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Exploring the limits to sustainable pellet production for international markets: The impact of increasing pellet production in the US Southeast on feedstock use, production cost and carbon sequestration in forest areas

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Abstract

With rising demand for wood pellets from the US Southeast (US SE), the environmental limits to additional biomass demand are increasingly questioned. This study analyses the impact of increased pellet production in the US SE until 2030 on feedstock allocation, carbon flux in forest areas and costs of pre-treatment and transport of feedstock and pellets. This by linking locations of forest biomass supply and demand through supply-side logistics, allocating feedstock based on lowest costs of pre-treatment, transport of feedstock and pellets, for the entire wood products sector. The impact is analysed for different scenarios with varied pellet production levels, additional inclusion of logging residues and optimization either on costs or on maintaining total carbon stock in sourcing areas of new pellet mills. In a scenario of 20 Mt pellet production, the roundwood share increases from 0% in 2020 to 37% pulplogs and 11% sawlogs in 2030. Costs increase with 57% towards 2030 compared to 2020, largely because of higher costs for pulplogs and sawlogs. In a scenario without pellet production, forest carbon removal in the US SE is 3 Mt CO_2/year lower than in 2020. In the Reference scenario, additional carbon removal of 6, 21 and 38 Mt CO_2/year is observed for 10, 20 and 30 Mt pellet production, respectively. In all cases, the forests of the US SE remain a net sink until 2030. The impact of a selection criteria for new pellet mill locations based on keeping local growth/drain ratios above 1 in sourcing areas is small since this mostly results in displacement of impacts and does not affect the total feedstock availability. Additional mobilization of logging residues is a key strategy to reduce carbon impacts, resulting in a smaller additional flux of 2, 11 and 29 Mt CO_2/year for 10–30 Mt pellet production.

KEYWORDS

carbon flux, feedstock availability, logistics, resource allocation, spatially explicit, sustainable potential, wood pellet production

1 | INTRODUCTION

The consumption of wood pellets for energy purposes, as a means of phasing out fossil fuels and reducing greenhouse gas (GHG) emissions, is expected to increase in several world regions, including Europe and Asia (Bioenergy Europe, 2019). While Asia is the largest producer of pellets in the world, Europe is the largest consumer, supplementing 19 Mt of production with 9 Mt of imports, largely from the United States (Bioenergy Europe, 2019). In the United States, production of pellets for export markets has been growing significantly, from 0.5 Mt pellet export in 2000 to 7 Mt export in 2018 (Lamers et al., 2015; USDA Foreign Agricultural Service, 2020). The current dominance in wood pellet production coupled with extensive availability of additional forests for wood harvesting and the proximity to import regions in Europe make the United States attractive for even higher levels of pellet production. The Southeast of the US (US SE) has been the dominant producer for the export market, benefitting from a developed timber market, sufficient feedstock availability and proximity to European markets.

The demand for bioenergy and biomaterials is expected to increase significantly in Europe as well as other world regions (Daioglou et al., 2019; Matzenberger et al., 2015). Considering the risks of using agricultural commodities, related to competition with food and feed, and the feasibility of using woody biomass for a range of purposes such as production of energy, biofuels and biomaterials, the demand for lignocellulosic biomass is expected to grow in the near future (Vera & Hoefnagels, 2019). Pellet supply chains were developed to facilitate long-distance transport. The demand for pellet imports to especially western Europe is expected to increase with demand increases (Obernberger & Thek, 2010; Thrän et al., 2017). The question is what the impact will be of increased pellet production in production regions such as the US SE, and what the local limits are to pellet production and trade.

Whether biomass use contributes to the lowering of GHG emissions and the abatement of climate change depends among others on specific supply chain conditions. The European Commission has raised concerns about the sustainability impacts of using biomass for energy, especially relating to forestry biomass. Issues include the balance between supply chain and end use emissions and carbon sequestration, and the competition for resources between energy production and other forest products markets (European Commission, 2017). For pellets imported into the EU, the Renewable Energy Directive (RED II) imposes minimum sustainability criteria (European Parliament, 2018). Bioenergy can contribute to renewable energy targets, and be eligible for financial support, only if certain sustainability criteria are fulfilled (European Parliament, 2018). The prescribed criteria to analyse GHG emissions include the impact of carbon stock changes, either by including carbon stock changes in GHG emission commitments, for countries that have ratified the Paris Agreement, or, if this is not the case, by having management systems in place ensuring that carbon stock and sink levels are maintained. What is not included in this methodology however is carbon flux changes within forested areas, for instance as a result of a different balance between tree growth and harvesting (European Parliament, 2018). To analyse the potential for carbon savings through wood pellet consumption, it is considered essential to also include landscape emissions resulting from forestry management. Only if the growth of carbon in forest areas exceeds the drain of carbon through tree harvesting can bioenergy produced from these forest areas be considered renewable carbon-neutral.

Research on forestry-based bioenergy systems has shown that the impact of increased bioenergy production depends among others on demand for timber and other products, price changes of timber, the context driving these changes as well as changes in forest management and land use (Cintas et al., 2017; Duden et al., 2017; Latta et al., 2013; Rafal et al., 2013). The impact of pellet production can only be analysed in relation to the existing forest products system. Pellets can be produced from primary feedstock (i.e. feedstocks harvested with the primary purpose of producing pellets) or secondary feedstock (i.e. feedstocks that become available as a consequence of harvesting wood for other purposes, such as saw logs or pulp wood). Examples of the latter are logging residues left in the forest or sawmill residues. The use of primary feedstocks can be in competition with other industries, use of secondary feedstock usually deliver economic synergies (e.g. higher revenues for forest owners) but especially process residues may also be in competition with other industries (e.g. panelboard producers). So far, the pellet industry sector in the US SE has not been constraint by wood fibre supply, with growth in wood inventories still outpacing removals (Forest2Market, 2017). On a local level, additional demand for wood products, including pellets, has resulted in increased competition for feedstocks such as industrial residues (Forest2Market, 2017). Growth in pellet production has resulted in increased use of pulpgrade roundwood for pellet production, partly because of limited availability of industry residues and partly because of low prices for roundwood (Abt et al., 2014; Forest2Market, 2017). On the other hand, low-grade residues, such as forest residues, remain underutilized and available (Hoefnagels et al., 2014). Additional pellet production could result in better utilization of industry and forestry residues, but also in increased consumption of harvested wood from production forests, whether this is in the form of roundwood or logging residues.

This study analyses the impact of increased pellet production in the US SE on feedstock allocation, the type of feedstock consumed in the pellet sector, the carbon flux in forest areas and costs of pre-treatment and transport of feedstock and pellets. Scenarios are included to analyse the impact of different levels of pellet production quantity. Based on the spatially explicit availability of feedstock and transport distances to export ports, the optimum location of additional pellet production will be modelled, thereby allowing an analysis of the changes in cost components related to the transport of feedstock and pellets. Additional scenarios are designed to analyse whether the impact of increased pellet production can be reduced by including limitations in new locations of pellet production, based on carbon growth in sourcing areas, or by including increased availability of logging residues. The combination of an integrated systems perspective with a spatial resolution high enough to allow for detailed analysis of regional differences can provide valuable information on the regional impact of increased pellet production. Increased pellet production and export is dependent on efficient production and supply chains, ensuring competitive prices of biomass to enable competition with fossil fuels. At the same time, while an open market is aimed at minimizing costs, sustainability impacts need to be guaranteed as well. Results will explore the impact of expanding feedstock extraction in the US SE on production cost ranges and impacts on US SE forest carbon fluxes. Through the different scenarios used, this work will also show which policy decisions could increase the potential for sustainable production and exports.

2 | MATERIALS AND METHODS

2.1 | Geographical and temporal scope

The definition of US SE used in this study includes the states or Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee and Virginia. Whereas the focus will be on the US SE, products and feedstocks can move easily over state lines, and even internationally with relative ease. To account for any production shifts to other regions, and to avoid leakage of the impact of pellet production to other states, the modelling of resource availability and allocation was done on a US national level. This also includes imports and exports of the different types of wood-based products, which was set at FAOSTAT (Food and Agriculture Organization of the United Nations—FAOSTAT, 2019) reported trade volumes from 2019 and held constant through the remainder of the projection. The 126 export ports included in this study were taken from US International Trade Commission port-specific trade data and represent 98% of the total value of forest products trade over the 2009–2013 time period (U.S. International Trade Commission, 2020). Pellets for the export market are modelled to be traded through a subset of ports, including ports through which pellets were actually exported as of 2017 (Southern Environmental Law Center, 2017).

Availability, demand and allocation of feedstock use for pellet production are analysed until 2030. On the short to medium term, biomass trade in the form of wood pellets is expected to increase. On the longer term, developments in the bioenergy market become increasingly more uncertain, with an unknown future role of wood pellet imports into the EU.

2.2 | General model description

This analysis of feedstock allocation and carbon flux in the US will be based on the Land Use and Resource Allocation (LURA) model (Latta et al., 2018), developed to link specific locations of forest biomass supply to locations of demand through supply-side logistics. Feedstock availability in the model consists of primary feedstocks based on Forest Inventory and Analysis (FIA) statistics (Roesch & Reams, 1999), primary residues in the form of logging residues as well as secondary residues consisting of by-products of manufacturing processes (Figure 1). Yearly changes in demand of forest products in the United States, such as timber, pulp, paper and bioenergy, were modelled after exogenously projected macroeconomic developments, based on 2021 Annual Energy Outlook (AEO) projections (U.S. Energy Information Administration, 2019a), while changes in forestry feedstock supply resulted from FIA tree growth and harvest levels in 2018. The AEO projections were based on the reference scenario, assuming no new policies to mitigate climate change. Growth rates of forestry biomass were kept stable. Stand productivity increases as a result of improved forest management were therefore not included, even though historic trends point at significant improvements. For example, between 1953 and 2017, in the US South, growing stock on timberland increased 113%, on an only 3% larger forest area (Oswalt et al., 2020).

