fractions of each counterfactual (f_{APi} , f_{DCi} and f_{NTi} , for the three counterfactuals, respectively, see Fig. 2). The alternative product counterfactual leads to GHG emissions associated with production (ε_{APp}), avoided GHG emissions from replacing other products ($\alpha\varepsilon$) and disposal GHG emissions ($E_{APd}(t)$). Decomposition and not-thinning counterfactuals also lead to GHG emissions ($E_{DC}(t)$ and ε_{NT} , respectively).

$$B_i(t) = u \cdot t \cdot \left(\frac{SQ - e_{MH} - e_{TH} - e_{SM}}{H_{WP}} \right) + f_{APi} (u \cdot t \cdot (\alpha\varepsilon - \varepsilon_{APp}) - E_{APd}(t)) - f_{DCi} \cdot E_{DC}(t) - f_{NTi} \cdot u \cdot t \cdot \varepsilon_{NT} \quad (2a)$$

$B_i(t)$ = cumulative GHG balance of alternative scenario i over time (kg CO₂-eq.); f = fraction (dimensionless); $\alpha\varepsilon$ = avoided GHG emissions of alternative products (kg CO₂-eq. · tonne feedstock⁻¹); ε = GHG emissions (kg CO₂-eq. · tonne feedstock⁻¹); subscripts: APp = alternative products production; NT = not thinning; $E(t)$ = cumulative GHG emissions over time (kg CO₂-eq.); subscripts: APd = alternative products disposal, DC = decomposition.

Equation (2b) shows the cumulative GHG emissions over time from the in-forest decomposition counterfactual ($E_{DC}(t)$). Annually produced feedstock (u) decomposes via exponential decay (with half-life $t_{1/2DC}$). When also considering that feedstock that is produced earlier has decayed more than recently produced feedstock, the cumulative amount of feedstock that has decomposed at time step t can be represented as shown in the first part of Eqn (2b) (up to cc). Carbon in wet feedstock ($cc \cdot (1 - mc)$) that has decomposed is emitted as CO₂ (f_{DCCO_2}) or CH₄ (f_{DCCH_4}), or is stored in the soil (f_{DCsoil}), where it is GHG neutral (explaining the *zero*).

$$E_{DC}(t) = u \cdot \sum_{j=1}^t \left((t+1-j) \cdot \left(1 - \frac{1}{2}^{j/t_{1/2DC}} \right) \right) \cdot cc \cdot (1 - mc) \cdot 1000 \cdot \left(f_{DCCO_2} \cdot \frac{44.01}{12.01} + f_{DCCH_4} \cdot \frac{44.01 \cdot 34}{12.01} + f_{DCsoil} \cdot 0 \right) \quad (2b)$$

j = year of emission since start of decomposition (years); $t_{1/2DC}$ = half-life of exponential decay during in-forest decomposition (years); cc = carbon content dry feedstock (kg C · kg dry feedstock⁻¹); mc = moisture content of wet feedstock (kg H₂O · kg wet feedstock⁻¹).

Equation (2c) shows the cumulative GHG emissions over time from the *disposal* of alternative products ($E_{APd}(t)$). The summations over k (the year of disposal since production) in Eqn (2c) multiplied by the alternative product supply (u/H_{AP}) represent the cumulative amount of disposed alternative

product at time t . Part of disposal of alternative products takes place through incineration (with and without energy recapture, f_{IWk} and f_{IEk} , respectively), which causes net GHG emissions (\bar{e}_{IW} and \bar{e}_{IE} , respectively). Another part of disposed alternative products are landfilled (f_{LFk}). Landfilled products are assumed to decompose via exponential decay according to half-life $t_{1/2LF}$ releasing GHG emissions (\bar{e}_{LF}). The cumulative nature of these emissions is expressed as the summation over l (the year of emissions since initial disposal; similar to j in Eqn 2b). Note that disposal fractions (f_{IWk} , f_{IEk} , f_{LFk}) are dependent on the year of disposal since the product was formed (k), see Table S3.

$$E_{APd}(t) = \frac{u}{H_{AP}} \cdot \left(\sum_{k=1}^t ((t+1-j) \cdot (f_{IWk} \cdot \bar{e}_{IW} + f_{IEk} \cdot \bar{e}_{IE})) + \sum_{k=1}^t \sum_{l=1}^{t+1-k} \left((t+2-k-l) \cdot \left(1 - \frac{1}{2} \right)^{l/t_{1/2LF}} f_{LFk} \cdot \bar{e}_{LF} \right) \right) \quad (2c)$$

H_{AP} = conversion efficiency alternative product production (tonne feedstock \cdot tonne alternative product $^{-1}$); k = year of disposal since production of alternative product (years); \bar{e} = GHG emissions (kg CO₂-eq. \cdot alternative product $^{-1}$); subscripts: IW = incineration without electricity production, IE = incineration with electricity production, LF = landfill; l = year of emission since initial disposal (years).

Equation (2d) shows the overall lifetime landfill GHG emissions per tonne disposed alternative products (\bar{e}_{LF}). Methane that is produced in the landfill (MP) is partly released to the atmosphere (f_{LFCH_4}), partly flared ($f_{LFflare}$) and partly burned for electricity production (f_{LFel}). The latter is considered GHG neutral, as emissions from natural-gas-based electricity are avoided using landfill methane. Part of CO₂ production in the landfill (CP) is emitted to the atmosphere (f_{LFCO_2}), whereas the remainder remains in the landfill.

$$\bar{e}_{LF} = MP \cdot \left(f_{LFCH_4} + f_{LFflare} \cdot \frac{44.01}{16.04 \cdot 34} + f_{LFel} \cdot 0 \right) + CP \cdot f_{LFCO_2} \quad (2d)$$

MP = overall landfill CH₄ production (kg CO₂-eq. \cdot t alternative product $^{-1}$); CP = overall landfill CO₂ production (kg CO₂-eq. \cdot t alternative product $^{-1}$).

