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# Assessing the potential for unaccounted emissions from bioenergy and the implications for forests: The United States and global

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## Abstract

Development of the bioenergy sector is being actively pursued in many countries as a means to reduce climate change and fulfill international climate agreements such as the Paris Agreement. Although biomass for energy production (especially wood pellets) can replace carbon-intensive fossil fuels, its net greenhouse gas impact varies, and the production of wood pellets can also lead to intensification in forest harvests and reduction of forest carbon stocks. Additionally, under specific conditions, emissions associated with imported biomass feedstocks may be omitted from national accounts, due to incompatibilities in accounting approaches. We assessed the risks and potential scale of emissions omitted from accounts (EOA) among key trading regions, focusing on the demand for wood pellets under different levels of climate mitigation targets. Our results suggest that the global production of wood pellets would grow from 38.9 to 120 Mton/year between 2019 and 2050 in a scenario that limits global mean temperature increase to 1.5°C above pre-industrial levels. A large portion of this occurs in North America (36.8 Mton/year by 2050), Europe (47.6 Mton/year by 2050), and Asia (23.3 Mton/year by 2050). We estimate that in a 1.5°C scenario, global EOA associated with international trade of wood pellets has the potential to reach 23.81 $MtCO_2eq$/year by 2030 and 69.52 $MtCO_2eq$/year in 2050. Emissions resulting from European biomass energy production, based on wood pellet imports from the United States, may reach 11.68 $MtCO_2eq$/year by 2030 and 33.57 $MtCO_2eq$/year in 2050. The production of wood pellet feedstocks may also present a substantial carbon price arbitrage opportunity for bioenergy producers through a conjunction of two distinct GHG accounting rules. If this opportunity is realized, it could accelerate the growth of the bioenergy industry to levels that harm forests' function as a carbon sink and omit actual emissions in national and global accounting frameworks.

KEYWORDS
bioenergy, forest carbon stocks, greenhouse gas emissions, International trade, Paris Agreement, wood pellets

# 1 | INTRODUCTION

Projections for long-term climate change mitigation often prominently feature the replacement of fossil fuel energy with bioenergy as an emissions reduction strategy (Creutzig et al., 2015; Rogelj et al., 2018), often through bioenergy with carbon capture and storage (BECCS; Clarke et al., 2014; Fuss et al., 2014; IPCC, 2018, 2019; Roe et al., 2019; Rogelj et al., 2018). However, policies to promote the growth of forest-derived bioenergy production could pose risks to long-term forest carbon stocks, forest health, biodiversity, and sustainable development goals (Reid et al., 2020; Smith, Soussana, et al., 2019). Growth in bioenergy production could be accelerated beyond optimal levels in part because emissions could be omitted from accounts (EOA) that track progress toward countries' climate mitigation pledges under the Paris Agreement. EOA can occur through incompatibilities in the system boundaries of accounting approaches used in different countries (Grassi et al., 2018; IPCC, 2019; Norton et al., 2019; Rüter et al., 2019; Sato & Nojiri, 2019). As such, projecting the net effect of bioenergy production on greenhouse gas (GHG) emissions is complicated and requires an understanding of lifecycle emissions associated with bioenergy feedstocks, effects of feedstock demand, and the unique accounting framework that applies to bioenergy production. Here, we develop projections of the potential growth in biomass energy production, resulting GHG emissions, and the potential for EOA to accelerate biomass feedstock trade and utilization in response to different levels of climate ambition. To the best of our knowledge, these are the first quantitative estimates of the potential for EOA under different climate ambition scenarios.

## 1.1 | The complexity of the bioenergy emissions profile

Bioenergy is sometimes assumed to be carbon neutral, as the possibility of sustainable harvest and subsequent regrowth of biomass feedstocks could ultimately lead to a balance of GHG emissions and removals over time. However, its carbon neutrality requires a number of conditions to be met over the relevant timeframe of the analysis (Krug et al., 2014), and quantifications of net emissions from bioenergy can vary according to the temporal and spatial system boundaries of the assessment and reference scenario (Agostini et al., 2019; Berndes et al., 2016; Cowie et al., 2021; Giuntoli et al., 2020; Ter-Mikaelian et al., 2015). Differing approaches to these factors have contributed to confusion and debate among policymakers and stakeholders about the appropriate role of forest-based bioenergy in climate change mitigation efforts and the characterization of this fuel source as carbon neutral (e.g., Berndes et al., 2016; Brack, 2017; Cornwall, 2017; EASAC, 2018; Haberl et al., 2012; Searchinger et al., 2009; Walker et al., 2013). We address the key factors in stepwise fashion below.

The emissions associated with bioenergy include the following: those from combustion of the feedstocks and from management and harvesting; supply chain activities such as transporting, processing, and combustion efficiencies; and emissions created or displaced by substitution of bioenergy for other energy sources (Lamers & Junginger, 2013; Röder et al., 2015). Emissions can also be affected by intensification of forest management and harvests of wood—which can have lasting effects on future sequestration potential and GHG fluxes (Buchholz et al., 2019; De Oliveira Garcia et al., 2018). For example, intensive biomass harvest can deplete soil organic carbon more rapidly than conventional harvests (Achat et al., 2015) and plantation forests with fertilizer application may generate significantly higher nitrous oxide emissions compared to natural forests (Schulze et al., 2012).

Whether combustion emissions are eventually balanced by sequestration in a relevant timeframe is determined by conditions that regulate the growth (and subsequent regrowth) of the biomass feedstock (Birdsey et al., 2018; Buchholz et al., 2016; Dwivedi et al., 2019; Sterman et al., 2018; Ter-Mikaelian et al., 2015). At the landscape scale, sequestration may increase in response to indirect effects triggered by shifts in economic conditions, including rising timber prices driven by increased demand of biomass for energy, motivating an expansion of forest area (or slowing the conversion of forests to other uses), and thus increasing total carbon stocks (Aguilar et al., 2020; Baker et al., 2018; Costanza et al., 2017; Daigneault et al., 2012; Favero et al., 2020; Miner et al., 2014; Nepal et al., 2015). Alternatively, demand could trigger conversion of existing forests to plantations (Favero et al., 2020) or other high-carbon areas to biomass feedstock production, as occurred for biofuel production (Lark et al., 2015).

Forestry and mill waste, residues, and byproducts are already used as low-cost bioenergy feedstocks. Demand for primary products controls the availability of these waste materials. Once waste feedstocks are exhausted, the additional demand for biomass drives up costs in related markets (e.g., timber, paper; Daigneault et al., 2012) and ultimately affects markets for underlying production inputs (e.g., land; Forsell et al., 2016). Such changes in the production and supply chains of biomass feedstock have implications for forest carbon stocks in source areas, the GHG emissions profile of the energy produced, and the associated lifecycle assessment of biomass energy, as well as other environmental outcomes (Gusti et al., 2020).

On top of the challenges in assessing and reporting emissions from forest-derived bioenergy, the accounting rules for GHG fluxes that occur during this lifecycle—especially when feedstocks are traded internationally—add yet another layer of complexity.

## 1.2 | Accounting rules can obscure biomass emissions

The structure of accounting frameworks themselves can contribute to a lack of transparency in countries' GHG inventories and accounts, obscuring the actual quantity of global GHG emissions associated with bioenergy (Gunn et al., 2012; IPCC, 2019; Norton et al., 2019). Since the 1990s, countries have followed IPCC guidelines (IPCC, 1996) that recommended reporting and accounting for emissions from the combustion of harvested biomass feedstocks in the land use, land-use change, and forestry (LULUCF) sector, rather than counting such emissions in the energy sector. In keeping with other literature (e.g., Grassi et al., 2018), we use "reporting" to refer to GHG fluxes documented in national inventories and "accounting" to refer to GHG fluxes that are counted toward national targets—including those submitted in nationally determined contributions (NDCs) under the Paris Agreement. Over time, emissions from the combustion of biomass (including wood pellets) became subject to distinct reporting and accounting rules that applied to agriculture, forestry, and other land use (AFOLU; EASAC, 2017; Norton et al., 2019). In particular, countries were allowed to account for AFOLU emissions and removals against projections of increased future harvests from forests, rather than against the historical estimates, as is the case for all other sectors (Brack, 2017; Krug, 2018). Countries that adopted projected baselines could experience increases in their real forest emissions (through harvest) without those increases being counted against their pledges to reduce GHG net emissions (i.e., no increase in emissions is seen relative to their AFOLU baseline; Brack, 2017; Krug, 2018).

At the same time, countries were allowed to elect from several possible accounting approaches in regard to the carbon embodied in imported harvested wood products (HWPs; see Table 1; Krug et al., 2014; Rüter et al., 2019). The "production approach"—the default under the Paris Agreement (Annex to UNFCCC Decision 18/CMA.1, paragraph 56)—allows countries to omit the carbon content of imported HWPs, under the assumption that the country of origin would have already accounted for them (Rüter et al., 2019). However, mismatched accounting approaches can result in emissions being omitted from accounts in any nation and from global or regional estimates (Grassi et al., 2017; Rüter et al., 2019). The potential scale of these omitted emissions is one focus of our analysis.