Roundwood classified as sawlog has to be at least 2.4 m long and have a diameter at breast height of at least 23 cm in the case of softwood (SW) and 28 cm in the case of hardwood (HW; U.S. Forest Service, 2019; Waddell et al., 2014). A maximum number of defects is generally specified in regional standards. Pulplogs is defined as roundwood that

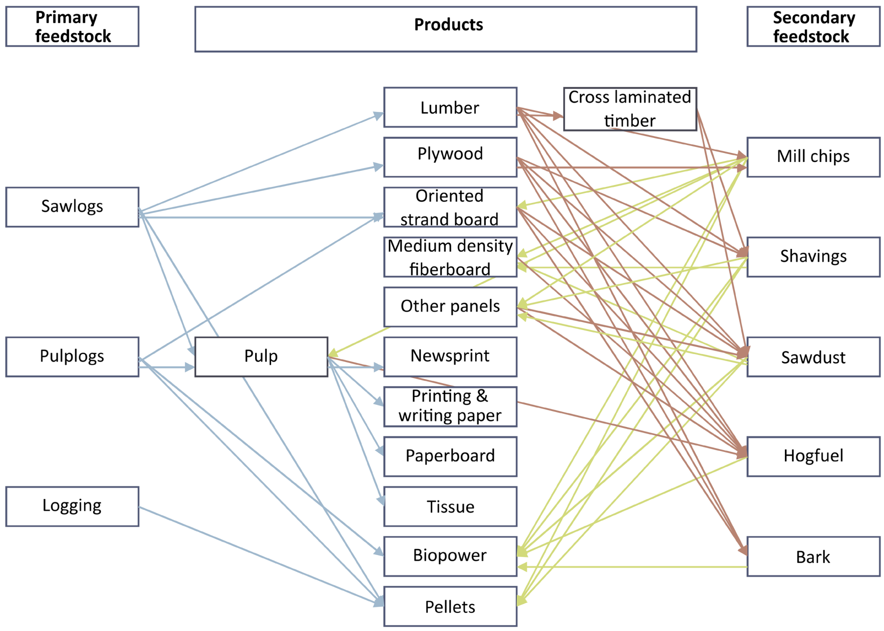

FIGURE 1 Primary feedstocks used for the production of wood-based products and energy (blue arrows), secondary residues generated during primary production (brown arrows) and secondary feedstocks used for the production of wood-based products and energy (green arrows) in the LURA model

does not meet these quality standards, but does contain a minimum of 50% sound wood fibre by volume (U.S. Forest Service, n.d.; Waddell et al., 2014). Each plot can be harvested either through clear-cut harvesting or through thinning, which is modelled in the form of removal of 35% of the standing volume in a plot. This is a separate decision in every modelling run, independent of previous harvest operations, although future harvesting decisions are indirectly impacted by a change in feedstock availability on harvested plots. The proportion between total thinning and clear-cuts needs to be maintained, based on the historic proportion as indicated in the FIA inventory data. Logging residues are generated alongside logging activities and consist of damaged and degraded small-diameter timber and tops and branches. The roundwood portion of logging residues consists of an assumed defect proportion of 3% of total logging volumes, except for Washington, Oregon, Montana and Idaho which have ownership-level estimates based on sampling of logging sites in these states (Martinkus et al., 2019). The amount of biomass available in the form of tops and branches depends on the type of tree and the tree size and was based on FIA methodology (Burrill et al., 2018). The carbon sequestered in sawlogs, pulplogs and logging residues is assumed to be emitted to the atmosphere at the moment of harvesting. This is a simplification which does not account for actual use or alternative scenarios. In reality, for instance, sawlogs used for timber production result in the storage of carbon for a considerable time and logging residues which are not utilized will either be burned in forest areas or will decay naturally over a longer period. This simplification is estimated to have a large impact on the absolute carbon flux calculated but only a small impact on the comparison between different pellet production scenarios, making it justifiable for the purpose of this work.

The supply of both primary and secondary feedstocks is spatially explicitly covered in the model. Primary feedstock is available at the locations of 164,723 measured FIA plots, of which 47,993 are in the US SE. The spatial locations of demand and supply of secondary residues supply are based on actual locations of the different wood-based products industries. The mill locations and capacity data were updated from the 2365 facilities included in the original LURA database, as described in Latta et al. (2018), to a total of 3365 facilities. In addition to mill openings and closures and capacity adjustments, the biggest change was the inclusion of over 900 smaller HW lumber mills better reflecting the spatial heterogeneity of HW sawlog utilization. These updates to the original LURA mill database came largely from University of Georgia's Wood Demand Research Program and the RISI Mill Asset Database (RISI, n.d.). For each industry, the different types of feedstocks used for production were assessed, as well as the secondary feedstocks generated during primary production, as illustrated in Figure 1. Some production processes, including pellet production, require the generation of heat for feedstock drying. This heat is assumed to be provided by the combustion of biomass, thereby contributing to total feedstock requirements. For pellet production, no distinction is made between different feedstock types whether these are used for heat production or end up as part of the final product. The precise quantity of feedstocks used and produced is shown in Appendix A. Allocation of feedstock from supply locations to demand locations is done for every yearly iteration, based on an economic optimization at system level without any form of foresight. This optimization includes the costs required to transport feedstock to mill gates and pre-treat it for further processing. This includes the costs of feedstock transport from forest plots to mill and from mills to mills. For those products being exported, including pellets also costs of transportation of products to ports is included. Costs of harvesting and chipping is also included in the case of sawlog and pulplog consumption. The model only allocates for lowest system costs and does not consider differences in feedstock prices or paying capacities of specific industries. Detailed information on LURA inputs and methodology can be found in Latta et al. (2018).

2.3 | Scenarios

Three variables were selected that have a major impact on feedstock availability and allocation to pellets: the variation in pellet export quantity, the locations of future pellet mills and the availability and utilization of logging residues (see Figure 2; Table 1).

2.3.1 | Variation in export level

Demand for wood pellets for export was varied exogenously: to capture the uncertainty in future pellet demand, three different projections were used. Pellet demand was assumed to increase linearly, varied in three different projections. In recent years, pellet exports from the United States have increased from 1.9 Mt in 2012 to 6.9 Mt in 2015 (Thrän et al., 2017). Growth stalled in 2016 and 2017 as major demand markets in Europe slowed down, but increased again in 2018 with demand being picked up in several European countries (Canadian Biomass, 2019). Pellet exports increased with 970 kt between 2017 and 2018, and with 880 kt between 2018 and 2019 to a total of 8.8 Mt (U.S. Energy Information Administration, 2019b; USDA Foreign Agricultural Service, 2020). Future pellet production and export developments are uncertain, depending on market and policy developments. Fingerman et al. (2019) have reviewed export potentials as analysed in different literature studies, resulting in a range of 0–28 Mt in 2030. The different projections used in this study therefore represent the full range of likely pellet export quantities. The Medium projection, considered the reference scenario, was based on a yearly increase of about 1 Mt of exported pellets, totalling 20 million Mt in 2030. The Low and High projections capture the uncertainty of future developments, ranging between almost no additional growth and a higher linear growth rate, amounting to 10 and 30 Mt of exported pellets in 2030, respectively. Next to these scenarios, a reference scenario (Zero pellets scenario) was included in which pellet production for export reduces to 0 from 2020 onwards.

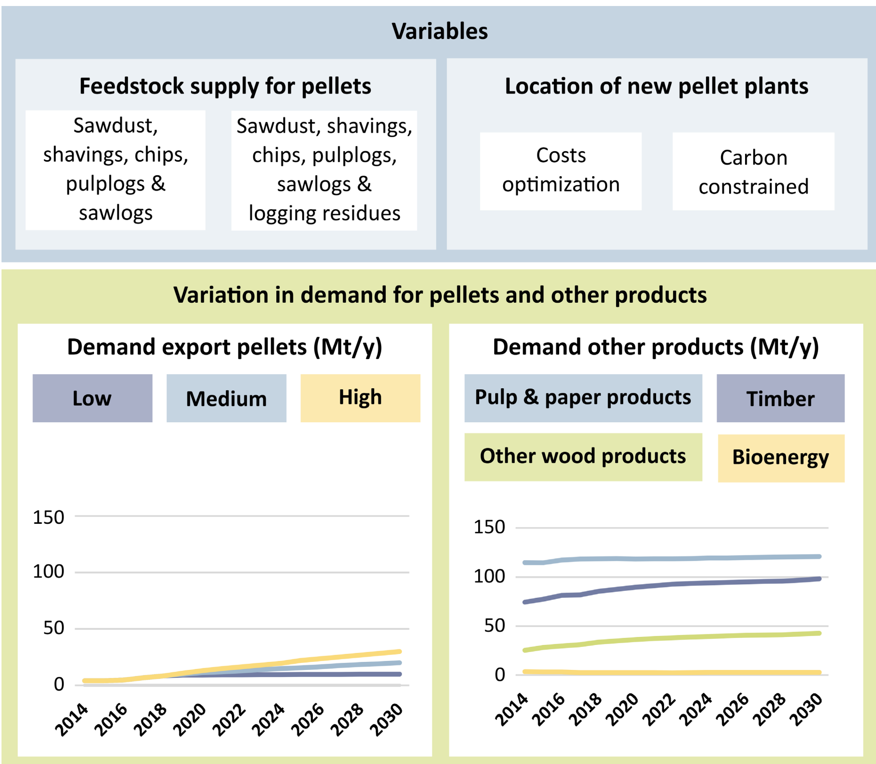

FIGURE 2 Overview of the different scenario approaches used. Nationwide demand for other products is included to illustrate the quantity compared to pellet production. The pellet production as shown in this figure only applies to pellets produced for the export market, predominantly produced in the US SE. The production quantity of pellets for the domestic market is very minor compared to export pellets and is included in the Bioenergy category. A complete overview of demand development for the different products is shown in Appendix B

TABLE 1 Overview of the scenarios used in this study

Scenario	Inclusion of logging residues	Method of pellet mill expansion	Quantity of pellet exports in 2030 (Mt)
Zero pellets	No	Costs	0
Reference—low	No	Costs	10
Reference—medium			20
Reference—high			30
Carbon—low	No	Carbon	10
Carbon—medium			20
Carbon—high			30
RefLogRes—low	Yes	Costs	10
RefLogRes—medium			20
RefLogRes—high			30
CarbonLogRes—low	Yes	Carbon	10
CarbonLogRes—medium			20
CarbonLogRes—high			30

2.3.2 | Driver of expansion

Across all scenarios, manufacturing locations of all industries are unchanged, with only the manufactured quantity per location changing from year to year. An exception to this modelling approach is the yearly addition of new locations of pellet mills. Considering the significant increase in total pellet manufacturing, it was not considered possible to achieve production increases solely by assuming capacity increases at existing locations since this would result in unrealistically large increases at individual mills. Total annual pellet production at existing locations is therefore capped at 9 Mt in the LURA model, the pellet production capacity in the US South at the end of 2019 (U.S. Energy Information Administration, 2020). Although the total production quantity at existing locations is fixed, manufacturing quantities of individual pellet plants are allowed to change based on relative cost-effectiveness, as will be explained in more detail in Section 2.4.3. The model used in this study focusses on feedstock allocation and does not include other cost factors such as capital costs of manufacturing facilities. Additional expenses for capacity expansion or building new pellet mills are not included, and therefore play no part in the design of total manufacturing expansion. Additional pellet production beyond the 9 Mt will be placed at new locations from 2020 onwards. These new locations are modelled to be of a fixed size, as was dictated by modelling limitations. The creation of a set of potential locations will be further explained in Section 2.4.3. For the method of actually selecting a new location from this set, two different approaches were used.