Lastly, to allow for comparison with GHG footprinting studies (e.g. Dwivedi *et al.*, 2011, 2014a), the percentages of GHG emission reduction of wood-pellet electricity compared to EU fossil grid electricity (ER) were calculated as well (Eqn 3). In GHG footprinting, biogenic CO₂ emissions are considered GHG neutral and no alternative scenarios are included.

$$ER = \left(\frac{1 - (SQ - e_{MH} - e_{SM} - e_{PM} - e_{PP} - e_{LO})}{ae} \right) \cdot 100\% \quad (3)$$

Sensitivity analyses

A sensitivity analysis was performed on the GHG parity times of wood-pellet electricity for parameters that most affect parity times (as determined by trying all parameters), and for

parameters whose values are uncertain based on literature. The variation in parameter value of the selected parameters was based on literature (Table 1). Two further sensitivity analyses were performed. First, economic allocation was applied to feedstock production GHG emissions, instead of mass-based allocation (see Table S2). Second, the timing of alternative product disposal was investigated to test the sensitivity of GHG parity times both to alternative product composition (as some products have longer use phases than others) and to uncertainty in disposal patterns in general (Smith *et al.*, 2006, see Table S3), including delayed final disposal due to recycling. The analysis consisted of delaying disposal of half of the alternative product produced by an additional 50 years compared to default values.

Results

Our results show how the GHG balances of wood-pellet electricity from different feedstocks compare to the GHG balances of individual counterfactuals (Fig. 3) and of alternative scenarios (Fig. 4). GHG parity times that result from this comparison form the main results of this study (Fig. 5, Tables S4 and S5). GHG footprinting outcomes are included as well, for comparison with previous studies. Lastly, the sensitivity of all results to parameterization is shown (Fig. 6).

Wood-pellet electricity

The GHG balance of wood-pellet electricity from all feedstocks is positive (i.e. wood-pellet electricity results in reduced GHG emissions compared to the EU fossil grid electricity it replaces; Fig. 3), because the avoided fossil electricity emissions are higher than net emissions from wood-pellet electricity itself. The GHG balance is *immediately* positive because of the landscape-level approach applied (which is considered appropriate for the US SE; Jonker *et al.*, 2013) and because only existing softwood plantations are considered, which means that land- or forest use change emissions were excluded. The GHG balance of wood-pellet electricity differs little among feedstocks (Fig. 3). The only deviations are caused by thinning and saw milling emissions, which slightly lower the GHG balance of wood-pellet electricity from commercial thinnings and from mill residues, respectively.

Wood-pellet electricity vs. individual counterfactuals

The GHG balance of the alternative product counterfactual is determined by manufacturing emissions, temporary carbon storage in the product and product disposal emissions. Temporary carbon storage has a positive effect on the GHG balance. However, the average GHG emissions from the production of alternative products

Table 1 Parameters analysed and parameter variation range studied in sensitivity analysis

Parameter	Minimum (% of default value)	Maximum	Sources and notes
GHG emissions of plantation management and harvesting (e_{MH})	75	125	a
enhanced growth of thinned forest (affects e_{MH})	0	200	b
GHG emissions of wood-pellet electricity supply chain ($e_{PM} + e_{PP} + e_{LO}$)	75	125	a, c
GHG emissions of production of alt. products (e_{APp})	77	128	d
GHG emissions disposal of alt. products ($E_{APd}(t)$)	50	200	e
Half-life of carbon during (exponential) in-forest decomposition ($t_{1/2DC}$)			
Small roundwood and commercial thinnings	27	136	f
Harvest residues	69	123	g
Fraction of decomposed carbon stored in forest soil ($f_{DC\ soil}$)	50	200	e, h
Fraction of CH ₄ (and N ₂ O) released during in-forest decomposition ($f_{DC\ CH_4}$)	50	200	e
Softwood plantation yield (affects e_{MH})	75	125	a, i

a: A wide range of literature is available for these parameters – with relatively little variation among studies (see main text and Table 1). Therefore, uncertainty was limited to 75%–125%. b: The growth rate of thinned plantations was varied such that final biomass stocks on a thinned plantation were reduced by either 0% or 100% of the amount of biomass taken out during thinning; the default setting was a reduction of 50% (see main text). Growth linearly affects yield, which affects e_{MH} (see note i). c: GHG emissions from feedstock production, sequestration and any CO₂ emissions from biogenic carbon are excluded. d: Matthews *et al.* (2015). e: Few studies on these parameters exist and uncertainty was therefore deemed high at 50–200%, that is, doubling or halving parameter values. f: Based on Palosuo *et al.*, 2001; Liski *et al.*, 2002; Radtke *et al.*, 2009; Zanchi *et al.*, 2012; Dunn & Bailey, 2012; and Russell *et al.* (2014). (g) Based on Liski *et al.* (2002) and Mobley *et al.* (2013). h: Decomposition GHG emissions ($f_{DC\ CH_4}$ and $f_{DC\ CO_2}$) change accordingly. i: Plantation yield inverse linearly affects GHG emissions of plantation management and harvesting. In terms of GHG balance; yield sensitivity analysis is therefore essentially the same as for e_{MH} .

are higher than their avoided emissions which has a (strongly) negative effect on the GHG balance. The avoided emissions of the alternative products were determined as the GHG emissions of the products they replace. The alternative products (i.e. pulp and paper, OSB and other panels) in this study are more GHG intensive than the products they replace (i.e. recycled paper, blockwork external wall cladding, plasterboard partition wall, see Table S1 note ab and Matthews *et al.*, 2015). Overall, wood-pellet electricity (from all feedstocks) has GHG parity times of 1 year when compared to the alternative product counterfactual (Table S4). Product disposal only has a minor effect on parity time, as most alternative products are still in use after this first year (see Table S3). After parity is reached, wood-pellet electricity has larger and increasing GHG benefits (Fig. 3). Ultimately, despite alternative products embedding carbon, their GHG balance becomes negative after about 40 years (Fig. 3), because alternative product production GHG emissions are larger than avoided emissions (as explained above), and because methane is emitted from an increasing amount of disposed material.