TABLE 1 Summary of approaches for estimating annual changes in carbon stocks and $CO_2$ fluxes related to the harvested wood products (HWP) pool, adapted from Rüter et al. (2019)

| Conceptual framework | Approach | Description | Type of reporting | Reported by |
|---|---|---|---|---|
| *Inference*: Estimate $CO_2$ emissions and removals related to HWP by measuring changes in carbon stocks in defined HWP pools from year to year | Stock change | Estimates emissions within national boundaries in the HWP pool, which comprises all domestically harvested wood products | Stock change | Consuming country |
| | Production (default) | Estimates changes in stocks in HWP pool, including those products used domestically and those exported and used elsewhere, but not including imported products | Stock change | Producing country, regardless of where HWP are consumed or used |
| *Direct measurement*: Identify and quantify actual $CO_2$ fluxes from and to the atmosphere | Atmospheric flow | Estimates fluxes from HWP within national boundaries | $CO_2$ fluxes | Producing country, regardless of where HWP are consumed and used |
| | Simple decay | Estimates fluxes from HWP within national boundaries | $CO_2$ fluxes | Consuming country |

The use of discretion in reference levels and accounting approaches created the possibility for countries to trade and utilize biomass feedstocks without the embodied carbon emissions being accounted against any country's climate commitment (even if they are included in the national GHG inventories), as illustrated in Figure 1 (Brack, 2017; Cowie et al., 2021; Norton et al., 2019; Searchinger et al., 2009). Because countries design and implement policies to achieve their national targets (i.e., "accounts"), there is a risk that biomass feedstocks could be imported without being subjected to emissions penalties meant to deliver emission reductions. The ability to bypass these penalties could create a comparative advantage for these imports, relative to domestically produced feedstocks or other sources of energy.

The potential problems that could arise from these separate factors were identified and addressed in non-binding guidance (Greenglass et al., 2010; Krug et al., 2014; Rüter et al., 2019), but no universal solution was developed, and the flexibilities allowed by the accounting guidance were perpetuated under the Paris Agreement. Some bioenergy producers—operating in countries where emissions from imported feedstocks were not accounted—have substantially increased their imports of wood pellets from the United States. In the process, they may have avoided regulatory disincentives on emissions that would have otherwise applied. In the future, all countries have the opportunity to exploit the potential for policy arbitrage on the basis of EOA simply by adjusting their choice of accounting approach (Sato & Nojiri, 2019).

## 1.3 | Left unchecked, emissions omitted from accounts could metastasize

Emissions from bioenergy have sometimes been characterized as categorically low or zero carbon by institutions (IRENA, 2020) and carbon markets (e.g., Directive 2008/101/EC of the European Parliament and of the Council, 2008). Such treatment may exempt this energy source from penalties on carbon emissions or encourage its use as a substitute for fossil fuels. These policy incentives can have a strong cascading effect on future demand of woody biomass (Favero et al., 2020; Forsell et al., 2016; Lauri et al., 2017). In the last decade, the global wood pellet market grew rapidly (increasing on average 12% annually from 2012 to 2019; FAO, 2020), driven by increases in imports in parts of Europe and East Asia and fueled by increases in exports from North America and southeast Europe (Thrän et al., 2019).

As countries act to reduce their GHG emissions to meet their pledges under the Paris Agreement, many will

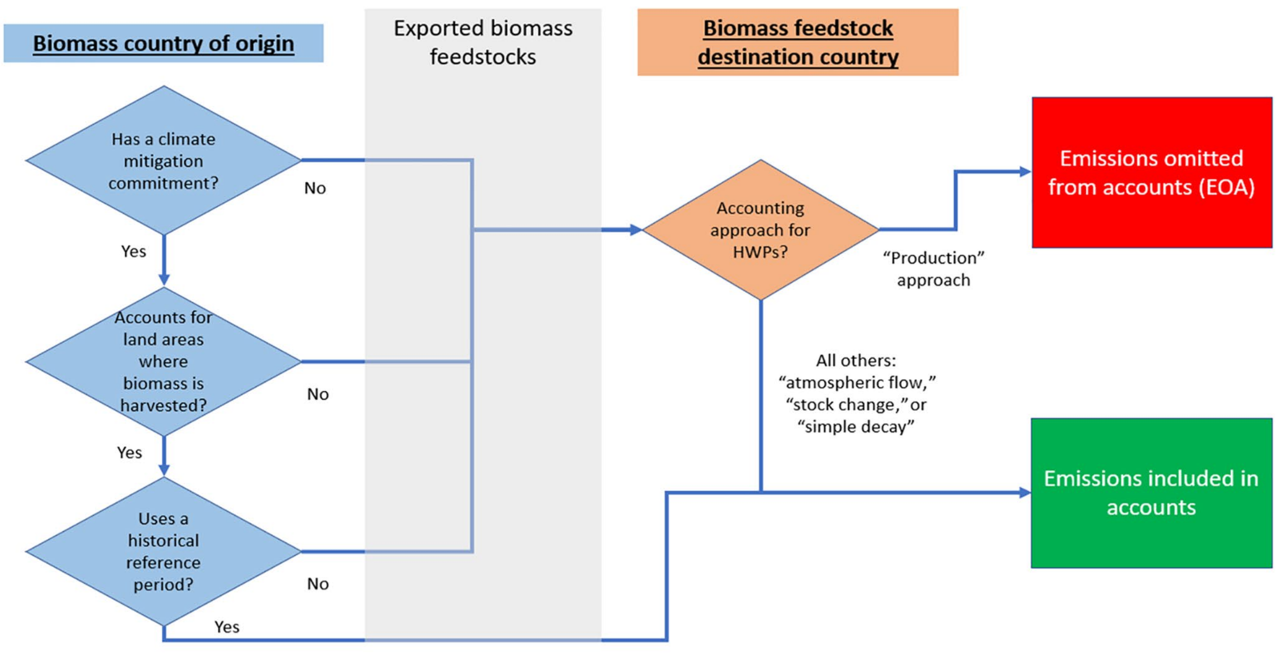



**FIGURE 1** Illustration of how emissions can be omitted from accounts (EOA). A combination of conditions must occur among biomass feedstock exporter and importer countries for emissions to be omitted. Exporter countries that (1) have no international climate commitments (e.g., not a Party to the Paris Agreement); (2) do not account for land areas where biomass is harvested or do not report with sufficient detail; or (3) that use a projected forest emissions reference level (instead of a historical reference level) establish the preconditions for EOA. If biomass feedstocks from these countries are imported and utilized by a country that applies the "production approach" to account for harvested wood products, then the emissions could be omitted from any country's accounting

implement policies designed to increase the economic costs of emissions, particularly in the energy sector (Aldy et al., 2010). When EOA occurs, the value of trade and utilization of biomass for energy production does not reflect the value of actual emission reductions, since the costs of emissions fall asymmetrically on different trading partners; instead, it reflects a failure to accurately document and account for emissions. Within the bioenergy value chain, feedstock producers, traders, and bioenergy producers would avoid the costs affecting other forms of energy production, which would tend to confer an economic advantage to bioenergy that relies on EOA. This approach could lead to opportunities for regulatory arbitrage between countries that utilize bioenergy and those that produce biomass feedstocks.

Beyond the energy system, the consequences for forests could be significant. Globally, forests harbor most of Earth's terrestrial biodiversity (FAO & UNEP, 2020), contribute essential ecosystem services (Brockerhoff et al., 2017), and serve as an important carbon sink (Harris et al., 2021; Pan et al., 2011). Throughout much of the world, forests are likely to remain a net carbon sink for the foreseeable future (Harris et al., 2021), but small shifts in disturbance regimes can substantially influence the strength of these sinks (Anderegg et al., 2020; Pugh et al., 2019). In the United States, projections suggest the strength of the forest sink may decline (Wear & Coulston, 2015), or it may remain relatively stable or even increase in response to market-driven changes in forest management and subsequent increases in sequestration rates (Tian et al., 2018). If the strength of the sink declines, U.S. emissions abatement targets in non-forest sectors would need to compensate; thus, reductions in the size of the sink are functionally equivalent to an increase in emissions. However, this sink has already been weakened by direct anthropogenic activities (e.g., land-use change, forest harvest and degradation, impacts on ecological processes; IPCC, 2018, 2019) and indirect effects exacerbated by climate change, such as pests, wildfires, and other natural disturbances (Anderegg et al., 2020).

Reforestation, avoided deforestation, and forest restoration are low cost and readily deployable strategies to increase net sequestration and storage (Griscom et al., 2017); on the other hand, land-intensive strategies such as large-scale afforestation or the expansion of bioenergy monoculture plantations may impede goals related to both biodiversity preservation and sustainable development (Pörtner et al., 2021). Furthermore, policies aimed at promoting sink-enhancing activities could falter if they are outcompeted by additional demand for biomass feedstocks, which in Europe have received some EUR 6.5 billion per year (Smith, Smit, et al., 2019). If the possibility for EOA is eliminated, bioenergy and sequestration could work in tandem toward climate mitigation goals (Favero et al., 2020).

### 1.4 | Assessing the potential scale of EOA and effects of feedstock demand

We analyzed the potential scale and impacts of these issues by addressing four interrelated research questions:

1. What is the future potential scale of wood pellet production and associated scale of EOA, driven by projected demand for bioenergy and climate mitigation ambition?
2. Where would forest harvests likely increase to meet the demand for biomass feedstocks, and by how much?
3. What would be the potential impacts of these increased harvests, in combination with other factors, on forest carbon stocks in the U.S. Southeast, the leading global source of wood pellets?
4. What is the potential economic value of regulatory arbitrage opportunities that arise from EOA?

