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How the future of the global forest sink depends on timber demand, forest management, and carbon policies

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Abstract

Deforestation has contributed significantly to net greenhouse gas emissions, but slowing deforestation, regrowing forests and other ecosystem processes have made forests a net sink. Deforestation will still influence future carbon fluxes, but the role of forest growth through aging, management, and other silvicultural inputs on future carbon fluxes are critically important but not recognized by bookkeeping and integrated assessment models. When projecting the future, it is vital to capture how management processes affect carbon storage in ecosystems and wood products. This study assesses future forest carbon calculated by global forestry models that manage forests to provide wood products and carbon. The results indicate forests will remain a carbon sink in the future, sequestering 1.2-5.8 GtCO2e/yr under a wide range of drivers and conditions, including increased demand for wood products, agricultural land, and carbon. Improved forest management can jointly increase carbon stocks and harvests without expanding forest area.

Keywords

Model intercomparison; land use; carbon; bioenergy; climate change mitigation; Shared socioeconomic pathways; shared policy analysis

1. Introduction

The global forest sector is widely recognized in the scientific and policy communities for its contribution to the global carbon cycle and climate change mitigation [1–7]. Natural climate solutions such as avoided deforestation [8], afforestation [9,10], forest restoration [11], and improved forest management [12,13] are important components of climate change mitigation goals. Despite this noted importance, knowledge gaps regarding the combined impact of future socioeconomic, management, and policy change on forest carbon stocks and greenhouse gas (GHG) emissions remain [14,15].

Global-scale terrestrial carbon storage analyses often use bookkeeping methods that assign carbon density parameters to land cover types and track land use over time [16] or project impacts from discrete land use change (LUC) decisions via integrated assessment models (IAM)[4,15]. Using LUC as the primary driver of forest dynamics ignores a critical component of the terrestrial carbon cycle – carbon storage in existing forests – which is affected by harvesting, management interventions, and natural disturbance [17]. Further, management of existing forests and investment in new forestland is driven by socioeconomic change, market dynamics, and interactions between pulpwood, sawtimber, and bioenergy demand systems not fully represented by IAMs and ignored entirely in bookkeeping and dynamic global vegetation models. In addition, while historical assessments of forest area and carbon flux are useful for identifying where impacts occur, they often fail to recognize the socioeconomic drivers behind these impacts[18]. Market and management dynamics are important when modeling land use and carbon, especially for forests.

This paper utilizes a first of its kind forest model inter-comparison project (ForMIP) to estimate future forest area, carbon, harvests, and market outcomes across harmonized scenarios using three detailed economic models of the global forest sector – the Global Timber Model (GTM), Global Biosphere Management Model (GLOBIOM), and Global Forest Products Model (GFPM). This study contributes to a rich literature of model inter-comparison exercises in the climate domain, including the Energy Modeling Forum (EMF) [19,20], the Agricultural Model Comparison Project (AgMIP) [21,22], and the Land Use Model Inter-comparison Project (LUMIP) [23,24]. Our focus on the inter-comparison of forest sector models (FSM) is critical given the sector's outsized influence on the global carbon cycle relative to its contribution to the global economy as well as its recognized importance as a potential source of mitigation[8]. In particular, FSMs reflect heterogeneity in the forest resource base, ecological constraints, management opportunities, product markets, and land use and management responses to market and environmental change [2,25–37].

We model future socioeconomic and climate policy change across three FSMs and 81 pathways through 2105 using the Shared Socioeconomic Pathways (SSP)[38–40], Representative Concentration Pathways (RCP)[15,39], and Shared Policy Assumptions (SPA)[41] approach commonly applied by IAMs. We add to the literature by a) harmonizing SSP-RCP-SPA assumptions in FSMs [39,40] and b) illustrating how incorporating a more detailed representation of the forest sector can capture forest ecosystem, market, and carbon dynamics not accounted for in bookkeeping and integrated assessment models[3,15,42].

Results highlight the key role that existing forests play in the future global carbon balance, as well as how forest management and new tree planting are driven by both socioeconomic development and climate policy incentives. We demonstrate that economic growth and increased demand for forest biomass and land does not necessarily lead to forest carbon loss, thus global harvests and carbon storage can jointly increase with adequate incentives. We suggest that future IAM exercises should better represent forest product markets and management dynamics, and that forest climate mitigation policies should be complemented by incentives to enhance demand for forest products and biomass.

2. Materials and Methods

Our analysis presents results from a harmonized scenario analysis across three detailed and widely published models of the global forest sector (Table 1): the Global Timber Model (GTM): an intertemporal optimization model of global forest sector [13,56,57]; the Global Biosphere Management Model (GLOBIOM): a partial equilibrium model of the global land use sectors [14,58,59]; and the Global Forest Products Model (GFPM): a global forest product markets and timber supply simulation model [26,60].