GHG parity times of wood-pellet electricity as compared to the in-forest decomposition counterfactual are 6 years for harvest residues, and a substantially longer 30 years for small roundwood and commercial thinnings (Fig. 3, Table S4). The latter two decompose more slowly and hence store carbon for longer period of time,

resulting in a more positive GHG balance. GHG emissions (including methane) from an accumulating amount of decomposing material eventually become larger than the GHG benefits of carbon stored in decomposing matter, causing a negative GHG balance after 18 years for harvest residues, and after about 80 years for small roundwood and commercial thinnings (Fig. 3). In the long run, the GHG balance of the decomposition counterfactual becomes more negative than that of the alternative product counterfactual. This means that in-forest decomposition may cause larger absolute GHG emissions than alternative products, despite the fact that decomposition results in longer GHG parity times. This result is especially relevant for harvest residues, where decomposition is relatively fast (Fig. 3).

The counterfactual of not thinning was assumed to be GHG neutral (as explained in counterfactual section of the methods), resulting in immediate GHG parity when compared to wood-pellet electricity, and in accumulating GHG benefits in the long run (Fig. 3, Table S4).

Wood-pellet electricity vs. alternative scenarios

The largest differences among feedstocks are found in the GHG balance of their alternative scenarios (Fig. 4), which consist of combinations of individual counterfactuals' GHG balances (Fig. 3). Using small roundwood results in the longest GHG parity times for wood-pellet

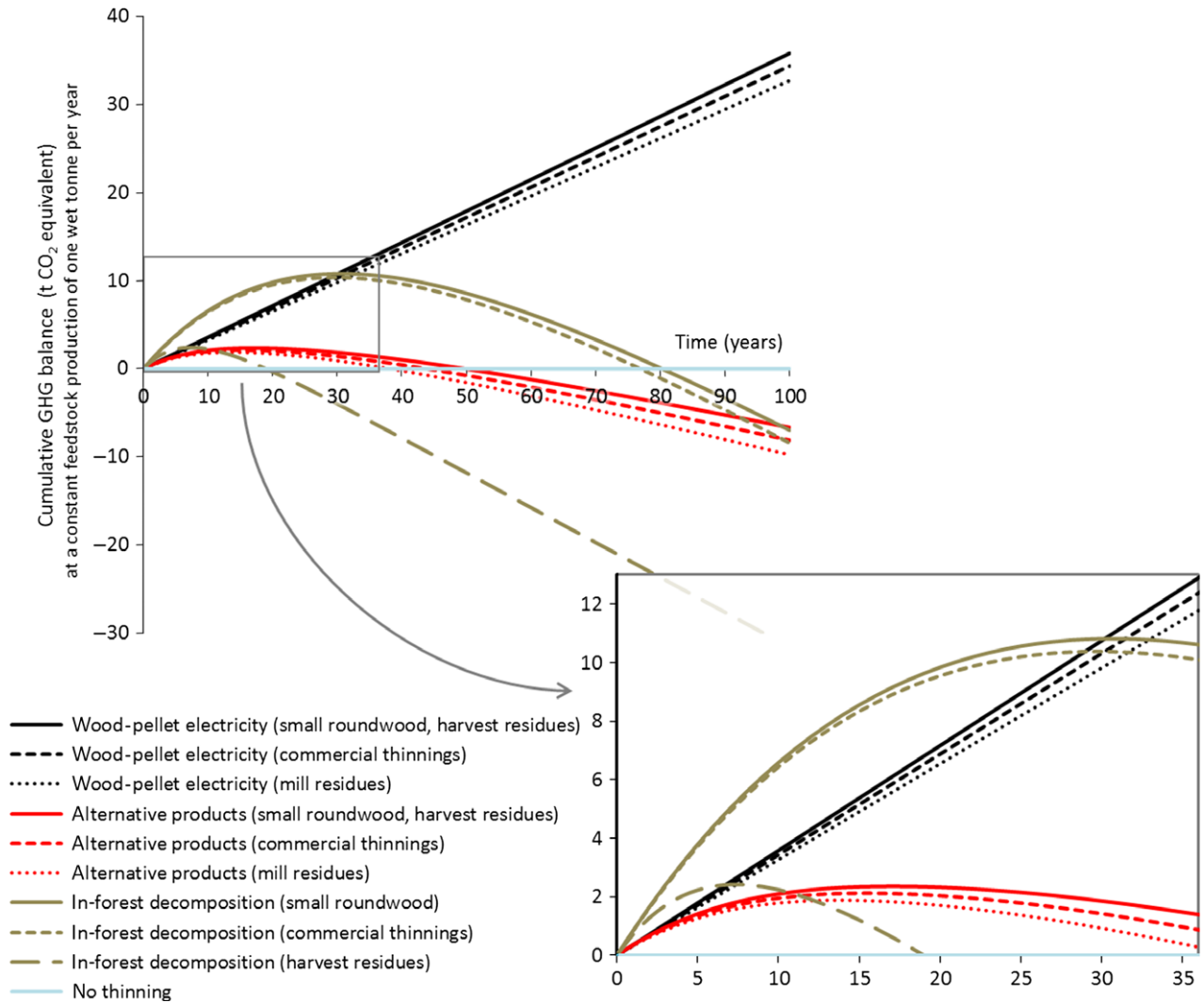


Fig. 3 Cumulative GHG balance of wood-pellet electricity and this study's three individual counterfactuals (alternative products, in-forest decomposition and not thinning) shown per feedstock type at constant feedstock production of one wet tonne per year.