This analysis builds upon related work (e.g., Favero et al., 2020; Tun et al., 2019), including past assessments that have quantified and estimated the level of GHG emissions omitted from national GHG accounts under the Kyoto Protocol (Brack, 2017; Searchinger et al., 2009). We extended past assessments by analyzing (1) the interactions of several aspects of the existing accounting framework that may impact future levels of EOA, globally, under different levels of climate ambition, (2) the value of carbon price arbitrage resulting from trade between regions, and (3) the impact that this may have on the capacity for remaining forest ecosystems to sequester and store carbon amidst ongoing disturbances in the region that is currently the leading source of global wood pellets: the U.S. Southeast. After tripling exports from 1.9 Mton in 2012 to 6.02 Mton in 2018, the United States is now responsible for 25% of all exports (FAO, 2020). Since the U.S. Southeast accounts for roughly 55% of the total forest production of the United States (Oswalt et al., 2019) and the entire U.S. supply of industrial wood pellets was derived from that region (Figure 2), we sought to understand the potential sensitivity of the forest carbon sink in the U.S. Southeast to a range of impacts, including the impact of increased demand of biomass feedstock.

## 2 | MATERIALS AND METHODS

### 2.1 | Combining two relevant approaches

To analyze how future demand of bioenergy may affect global wood pellet trade and the forest landscape within the United States, we applied a two-step approach (see Data S1). In step one, we used the Global

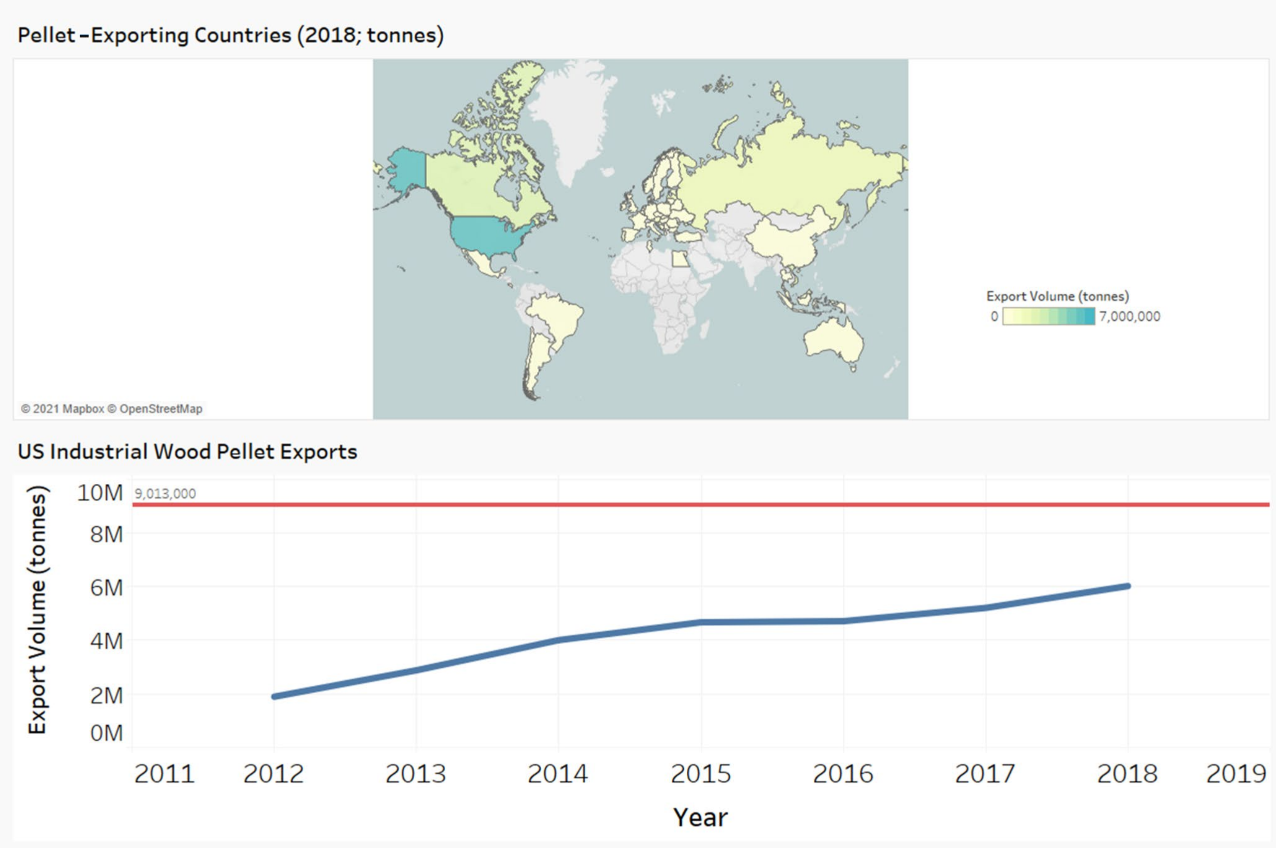



**FIGURE 2** 2018 wood pellet export volume in tons by country (FAO, 2020) (top). Blue line indicates U.S. wood pellet export volume in tons 2012–2018 (FAO, 2020), red line indicates total capacity in 2018 (U.S. EIA, 2020) (bottom)

Biosphere Management Model (GLOBIOM; Havlík et al., 2011, 2014; Lauri et al., 2019) to develop quantitative estimates of the production of biomass feedstocks in different regions of the world and the volume and economic value of trade flows in these feedstocks among geographic regions under four climate change mitigation scenarios, ranging from high ambition (RCP 1.9) to low ambition (RCP 8.5). In step two, we downscaled the GLOBIOM harvest estimates for each scenario to the U.S. Southeast, utilizing the carbon flux data from the NASA Carbon Monitoring System (CMS; Hagen et al., 2016). We then compared the projected fluxes from biomass harvest levels under each scenario to published estimates of the effects of other disturbances, including climate impacts, on the region, as a way to estimate the combined effect of these factors on the regional forest carbon sink.

## 2.2 | Using GLOBIOM to analyze global trade in biomass feedstocks

We used the GLOBIOM model to analyze the global development of the wood pellets sector (e.g., production capacities, price developments, international trade, and consumption levels) in response to future bioenergy demand levels. GLOBIOM is a global, recursive dynamic, spatially explicit, partial equilibrium model of the forestry, agriculture, and bioenergy sectors, with bi-lateral trade flows. The model computes a market equilibrium sequentially for each 10-year time step, starting from the year 2000, by maximizing the sum of consumer and producer surplus (i.e., welfare) subject to resource, technological, demand, and political constraints. In each time step, the market price for each commodity is adjusted endogenously to equalize supply and demand for each product and region, including a total of 26 wood-based commodities (Lauri et al., 2021).

GLOBIOM employs a bottom-up approach where the supply side of the model is built on a high-resolution spatial grid (Takayama & Judge, 1971). Land is disaggregated into simulation units—clusters of 5 arcmin pixels that were created based on altitude, slope, and soil class, 30 arcmin pixels, and country boundaries. On the demand side, a representative consumer for each economic region optimizes consumption and trade in response to product prices and income. For this specific assessment, we applied the EU-version of the GLOBIOM model, where the globe is represented at the level of 58 geographic regions, connected through bilateral trade flows (27 EU member states and 31 regions outside the EU). We mainly present model results aggregated to six regions: North America, Latin America, Europe (including the UK), Africa, the former Soviet Union, and Asia (see Table S1 for a full description of countries and regions). Bi-lateral trade of commodities is endogenously represented between each geographic region. To represent the interplay between different sectors endogenously within GLOBIOM, the model receives biophysical data from detailed models that represent the forest (G4M; Gusti & Kindermann, 2011; Kindermann et al., 2008), livestock (RUMINANT; Herrero et al., 2013), and crop sectors (Baker et al., 2018; EPIC; Leclère et al., 2014).

## 2.3 | Comparing climate ambition scenarios

We undertook a structured exploration of bioenergy demand and biomass feedstock production under various levels of climate change mitigation efforts to represent future potential trajectories for the global development of climate change mitigation efforts and their effects on global biomass production. Within each scenario, GLOBIOM institutes a uniform price on GHG emissions to achieve the specified global emissions trajectory; this price represents the penalty for emissions or the reward for sequestration, and the model solves for the optimal commodity trade flow among regions, based on production capacity and demand across regions. We applied the SSP (Shared Socioeconomic Pathway) and RCP (Representative Concentration Pathways) scenario frameworks developed for the Intergovernmental Panel for Climate Change (IPCC; Moss et al., 2010; O'Neill et al., 2014, 2017; Riahi et al., 2017; Van Vuuren et al., 2012). We limited our analysis to only considering the SSP 2 scenario because wood pellet production and consumption are more sensitive to changes in bioenergy demand than to changes in global GDP and population. We considered the full range of the RCP scenarios that reflect increasing levels of radiative forcing by 2100 to account for the full range of potential future bioenergy demand levels (RCP 1.9, RCP 2.6, RCP 4.5, and RCP 8.5 scenarios; Collins et al., 2011; Martin et al., 2011). Our high-demand scenario (RCP 1.9) represents a restriction of the global-mean temperature increase in 2100 to 1.5°C with approximately 66% probability (Rogelj et al., 2018), whereas the low-demand scenario (RCP 8.5) represents a probable temperature range of 2.6–4.8°C in the year 2100 (Collins et al., 2013). For further information on sources of emissions and removals accounted for and how the bioenergy demand has been estimated for each RCP scenario, we refer to Fricko et al. (2017). Additional information on how the bioenergy demand has been implemented in GLOBIOM is provided in Data S1.

Because our analysis was aimed at finding the potential for EOA, we did not assume that countries would continue their current accounting approaches. Instead, we treated the total volume of emissions from traded wood pellets as the upper estimate of potential for EOA, since countries have the flexibility to adopt accounting approaches that avoid accounting for these emissions. To estimate the potential arbitrage value of trade in wood pellets, we applied the relevant carbon price in each scenario to the traded volumes of wood pellets, to find the potential economic value of arbitrage in wood pellet trade. Our estimates correspond to a situation in which emissions from wood pellets traded across regions avoid all economic penalties; however, these estimates do not fully capture the EOA potential from country-to-country trade. We subtract the endogenously modeled price of wood pellets from the value of avoiding emissions penalties to estimate the net cost of utilizing imported wood pellets for bioenergy production.