The scenario design conforms to SSP components and forest sector pathway narratives described in [40], offering five alternative baseline scenarios with varying degrees of macroeconomic and socioeconomic change [38,61]. SSP scenarios link with representative concentration pathways (RCPs) to simulate how forest sector adjustments can help achieve global climate targets, but not the physical impacts of climate change. Key elements of these pathways include population and economic growth, demand for wood products and biomass for energy production, climate mitigation policy (via carbon prices), technological change, land use regulations, forest management intensity, and competing land rents (Table 2). All three models use the same scenario narratives and key SSP-RCP data (e.g., population, GDP, forest bioenergy demand, and carbon price) as inputs to facilitate a consistent model inter-comparison across 81 scenarios. The following sections provide additional information on our scenario design and the models used in this assessment.

Table 1. Key forest sector model elements

Element	GTM	GFPM	GLOBIOM
Economic Regions	16	180	59
Resolution	regional	country	0.5°-2° grid
Sectors	Sawtimber, pulpwood, bioenergy	forest product industry	Forest industry, forestry, bioenergy, agriculture
Forest types^	302	1	6
Climate effect on forests	no	no	no
Forest products*	3	14	35
Forest products trade	n/a	Bilateral trade,	Bilateral trade, non-linear trade costs, trade-inertia constraints based on historical trade
Base year	2015	2015	2000
Calibration	Model calibrated to 2015 FAOSTAT and FRA	Model calibrated to FAOSTAT and FRA data from 2014- 2016	Model calibrated to FAOSTAT and FRA data from 2000-2020
Temporal scale	10-year	5-year	10-year
Dynamics	Intertemporal	Recursive dynamic	Recursive dynamic
Biomass policy	Fixed demand	Fixed demand	Constant elasticity demand functions, which are shifted over time
Carbon policy	Carbon tax/subsidy based on carbon price applied to all pools, including HWP	Carbon tax/subsidy based on carbon price applied to forest biomass, not for HWP	Carbon tax/subsidy based on carbon price for deforestation/afforestation/ management, not for HWP
Endogenous response	Product price, forest area, management intensity	Product price, Timber harvest, Import, and export	Prices, quantities, land-use and management endogenous, supply side solved spatially-explicit, demand side and trade solved in regional level
Land use transition function	Agricultural land rents	Environmental Kuznets Curve	Land-use changes endogenous based on economic surplus maximization, non-linear land-use change costs, feasible areas and mapping of allowed land-use changes

^ Forest types (e.g,. PNW Douglas fir, coniferous, deciduous, etc/)

* Products (e.g., sawlogs, pulp, etc.)

2.1 Shared socioeconomic and relative concentration pathways

Global level shared socioeconomic pathways (SSPs) have been developed to specify five distinct pathways for the development of socioeconomic futures as they might unfold in absence of any explicit measures or policies to limit climate change or enhance adaptive capacity [41,43]. The SSPs are primarily intended to enable climate change-focused research and policy analysis, but the broad perspective and set of indicators mean that they can also be used for non-climate related scenarios such as economic and/or sustainable development [41]. Furthermore, the SSPs can be combined with Relative Concentration Pathways (RCPs) to simulate actions required to meet specific global GHG emissions trajectories.

Narratives for the current set of SSPs describe various combinations of high or low challenges to adaptation and mitigation (Table 2). The pathways range from a 'sustainable' world that is highly adaptive and faces relatively low socio-economic challenges (SSP1) to one that is fragmented with relatively weak global institutions and faces high population growth (SSP3). SSP4 assumes that there will be increasing inequality in global development, while SSP5 features rapid development that is driven by fossil fuels and technological change. A fifth narrative (SSP2) describes moderate challenges of both adaptation and mitigation with the intent to describe a future pathway where development trends are not extreme in any dimension and hence follow a middle-of-the road pathway relative to the other SSPs. SSP2 is often referred to as the 'business as usual' pathway because many indicators closely follow historical trends.
This paper builds off of specific aspects of the five global SSP narratives published in the literature, by expanding on how the global forest sector could be affected by each pathway. The elements that are important to the sector include economic and population growth, international trade, technological change, wood product demand, land use regulations, and climate policy and are assumed to vary across each SSP-RCP combination.

Table 2. Key elements for global forest sector shared socioeconomic pathways (SSPs)

Element	SSP1 (Sustainability)	SSP2 (Middle of the Road)	SSP3 (Regional Rivalry)	SSP4 (Inequality)	SSP5 (Fossil-fueled Development)
Economic growth	High	Medium	Low	HIC: High LIC: Low	High
Population Growth	Low	Medium	High	HIC: Low LIC: High	Low
Market connectivity	Global	Regional to Global	Local to Regional	HIC: Global LIC: Regional	Global
Technological change	High	Medium	Low	HIC: High LIC: Medium	High
Land use regulation	Very high	Medium	Low	HIC: High LIC: Med-low	Medium
Forest management intensity	Medium-high	Medium	Low	HIC: High LIC: Low	High
Forest product demand	Medium-high	Medium	Low	HIC: High LIC: Low	Very high
Woody-biomass demand	High	Low	High	HIC: Med-low LIC: Med-high	Low