- The *Cost optimization* approach was used for the reference scenarios, and was based on market-driven expansion, with new mills being placed wherever costs are the lowest. For each of the potential new location, the model first evaluated the potential logging residue supply costs from the prior year market solution radiating out from the mill site in €9/dry tonne increments until the required mill capacity was met. It then calculated the weighted average feedstock cost for the site including grinding, hauling forest to mill and hauling mill to port. The potential mill location with the lowest weighted average feedstock cost was chosen and the process repeated until the desired number of new production sites were met. In each case, the least cost export destination port capacity was increased to coincide with the mill capacity expansion.
- The *Carbon constrained* approach presumes the existence of policies prohibiting the use of feedstock from areas with a positive carbon flux, being the sum of carbon sequestration through tree growth (negative flux) and carbon removals in harvested trees (positive flux). This is considered a very strict interpretation of the RED II requirement that a management system needs to be in place at sourcing level to maintain or improve carbon stock and sink levels (European Parliament, 2018). In this approach, the net change in live tree carbon within a 2-h round trip hauling distance from each potential new mill location was calculated using the prior period harvesting activity and current period forest growth. The sites were then ranked by highest carbon growth rate and new locations chosen from the top of list. The least cost export location capacity was also expanded to meet the new production at each facility.

2.3.3 | Inclusion of logging residues

Logging residues are of lower quality, contain more contaminants and produce pellets with a higher ash content, and are therefore a suboptimal feedstock to use for pellet production. Therefore, the standard analysis was based on no utilization of logging residues. At the same time, utilizing this feedstock would reduce the amount of roundwood required for pellet production and could greatly contribute to the GHG efficiency of producing energy from wood pellets. Harvesting and mobilization of residues requires several processing steps such as the piling of residues into slash piles, drying of these piles for an extended period, subsequent loading of residues by grabbing biomass and chipping at roadside before transport. A specific issue with logging residues furthermore is contamination with sand and leaves, especially in the lower part of slash piles, preventing the collection of every last bit of feedstock. These mobilization steps require the development of new supply routes and procedures, while the potential biomass is of low value compared to the sawlog part of forests. For these reasons, the assumption was made that only 25% of the calculated availability of logging residues can be mobilized cost effectively. This is on the conservative side when comparing with studies on the recovery rates of harvest residues. In a review study, Thiffault et al. (2015) have calculated an average recovery rate of 52% with a standard error of 18% across 68 studies, of which 17 studies are based on sites in the United States. This study, however, also concludes that recovery rates are higher in the Nordic countries, Finland, Norway and Sweden than in Canada and the United States. The reasons for this are hypothesized to be high policy support, technological learning and uniformity of Nordic SW plantations facilitating machinery tasks (Thiffault et al., 2015). The additional removal of nutrients from forest areas was assumed to be small. After harvesting, slash piles of tops and branches are presumably left to dry for an extended period. This allows for the decomposition of leaves, providing nutrients back to the soil while facilitating collection of the remaining wood (Rudolphi & Gustafsson, 2007; Thiffault et al., 2015). The use of logging residues in pellet plants could require adaptations since logging residues are expected to have a higher content of contaminants such as sand, leaves and twigs, providing a less clean feedstock. Consumption of logging residues is however considered feasible in a mixture with other residues or feedstocks, for instance to provide the heating fuel required or as a minor share in finished pellets. This is supported by examples in practice, in British Columbia for instance, forest residues accounted for 17% of feedstock used by pellet plants in the first quarter of 2017 according to Wood Resources International LLC (2017).

Varying these two variables results in the creation of different scenarios, summarized in Table 1. The Reference scenario was based as much as possible on business as usual, that is, excluding the use of logging residues, and selecting new pellet mill locations based on lowest costs of all cost components included in the LURA model. The Reference scenario in combination with a pellet demand for export of 20 Mt is considered the most likely scenario based on current policies and pellet production trends and will be used to highlight the impact of expansion of pellet production. The other scenarios will be used to analyse the impact of uncertainty in total pellet demand and the potential impact of policies steering the location of pellet mills and the use of logging residues.

2.4 | LURA methodology

2.4.1 | Feedstock allocation based on a total of cost components

The model optimization in this work is based on a lowest total cost principle, minimizing the total of cost components for all harvested, pre-processed and transported commodities and products. This total cost optimization determines the allocation of commodities to processing mills and is done for every yearly iteration. Total costs consist of a combination of harvesting and chipping costs, costs of hauling of feedstock from forest plots or mills and costs of transport of products from or to export ports if applicable.

Both harvesting costs and chipping costs are only required for sawlogs and pulplogs. In the case of harvest costs, the costs are highest for the first tonne and decrease with increasing harvested quantity per hectare. In principle, no distinction is made between harvesting and chipping costs of pulplogs and sawlogs. This could, however, result in very unrealistic modelling of feedstock allocation compared to actual market dynamics. For instance, this lack of distinction would mean that clear-cutting of large plots of pulplogs and sawlogs results in lower costs than thinning of only pulplogs, since costs are a function of harvested quantity per hectare. To prevent the extensive and unrealistic consumption of sawlogs in pellet manufacturing and other industries, additional downgrade costs of 19 €/dry tonne were included in case sawlogs are used by industries not requiring high-quality wood, such as the pellet, pulp and paper industries.

Hauling costs of both forestry feedstock and products were calculated based on the travel distance and permitted speed on actual road networks. Calculations were based on a speed equal to the maximum speed. Total costs are a combination of a distance-based component, consisting of fuel costs, and a time-based component, consisting of hourly trucking costs including trucker wages, benefits and truck lease. Roundtrip costs were calculated by doubling one-way costs, assuming a simplified equal fuel efficiency and include 15 min loading and unloading time. The cost factors used in the calculation are based on (Latta et al., 2018) and were converted from dollar to euro using the average exchange rate over 2019 (X-Rates, 2019). See Appendix C for more details on the costs of different components and the full set of cost factors used.

2.4.2 | Production locations

The production locations of all products except exported pellets were taken from a combination of sources (Latta et al., 2018; RISI, 2012; Smith et al., 2000; Spelter, 1996; Spelter et al., 2009; U.S. Energy Information Administration, 2012a, 2012b). For an overview of currently active pellet mills, two different datasets were compared, a Forisk Wood Bioenergy US Database, updated as of October 13th, 2017 (Forisk, n.d.) and a RISI Wood Pellet Capacities database, updated at the beginning of 2018 (RISI, n.d.). The Forisk database contains information on the operational status of pellet plants, whereas the RISI database contains information about the grade of pellets produced, either industrial export or domestic pellets. A cross-section of the two lists was made, keeping only the pellets plants that are operational or under construction and are producing industrial pellets. Several pellet plants were only included in one of the two databases. In these instances, additional information was used to determine the status and pellet grade, for instance from company websites. This resulted in the addition of three pellet plants to the list. The final list of pellet plants includes 23 pellet plants in the Southeast of the US, with a capacity to produce 8.3 million tonne pellets and 17 pellet plants in other US regions with a much smaller total capacity of 0.7 million tonne pellets.

2.4.3 | Capacity changes

Demand changes of all products except pellets for the export market, to be referred to as 'other products' were accommodated at existing production locations, with production capacities updated yearly to simulate responses to market changes. Capacity changes depend on the total demand change from year n to year $n + 1$ and on whether a specific mill is cost competitive compared to the average of all mills in year n. A mill is classified as cost competitive if the costs of producing a commodity at the specified mill are lower than the average costs of all commodities produced at all mills. In case total demand for a specific commodity decreased, all mills performing below average are depreciated proportionally in that year. If total demand decreases, capacity at the poorly performing mills is depreciated with 5% while capacity at all cost competitive mills is increased proportionally to accommodate the remaining demand, following the existing methodology in the LURA model (Latta et al., 2018).

For pellet mills producing for the export market, this method was applied to the existing pellet mills. Additionally, new mill locations were added each year, selected from a collection of potential locations, to accommodate the very large increase in total manufacturing quantities. The potential new mill locations were created in ArcGIS by overlaying a 50 km grid on the US SE. The choice for a 50 km grid was a balance between adding enough potential locations to cover regional differences in feedstock availability and transport requirements while keeping the model runtime manageable. Placing pellet plants in the centres of the grid cells resulted in a set of 545 potential new locations. The production of pellets for the export market at existing pellet mills, capped at 9 Mt, includes 17 potential production locations outside of the US SE. Since the new pellet mill locations are placed only in the US SE, the additional manufacturing quantities, especially in the Medium and High scenarios, will result in a large burden placed in one region. All new pellet mills were assumed to have a fixed capacity, depending on the total demand modelled. To model the Low pellet demand, one small mill of 100 kt/year production was added every year. The small increase in manufacturing in the Low scenario could also be realized by a modest growth of existing mills. However, the decision was made to use a uniform method for all three projections and to therefore also add new locations in case of Low pellet demand. In the Medium and High projections, pellets mills of 400 and 800 kt/year were added, respectively, two or three mills each year, following a linear growth curve as best as possible (see Table 2). The size of 800 kt/year represents the size of the largest currently operating pellet plant in the US SE (Biomass Magazine, 2020). The production increases required to realize 30 Mt in 2030 are so significant that this requires a serious upscaling of pellet production activities. The assumption was made that this would be done using the largest feasible size of pellet plants. The size of 400 kt/year is representative of the average size of pellet mills currently producing for the export market, and is considered a good assumption to use in a projection of continuous business as usual increases in total production (Biomass Magazine, 2020; Southern Environmental Law Center, 2017).