## 2.4 | Applying the NASA Carbon Monitoring System (CMS) to assess implications for forests in the U.S. Southeast

### 2.4.1 | Evaluation of potential change in net GHG emissions in the U.S. Southeast forests

Forest stock changes that occur as a result of timber harvests are often additional to losses associated with disturbance regimes (Williams et al., 2016). Biomass demand may stimulate an increase in harvest rates and management intensity (Buchholz et al., 2019, 2021). A recent analysis of wood pellet procurement landscapes in the Southeast from 2005 to 2017 found stable or modestly increasing carbon stocks in living biomass and reduced carbon stocks in soils and standing dead trees (Aguilar et al., 2020). In the Southeast, wood pellet feedstocks include both primary fiber, comprising roundwood (including thinnings) and harvesting residuals (e.g., bark, unmerchantable trees, tops, and limbs), and secondary fiber, comprising sawmill or wood product manufacturing residuals and post-consumer, with many large pellet mills utilizing around 70%–100% primary fiber (Kittler et al., 2020; U.S. EIA, 2020).

We evaluated the potential change in net GHG emissions in the U.S. Southeast associated with estimates of harvest rates projected for North America in the GLOBIOM model for the RCP scenarios analyzed in step one, described above (Table S2). To provide context, we compared the potential scale of forest carbon stock changes to published estimates of the effects of expected disturbances in the U.S. Southeast, including fire, insect outbreaks, wind, and forest conversion to non-forest (e.g., agriculture or development). For each RCP scenario, we then evaluated the combined effects of these factors on forest carbon stocks and fluxes in the region in 2030 and 2050 (see Data S1).

We identified forest-related emissions using the NASA Carbon Monitoring System database (Hagen et al., 2016) which provides maps of estimated carbon in forests of the 48 continental states of the United States for the years 2005–2010. We refer to this as the "reference period" below. Carbon (termed "committed carbon") stocks were estimated for forest aboveground biomass, belowground biomass, standing dead stems, and litter for the year 2005. Carbon emissions were also estimated from land-use conversion to agriculture, insect damage, logging, wind, and weather events in the forests for the years 2006 through 2010 (Hagen et al., 2016). Finally, committed net carbon flux was estimated as the sum of carbon emissions and sequestration and serves as the reference period emissions for comparisons in Figure 2.

We derived subnational pellet production estimates to allocate the projected changes in regional wood production from the national-level estimates generated by the GLOBIOM model. We calculated the percentage change (increase) in national wood production from 2020 to 2030 and from 2020 to 2050 using the GLOBIOM results for each of the four RCP scenarios described above. To account for regional forest specifics, we applied harvest level projections from GLOBIOM but endogenously calculated changes in forest carbon stocks. For simplicity, we added the projected percentage change in production to the "logging" emissions baseline estimated by Hagen et al. (2016) to estimate the changes in forest-sector emissions for the U.S. Southeast region (Figure 2). We assumed a direct relationship between production and emissions from logging activities. We did not modify carbon sequestration rates in remaining forests in the model because management activities, including harvests, could increase or decrease forest sequestration rates depending upon how they are carried out. For example, there are different productivity implications from deriving additional feedstocks from loblolly pine (*Pinus taeda*) plantation thinnings versus harvesting in bottomland hardwood forests (e.g., Giuntoli et al., 2020). Because of uncertainty associated with these unobservable factors, we did not change the default sequestration rates in our analysis, an approach that we consider to be conservative with regard to changes in emissions associated with harvest rate changes. We also conservatively applied the national-level production rate of change to the U.S. Southeast region. Since the U.S. Southeast currently represents about 55% of the total U.S. timber production, we assumed that the greatest increases in wood pellet production would occur in this region, at least initially, because this is where extra pellet production capacity exists (Figure 3). Given the importance of the region for wood pellet production, the harvest impacts in the U.S. Southeast could be greater than what we estimate below.

# 3 | RESULTS

## 3.1 | Estimated global production and trade of wood pellets

On a global scale, the production of wood pellets for bioenergy purposes has grown in recent years, rising from 18 Mton/year in 2012 to 38.9 Mton/year in 2019 (FAOSTAT, 2020), a 116% (17% average annual) increase. We project that the production of wood pellets will increase continually as the demand for bioenergy rises and countries take concrete actions to mitigate climate change. The level of climate mitigation (reflected in the RCP scenarios) has a relatively minor impact on the level of bioenergy demand and wood pellet production in 2030 but a more significant impact on production by 2050 (see Figure 4). In 2030, global production of wood pellets increases to 64 Mton/year under the high-demand scenario (RCP 1.9), a 73% total increase and a continued average annual increase of production by 15% from 2019 onward. In contrast, in the low-demand scenario (RCP 8.5), production of wood pellets shows virtually no growth. The growth of wood pellets production in a high-demand scenario (RCP 1.9) does not abate over time: in 2050, production is 120 Mton/year, and 224% higher than the low-demand scenario (RCP 8.5; see Table S2).

Production of wood pellets continues to be dominated by the current major producing regions (i.e., Europe, North America, Former Soviet Union), but also increases significantly in Asia. At the same time, production of wood pellets in Latin America and Africa remains limited due to the inherent cost of feedstock and the availability of low-cost feedstocks such as forest industrial byproducts. Specific countries within these regions (e.g., Brazil) are projected to remain important suppliers of biomass for the production of wood products and non-pellet feedstocks (Favero at al., 2020; Lauri et al., 2017, 2019).

For North America (see Table S2), production of wood pellets continues to increase over time, rising from 5.0 Mton/year in 2012 to 11.2 Mton/year under the low-demand scenario (RCP 8.5) and 16.1 Mton/year under the high-demand scenario (RCP 1.9) by 2030 (an average annual increase of 5%–7%). Under the low-demand scenario, production increases until 2030 and remains at 11.2 Mton/

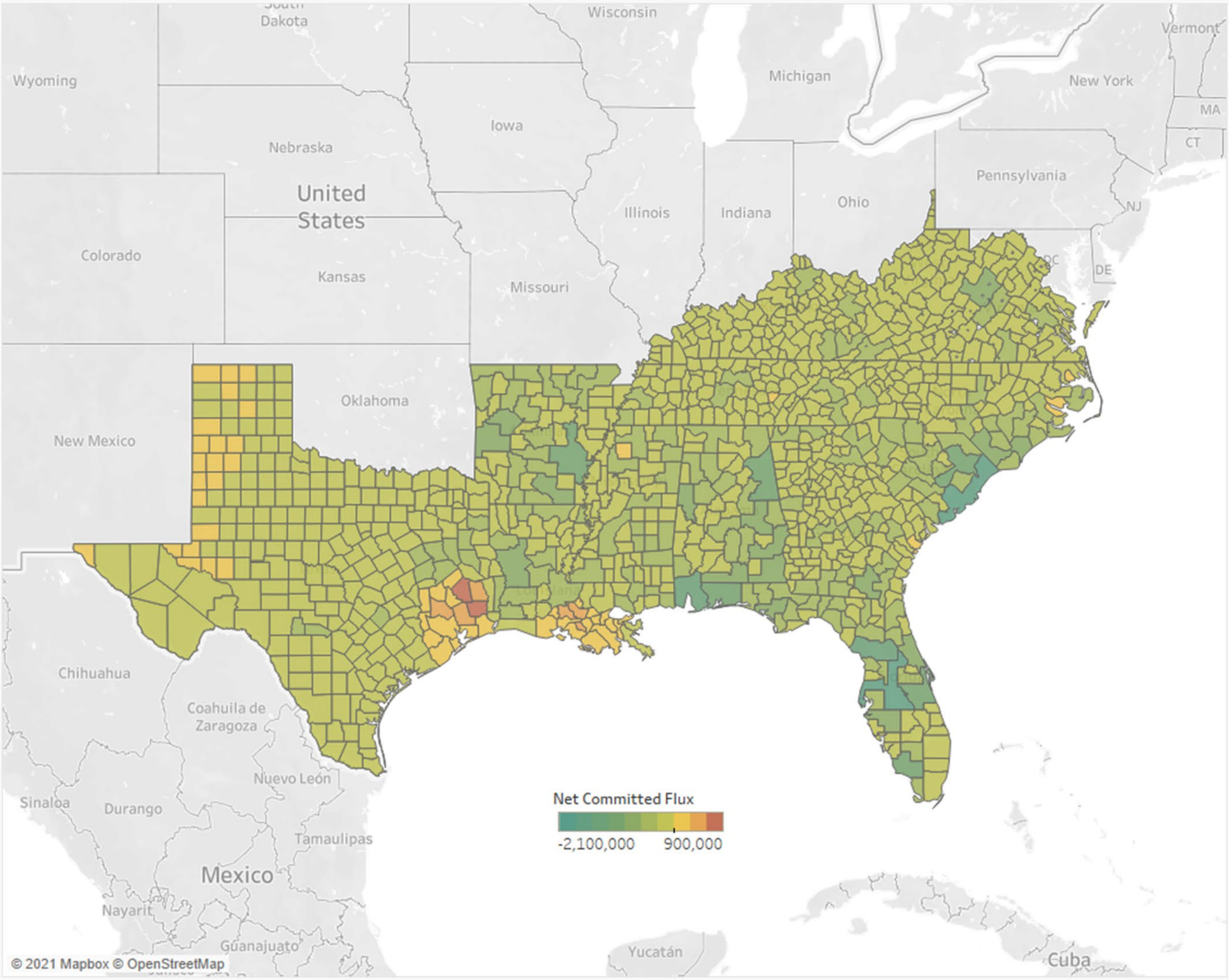



**FIGURE 3** Net committed annual flux of GHG emissions (Mt $CO_2$-e/year) of forest disturbance and sequestration for the U.S. Southeast (2005–2010) based on NASA Carbon Monitoring System data (Hagen et al., 2016)

year until 2050, but under the high-demand scenario, it rises to 36.8 Mton/year by 2050 (see Figure 4), representing a 19% average annual increase since 2012. Most of the wood pellets produced in North America are expected to be exported and consumed in other regions. The proportion of wood pellets that are exported remains relatively stable across the climate mitigation scenarios (rising from 76% to 81%), suggesting that wood pellet producers in North America will be influenced to a high degree by the bioenergy demand in other countries and regions.