electricity, of 3–21 years (Figs 4 and 5, Table S5), as the alternative scenario (especially at low feedstock demand for alternative products) consists of a large share of in-forest decomposition. Due to the feedstock's relatively large size, decomposition is relatively slow, and carbon is stored for a long time. At higher demand, more roundwood is used for alternative products (rather than being left to decompose), which is a worse alternative in terms of GHG emissions, hence shortening GHG parity times of wood-pellet electricity.

The alternative scenarios for commercial thinnings have similar GHG balances to those of small roundwood (Fig. 4). However, since part of all alternative scenarios for commercial thinnings is *not thinning*, which was considered GHG neutral (as explained in the methods section), the alternative scenarios' GHG balances

are lowered. This means that, for commercial thinnings, wood-pellet electricity has near-instant GHG benefits (GHG parity times of 0–1 year) over the alternative scenarios at all levels of feedstock demand (Fig. 5, Table S5).

Wood-pellet electricity from harvest residues has short GHG parity times (5–6 years; Fig. 5, Table S5) at all levels of feedstock demand. These short GHG parity times are caused by the fact that the alternative scenarios for harvest residues largely consist of decomposition, which is relatively fast for harvest residues due to their small size, resulting in small GHG benefits from carbon storage (Fig. 4). In the long run, using harvest residues for wood-pellet electricity causes relatively large absolute GHG savings, as the alternative scenario (largely fast decomposition) leads to large GHG emissions.