The LURA model allows for the results to deviate 0.5% from exogenous demand levels to account for potential inconsistencies as port and production facilities depreciate or expand over time that could result in an infeasible solution. The objective function structure minimizes those deviations yet it results in slightly different modelled growth rates and

TABLE 2 All feedstock types included in this study

Feedstock	Type	Used for pellet production	Assumed moisture content
Sawlogs	Primary	Yes	47%
Pulplogs	Primary	Yes	47%
Logging residues	Forest residues	Yes	47%
Mill chips	Industry residues	Yes	0%
Shavings	Industry residues	Yes	0%
Sawdust	Industry residues	Yes	0%
Hog fuel	Industry residues	No	0%
Bark	Industry residues	No	0%

pellet mill additions in each scenario. Figure 3 shows the growth rates and the number of pellet mills added in each year for the Reference scenario. As explained previously, the selection of locations differs in the cost-based and carbon-based approaches, resulting in a different set of new pellet mills. The modelled locations of pellet mills in the different scenarios are shown in Appendix D together with the modelled growth rates in different scenarios.

2.5 | Input data

2.5.1 | Feedstock availability

Spatially explicit availability of biomass within the United States was estimated based on the FIA program of the US Forest Service. For the conterminous United States, data were collected from over 150,000 FIA plots, with measurements of just under 5 million trees. FIA plots are the result of random selection of a location within hexagonal cells positioned in a grid across the entire conterminous US and consist of four subplots totalling 0.07 ha in size. FIA plot data contain additional information on the type of land and trees in the plots as well as data on ownership type. Data on the type and size of trees are used to distinguish between SW and HW and between pulplogs and sawlogs.

The development of forest stocks in future years was estimated by applying growth curves to existing forested areas. Growth rates are determined based on measured volume and age of plots and differ for unique combinations of productivity class, forest type and ecoprovince, which are areas with relatively consistent natural characteristics, including climate, geography, soil type and potential natural communities (Latta et al., 2018). Growth in the LURA model is limited to yield increases on existing forested plots and does not include land-use change (e.g. conversion from agricultural or fallow land to plantations or conversion from natural pine stand to pine plantations) or forest management changes (e.g. changes in productivity due to improved fertilizer application or tree species selection and genetic engineering) (Duden et al., 2017; Noormets et al., 2015). Furthermore, potential impacts of management practices, such as fertilizer application, were not included. An exception to this is the impact of tree thinning. As a result of thinning, the average density of remaining trees is reduced, which then changes the growth equation for subsequent years. Total growth on each plot in every yearly time step was recorded, distinguishing between net growth of standing trees, regenerative growth after a clear-cut and additional growth resulting from thinning.

Availability of secondary residues was included by assuming fixed output of residues per production process, as shown in Table B.2 in Appendix B. These production processes, and the output in the form of by-products, were assumed to remain unchanged until the end of the modelling timeframe. Total mill feedstock availability changes in every iteration as production quantities and locations of wood and paper industries change.

2.5.2 | Feedstock demand

Future demand for other products was modelled after the Reference case of the US EIA 2019 AEO. These AEO scenarios are modelled after economic and demographic trends while assuming unchanged laws and regulations (U.S. Energy Information Administration, 2018). The initial 2014 demand levels for forest products were determined based on FAO statistics on production, exports and imports as well as various data sources on the location and capacity of several forest product mills (Abt et al., 2010; RISI, 2012; Smith et al., 2000; Spelter, 1996; Spelter et al., 2009; U.S. Energy Information Administration, 2012a, 2012b). A complete list of total base capacities and demand, as well as projected demand changes is given in Appendix B. Pellets produced for domestic use were assumed to fall within the AEO projections for bioenergy development. Future demand

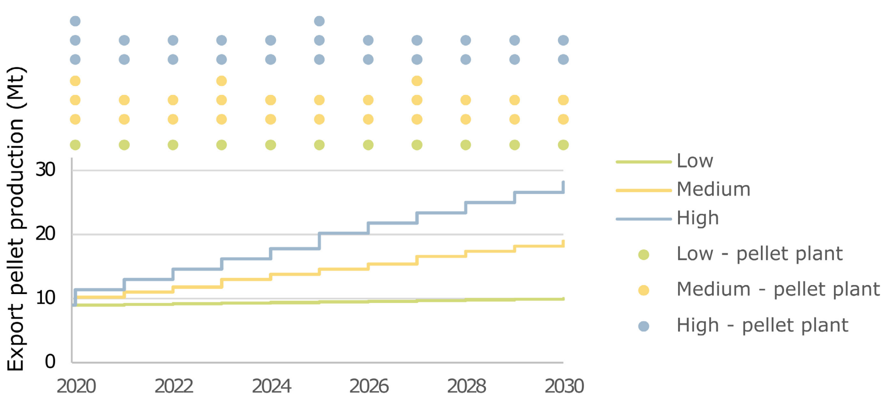

FIGURE 3 The modelled growth rates observed for the reference scenario. Also shown the number of pellet plants added each year in the Low scenario (of 100 kt size), the Medium scenario (of 400 kt size) and the High scenario (of 800 kt size)

for pellet export was modelled separately from non-pellet demand, in the Low, Medium and High projections, as explained above.

3 | RESULTS

The model was solved for all 12 scenarios along with a no export pellet scenario for the years 2020–2030. The LURA results are nationwide and for all 20 final demand and intermediate products. However, we focus on the variation in export pellet feedstock and cost characteristics in the US SE in our results.

3.1 | Feedstock composition

3.1.1 | Feedstock use for pellet production in the Reference scenario in the US SE

Results for feedstock composition show that pellet production in 2020 is largely based on milling residues, mainly SW Mill chips (30%) and SW shavings (29%), see Figure 4. This can be explained by the fact that costs of all residues (logging and milling) in the LURA model are lower compared to costs of pulplogs and sawlogs since these feedstocks do not require harvesting and chipping. Grinding of logging residues is assumed to take place in forests, using diesel-powered grinders. Chipping of roundwood at mills, using electricity, is more cost-effective. The ground logging residues can however be transported more efficiently, thereby lowering hauling costs. At long distances, the high costs of collection and grinding of logging residues are offset by transportation savings and logging residues are utilized while at shorter distances the lower electrical chipping costs outweigh the higher costs of hauling pulplogs and sawlogs. Cost optimization results in increased production at mills located close to sources of available mill residues. Logging residue availability, however, depends on the production of timber and is therefore inherently limited. In 2020, the majority of total residues is allocated to export pellet production, 83% of mill chips, 76% of sawdust and 70% of shavings. Towards 2030, in all scenarios the utilization of residues reduces, in the Medium scenario from 79% overall utilization to 47% utilization. This can be explained by the reducing availability of residues for pellet production as demand for pellets increases, as well as by the fact that forest growth exceeds removals across the entire modelling period, resulting in increasing availability. In the Low scenario, in 2030, the total share of residues makes up 97% of the total feedstock use. In the Medium and High scenario, this reduces to 52% and 35%. The large consumption of pulpwood can partially be explained because of the additional downgrade costs of sawlogs and partially by the fact that demand of other industries is larger for sawlogs than for pulplogs, resulting in a larger availability for pulplogs for pellet production. The type of feedstock used depends on the availability close to pellet mills. The locations of pellet mills producing for the export market, as modelled using the Reference and Carbon approach, are visualized in Appendix D.

Harvesting costs decrease as harvested quantity increases and therefore there is a cost advantage to hauling large quantities from the same forest plots. This is not limited to pellet production, combined harvesting for pellet production and other industries results in lower system costs. Still, the spatial aspect of transport distance from forest plots to pellet mill locations quickly outweighs lower harvesting costs. Another aspect to consider is the balance between clear-cut harvesting and thinning. As a result of the higher overall proportion of clear-cuts, as based on FIA inventory data, roundwood used for pellet production is, in 2030, predominantly taken from clear-cuts, and only 12% of total sawlogs and pulplogs used are harvested through thinning. In real-world practices, clear-cut harvesting is done based on a combination of different demand sources of sawlogs and pulplogs. The demand for low value feedstock for pellets is not expected to be the main driver behind clear-cuts (Forest2Market, 2015). In

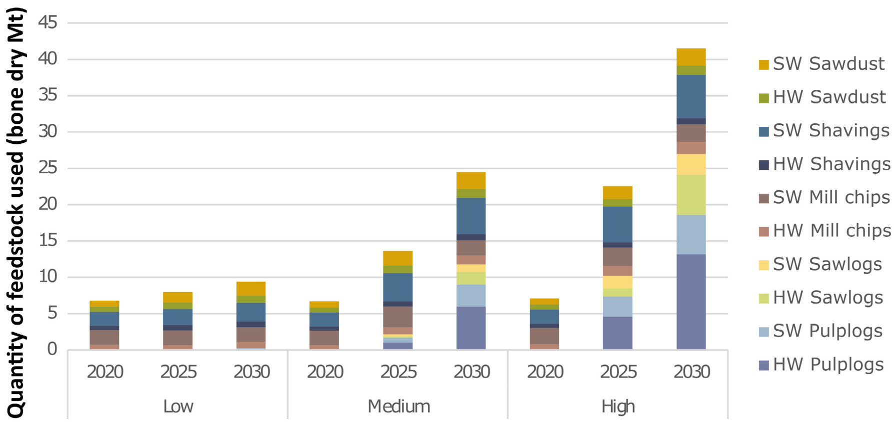

FIGURE 4 Feedstock used for pellet production in the US Southeast in the Reference scenario for the Low, Medium and High projections in 2020, 2025 and 2030. The use of logging residues is excluded in this scenario. SW, softwood; HW, hardwood

the modelling results, of the total sawlog quantity harvested in all scenarios and years, only 11% is harvested from plots on which the share of pulplogs harvesting is less than 25% and no sawlog is harvested from plots without at least a small share of pulplog harvesting.

3.1.2 | Total feedstock consumption for all forest products in the US SE

When comparing use of feedstock for pellet production with other industries, the allocation of mill residues to pellets becomes apparent, as shown in Figure 5. In the Reference scenario, 37% of pellet production is based on pulplogs and 11% based on sawlogs in 2030. The LURA model does not restrict the use of sawlogs for pellet production; however, it does include additional downgrade costs of €19/t when consuming sawlogs in pulp, panel or pellet operations, thereby favouring the use of pulplogs instead of sawlogs. In the case of clear-cut harvesting, limited local demand for sawlogs and high local demand for pulplogs, it could, however, be the case that sawlogs are a local by-product of pulplog demand and are the most cost-effective feedstock option to allocate to pellet production.

In all projections, the largest part of milling residues used in the forest products sector is allocated to the production of export pellets, this share increases from 52% in the Low projection to 79% and 78% in the Medium and High projections. Part of this increase in process residue use can be explained by the increased total utilization of these residues, as explained in the previous section. However, as Figure 5 shows, part of the mill residues used for export pellet production were previously used in other production processes. This displaces part of the burden of increased pellet production onto other products.