HIC: High-income countries; LIC: Low-income countries

2.2 Harmonized Input Data

Most of the harmonized model input data was based on the IIASA SSP database [43]. Core SSP inputs included global GDP and population growth, while harmonized RCP-SSP data included carbon prices and wood-based bioenergy demand (Table S1). Carbon prices and total bioenergy demand for each SSP-RCP combination were based on the MESSAGE-GLOBIOM estimates in the SSP database (Figure S1). The amount of woody biomass that contributed to the total bioenergy demand was based on [52], using constant conversion factors of 7.2 GJ/m3 wood (Figure S2). The models were calibrated to 2015 global forest area based on [62]. Other inputs such as biomass, timber, and carbon yields were specific to each model. All models have endogenous prices and can account for land use change.

2.3 Forest Sector Models

2.3.1 Global Timber Model (GTM)

GTM is an economic model of forests that maximizes the net present value of consumers' and producers' surplus in the forestry sector. The model has been used to assess global and regional forest impacts associated with timber markets [56], forest conservation [57], deforestation [8], climate policy [13], land use change [46], bioenergy [31], and climate change impacts [55]. GTM's objective function maximizes the net present value of total surplus, by optimizing the age of harvesting timber and the intensity of regenerating and managing forests. GTM relies on forward-looking behavior and solves all decadal time periods at the same time over a 200-year horizon. The model accounts for nearly 300 forest types in 16 regions across the globe. Forest resources are differentiated by ecological productivity and by management and cost characteristics. The model accounts for the varying impacts of the SSPs through the adjustment of population and GDP growth, land rental rates, management costs, technological change, and consumer preferences (Table S2). Carbon accounting in this version of GTM tracks stocks of aboveground biomass, harvested wood products, and harvest residuals.

2.3.2 Global Forest Products Model (GFPM)

GFPM is a recursive dynamic FSM that tracks 14 commodity groupings across 180 individual countries. The model been the main tool in recent global forest-sector outlook studies published by the US Forest Service and FAOSTAT [63,64], and has been used to assess impacts of harvested wood products accounting [26], carbon markets [65,65], international trade policy [66,67], and land use development [27]. The GFPM simulates the evolution of the global forest sector by calculating successive yearly market equilibriums by maximizing a quasi-welfare function, as given by the sum of consumer and producer surpluses net of transaction costs. The model computes market equilibrium for each periodic timestep from 2015 to 2105, subject to a number of economic and biophysical constraints, including a market-clearing condition which states that the sum of imports, production, and manufactured supply of a given product in a given country must equal the sum of end-product consumption, exports, and demand for inputs in downstream manufacturing. GFPM equilibria were estimated based on country specific demographic and economic growth, as well as other pathway specifics for each SSP. Regional land-use change drivers were represented through an environmental-Kuznets-curve relationship with forest area. Other SSP parameters were captured within GDP and population projections and operationalized within the GFPM modeling framework through shifts in demand, supply, technological change, transportation and shipping costs. Carbon accounting in this version of the model includes aboveground biomass stocks.

2.3.3 Global Biosphere Management Model (GLOBIOM).

GLOBIOM is a partial equilibrium model representing land- use based activities: agriculture, forestry and bioenergy sectors [58,68]. The model is part of the IIASA-IAM framework and has been used since the late 2000s for various land-use and climate change mitigation scenario assessments. The model is built following a bottom-up setting based on detailed grid cell information, providing the biophysical and technical cost information. Production adjusts to meet the demand at the level of 30 economic regions. International trade representation is based on the spatial equilibrium modelling approach, where individual regions trade with each other based purely on cost competitiveness because goods are assumed to be homogenous. Market equilibrium is determined through mathematical optimization which allocates land and other resources to maximize the sum of consumer and producer surplus. The model is run recursively dynamic with a 10-year time step from 2010 to 2100. The forestry sector is represented in GLOBIOM with categories of primary products which are consumed by industrial energy, cooking fuel demand, or processed and sold on the market as final products. These products are supplied from managed forests and short rotation plantations. Harvesting cost and mean annual increments are informed by the G4M global forestry model [69,70] which in turn calculates them based on thinning strategies and length of the rotation period. The model optimizes over six land cover types: cropland, grassland, short rotation plantations, managed forests, unmanaged forests and other natural land. Economic activities are associated with the first four land cover types. Carbon accounting in this version of the model includes aboveground biomass stocks.

2.4 Scenario Analysis.

All models (n=3) were run for each feasible RCP (n=6) and SSP (n=5) combination for a total of 81 scenarios (SSP3-RCP1.9, SSP3-RCP2.6, and SSP1-RCP8.5 were deemed infeasible). Estimates of forest carbon, forest area, timber harvest, and timber price were reported at the global and six region level (North America, Latin America, Europe, Former Soviet Union, Africa, Asia + Oceania). Results are largely reported as changes from 2015.