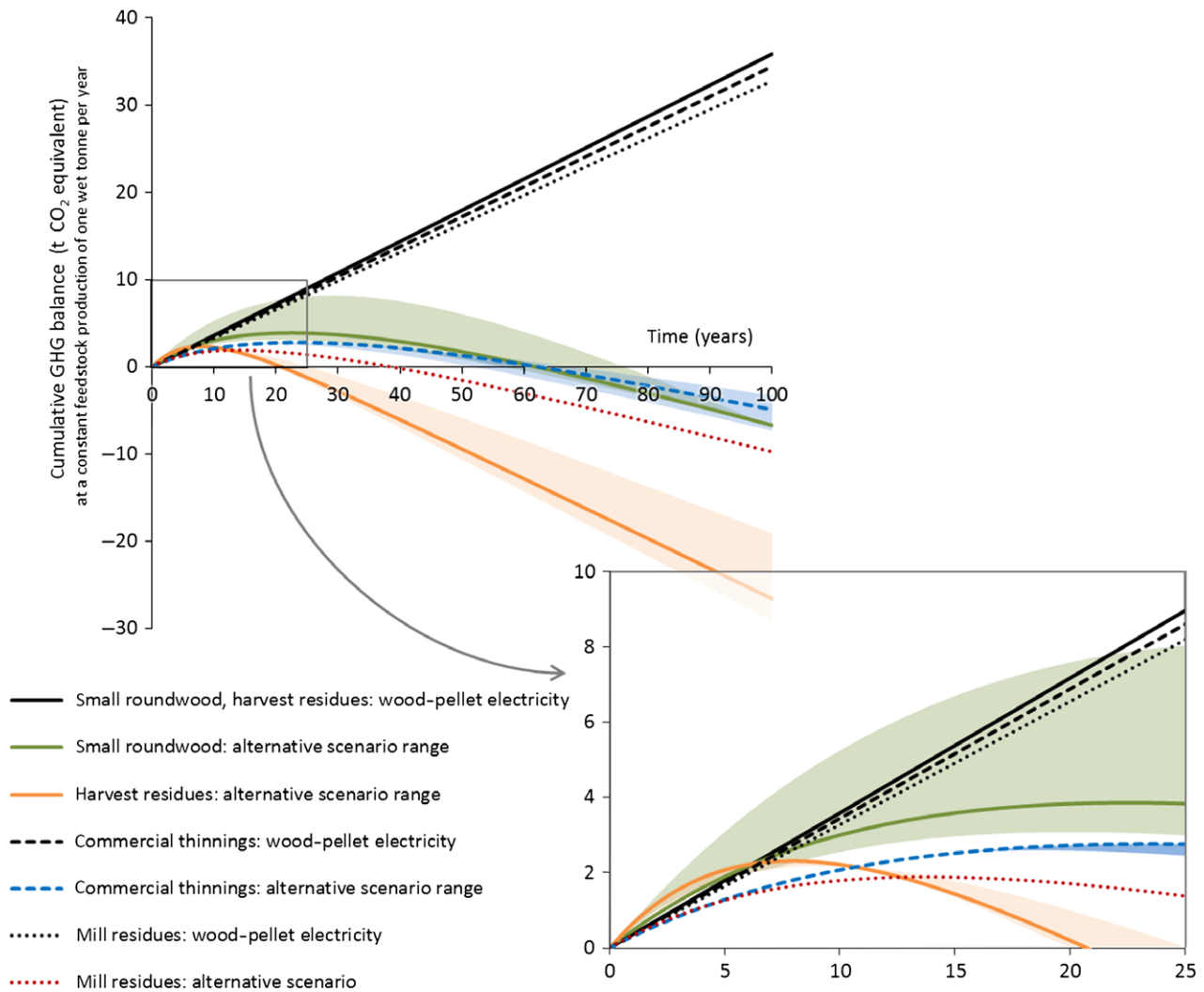


Fig. 4 Cumulative GHG balances of wood-pellet electricity and alternative scenarios per feedstock type at constant feedstock production of one wet tonne per year. Lines indicate alternative scenarios with average demand for feedstock to produce alternative products. Shaded areas indicate the range of alternative scenario outcomes from low feedstock demand (upper end of shaded area) to high feedstock demand (lower end of shaded area); harvest residues form an exception, for low demand leads to the lowest GHG balance (lower end of shaded area). The GHG balances of all alternative scenarios for mill residues are equal, due to equal scenario composition (Fig. 2). Note that negative balances indicate net GHG emissions, and that sensitivity analyses are not included in this figure.

The alternative scenario for mill residues consists entirely of the production of alternative products, at all levels of feedstock demand (Fig. 2). As explained in the previous section, the GHG balance of alternative products quickly becomes lower than that of wood-pellet electricity, resulting in GHG parity times of 1 year.

Demand for feedstock to produce alternative products only had a strong effect on GHG parity times of small roundwood. For small roundwood, a larger demand means replacing more (GHG intensive) alternative products and less (slow) decomposition. Alternative scenario composition of mill and harvest residues was not or minimally influenced by demand (Fig. 2). For

commercial thinnings, the alternative scenarios are dependent on demand, but consist mostly of either the not-thinning counterfactual or the alternative product counterfactual, which both cause a lower GHG balance.

GHG footprinting

When applying a GHG footprinting approach (i.e. considering biogenic CO₂ emissions GHG neutral and not including alternative scenarios), GHG emission reductions of wood-pellet electricity compared to fossil EU grid electricity are 71% (for small roundwood and harvest residues), 69% (for commercial thinnings) or 65%

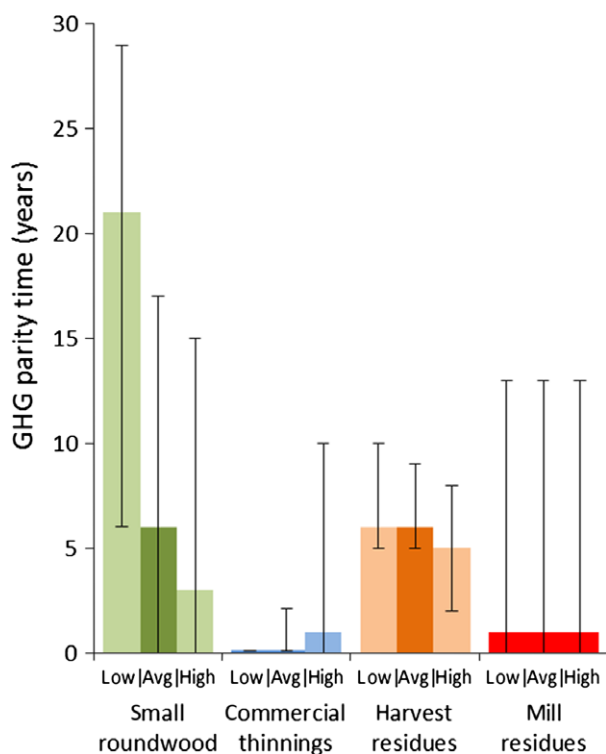


Fig. 5 Greenhouse gas parity times of wood-pellet electricity from different feedstocks, as compared to the feedstocks' alternative scenarios, at low, average and high demand for feedstock for alternative products. Error bars indicate the range of GHG parity times found in the sensitivity analysis.

(for mill residues), as shown in more detail in Fig. S3. The GHG reduction percentage of wood-pellet electricity from mill residues was also calculated using JRC methodology (JRC, 2014), which considers mill residues a pure by-product and excludes plantation management, harvesting and saw milling emissions; this leads to a 75% GHG emission reduction (Fig. S3).

Sensitivity analyses

GHG parity times of wood-pellet electricity are sensitive to five of the investigated parameters (Fig. 6, Table S6). First, sensitivity is, in most cases, highest for GHG emissions of the production of alternative products. For alternative scenarios with a large alternative products component (mill residues, other feedstocks at high demand for feedstock to produce alternative products), halving production of GHG emissions increases GHG parity time by up to 12 years (Fig. 6). Furthermore, GHG parity times of harvest residues become shorter than those of commercial thinnings (at high demand) and mill residues in general. Second, by doubling or halving the emissions from alternative product disposal, GHG parity times are respectively reduced or extended

by a maximum of five years (Fig. 6). When varying this or any of the remaining parameters, the order of feedstocks in terms of GHG benefits does not deviate from the ranking under default parameterization. Third, when in-forest decomposition forms a large component of the alternative scenario (i.e. small roundwood at low demand and harvest residues at all levels of demand), doubling or halving the fraction of decomposed carbon, that is stored in the forest soil, increases or decreases GHG parity times by a maximum of 8 years (Fig. 6). Fourth, when in-forest decomposition forms a large component of the alternative scenario, varying the half-life value of (exponential) in-forest decomposition of feedstocks proves another sensitive parameter. GHG parity times for harvest residues change by up to 3 years (Fig. 6). For small roundwood, assuming the shortest half-life (5 years) even reduces GHG parity times of wood-pellet electricity from 21 years to 6 years. Fifth, variation in wood-pellet electricity supply chain emissions (Table 1) changes parity times by 1–3 years (Fig. 6). Lastly, delaying half of the GHG emissions from alternative product disposal by 50 years causes a maximum GHG parity time increase in 6 years (Table S6).