Part of the increase in sawlog and pulplog consumption in the US SE is caused by a relative shift of lumber production towards the US SE, caused by the extensive availability of feedstock. Still, the additional demand for pellets also has an impact on total demand for roundwood. When comparing feedstock use in 2020 to the results for 2030, total pulplogs and sawlogs feedstock removal in tonnes increases to 114%, 125% and 139% in the Reference Low, Medium and High scenarios, respectively. The largest part of this increase is caused by increased demand for other products than pellets. When compared to the Zero pellet scenario, the pulplog and sawlog removal increases to 103%, 107% and 109% in the Low, Medium and High scenarios, respectively. The difference between these projections can be fully explained by the added demand of additional pellet production. As will be shown in Section 3.2, changes in total harvesting have an impact on the net carbon flux.

3.1.3 | Additional feedstock scenarios in the US SE

The impact of the scenarios with logging residues as additional feedstock source is shown in Figure 6, showing the feedstock consumption in 2030 in the Medium projection.

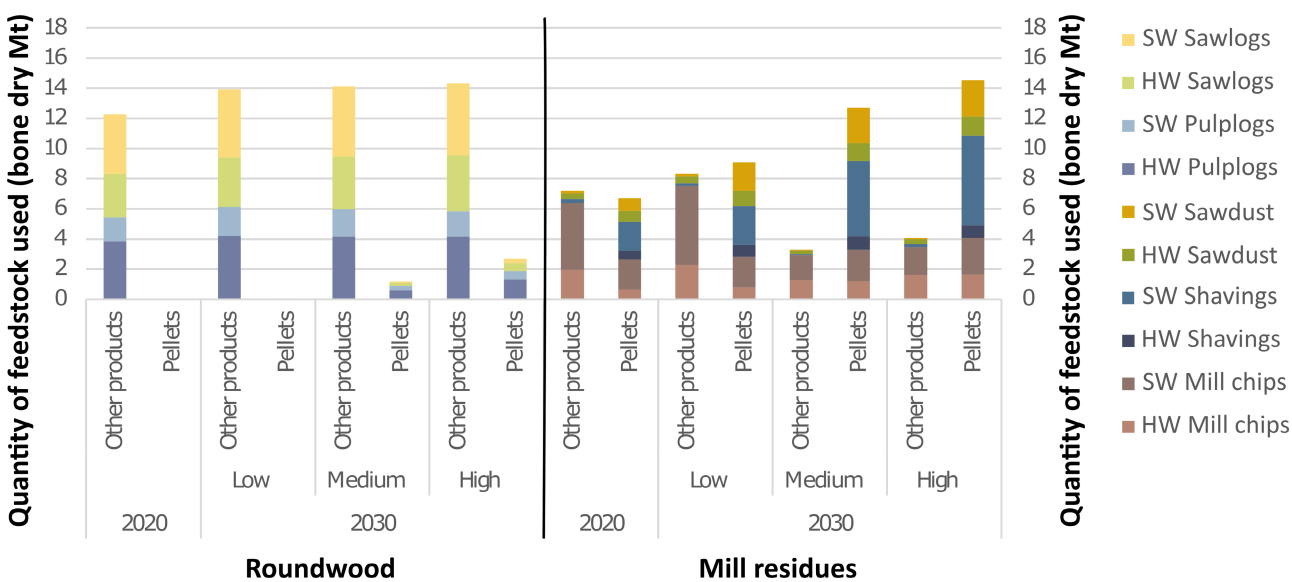

FIGURE 5 Roundwood and mill residues used for pellets and other products in the US Southeast, in the Reference scenario for the Low, Medium and High projections in2030. Note the differences in scale of the vertical axis. SW, softwood; HW, hardwood

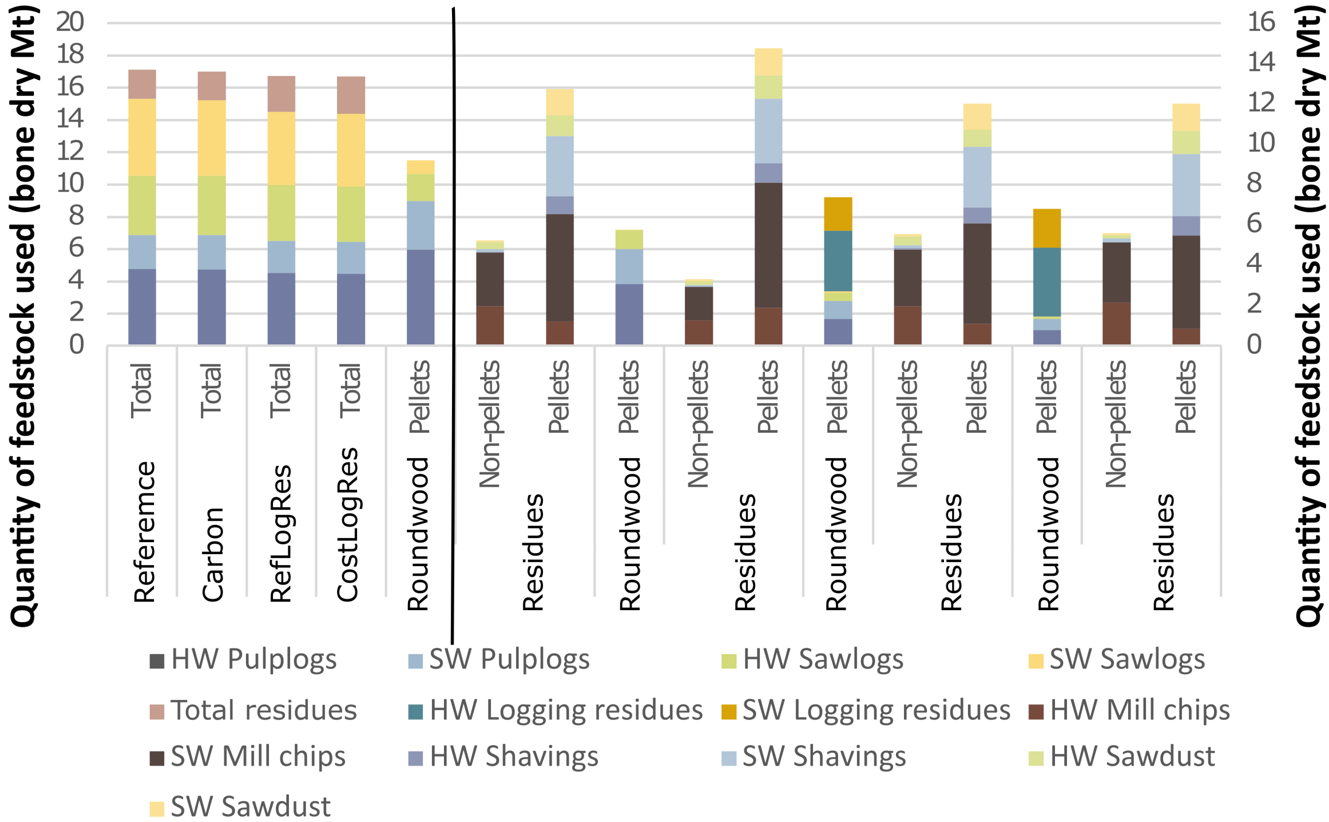

FIGURE 6 Feedstock consumption in 2030 in the US Southeast for the Medium projections (20 Mt pellet production) across different scenarios varying the inclusion of logging residues and the allocation of new pellet mills. SW, softwood; HW, hardwood

In the two scenarios including logging residues, the share of roundwood used for pellet production has reduced considerably. The inclusion of logging residues can contribute to the feedstock consumption of pellet mills, making up 28% of total pellet production in 2030 in the CarbonLogRes Medium scenario and 24% in the RefLogRes Medium scenario. The use of logging residues largely replaces roundwood production. Roundwood use for pellet production is higher in the RefLogRes scenario, assuming carbon-constrained selection of new pellet mill locations (14%), than in the RefLogRes scenario using cost-based expansion (8%). Total residue consumption is also largest in the CarbonLogRes and RefLogRes scenarios, caused by the additionally available source of logging residues. When excluding logging residues, total residue consumption is largest in the Carbon scenario, although the difference with other scenarios is small. The use of logging residues also replaces the consumption of chips for pellet production to a significant extent. Of all the residue types, the use of SW mill chips is the largest contributor to pellet production. The availability of logging residues replaces a significant share of SW mill chip consumption, in turn increasing the share of mill chip use in other industries. Hence, stimulating logging residue availability decreases consumption of roundwood as well as competition with other industries for mill residues.

3.2 | Carbon flux

The increased demand for pellets as well as other wood-based products results in carbon flux changes in any scenario or projection (see Figures 7 and 8). This is based on an atmospheric approach, with positive carbon flux signifying an increase in atmospheric stock (carbon emissions) and negative flux signifying a decrease in atmospheric stocks (carbon sequestration) and based on the assumption that, consistent with Intergovernmental Panel on Climate Change methodology, all removals are counted as emissions. A large part of the carbon flux increase compared to 2020 is caused by changes in the demand for other products, as can be seen when comparing the flux developments to the Zero pellet scenario. The difference between the Zero, Low, Medium and High projections can fully be accounted to pellet production. The modelling assumptions of overall increasing demand for timber, pulp and paper have a significant impact on total results. Should demand for forest products develop significantly different from the modelling assumptions in this study then this would have a large impact on the feedstock availability for the pellet industry and the carbon flux results.

There are ways to minimize the impact of increased production of wood-based products, as shown especially for the LogRes scenarios in Figure 7. Logging residues are harvested as by-product, regardless of use or demand, and are therefore already included as direct emissions. Utilizing these residues for pellets therefore does not result in additional emissions compared to a no pellet scenario, other than supply chain emissions. The lowest increase in flux is observed for the CarbonLogRes scenario, resulting in a total flux in the US SE of −79, −73 and −57 Mt CO_2/year. In this scenario, the difference between the Zero and Low scenarios is 3 Mt CO_2/year, the difference between Low and Medium 6 Mt CO_2/year and the difference between Medium and High 15 Mt CO_2/year. When comparing the different scenarios for exports of 20 Mt pellets in 2030, the LogRes scenarios result in avoided carbon emissions. The scenarios without logging residues result in net emissions in the US SE for the Reference and Carbon scenarios of 21 and 18 Mt CO_2/year. respectively. For the RefLogRes and CarbonLogRes scenarios, the total emissions are quite a bit lower, at 11 and 9 Mt CO_2/year, respectively. The benefit of including logging residues is even larger when comparing the results for the entire US, resulting for instance in additional sequestration of 11 Mt CO_2/year in the RefLogRes scenario compared to the Reference scenario.