3. Results

In 2015, 4.0 billion ha of global forests stored 277 GtC of aboveground carbon stock and produced 2.3 billion m3 of industrial roundwood with an average output price of $80/m3 (FAO, 2015, Table 3). Our results focus on global and regional changes between 2015 and 2105 under different socioeconomic (SSP 1-5) and climate policy (RCP 1.9-8.5) scenario combinations. The ‘baseline’ scenarios for each SSP represent the case where no climate policy is necessary to achieve a given RCP target. Most of the 81 SSP-RCP-Model combinations estimate increases in forest area (85%), carbon storage (95%), wood harvests (100%), and timber prices (100%) from 2015-2105. Figure 1 shows the range in projected model outcomes, with lines representing average results across models for each SSP-RCP combination, and shaded areas representing low and high reported values across the individual models.

Table 3. Key forest sector model outputs for 2015 baseline calibration

Metric	GTM	GFPM	GLOBIOM
Total Harvest (Mm3/yr)	1,603	2,013	1,596
Roundwood Harvest (Mm3/yr)	1,544	1,954	1,537
Biomass Harvest (Mm3/yr)	59	59	59
Forest Area (Mha)	3,960	3,997	4,033
Total Forest Non-soil C Stock (GtC)	253	287	281
Mean Roundwood Price ($/m3)	$79	$102	$55

3.1 Forest Area

Mean global forest area across all scenarios is projected to increase by 495 Mha from 2015 to 2105, with a range of -605 to +1435 Mha (Figure 1b). The SSP1 and SSP5 pathways see higher levels of forest area due to relative income and productivity growth that drives resource investments and raises the opportunity costs of forest conversion. Scenarios with lower income growth and reduced trade flows (i.e., SSP3 and SSP4) combined with low or zero value for forest-based mitigation options would lead to a reduction in global forest area.

The different climate mitigation policies for the six RCPs introduce the largest variation in area. The baseline pathways result in limited expansion or loss in forest area. Our SPA climate mitigation strategies that promote biomass for energy, subsidize forest carbon sequestration and tax deforestation start with RCP 6.0 for all but the SSP1 case, and increase in stringency to RCP 1.9. The RCP 1.9-SSP5 scenario produces the largest net increase in global forest area over the next century, up nearly 1,500 Mha. For context, this 37% increase on 2015 forest area is roughly equivalent to the current forest area in the Americas. Under this scenario, carbon prices are expected to reach $1,500/t$CO_2$ by 2080 and forest-based bioenergy demand more than 4.6 billion m^3 (about 30% of total projected energy supply) while global GDP increases from $10,000/capita in 2015 to about $140,000/capita in 2105.

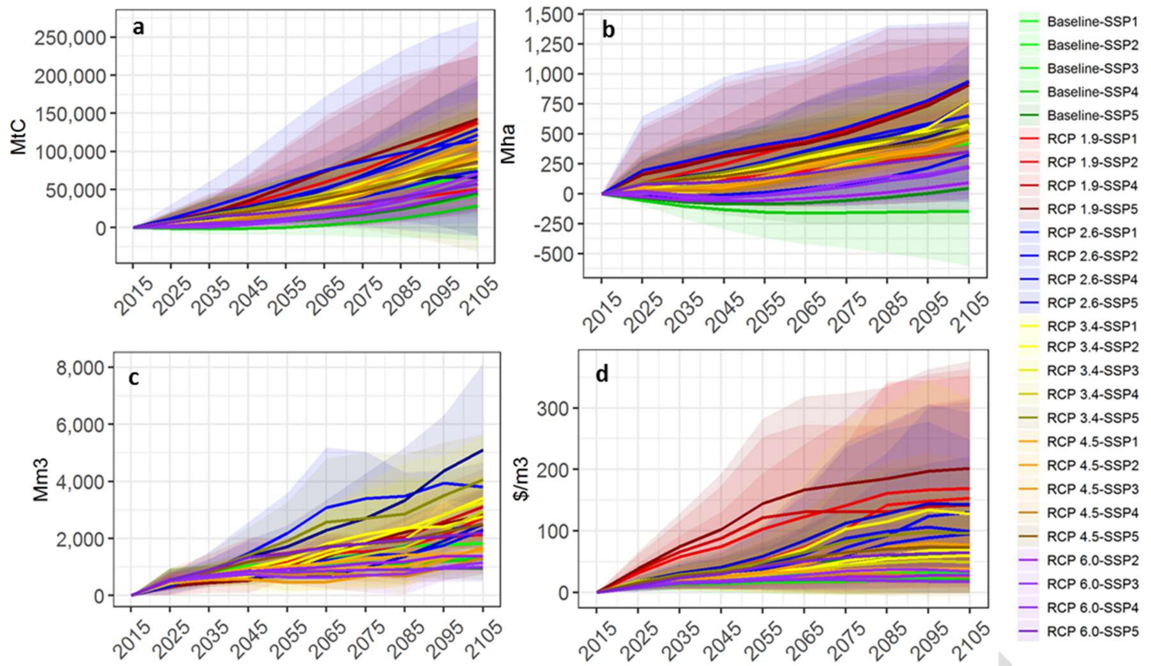

Figure 1. Global change in a) carbon stock (GtC), b) forest area (Mha), c) timber harvest (Mm3), and d) timber price ($/m3) from 2015 for all model SSP-RCP combinations. Lines indicate means, and shading shows upper and lower bound of individual model estimates.