The production of wood pellets also increases in Asia, rising from 0.3 Mton/year in 2012 to 5.2 Mton/year in 2030 and 2050 under the low-demand scenario, with sharper increases to 11.4 Mton/year in 2030 and 23.3 Mton/year in 2050 under the high-demand scenario (a sustained pace of ~60% average annual increase from 2012 to 2050; see Figure 4). A large part of this increase serves new bioenergy demand within the region, particularly in South Korea, Japan, China, Malaysia, and the rest of South East Asia—Pacific countries (RSEA-PAC; including Vietnam, Cambodia, North Korea, Laos, and Mongolia). South Korea, Japan, and China remain the main consumers of wood pellets within Asia, accounting for 94% of the total annual consumption in 2050. Though wood pellet production in the region increases significantly under more ambitious mitigation scenarios, demand and utilization within the region preclude large-scale export (Figure 5).

The production of wood pellets within Europe is also expected to rise as the demand for bioenergy increases; however, the increase in production would fall far short of the rising pace of demand for biomass feedstocks, particularly under more ambitious climate mitigation scenarios (see Figure 6). Under the low-demand scenario (RCP 8.5), production rises from 10.8 Mton in 2012 to 26.4 Mton in 2030 and 2050 (an average annual increase of 13%, 2012–2030), while under the high-demand scenario (RCP 1.9), production rises to 46.3 Mton/year in 2030 and 86 Mton/year in 2050 (average annual increase of 23% through 2030

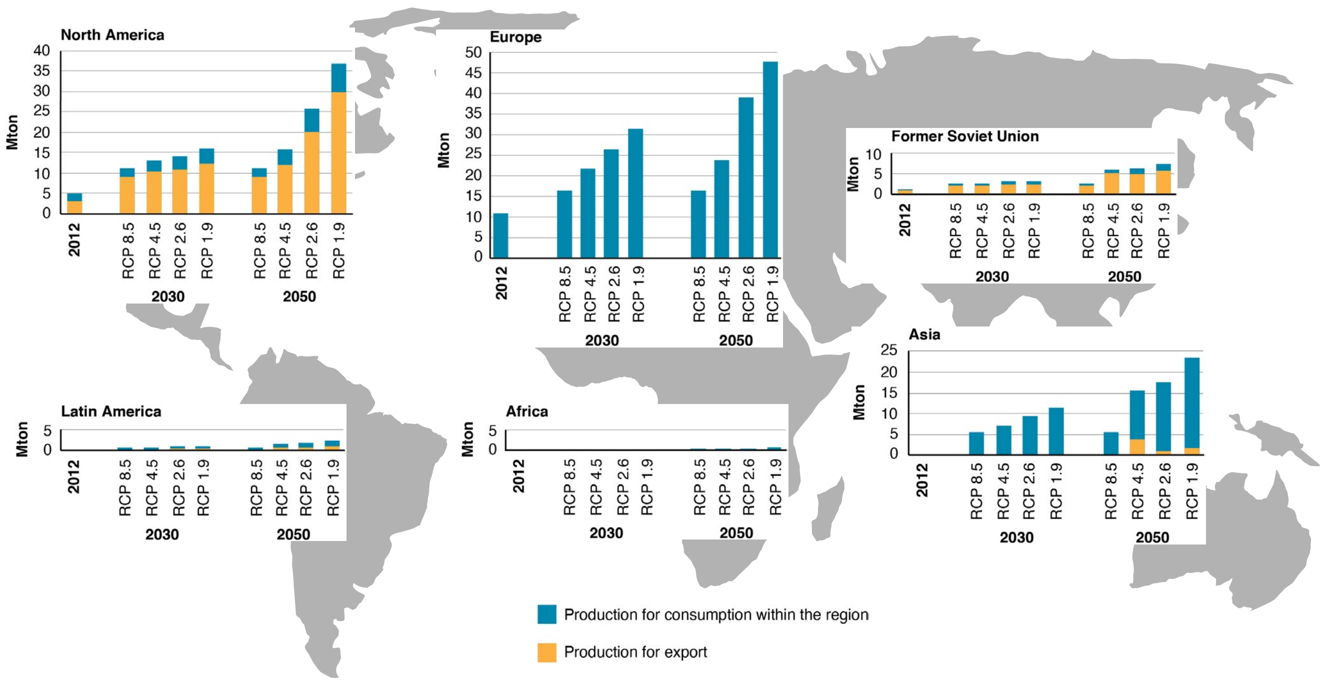



**FIGURE 4** Production of wood pellets per region for consumption within the region and for export to other regions (see Data S1 for exact figures)

and 21% through 2050), exclusively consumed within the region. Europe is expected to continue to be a major global importer of wood pellets, importing 10.1 Mton in the low-demand scenario to 14.9 Mton under high-demand scenario in 2030, and 10.1 Mton in the low-demand scenario to 38.3 in the high-demand scenario in 2050. In 2012, 73% of the wood pellets consumed within Europe were produced within the region, but this share is expected to fall to 62%–68% in 2030 and 51%–62% in 2050, with lower ends of these ranges corresponding to the most ambitious climate mitigation scenario. A large share of the imported wood pellets originates from North America, but imports from the Former Soviet Union and Asia are also expected to increase over time and with higher mitigation ambition.

## 3.2 | Projected impacts of increased harvests on the forest carbon sink in the U.S. Southeast

Overall net carbon emissions were similar across all scenarios because the changes in harvest emissions tended to be counterbalanced by opposite trends in emissions attributed to climate-driven disturbances. Net emissions differences between the scenarios and the reference period ranged from 106 to 181 $MtCO_2$-e/year (mean = 147 $MtCO_2$-e/year; 18%–30% reduction in sink strength). Changes to harvest rates are a primary driver of emissions changes in the different scenarios analyzed in the GLOBIOM model. Similarly, harvest emissions were the greatest overall annual contributor (77% of emissions before considering sequestration in the forest) to emissions in the 2005–2010 reference period in our sensitivity analysis of subnational emissions in the U.S. Southeast. In 2030, the GLOBIOM results projected a nominal 7%–8% increase in harvest rates for the region for both low- and high-demand scenarios. However, by 2050, harvest rates increased by 13% in the low-demand scenario (RCP 8.5) and by 29% in the high-demand scenario (RCP 1.9). Emissions from harvest activities should be considered in the context of increased emissions and reduced sequestration rates in the forests from more prevalent disturbances under the higher emission scenarios (RCP 4.5 and 8.5; Figure 7). Emissions from land-use conversion were 32%–83% higher than wildfire emissions and were an overall greater contributor to net emissions in all RCP scenarios (Figure 7). When all forest GHG fluxes are considered together, the high-demand scenario (RCP 1.9) with higher harvest rates and higher wildfire net emissions in 2050 led to the steepest loss of the region's forest carbon sink (see Figure 7).

## 3.3 | Omitted emissions resulting from trade in feedstocks

For each scenario, we estimated potential for EOA in 2030 and 2050 due to biomass feedstock imports. Given