The difference between scenarios was also analysed for the entire United States, as opposed to only the US SE, to account for displacement of manufacturing of products other than pellets, as shown in Figure 8. For the Reference scenario, the additional production in the Medium case results in increased emissions of 21 Mt CO_2/year in 2030, compared to the Zero pellets scenario in the entire US. This is much smaller for the Low scenario, at 8 Mt CO_2/year and

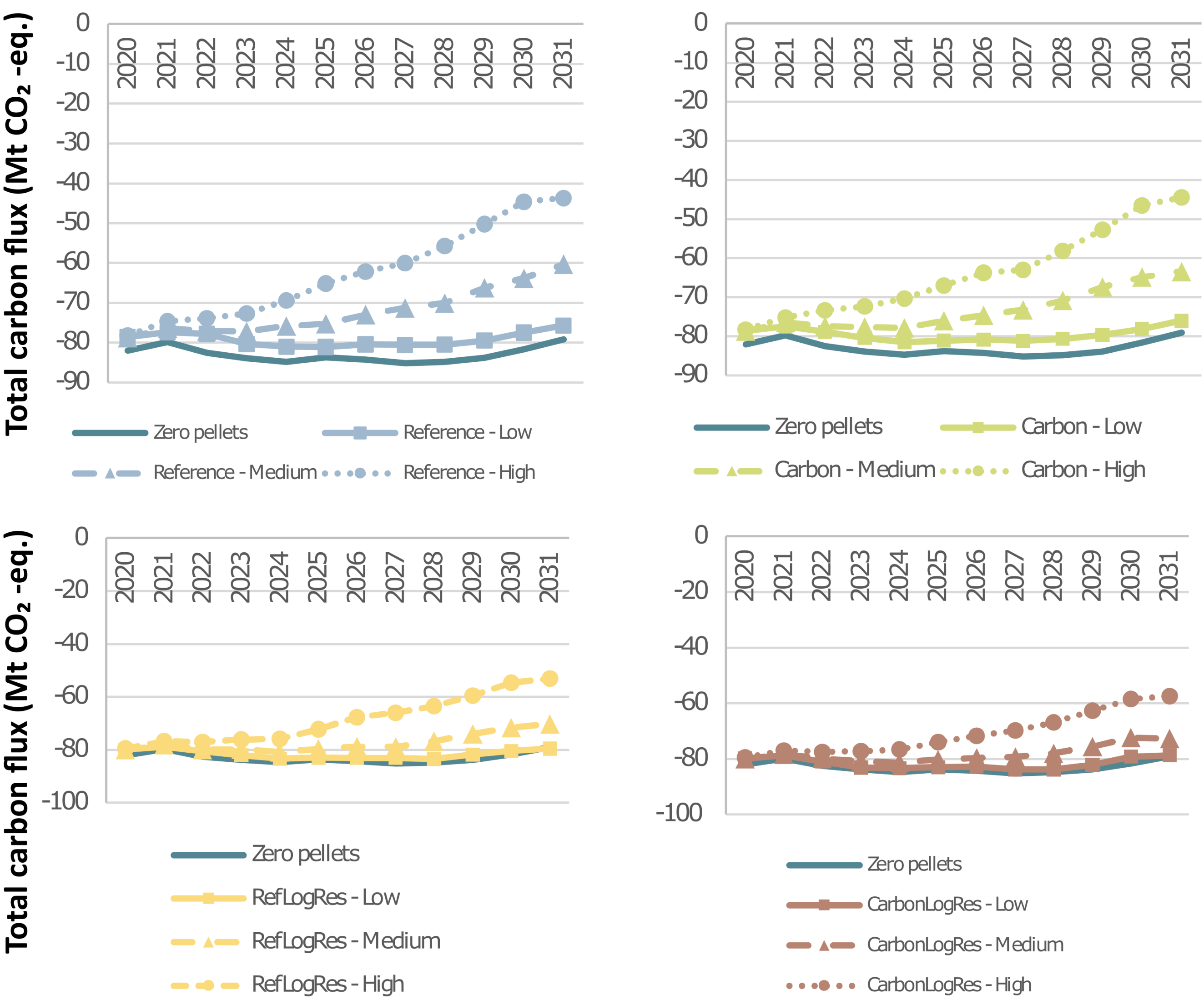

FIGURE 7 Total flux developments in the southeast of the US until 2030—for a no pellets scenario and for the 12 scenarios varying total export quantity, inclusion of logging residues and allocation of new pellet mills. Negative fluxes indicate a net increase in forest carbon stocks, while a positive flux signifies net emissions to the atmosphere

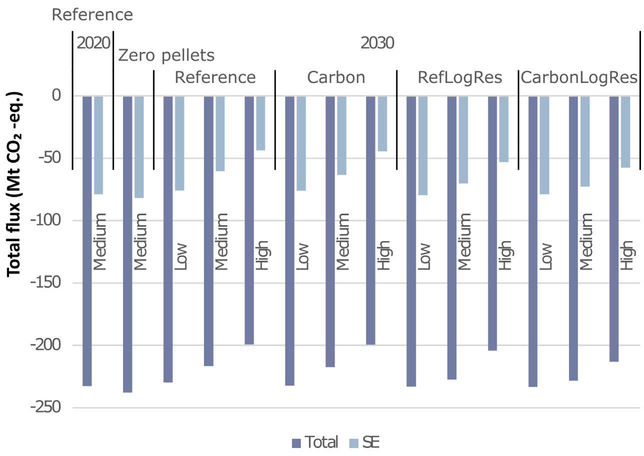

FIGURE 8 Flux in the entire United States (Total) and the southeast United States (US SE)—in the Reference scenario in 2015 and in the no pellets scenario plus the four different pellet scenarios for Low, Medium and High projections in 2030. Negative fluxes indicate a net increase in forest carbon stocks, while a positive flux signifies net emissions to the atmosphere

much larger for the High scenario, resulting in additional emissions of 39 Mt CO_2/year compared to the Zero pellet scenario.

3.3 | Spatial carbon flux

The carbon flux resulting from harvesting and tree growth varies significantly throughout the US SE, depending largely on harvesting patterns. In areas with high demand for roundwood, harvesting of pulplogs and sawlogs tends to be high, resulting in positive carbon flux. In forested areas with little demand from timber and pellet industries, tree growth exceeds harvesting, resulting in negative flux. Figure 9 shows the regional flux difference between the various scenarios and the Zero pellet scenario, for the 20 Mt pellet export scenarios in 2030, aggregated to 50 × 50 km areas. Pellet production has an impact on spatial flux throughout the entire SE US, with positive and negative impacts dispersed over the entire area. Not surprisingly, areas where flux has increased relative to the Zero pellet scenario (more carbon emissions) coincide quite well with the locations of pellet production, as shown in Appendix D, although there is by no means a perfect spatial match since regional expansion of pellet production has a spatial impact on other industries as well.

In the Reference scenario, areas with negative flux are located close to export ports, especially in Virginia and North Carolina. Areas with positive carbon flux are scattered across the entire US SE, in the Reference scenario predominantly in South Carolina, Tennessee and Alabama. The Carbon scenario by comparison results in a more even spread of areas with negative and positive carbon flux, with positive flux areas located somewhat more towards the Gulf Coast and the negative flux areas more towards the East Coast. Both the RefLogRes and CostsLogRes scenarios result in less areas with negative flux and more areas with positive flux, but do not show a remarkedly different distribution of these areas compared to the Reference and Carbon scenarios.

The total amount of sawlog and pulplog harvesting, as well as the spatial distribution does differ significantly in the four scenarios, as shown in Figure 10. In the Reference and RefLogRes scenarios, logging for pellet production takes place close to export ports, especially the Chesapeake and Savannah ports. Considering the large distance from some pellet plants to export regions, compared to the much smaller sourcing areas of feedstock, it is not surprising that mills close to export ports have a cost-effectiveness advantage. In the Carbon and CarbonLogRes scenarios, logging for pellet mills occurs in the more inland regions of Mississippi, Tennessee and Kentucky.

3.4 | Costs

The LURA model calculates cost of pellet production excluding the price of feedstock, the most significant component of total supply chain costs of pellet production. To provide a better comparison with pellet prices, feedstock cost components were added to the total costs. For sawdust, shavings and chips, FOB (free on board) prices of residues were added, the price that sawmills get paid for their feedstock by consumers such as pellet mills, based on data from 2017, taken from (Forest2Market, 2017). The FOB prices were averaged for a small difference between SW and HW and were converted from short tonnes to metric tonnes and to Euros, using an exchange rate of 0.9 €/$ (X-Rates, 2019), resulting in feedstock costs of 57 €/dry tonne of chips and 40 €/dry tonne of sawdust and shavings. For pulplogs and sawlogs, stumpage prices were added as feedstock costs, also from 2017 to provide a fair comparison with residue prices, taken from (Greene, 2019). Costs were again averaged over SW and HW, converted to tonnes and Euros, as well as converted to dry tonnes using the same conversion rate as assumed in the LURA model, and as shown in Appendix A. This results in feedstock costs of 28 €/dry tonne for Pulplogs and 81 €/dry tonne for sawlogs, excluding additional cost of harvesting and chipping, which were taken from the LURA model as explained previously. Costs for sawlogs furthermore include the downgrade costs. Pelletizing and shipping costs vary less with feedstock specifics and were also included based on (Visser et al., 2020). In the case of pelletizing costs, there is a small cost difference between

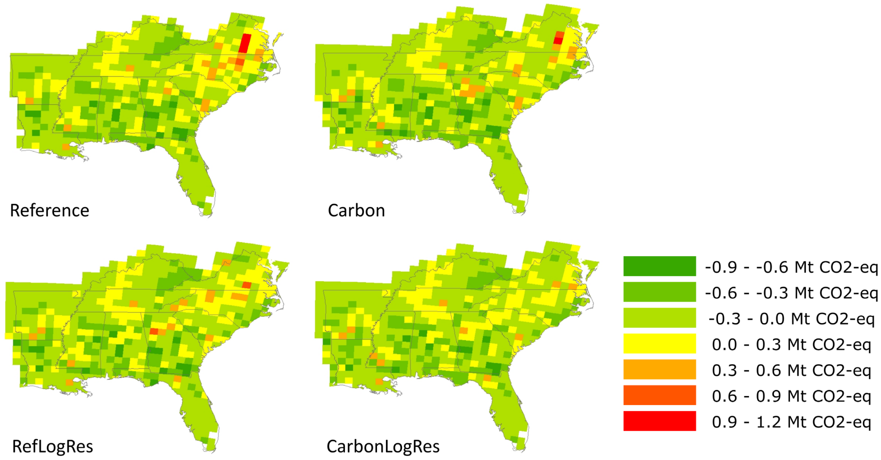

FIGURE 9 Total CO_2 flux difference in the 20 Mt scenarios in 2030, of the different scenarios compared to the Zero pellets scenario, in the Southeast US, on a 50 × 50 km grid. A positive carbon flux in this figure signifies increased emissions to the atmosphere