Less stringent climate policy assumptions (i.e., higher RCP scenarios) in combination with lower income growth SSPs result in less afforestation overall. Out of the 81 runs, 12 (15%) show a possible decline in forest area. All these reductions occur under the baseline and/or the RCP 6.0 pathways, hence a combination of no to low climate policy initiatives and slower economic growth that fails to stimulate timber demand. Under the baseline-SSP3 scenario – which has the greatest forest loss – global forestland declines by an average of 144 Mha by 2105, or 3.6% below current forest area. Total forest area change by region is reported in Figure 2.

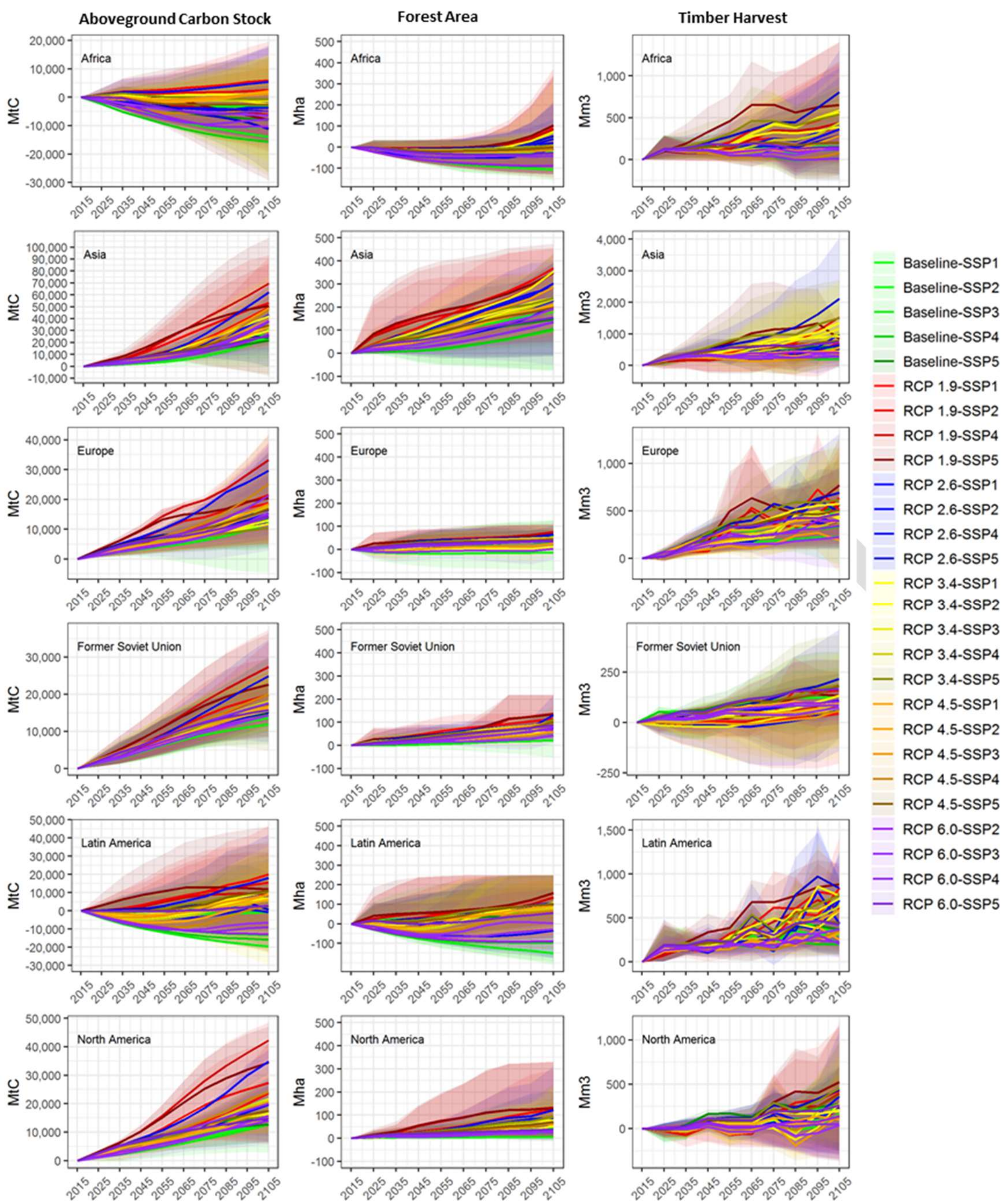

Figure 2. Regional change in aboveground carbon stock (GtC), forest area (Mha), and annual timber harvest (Mm3) from 2015 for all model SSP-RCP combinations. (scales vary per region)