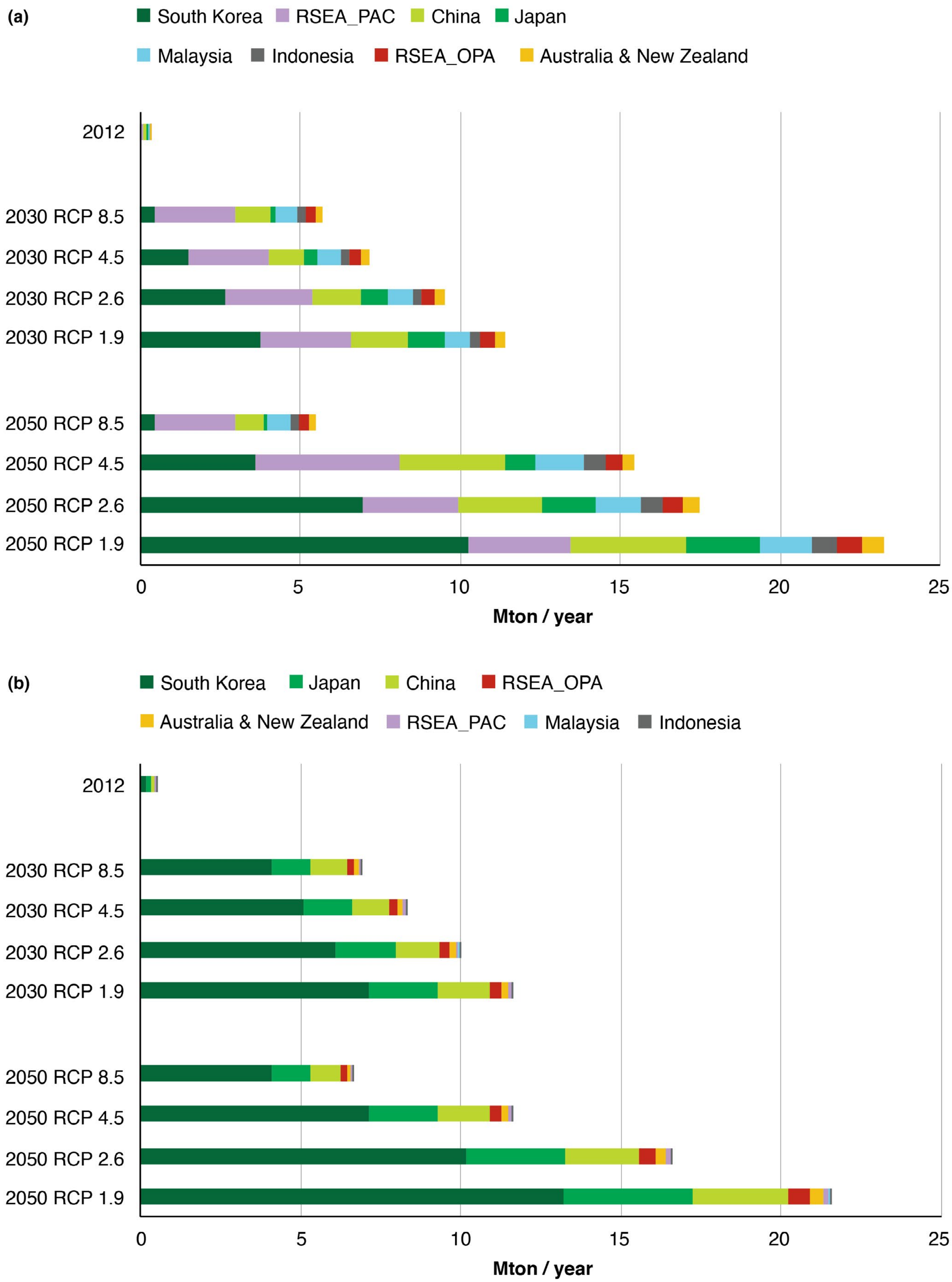



**FIGURE 5** Domestic production (top) and domestic consumption (bottom) of wood pellets separated by regions and countries for Asia

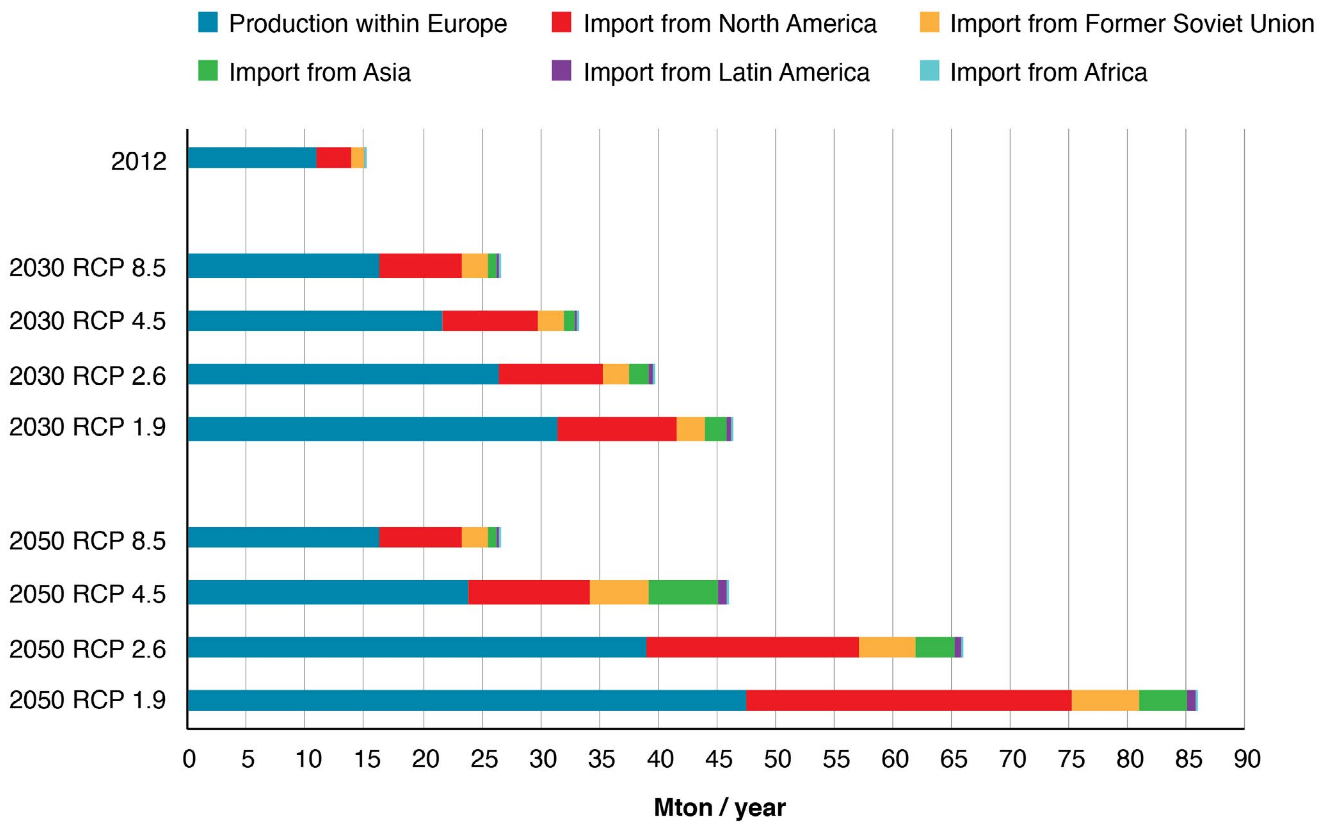



**FIGURE 6** Production of wood pellets with Europe and import quantities from outside of Europe for the different scenarios

that the United States is expected to remain the largest major exporter of wood pellets, we used the U.S. emission factor for the combustion of wood for energy (0.434 MtC per Mt wood biomass; U.S. EPA, 2021; Lindstrom, 2006) and the volume of wood pellets imported for each region to estimate its associated EOA. We estimate that global EOA due to interregional trade could reach 23.77 $MtCO_2eq$/year under a low-demand (RCP 8.5) scenario and 71.08 $MtCO_2eq$/year under a high-demand (RCP 1.9) scenario (see Table 2a), with cumulative emissions from 2020 to 2050 surpassing 1300 $MtCO_2eq$ in the high-demand scenario. Import of wood pellets from the United States to Europe accounts for most potential EOA, at 6.85 $MtCO_2eq$/year under a low-demand (RCP 8.5) scenario in 2050 and nearly five times higher under a high-demand (RCP 1.9) scenario (see Table 2a).

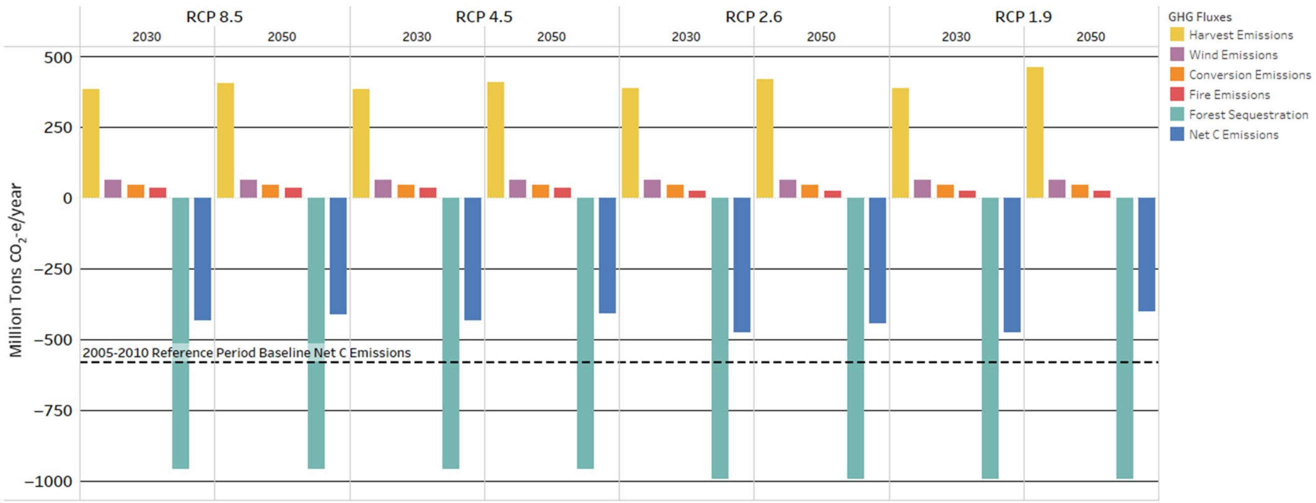
## 3.4 | Arbitrage value of omitted emissions

Using the carbon content in imported biomass feedstocks in our results, we estimated the potential quantity of EOA. Our approach simulated trade in wood pellets across regions; as a result, it may not fully capture the potential for regulatory arbitrage among countries within regions (see Supplemental Information Table S1 for the list of GLOBIOM regions).

For Europe, the potential amount of EOA in 2050 related to the import of wood pellets could exceed the economy-wide emissions in 2018 of a number of smaller Member States (see Table 2b). If European countries continued to apply the production approach when estimating emissions associated with harvested wood products, the emissions associated with imported wood pellets may not be included in national GHG inventories or accounted for when countries assess their progress toward domestic emission reduction targets. Therefore, bioenergy producers using imported wood pellets could bypass the financial disincentives that would apply to these emissions if they were being accounted for in other sectors.