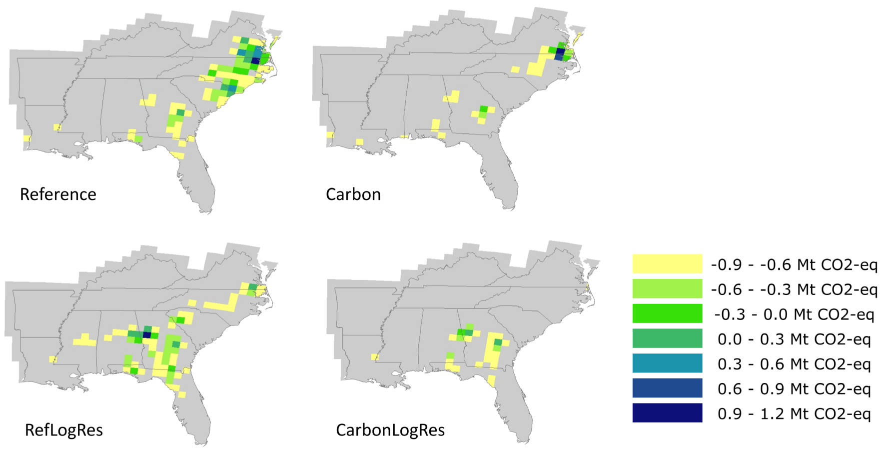

FIGURE 10 Harvesting of pulplogs and sawlogs for pellet manufacturing in the Southeast US for the 20 Mt scenarios, on a 50 × 50 km grid

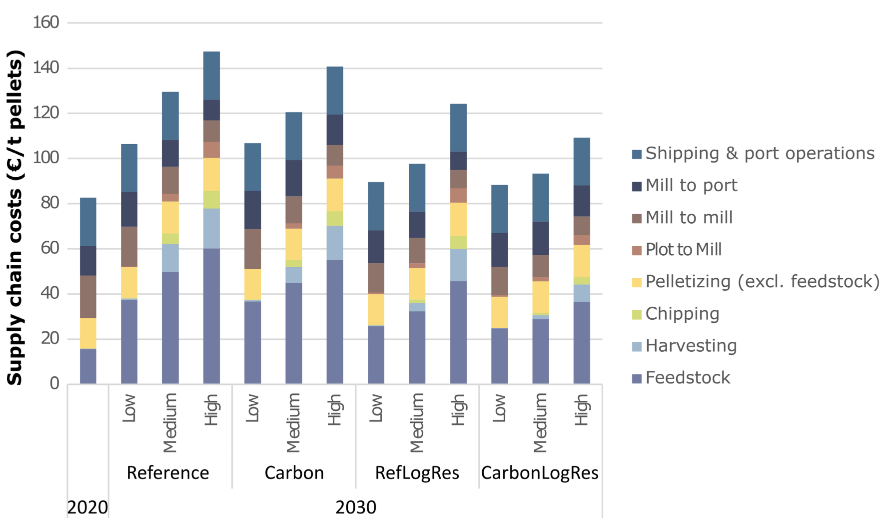

FIGURE 11 Costs of several supply chain components for the different scenarios and projections. Costs of feedstock, pelletizing, port operations and shipping to the port of Rotterdam, the Netherlands, were based on (Forest2Market, 2017; Greene, 2019; Visser et al., 2020) (i.e. not on the modelling results from this article).) and added to provide a better comparison with current pellet prices

the use of course or finely ground material, caused by the additional capital costs for a grinder. This was included by assuming different pelletizing costs for sawdust and shavings (Visser et al., 2020).

Total costs of pre-treatment and pellet hauling increase with increased pellet production and increased demand for biomass, as shown in Figure 11. Increases in costs are largely the result of the use of pulplogs and especially sawlogs for pellet production since these feedstocks come at the expense of additional feedstock and pre-treatment costs. Transport costs of feedstock from forest plots to pellet mills are very low as a result of allocation of feedstock based on costs. The extensive availability of forestry feedstock means there are almost always forest plots located close to pellet mills. As pellet production increases, as shown in the Medium and High projections, total costs increase, again as a result of the growing use of pulplogs and sawlogs. The plot to mill transport requirements increase especially in the High scenarios, as logging feedstock is pulled from increasingly further away. The larger assumed sizes of pellet mills also contribute to the increased feedstock sourcing areas. In all different scenarios, the mill to port transport requirements reduce slightly as expansion of pellet production is allocated to pellet mills relatively close to export ports. Transport costs of residues from processing mills to pellet mills reduce slightly in the different projections. This is likely the result of a lower share of mill residues in the total pellet feedstock mix, thereby reducing this transport component per tonne of produced pellets.

The difference between the scenarios clearly highlights the impact of logging residue availability. In the two scenarios utilizing this additional source of feedstock, total costs for logging feedstock reduces. Logging residues also require collection, chipping and transport, but are assumed to have no stumpage fee, thereby resulting in low feedstock costs. Collection and chipping costs are taken equal to harvesting and chipping costs for roundwood. Harvesting and collection costs of a combination of pulplogs, sawlogs and logging residues are slightly lower since costs of pre-treatment go down with increasing volume, assuming economies of scale. The additional sourcing of logging residues combined with pulplogs or sawlogs increases the harvested volume, thereby lowering costs. Transport costs are likewise lowered since logging residues in plots close to pellet mills can be allocated completely to pellet production.

A seemingly surprising result is that the costs in the Reference and RefLogRes scenarios are not lower than the scenarios including Carbon restrictions in pellet mill expansion. In fact, the lowest observed costs for the High scenarios are for the CarbonLogRes scenario. This indicates that current low costs, at each year of new mill location selection, as modelled through a myopic approach in this article, are not necessarily a good predictor of future low costs. High forest growth and positive growth-to-drain values, an aspect included in the Carbon scenarios, are perhaps better indicators of future low costs. Furthermore, since expansion of pellet manufacturing is modelled through expansion of fixed capacity pellet mills, there is no continued response to changed supply feedstock and demand of other product manufacturers.

3.5 | Exploration of carbon footprint of pellets delivered to Europe

When compared to total supply chain emissions, the carbon flux increases shown in this article are significant. The smallest modelled carbon impact is observed for the CarbonLogRes Low scenario. The increase in emissions of 1.2 Mt CO_2/year for 10 Mt pellets translates to 41 g CO_2/MJ_{el} when assuming an energy content of 17.5 GJ/t and efficiency of electricity production of 40%. This is higher than total supply chain emissions of pellets imported to Europe from the US SE, as calculated by Visser et al. (2020), assuming 50 km feedstock transport, 200 km pellet transport and shipping between Savannah and Rotterdam, amounting to 38 g CO_2/MJ_{el} for roundwood and 25 g CO_2/MJ_{el} for sawmill residues. The results for the Reference scenario show much larger carbon emissions. The 21 Mt difference between the Medium and Zero pellet scenario translates to 304 g CO_2/MJ_{el}, a factor 10 larger than supply chain emission for pellets from sawmill residues. To place the CO_2 flux increase in forest areas as found in this study in historic perspective, a simplistic assumption was made that the growing stock between 1953 and 2012 was linear and continued until 2030. When applying this growth rate to the quantity of carbon sequestration in tree growth in the US SE in 2014, by 2030, an additional 22 Mt CO_2 would be sequestered annually. This exceeds the carbon flux increases in all of the Medium scenarios. In reality, further stock increases are not occurring by default, and are driven by changing management practices due to, for example, changing profitability of different forest products, which have not been assessed in this paper.

An aspect to point out is that the RED II methodology to calculate GHG savings of wood pellet consumption does not include the biogenic emission as calculated in this study. Emissions from carbon stock changes caused by land-use change have to be included in supply chain emissions, but this is not the case for emission resulting from carbon stock changes as a consequence of altered management such as landscape emission impacts within forest areas (European Parliament, 2018). At the same time, biomass use is only eligible for financial support and can only contribute towards renewable energy target if changes in carbon stock are included in reporting of land use, land-use change and forestry emissions or if systems or laws are in place to ensure that carbon stocks are maintained or increased in forest sourcing areas. Land use and forestry emissions do not need to be allocated to pellet production, which would be a very difficult exercise since forestry emissions are impacted by the entire forest products system, but instead have to be accounted for in national or sub-national laws or country commitments to GHG emission reductions (European Parliament, 2018). The results shown above therefore do not affect whether pellets would meet the GHG reduction thresholds but do emphasize the need to carefully manage landscape carbon emission impacts to assure sustainable production of wood pellets.

4 | DISCUSSION

This article has analysed the impact of increased pellet production in the US SE on feedstock allocation, the type of feedstock consumed in the pellet sector, the carbon flux in forest areas and costs of pre-treatment and transport of feedstock and pellets. The feedstock portfolio use for pellet production changes quite significantly in the different projections until 2030 compared to current use. The consumption of milling residues for pellets exceeds the consumption of sawlogs and pulplogs in the Reference Low and Medium scenarios. In the High scenario, however, the share of pulpwood increases strongly to about 65% of the total feedstock consumption. This is considered undesirable from a sustainability perspective since research has shown that carbon parity times are much longer for additional harvest of roundwood than for industrial residues (Hanssen et al., 2017; Jonker et al., 2014). Furthermore, EU policies are steering towards a cascading use of biomass, favouring material production over energy production, especially for high-quality roundwood (European Commission, 2021).

4.1 | The impact of increased pellet production on feedstock use and carbon flux

The balance between carbon sequestration through tree growth and carbon emissions through tree harvesting remains negative throughout the modelling horizon. Additional pellet production however does have a negative impact on the balance, resulting in relatively more carbon emissions. The largest difference between the scenarios can be observed for the different quantities of pellet production in 2030. At low levels of pellet production and expansion, up to 10 Mt pellets in 2030, there is little difference in carbon flux between the scenarios. At high levels of pellet production, of 30 Mt, there is a considerable difference from the assumed pellet mill expansion strategy and use of logging residues between scenarios. The pellet industry should mind the impact of production increases and should take this into consideration in the development of future additional capacity.