3.2 Forest Carbon Stocks

The models project an increase in global forest carbon stocks in the future under 95% of the modeled scenarios, with an average gain of 87 GtC of forest carbon (30%) between 2015 and 2105, equivalent to 1.0 Gt/yr. Even most of the scenarios that show projected forest area loss project increased carbon stocks by 2100. The increased carbon storage is a function of afforestation, shifting harvest patterns, and management intensification. SSP4-RCP1.9 results in the largest increase in forest carbon, up 143 GtC from 2015 to 2105 (93%), or 1.6 GtC/yr. Only four model-scenario combinations result in losses of carbon stock over time: GTM's baseline-SSP3 and GFPM's SSP5-RCP 1.9, 2.6, and 3.4 scenarios. When averaging estimates across the three models, we find that the least optimistic scenario (Baseline-SSP3) still yields an additional 28.7 GtC (0.32 GtC/yr) by the end of the century, a 20% increase over current stocks.

Considering all model, RCP, and SSP combinations (n = 81), projected global forest carbon stocks increase by an average of 26.9 and 86.7 GtC (0.67 and 0.96 GtC/yr), respectively, by 2055 and 2105 relative to the 2015 base period (Figure 1b), an increase of 10% by 2055 and 30% by 2105. The rate of increase in carbon sequestration increases in the second half of the century from 0.7 Gt CO2 yr^{-1} to 1.2 Gt CO2 yr^{-1}. Regional forest C changes are relatively consistent with forest area change (Figure 2). The greatest variability in long-term carbon stock changes are in Latin America (-25 to 45 GtCO2e by 2105) and Asia (-5 to 105 GtCO2e) by 2105. We also project increased carbon accumulation in the temperate and boreal regions for most scenarios. Carbon accumulation in the temperate and boreal regions results from intensified management, planting more productive timber species, and improved silviculture on existing stands.

3.3 Timber Harvests and Prices.

Global timber harvests increase by 0.5 to 8.1 billion m^3/yr between 2015 and 2105 (Figure 1c). SSP population and income growth trajectories shift the demand for pulpwood and sawtimber while forest bioenergy demand increases with the level of climate policy ambition. Total demand growth between 2015 and 2105 is highest under SSP5 regardless of the RCP, ranging on average from a 2.1 billion m^3/yr increase under the baseline to a 5.1 billion m^3/yr increase for RCP 2.6 (Figure 3). Harvests consistently increase at lower rates for SSP4, with SSP3 following a similar trend for the base, RCP 6.0 and RCP 4.5 climate targets (1.0 – 1.6 billion m^3/yr increase by 2105). SSP1 sees harvests increase more in RCPs 1.9 – 3.4, up by 2.3 – 2.7 billion m^3/yr compared to 2015.

Total harvests are largest for RCPs with higher carbon prices and bioenergy requirements (RCPs 1.9-3.4), with industrial roundwood harvest levels being more consistent across RCPs, but not SSPs. This variability across SSPs highlights that socioeconomic conditions greatly affect industrial roundwood harvests, with biomass removals more heavily influenced by climate policy incentives and new market demand for wood-based bioenergy. Regionally, projected (median) harvests increase the most by 2105 in Latin America (440 Mm^3/yr), Europe (466 Mm^3/yr), and Asia (615 Mm^3/yr) (Figure 2). The increase in harvests are generally correlated with regional forest area expansion, particularly in the tropical regions of the globe.

Projected global timber prices, which are endogenous outcomes in each model, increase across all scenarios. Price changes are a byproduct of demand pressures, competition between timber production and preservation of existing natural forests for carbon sequestration, and long-term resource scarcity. Global timber prices are projected to increase between \$17/m^3 and \$198/m^3 over the next century (Figure 1d). Timber prices are highly correlated with harvest volume, particularly with the more stringent climate mitigation pathways that have large increases in wood biomass demand. Projected prices increase the most under SSP5, which includes high income growth which drives demand for forest products, ranging from a \$63/m^3 real increase over the next century for the baseline to a \$198/m^3 real increase for RCP 1.9. Prices increase the least for SSPs 1 and 4, increasing from \$21 to \$120/m^3 real increase by 2105, with the highest increases associated with the high biomass demand under the more stringent RCPs (2.6 and 1.9). The lower increases in timber prices for these scenarios are attributed to a combination of relatively low demand growth for both industrial roundwood and biomass.