In addition to the future level of EOA, we explored the potential arbitrage value of differential pricing of emissions among countries by comparing our results for the low-demand (RCP 8.5) to the high-demand (RCP 1.9) scenario. We used carbon prices simulated in the MESSAGE-GLOBIOM model (Fricko et al., 2017; see Data S1), which projects a carbon price in Europe of US$435.85 per ton $CO_2$-e in 2050 for our high-demand scenario (IIASA, 2020; Rogelj et al., 2018).

Using the MESSAGE-GLOBIOM simulated emission prices and the difference in volumes of imported




| | RCP 8.5 | | RCP 4.5 | | RCP 2.6 | | RCP 1.9 | |
|---|---|---|---|---|---|---|---|---|
| | 2030 | 2050 | 2030 | 2050 | 2030 | 2050 | 2030 | 2050 |
| Harvest Emissions | 384 | 405 | 384 | 409 | 387 | 419 | 387 | 462 |
| Wind Emissions | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 |
| Conversion Emissions | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| Fire Emissions | 34 | 34 | 34 | 34 | 25 | 25 | 25 | 25 |
| Forest Sequestration | -958 | -958 | -958 | -958 | -996 | -996 | -996 | -996 |
| Net C Emissions | -434 | -413 | -434 | -409 | -478 | -446 | -478 | -403 |

**FIGURE 7** Projected annual GHG flux associated with forest disturbances and forest sequestration pools in the U.S. Southeast for RCP emissions scenarios. Dotted line indicates 2005–2010 reference period annual net forest GHG fluxes (−584 Mt $CO_2$-e/year). A net sink for all scenarios indicates the continued accumulation of aboveground forest carbon stocks in the region; a weaker sink under some scenarios implies that the United States would need to compensate in other ways to meet its economy-wide emissions target

feedstocks between the high- and low-demand scenarios, we estimated the potential value of arbitrage opportunities from EOA. In the high-demand (RCP 1.9) scenario, the market price of wood pellets rises from US$208 per ton (2030) to US$237 per ton (2050). However, the simulated carbon prices diverge significantly even more between these scenarios, leading to a differential of about US$340 by 2050. If European bioenergy producers utilize EOA to avoid paying the price for GHG emissions, their savings would be valued at US$14.6 billion per year (in 2020 US$) by 2050 (Table 3). By that time, the value of avoiding these penalties on emissions would far exceed the estimated cost of the feedstocks themselves, which are estimated at around US$5 billion in 2050 (Table 3). This illustrates how higher climate ambition, coupled with EOA, could lead to remunerative opportunities for biomass energy production.

## 4 | DISCUSSION

### 4.1 | Omitted emissions could drive higher demand for wood pellet production

Our results highlight the strong correlation between climate policy ambition and increased utilization of biomass energy (specifically, wood pellets), with consequent implications for forest health, carbon sinks, and accurate accounting of emissions. More ambitious climate mitigation scenarios feature strong growth in the use of biomass energy, particularly in the European and Asian regions, along with an increase in the importing of wood pellets to Europe due to their cost competitiveness in relation to other potential energy sources. In our scenarios, Europe satisfies part of its growing bioenergy demand through trade, at first relying primarily on North America, but eventually importing significant quantities of biomass from Asia and the Former Soviet Union. In response, from 2012 to 2050, production of wood pellets in North America is projected to increase seven-fold (from 5.0 to 36.8 Mton/year) and production in Asia is expected to increase by more than 60-fold (from 0.3 to 23.3 Mton/year).

These findings raise the possibility that within existing accounting frameworks, asymmetrical efforts to increase the ambition of climate mitigation in individual countries could increase arbitrage opportunities from feedstock trade. Even if countries pursue more ambitious (but uneven) climate mitigation efforts, the unaccounted emissions from bioenergy could undermine those collective efforts. Globally, EOA from bioenergy are difficult to detect, quantify, and address, because they are effectively “invisible” to the established policy mechanisms. These conditions could lead to heightened demand for

**TABLE 2** (a) Estimated levels of potential emissions omitted from accounts (EOA) in 2030 and 2050 due to biomass feedstocks imports, for each scenario. Columns show the potential for EOA for the European region and globally, as well as the cumulative estimated global EOA by 2050. (b) Annual reported emissions (excluding LULUCF) for selected European countries in 2018 (based on 2020 GHG Inventories reported to the UNFCCC), for comparison

| Year | Scenario | Estimated EOA in the given year, European region ($MtCO_2$) | Estimated EOA in the given year, global ($MtCO_2$) | Year | Scenario | Estimated cumulative EOA, global ($MtCO_2$) |
|---|---|---|---|---|---|---|
| *(a)* | | | | | | |
| 2030 | RCP 8.5 | 6.85 | 23.81 | | | |
| 2030 | RCP 4.5 | 8.89 | 25.84 | | | |
| 2030 | RCP 2.6 | 9.55 | 28.19 | | | |
| 2030 | RCP 1.9 | 11.68 | 30.92 | | | |
| 2050 | RCP 8.5 | 6.85 | 23.81 | 2020–2050 | RCP 8.5 | 732.39 |
| 2050 | RCP 4.5 | 8.89 | 43.84 | 2020–2050 | RCP 4.5 | 969.28 |
| 2050 | RCP 2.6 | 19.47 | 51.01 | 2020–2050 | RCP 2.6 | 1077.41 |
| 2050 | RCP 1.9 | 33.57 | 69.22 | 2020–2050 | RCP 1.9 | 1300.52 |

| Country | 2018 reported annual economy-wide emissions excluding LULUCF ($MtCO_2$) |
|---|---|
| *(b)* | |
| Malta | 2.2 |
| Cyprus | 8.8 |
| Luxemburg | 10.5 |
| Slovenia | 17.5 |
| Estonia | 20.0 |
| Croatia | 23.8 |
| Slovakia | 43.3 |
| Denmark | 48.2 |
| Sweden | 51.8 |
| Finland | 56.4 |
| Ireland | 60.9 |
| Hungary | 63.2 |
| Portugal | 67.4 |
| Austria | 79.0 |
| France | 444.8 |
| Germany | 858.4 |

**TABLE 3** Projected volumes of wood pellets traded from the United States to Europe under four different emissions scenarios

| Year | Emissions scenario | Wood pellet imports to Europe from U.S. (Mton/year) | Market price of wood pellet imports ($/ton) | Trade revenue from Europe to U.S. (M$) | Combustion emissions from imported wood pellets ($MtCO_2$/year) | Europe carbon price in the given year ($/t $CO_2$-e) | Avoided cost of emissions (M$) | Cost of imported wood pellets (+) less the avoided cost of emissions (−) (M$) | Net cost of utilizing imported wood pellets ($/ton of wood pellets) |
|---|---|---|---|---|---|---|---|---|---|
| | | (A) | (B) | (C) = (A)*(B) | (D) | (E) | (F) = (D)*(E) | (G) = (C) − (F) | (H) = (G)/(A) |
| 2030 | RCP 8.5 | 4.30 | $170 | $732 | 6.85 | $0.00 | $0 | $732 | $170 |
| | RCP 4.5 | 5.58 | $170 | $949 | 8.89 | $12.65 | $112 | $837 | $150 |
| | RCP 2.6 | 6.00 | $202 | $1212 | 9.55 | $41.84 | $400 | $812 | $135 |
| | RCP 1.9 | 7.34 | $208 | $1527 | 11.68 | $95.13 | $1111 | $416 | $57 |
| 2050 | RCP 8.5 | 4.30 | $170 | $732 | 6.85 | $0.00 | $0 | $732 | $170 |
| | RCP 4.5 | 5.58 | $215 | $1201 | 8.89 | $12.32 | $110 | $1091 | $195 |
| | RCP 2.6 | 12.23 | $227 | $2777 | 19.47 | $84.71 | $1649 | $1128 | $92 |
| | RCP 1.9 | 21.09 | $237 | $4999 | 33.57 | $435.85 | $14,630 | ***$−9631*** | ***$−457*** |

*Notes*: RCP 8.5 corresponds to the "low-demand" scenario and RCP 1.9 corresponds to the "high-demand" scenario as described in the text. Outcomes that yield net negative costs for utilizing imported wood pellet feedstocks are highlighted in bold italics. Values in the table reflect internally consistent projections from the GLOBIOM model and are not predictions of the future.

bioenergy, an over-investment in biomass energy production capacity, and a net increase in system-wide emissions.

We found the economic value of avoiding disincentives strongly affects the net value of biomass feedstocks, which changes from a cost of US$57 per ton of wood pellets (2030) to a net revenue of US$457 per ton in 2050. The lucrative nature of this outcome could give bioenergy producers a significant comparative advantage over other forms of energy production. Furthermore, these figures do not reflect any direct or indirect subsidies paid by governments, such as those currently available in the United Kingdom, to power producers substituting biomass for coal (see Norton et al., 2019), which would further augment the profitability of bioenergy.

## 4.2 | Potential regional and global impacts on forests

The opportunity for bioenergy production—particularly within Europe—to profit from imported biomass supplies could have significant impacts on forest stocks around the world. The anticipated demand would most heavily affect the forests of the U.S. Southeast, a forest carbon sink that has historically played a significant role in reducing the net emissions of the United States. In the United States, forests and other lands annually sequester the equivalent of approximately 12% of domestic emissions from other sectors (U.S. EPA, 2020). If harvests for biomass feedstock production reduce this sink, the United States may need to rely upon other, potentially more costly sources of mitigation to meet domestic climate policy goals.