Varying other investigated parameters (CH_4 and N_2O emissions from decomposition, plantation productivity, effect of thinning on growth, plantation management emissions) over their estimated parameter range (Table 1), or applying economic allocation to feedstock production GHG emissions, affects GHG parity times of wood-pellet electricity by less than 1 year.

Overall, the sensitivity analysis shows that results are robust across our wide range of alternative scenarios. The changes in GHG parity times through varying input parameter values are limited. Parity times of wood-pellet electricity range 0–21 years for default values, and 0–29 years in the sensitivity analyses, excluding interaction effects. The order of feedstocks in terms of GHG parity times *only* changes when substantially varying alternative product production GHG emissions.

Discussion

Comparison with previous studies

In our study, GHG parity times of wood-pellet electricity from US SE softwood plantation-derived feedstocks range 0–21 years under default parameterization and 0–29 years in sensitivity analysis. Previous studies with similar assumptions (reference electricity formed by an average fossil fuel mix for electricity, medium-intensity forest management) yielded different results because different alternative scenarios were assumed. Jonker *et al.* (2013) compared wood-pellet electricity to the

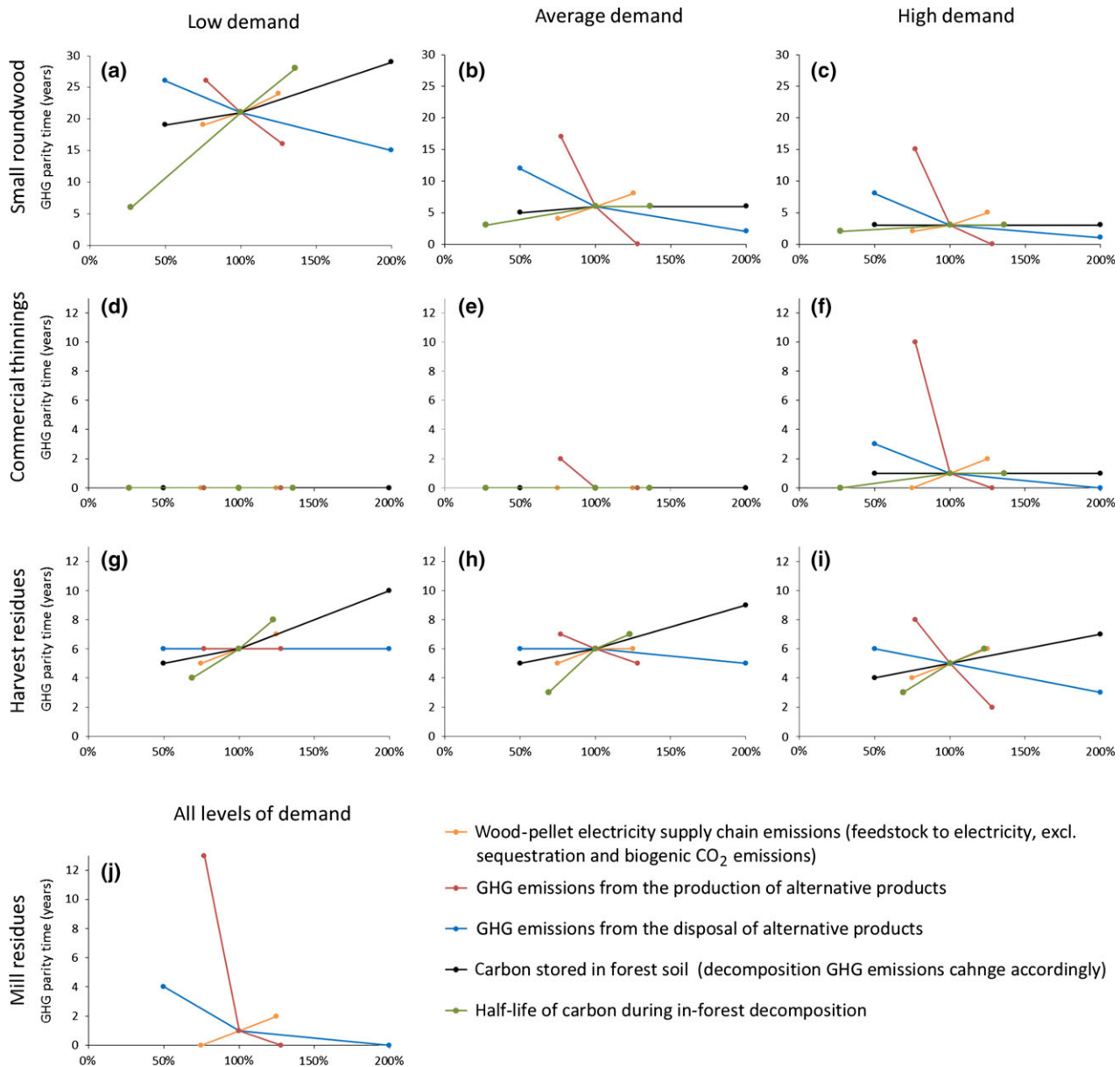


Fig. 6 Sensitivity analysis of GHG parity times of wood-pellet electricity from different feedstocks as compared to three alternative feedstock-use scenarios. Sensitivity analyses are performed for different feedstocks: (a–c) small roundwood, (d–f) commercial thinnings, (g–i) harvest residues, (j) mill residues, and for low-, average- and high demand for feedstock to produce alternative products, respectively. Percentual parameter variation is shown on the x-axis. Note that sensitivity analyses of all alternative scenarios for mill residues are equal, due to equal scenario composition.

alternative scenarios of *protection* (no trees harvested) and *natural regrowth* (trees harvested once, followed by natural regrowth), which resulted in GHG parity times of wood-pellet electricity of 55 and 41 years, respectively. Colnes *et al.* (2012) used a *business-as-usual* alternative scenario (harvest for traditional products only) that resulted in GHG parity times (*avant la lettre*) of about 40 years.