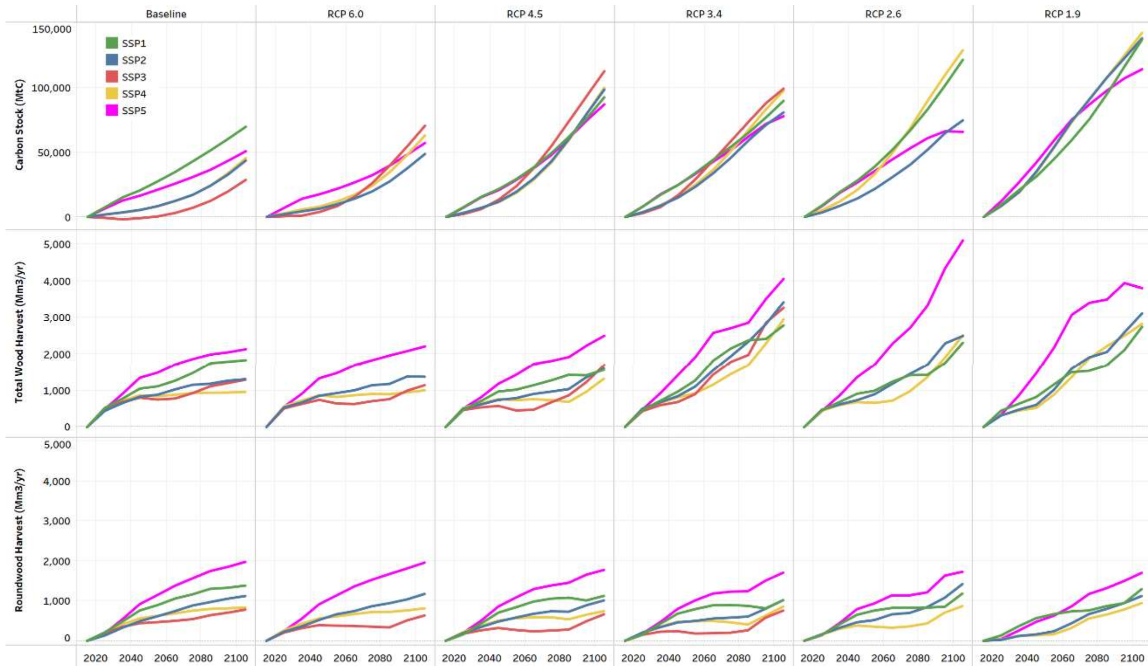

Figure 3. Mean change in a) global aboveground carbon stock (MtC), b) annual total wood harvest (Mm3), and c) annual industrial roundwood harvests (Mm3) from 2015 by RCP and SSP.

4. Discussion

Our multi-FSM assessment demonstrates how widely used socioeconomic and climate policy narratives and drivers can inform global forest sector projections of industrial wood harvests, timber prices, and forest carbon stocks. The models build upon decades of analysis in the forest sector that accounts for important economic and ecological features of this sector, including ecosystem function, dynamics, trade theory, forest management, and product heterogeneity and differentiation to name a few. With exception of a few cases, these features are not included in integrated assessment and bookkeeping models which could bias those estimates[42].

Overall, 95% of the scenarios indicate that forest C stocks will increase over the next 80 years. The finding that forest stocks will increase in the next century is robust across several conditions and drivers, including variation in model framework, economic growth, roundwood and biomass demand, and climate and land use policy (Figure 4). Changes in forest C stocks are positively correlated with changes in forest area and timber price, but less so with total wood and industrial roundwood harvests. Trends in harvesting patterns, and their effects on C stocks, show substantial variation across the model frameworks. For instance, higher total harvests result in lower carbon benefits for GFPM and the opposite for GTM. The difference is largely due to how these models incorporate forest management and account for future expectations. The analysis establishes the important role that harvesting and forest management play on the evolution of future forest stocks, which suggests that IAM analyses that do not account for these factors will incorrectly project future forest carbon flows.