Factors such as urban growth are already projected to diminish the size of forests in the U.S. Southeast, reducing the opportunities for forest production and sequestration (Wear & Coulston, 2015; Wear & Greis, 2002), with an estimated 118,300 $km^2$ of forestland expected to be converted to urban land between 2000 and 2050 (Nowak & Walton, 2005). In addition, climate change is expected to impact the remaining forests through increased frequency and intensity of wildfires and droughts, as well as greater damage from pests and severe weather events such as hurricanes (Seidl et al., 2017; USGCRP, 2018). Our analysis compared the relative scale of these impacts with the projected increase in harvest driven by biomass energy demand and found an inverse relationship between these two drivers of forest impacts: greater climate ambition leads to less severe climate impacts but deeper reductions in forest stocks as a result of harvest to meet bioenergy demand, whereas less ambitious climate scenarios are associated with more severe climate impacts and relatively lower impacts from forest harvest. This apparent tradeoff, in terms of outcomes for forests, can be avoided if global mitigation goals are met by means other than an overreliance on bioenergy.

In all scenarios we analyzed, the future forest carbon sink in the U.S. Southeast is diminished relative to the historical sink (Figure 7). Furthermore, our analysis suggests that the effect of bioenergy demand has the potential to outweigh the effects of climate change on forest stocks, since the smallest sink in our analysis corresponded to the ambitious RCP 1.9 scenario (402.8 $MtCO_2$-e in 2050, a 31% reduction compared to historical levels). However, the combination of effects is mixed across the various scenarios and is sensitive to model assumptions. In addition, the application of various forest management practices and second-order effects were not accounted for in our sensitivity analysis and are a worthwhile subject for future investigation.

Beyond the United States, our results suggest that biomass energy demand may also influence forest carbon stocks, net GHG fluxes, and forest ecosystem service delivery in other regions. Forests have expanded in Europe in recent decades, after enjoying a long period of recovery since WWII, and they are now reaching maturity (Nabuurs et al., 2013). The net GHG flux from these forests (including their harvested wood products) could shift in either direction in the future depending on the specific management practices employed to meet bioenergy demand. For instance, future biomass demand, driven by climate ambition, could subject European forests to even more intensive management and the implementation of more productive systems, such as monoculture plantations of non-native species—approaches that could diminish biodiversity and leave these forests more vulnerable to climate impacts and other disturbances (EASAC, 2017, 2019; JRC, 2021).

Outside of Europe, forests in the countries of the Former Soviet Union and East Asia regions may be particularly affected by growth in wood pellet demand. Notable expansions of forest have occurred in both regions in recent decades, raising the possibility that they could sustainably meet demand for biomass feedstocks without diminishing their overall forest carbon stocks (Potapov et al., 2015; Tun et al., 2019). Such an outcome would represent a departure from forest management trends in these regions. For example, in recent years, deforestation in Asia—driven by production of agricultural commodities (such as palm oil) and forestry products—has become a significant source of emissions (Pendrill et al., 2019) and resulted in major losses of biodiversity (Hughes, 2017). A surge in global demand for biomass feedstocks could have similar unintended consequences—and emissions there could be higher and more long lasting than in other parts of the world if feedstocks are sourced from drained forest peatlands, which generate ongoing emissions of methane when disturbed (Miettinen et al., 2017; Page & Hooijer, 2016).

### 4.3 | Limitations of these estimates

Our analysis should be interpreted within the limits that arise from information availability and analytical capabilities, especially for long-term projections. As with other analyses (e.g., Austin et al., 2020; Favero et al., 2020; Johnston & Radeloff, 2019; Kim et al., 2018; Lauri et al., 2017), we are not able to fully incorporate the long-term effects of climate change in our GLOBIOM simulations, although we did apply climate-driven adjustments to disturbance levels in our sensitivity analysis of the U.S. Southeast, to gauge their relative scale compared to the impacts of wood pellet demand. Higher RCP scenarios could trigger more localized disturbances in forests, through drought, pest outbreaks, and other impacts, which could decrease net carbon sequestration and increase net emissions. On the other hand, the diffuse effects of carbon fertilization and nitrogen deposition could lead to faster rates of forest growth and higher levels of carbon accumulation, which could increase net carbon sequestration (Mendelsohn & Sohngen, 2019; Smith et al., 2014). Additionally, our sensitivity analysis did not consider market-driven changes in management and forest area that would improve productivity and carbon sequestration rates. Research that has incorporated such market dynamics suggests that demand may stimulate investments in forest management, with potential for positive impacts on sequestration and carbon stocks, but negative impacts on biodiversity as the extent of intensively managed forest plantations increases (Favero et al., 2020).

Our ability to precisely estimate carbon fluxes associated with forests was complicated by a reliance on many different types of data. NASA CMS estimates at a continental scale had a standard error that was ±18% of the mean value (Harris et al., 2016). On smaller spatial scales, the potential error could be greater. Nevertheless, even when considering this range, the net differences projected in our sensitivity analysis are meaningful compared to potential climate impacts. Our approach to test the sensitivity of carbon fluxes in our analysis of forests in the southeastern U.S. is an example of how such issues could be assessed. Further assessments of other geographic areas will undoubtedly elucidate these dynamics.

Our assessment also does not consider a number of factors that can affect international trade, including changes in trade policies, import regulations, tariffs, institutional barriers, and infrastructural limitations (Janssens et al., 2020). Implementation of the European Union's Renewable Energy Directive (RED II) could have large impacts on European levels of imports of wood pellets (Searchinger et al., 2018). Similarly, policies that lead to demand for wood products competing for the same feedstocks, such as cross-laminated timber, or that provide incentives to landowners for forest carbon sequestration could attenuate the demand for wood pellets (Favero et al., 2020). Our analysis focuses on projections of wood pellet trade; future supply and demand of other woody feedstocks remains another key developing area of research (e.g., Daigneault & Favero, 2021; Lauri et al., 2019). The role of bioenergy as a renewable energy source and its potential for removing carbon from the atmosphere is still being debated (EASAC, 2019). We have characterized regionally optimized estimates of trade in wood pellets under low to high levels of future bioenergy demand scenarios (i.e., RCP 8.5 to RCP 1.9), but within these scenarios, countries could employ a range of pathways to reach climate neutrality (IPCC, 2018), each with different demands for levels of bioenergy and wood pellets. A detailed analysis that looks at the trade implications of country-level policy options (rather than regional) is a worthwhile subject for further research, given its potential for widespread impacts on forests.

## 5 | CONCLUSION

Our results highlight the problems that could arise if countries fail to account for emissions that stem from bioenergy production. We quantified the potential for growth in global wood pellet trade and the corresponding potential for EOA, regulatory arbitrage in trade between Europe and the United States, and the consequent effects on the forests of the U.S. Southeast. Potential increases in unaccounted emissions from the harvest of biomass feedstocks, made possible through artifacts of accounting rules, could accelerate the growth in bioenergy production beyond what is optimal for the climate or for forest health. Energy systems, once established, can become locked in, due to a range of political and economic factors that tend to maintain the status quo (Fouquet, 2016). The opportunity to exploit EOA—intentionally or unintentionally—could become increasingly attractive if power generators are insulated from the costs of policies designed to discourage GHG emissions.

Changes in UNFCCC accounting rules might address some of these issues (Norton et al., 2019). Increasing the transparency and accessibility of accounting for bioenergy emissions may help to illuminate the potential trade-offs between bioenergy emissions and forest carbon stocks (Cowie et al., 2021). One straightforward way to prevent EOA would be to require the use of compatible accounting approaches that ensure emissions associated with biomass feedstocks are fully accounted, either in the country of origin or the destination country—noting that accounting for them in the destination country would more closely parallel the accounting for imported fossil fuels and could allow better alignment of policies across sectors. Countries could also enhance trade regulations to specifically ensure that wood pellet import does not lead to EOA. Indeed, the 2019 IPCC Refinement recommends that countries compare their own approaches with those of countries from whom they import and to rectify their accounts so that carbon embodied in imported wood products (and subsequently emitted) is accounted for once and only once (Rüter et al., 2019). However, we are not aware of any countries currently undertaking such a process. Until a global policy fix is identified, this problem could persist.

A central issue for policymakers—and a motivating factor for this research—is consideration of the future landscapes that will be shaped by our response to climate change. In addition to weighing the potential effects of climate change impacts, policymakers must also consider how mitigation approaches could affect the integrity of terrestrial ecosystems. Will natural forest regeneration be the predominant mitigation strategy for forested landscapes, or will landscapes be dominated by plantation forests intensively managed for bioenergy feedstock production? Policies that continue to allow EOA from bioenergy could arbitrarily favor the second option, undermining countries' commitments under the Convention on Biological Diversity.

Foreclosing risks posed by bioenergy to the climate and global ecosystems is challenging but important. Clarifying boundaries and expectations about the potential scale of future bioenergy use could illuminate the kinds of interventions necessary to prevent unintended environmental, economic, or social negative outcomes (Creutzig et al., 2021; Reid et al., 2020). This in turn would aid in understanding the balance of climate mitigation that must be achieved across other sectors and activities. Understanding the interplay of the many factors that affect the GHG profile of bioenergy is vitally important if the role of biomass energy in climate mitigation is to be a positive one.

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## CONFLICT OF INTEREST

The authors declare no competing interests.

## AUTHOR CONTRIBUTIONS

All authors contributed to developing the research questions, analysis, and interpretation of results. Jason M. Funk conceptualized the research and led the writing of the manuscript; Nicklas Forsell analyzed and led the writing about the GLOBIOM runs; John S. Gunn analyzed and led the writing about the U.S. Southeast. All authors contributed to the drafts and gave final approval for publication.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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