We argue that our new feedstock-fate-based alternative scenarios are more relevant for wood-pellet

electricity than these land- or forest-use-based alternative scenarios. Land- or forest-use-based alternative scenarios assume a single end use for all forest products and implicitly assume that wood-pellet markets are the *main* driver of forest- and/or land use. Decisions on land- or forest use are, however, more likely influenced by saw timber and paper markets (Wear & Greis, 2013; Forest2market.com, 2014), landownership changes (Forest2market.com, 2014) and external pressures like urbanization (Wear & Greis, 2013). Feedstock-fate-based

alternative scenarios, on the other hand, differentiate feedstocks and fates of different forest products. Moreover, they consider the more relevant question of what happens to the (lower-value) feedstock once it is produced (rather than whether it is produced). This question is highly relevant because wood-pellet feedstocks are co-products of more valuable forest products (like saw timber), whose production largely determines feedstock availability.

Previous work indicates that wood-pellet electricity from residues (harvest residues and mill residues) leads to fast and/or large GHG benefits, as this feedstock would otherwise be burnt or decompose (McKechnie *et al.*, 2011; Colnes *et al.*, 2012; Zanchi *et al.*, 2012; Bernier & Paré, 2013; Lamers & Junginger, 2013a; Lamers *et al.*, 2014; Stephenson & MacKay, 2014; Dwivedi *et al.*, 2016). We come to similar conclusions regarding harvest residues (GHG parity times of 5–6 years and relatively large long term GHG savings), for their alternative scenario largely consists of rapid decomposition. For mill residues, we also found short GHG parity times (approximately 1 year), but for a different reason, the alternative scenario consists of the production of relatively GHG-intensive alternative products (as discussed in the next section).

Commercial thinnings and small roundwood are often not separately considered in previous work, but are lumped in the wider category of ‘whole trees’ (which also includes saw wood). GHG benefits of wood-pellet electricity from this category are low and/or slow, as additional tree felling is required, reducing carbon stocks (McKechnie *et al.*, 2011; Colnes *et al.*, 2012; Zanchi *et al.*, 2012). However, except for culled trees, whole-tree usage for pellets is unlikely, as other industries pay more for larger diameter parts of straight stems (see Table S2). In contrast to these studies, we found that commercial thinnings (0–1 year GHG parity times) and small roundwood at medium- and high demand for feedstock (3–6 years GHG parity times) lead to rapid GHG benefits, as the alternative is either not thinning at all or usage for relatively GHG-intensive alternative products. At low feedstock demand, the alternative scenario for small roundwood largely consists of decomposition, which delays GHG benefits of wood-pellet electricity (in this study, a 21-year GHG parity time), in line with Gustavsson *et al.* (2015). Since decomposition rates vary significantly and locally (Russell *et al.*, 2014, 2015), GHG parity times of small roundwood at low demand may also be substantially shorter (down to 6 years in the most extreme case). The default 21-year GHG parity time can be considered a conservative estimate.

GHG footprinting showed that GHG emissions of wood-pellet electricity from different feedstocks are 65–

75% lower than the EU fossil electricity mix (without considering alternative scenarios or temporal dynamics). This estimate is in line with the 50%–75% reduction found in previous studies on EU electricity from US SE wood pellets (Dwivedi *et al.*, 2011, 2014a; personal communication G.-J. Jonker, October 23, 2015).

Robustness of our approach

Sensitivity analysis showed that our wood-pellet electricity GHG parity times are robust for all studied alternative scenarios. What exact combination of counterfactuals is relevant to a wood-pellet feedstock remains a more hypothetical and to some degree subjective matter. This issue was largely negated by considering a wide range of alternative scenarios for each feedstock (at different levels of feedstock demand for alternative products) and by the outcome that for each feedstock GHG parity times are similar across these alternative scenarios (except for small roundwood at low demand). Saw wood demand may also influence alternative scenario composition, as it is an important driver of forest management and harvesting decisions (Aebiom, 2013). However, considering the range of alternative scenarios already studied here, we do not expect substantial changes in overall outcomes.

We captured the most important counterfactuals for wood-pellet feedstocks from softwood plantations via consultation with local experts (see section ‘Methods’). Other less frequent counterfactuals may include the following: (1) burning feedstock material as waste (which is common on non-plantation private forests), resulting in immediate GHG benefits of wood-pellet electricity; or (2) using feedstock material for local energy (beyond processing heat), which may cause fewer GHG emissions than electricity from long-distance transported wood pellets. As these counterfactuals are not frequent in softwood plantations, they would unlikely affect our conclusions.