When including mobilization of logging residues, a significant part of the roundwood use for pellets can be displaced. This also significantly lowers the impact on carbon flux in forest areas (as logging residues are no additional harvests and are assumed to be emitted instantly also in scenarios where no pellets are used). The impact of optimizing for carbon stock in sourcing areas of pellet mills on the other hand is relatively small. Results from the carbon scenarios show differences in regional spread of roundwood logging, but show very little impact on the total flux in the US SE. In other words, limiting the removal rate within sourcing areas of wood pellet mills might lead to new pellet mills being located in areas with higher carbon stocks, but overall removals across the entire US SE would remain the same. Only by increasing the overall feedstock availability, for instance through increased mobilization of logging residues, can the share of roundwood used for pellet production be reduced significantly. This leakage effect, of allocation of more sustainable feedstocks to pellet production pulling away from other sectors, has also been shown by Fingerman et al. (2019). This work concludes that when applying sustainability criteria to all wood product sectors in the US SE, there is no additional feedstock available for pellet production.

The increased consumption of roundwood results in increased costs of pellet production supply chain components in 2030. This impact is especially large for the High scenarios without logging residues. These cost estimates do not account for increased feedstock prices as a result of increased demand and competition. Pellets imported into Western Europe depend on subsidies to compete with fossil fuels. Significant increases in pellet production, reaching 30 Mt in 2030, might well result in price levels that make production and trade infeasible. As such, economic constraints may well limit wood pellet production to levels well below 30 million tonnes. The increase in costs as pellet production quantities increase points at the difficulty of including potential future market developments in current decision-making. This also shows that current costs are not a good indicator for future costs. Location scoping of pellet plants should not only be focused on current feedstock and transport costs, but also on longer term feedstock availability.

4.2 | Recommendations for future research

The results of modelling studies, such as presented in this study, should be interpreted carefully. One of the major simplifications of this study was the assumption of constant forest area. Changes in forest management and intensity were also not included. In the US South, timberland area has increased a marginal 2% between 1953 and 2012. In the same period, the total growing stock has, however, grown significantly with 107% (Oswalt et al., 2020; United States Department of Agriculture, 2014).

Increased mobilization of residues and limits to pellet mill expansion based on carbon growth in sourcing areas reduces the severity of carbon flux impacts, but still leaves a considerable additional carbon impact that—in the most extreme case—would nullify supply chain GHG savings compared to their fossil counterparts. The spatially explicit impact of increased pellet production varies for different regions and years. On a system level, for the entire US SE landscape, increased pellet production affects the overall balance between carbon removals and sequestrations, resulting in net carbon removals in all scenarios with especially large increases observed for the High scenarios. This research therefore clearly points at hard limits of potential pellet production within the modelled system of feedstock availability and demand, that can only be stretched by reductions in demand for other products or by improvements in forest management intensity and forest area. The exact limits however depend to a large extent on total demand for forest biomass and on land-use and management responses of demand changes. The limits to growth therefore need to be explored in more detail in future work, by including different demand scenarios and the potential impact on land use and management of the entire forest products system.

This article has used a simplified assumption of immediate emissions of all harvested wood. The impact of increased production of pellets and other wood products should be assessed by including production and waste scenarios of all relevant products. Increased production of timber could help to mitigate climate change, for instance through increased temporary sequestration of carbon and through the substitution of carbon-intensive materials such as concrete (Gret-Regamey et al., 2008). Energy recovery operations during the disposal of waste wood products could furthermore result in the production of bioenergy, thereby reducing the demand for primary or secondary feedstocks. As pellet production is part of a larger system of forest management and feedstock demand and supply, climate change impacts can only be assessed by analysing the entire system of wood products demand, forest management and substitution of non-renewable resources (Cowie et al., 2021). Only then can conclusions be drawn on the GHG emission impacts and benefits of wood pellet production and consumption. Further work needs to be done on the comparison of different alternative (no-) use scenarios, including alternatives for increased or decreased wood, paper and pellet production as well as alternative scenarios for use or decomposition of forestry biomass. This is especially relevant considering the economic impact of the ongoing COVID-19 pandemic. The uncertain development of the entire wood products sector could then also be included through the use of different scenarios.

Additional demand for pellets could be a driver for increases in forest area and improved management practices resulting in increased sequestration. The LURA model does not optimize for sustainability of forest production or the maximization of carbon stock, nor does it include market feedback responses. Especially in the US SE, where a large share of forests is owned by small private landowners, the extent of forested area is largely determined by demand for forest feedstock. Landowners are expected to make decisions on the replanting of forest areas partly based on expected future income, and increased demand for feedstock is expected to result in land use and management response (Galik et al., 2015). An existing study on the impact of additional pellet demand on land-use changes and forest dynamics, for instance, shows that increased demand may result in a larger growth in timberland area, mainly caused by large increases in pine plantation area (Duden et al., 2017). The total demand for pellets in this study is however significantly smaller at 12 Mt pellets, thereby not exploring the limits to growth as much as in his paper. Research by Jonker et al. (2018) on the impact of improved management practices shows that a forest plot with additional thinnings after 10 years results in a better carbon flux than the conventional scenario of thinning only after 15 years.

The pellet industry is a low margin industry with a considerably lower paying capacity for feedstock than for instance the timber industry (Lechner & Carlsson, 2014). Timberland developments will never be based only on expected pellet demand, but also on demand for higher value sawlogs and the overall portfolio of forest products. This study has modelled the allocation of woody biomass based on availability and lowest production costs. In reality, market prices are likely too high to allow for the use of saw timber (as projected in the High scenarios). The inclusion of paying capacities could have impacted the outcome of this study. Modelling the paying capacities of different industries could result in the shift of pellet production to other areas, where competition for feedstock is lower. The allocation of feedstock based on costs instead of prices is a limitation, but one that fits the scope of this paper in which market effects, such as supply and demand-based price and profit developments, were not considered. Future research should ideally combine price developments with a spatially explicit assessment of market responses in terms of land conversion and management changes.

Pellet demand and feedstock availability were modelled only until 2030 in this study. For the period beyond 2030, the general findings of this study remain relevant as well. Uncertainty in demand developments for various products increases with a longer modelling timeframe but is inherently uncertain in any case. The scenarios used in this study are designed to reflect that uncertainty in terms of pellet demand. On the longer term however, the re-growth of forest areas and also land-use changes become even more important to consider. The uncertainty in developments of demand for other products becomes larger also, impacting feedstock availability and carbon landscape impacts.

4.3 | Policy implications

The RED II requires the inclusion of carbon stock changes in GHG emission commitments for biomass to be eligible for support for countries that have ratified the Paris Agreement (European Parliament, 2018; Netherlands Enterprise Agency, n.d.). Additional legislation of Member States also highlights the importance of carbon stocks. The criterium for co-firing of biomass in the Dutch subsidy scheme SDE+ for instance requires the management of forest units for long-term conservation or expansion of carbon stocks (Netherlands Enterprise Agency, n.d.). These requirements prescribe the management of carbon stock in forest areas, but without specifying the specific spatial boundaries. In case of roundwood consumption, the actual forest areas harvested for pellet production will change continuously in response to wood availability and demand, making it difficult to establish a suitable unit area. Removals for other purposes (timber, pulp, etc.) still strongly dominate the carbon flux trends. These findings show that defining the geographical system boundaries has a strong impact on whether individual pellet mills can meet the criterion of maintaining forest carbon stocks; and that there is little point in applying such a criterion only to a small subsector, instead of holistically to all wood removals in a given area. Ensuring that carbon stocks do not decrease should be safeguarded by the entire wood products industry and not just by pellet producers, who only have a limited impact on regional forestry management and practices. Furthermore, the impact of increased production of pellets or other feedstocks on the long-term can only be assessed by consequently analysing the same spatial areas over time.

Our work has shown that a promising way to minimize additional landscape carbon emissions resulting from increased demand for forest products is to increase the total feedstock availability through mobilization of underutilized feedstock. Investing in development of new supply chains to utilize this feedstock source provides opportunities on the much longer term than 2030 (Jonker et al., 2018). Logging residues are more difficult to collect and process than, for example, pulpwood and need dedicated supply chains, for instance through integrated harvesting of high-value timber products with logging residues. Such chains have been developed and used for decades in, for example, Scandinavia, for the production of wood chips in district heating plants (Ericsson & Werner, 2016; Thiffault et al., 2015). In British Columbia, logging residues make up 17% of total feedstock production of pellet producers, providing evidence for the feasibility of utilization of these residues in pellet mills (Wood Resources International LLC, 2017). Increased consumption of this potential source of biomass can be supported or enforced through policies.

The use of logging residues is favoured over use of roundwood in the RED II criteria, through the exclusion of GHG emission allocation to residues (European Parliament, 2018). Should total supply chain emissions become a limiting factor, utilization of logging residues could increase the export potentials of pellets to the EU. EU member states also have the option of including additional criteria for production of bio-electricity or heat on top of the RED II and could therefore require, for example, the use of a minimum share of residues from forestry operations. Alternatively, a premium system could be designed to provide a monetary incentive to use low-grade biomass. The pellet production sector should seize the opportunity to utilize more logging residues. Reducing carbon emissions associated with pellet production is important to ensure regulatory compliance as well as improve societal approval. By focussing on sustainable feedstock selection, the pellet sector will improve future business environments.

This research has shown the importance of including demand for other forest products in an analysis of feedstock availability for pellet production. HW and SW lumber production increases until 2030, resulting in more availability of mill and logging residues, however, not enough to cover the even larger increase in feedstock demand in certain scenarios. The production of 30 Mt of pellets in all scenarios results in very significant increases of carbon flux as well as supply chain costs. This work shows that a scenario with 30 million tonnes of pellet demand additional to growing demand for timber and paper products, without use of logging residues, is likely to result in positive carbon fluxes which are unlikely to be compensated by forest area or management improvements. Further research is needed to confirm this, ideally spatially explicit, as these impacts may vary strongly between different sourcing regions.

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results are based on a rerun of the model using updated data. The Supporting Information includes a detailed description of these changes.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that defines the scenarios and product conversions of this study are available in the Supporting Information of this article and from the corresponding author upon reasonable request. The analyses presented here build partly on data publicly available in scientific literature and reports, and in online databases, and partly on mill location and capacity data purchased from forest consultancies, which are not publicly available, but made available to the authors provided non-disclosure. A more detailed description of data can be found in Latta et al. (2018).

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SUPPORTING INFORMATION

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