The alternative product counterfactual showed a relatively low and eventually negative GHG balance because the alternative products were relatively GHG intensive. This result is somewhat counterintuitive, as most wood-based products are relatively GHG-unintensive; lumber, for instance, can replace more GHG-intensive products like steel or concrete. However, this relationship does not hold for the wood-based alternative products of wood-pellet feedstocks: OSB (19% of alternative products) and other panels (1%) replace products with similar associated GHG emissions (based on Matthews *et al.*, 2015). Pulp and paper products (80% of alternative products) are even three times *more* GHG intensive than the product they replace, that is, recycled pulp and paper (with both virgin and recycled

pulp and paper starting from dry feedstock; based on Matthews *et al.*, 2015). Taking *GHG-unintensive* recycled paper as replaced product may seem to lead to an (overly) optimistic estimate of the GHG benefits of wood-pellet electricity (as the alternative product to wood pellets, i.e. virgin pulp and paper becomes relatively *GHG-intensive*). However, recycled paper is, in many applications, the only real alternative to virgin paper (as also assumed by Matthews *et al.*, 2015). Increasing the share of recycled paper in the United States seems feasible, as the EU paper recycling rate is, for instance, 7% higher than the US rate (EPA, 2013; ERPC, 2015). Moreover, when pulp and paper replace products other than recycled paper, these other replaced products are often also less GHG-intensive than virgin pulp and paper. Plastic packaging, for example, is about three times less GHG-intensive than paper packaging, due to lower weight requirements and a less GHG-intensive production process (Cadman *et al.*, 2005; NIAR, 2011; Franklin Associates, 2014).

We explicitly looked at wood pellets derived from *existing* softwood plantations. Results may be different for new plantations, as GHG emission or sequestration from converting previous land- or forest uses to plantations should be accounted for (e.g. Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009; Berndes *et al.*, 2013; Lamers & Junginger, 2013a), as well as potential associated albedo changes and other biogeophysical climate forcings (e.g. Cherubini *et al.*, 2012; Bright, 2015). Current availability of wood-pellet feedstock material will likely continue to suffice for wood-pellet exports towards 2030 (Fingerman *et al.*, 2016). This implies that a large share of wood-pellet feedstock will continue to be derived from existing softwood plantations, highlighting the importance of our study. In case demand for alternative products (pulp and paper, panels) increases, our high demand scenarios will be more relevant. When demand for alternative products does not increase and/or when pellet, paper and OSB mills avoid local competition for feedstock, our low demand scenarios may be more relevant.

We included direct wood-use change (WUC) effects by considering counterfactuals. We also accounted for avoided emissions of both wood-pellet electricity and of alternative products. These assumptions are internally consistent and account for indirect wood-use change (iWUC). Since we considered existing plantations, no direct land-use change (LUC) effects had to be accounted for. However, indirect land-use change (iLUC) effects could still be caused by WUC. As an hypothetical example, increased feedstock use for pellets could mean that more feedstock has to be produced on other land to meet demand from paper mills. This iLUC through WUC effect may not be large, as pellet

mills produce the least valuable product (see Table S3) and tend to have lower buying power than the competing industries, but requires further research nonetheless.

Implications of our findings

Based on robust results, we conclude that wood-pellet electricity from *existing* US SE softwood plantations reduces GHG emissions compared to EU fossil grid electricity within 0–29 years for all investigated wood-pellet feedstocks while taking feedstocks' alternative fates into account. The climate change mitigation potential of wood-pellet electricity can be maximized by sourcing wood pellets from commercial thinnings, mill- and harvest residues, leading to GHG benefits within several years, substantially faster than was found in previous work (e.g. Colnes *et al.*, 2012; Jonker *et al.*, 2013). However, the GHG balance of wood-pellet electricity from non-plantation forests or from newly created plantations, as well as sustainability concerns beyond climate change, need to be addressed separately.

We also find that allocating the studied feedstocks, that is, lower-value forest materials, to wood-pellet electricity rather than to paper and wood panels (e.g. OSB) reduces GHG emissions. Electricity and these alternative products serve very different purposes and are not interchangeable. Therefore, whether (feedstock use of) wood-pellet mills will replace paper or OSB mills ultimately depends on market dynamics of the different products. Whether it is desirable that they replace paper or OSB mills in terms of GHG emissions also depends on potential iLUC emissions. Nonetheless, our findings do imply that the climate change mitigation paradigm of prioritizing materials over bioenergy (e.g. Ellen-MacArthur Foundation, 2013; Vis *et al.*, 2016) does not hold in all circumstances and should in some cases be reconsidered.

Finally, we argue that for wood-pellet electricity from the studied feedstocks, alternative feedstock fates form a more relevant alternative scenario than alternative land- or forest-use scenarios. The reason being that the latter implicitly and (likely) inaccurately assume wood pellets are the main driver of forest- and land-use change and assume a single end use for all forest feedstocks. More generally, feedstock-fate-based analyses may be highly relevant for all bioenergy from lower value co-products of existing industries. The discussion on land- or forest use for bioenergy vs. carbon storage or traditional uses (e.g. Schlamadinger & Marland, 1996a,b; Marland & Schlamadinger, 1997; McKechnie *et al.*, 2011; Berndes *et al.*, 2013) should therefore also include trade-offs between using feedstock for bioenergy vs. alternative fates.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1. Forests in the US Southeast.

Figure S2. Growth curves of thinned and unthinned softwood plantations in the US Southeast.

Figure S3. GHG footprinting results: GHG emission reduction percentages of wood-pellet electricity.

Table S1. Input parameters of this study with references and detailed explanations.

Table S2. Mass fractions, relative prices, and mass-based and economic allocation factors of different forest products included in this study.

Table S3. Fractions of alternative products that are disposed via landfilling, incineration with electricity production, and incineration as waste.

Table S4. GHG parity times of wood-pellet electricity from different feedstocks, as compared to individual feedstock-fate based counterfactuals.

Table S5. GHG parity times of wood-pellet electricity from different feedstocks, as compared to each feedstock's alternative scenarios, at three levels of demand for feedstock.

Table S6. GHG parity times of wood-pellet electricity from different feedstocks, as compared to each feedstock's alternative scenarios, while delaying alternative product disposal.