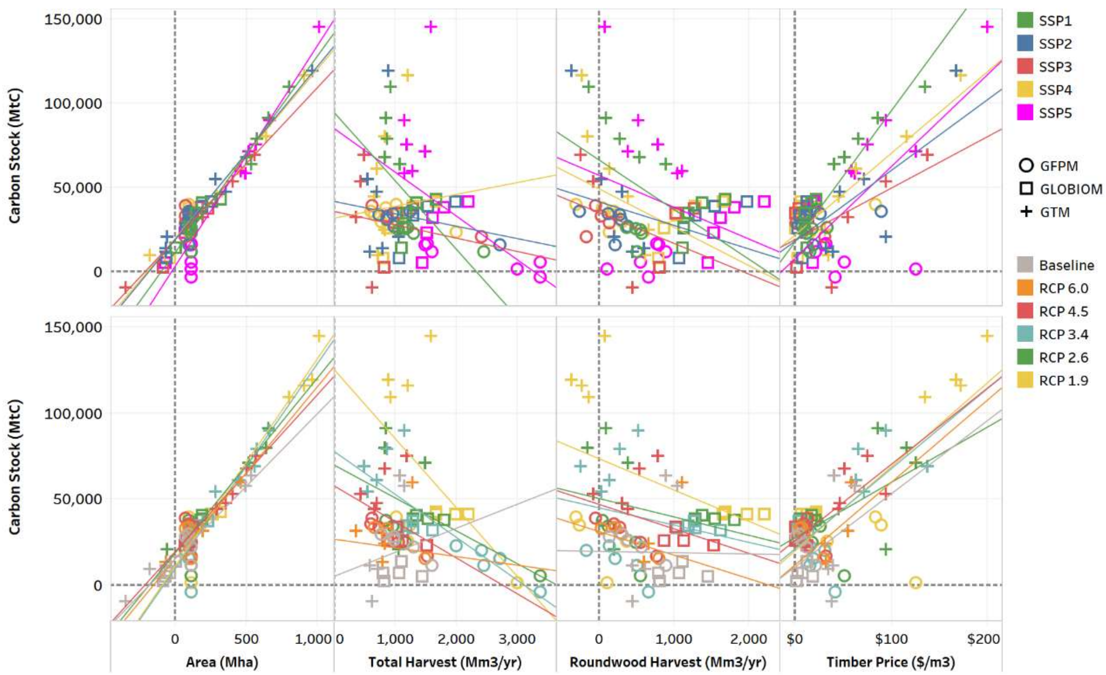

Figure 4. Change in global aboveground carbon stock (MtC) from 2015 relative to change in global forest area (Mha), annual wood harvest (Mm3) annual industrial roundwood harvests (Mm3) by RCP and SSP.

Our analysis builds on recent IAM assessments across SSPs and/or RCPs (e.g., 14, 39, 40) by explicitly representing forest management and harvest patterns on existing forests, timber markets, and carbon dynamics of forest harvest, growth, and management. Comparing our results to [15,43], we find similar variation across SSPs and the baseline, with expected loss in forest area under the lowest growth scenarios (e.g., SSP3). However, the FSMs show more forest expansion under high growth or sustainability focused SSPs, and greater variability in forest area across models. This cross-model variation reflects differences in assumptions such as income elasticities, treatment of time dynamics, market coverage, and other important attributes that influence intensive and extensive margin responsiveness to policy drivers. We show similar trajectories for forest area to the IAM assessments across RCPs, confirming the role of forest planting and avoided deforestation in achieving climate stabilization targets. The FSMs in this study place a large portion of newly planted land into managed forest uses, while the IAMs place nearly all of it into natural forests, where there no planned timber management or harvesting [4].

Our projected carbon stock changes range from 0.8–9.2 GtCO2e/yr across RCPs under SSP2 conditions through 2105 (Figure S4). Reported average emission reductions from land use, land use change, and forestry between 2010 and 2100 for SSP2 from [15,43] range from 5.1–9.2 GtCO2e/yr. The larger range in FSMs results from their more explicit modeling of forest sector ecology and management activities, including harvest, growth, regrowth, and management interventions. Further, FSMs reflect regional heterogeneity in forest types and age class structure, and changes in these attributes over time, coupled with harvest and regrowth dynamics are important components of the global forest carbon cycle. IAMs, as noted above, include nearly all the world's forests as unmanaged. Extensive and intensive margin interventions in the FSMs occur in response to both market and policy drivers. Forest investments under scenarios with high wood and/or carbon prices enhance forest carbon sequestration on existing forests, a result consistent with other studies [13,45–49]. It is critical for IAMs to develop more realistic representation of timber demand, forest management, and carbon dynamics on existing forestland to ensure that their modeling of interventions to increase forest carbon stocks are more soundly based on the biophysical and economic characteristics of the forest sector.

The broad findings of our study are generally aligned with other SSP-focused FSM assessments. With respect to changes in land area [27,50] estimated similar amounts of increases in global planted area as our study. Many FSMs estimated similar rankings of harvest volumes by SSP to our scenarios[29,35,51], including a threefold difference between the various SSPs, which is within the range of our global analysis[29]. Our projected increases in price changes for the RCP 1.9-3.4 scenarios – a strong driver of increased forest management and area – are similar to studies that also assume a large increase in the demand for bioenergy (33, 45). Similarly, studies indicate that timber prices could more than triple by the end of the century for SSP5 and increase slightly for SSP1 but remain relatively constant for the other pathways (37, 44).

Our study results offer important insights concerning climate policy design. Specifically, our projections can help policymakers prioritize regional forest planting, preservation, and management programs in climate mitigation strategies. Our use of economic models provides a more realistic assessment of forest sector mitigation potential that recognizes market opportunity costs of mitigation investments, which supports tradeoff analysis of different policy designs under alternative future socioeconomic conditions (see 12 for additional discussion).

We demonstrate key connections between forest product markets and long-term carbon storage, including the importance of complementary policies that could drive forest resource investment. Carbon accumulation and in most scenarios forest area are increased by higher timber prices (Figure 1d) due to timber demand (industrial wood and bioenergy), and carbon policy incentives. While simulated forest carbon stocks consistently increase over time, so do harvests, which increase an average of 1.1 bil m3 by 2055 and 2.4 bil m3 by 2105 (Figure 1c). This result suggests that it is possible to both increase forest harvest levels and forest carbon sequestration, and thus policies that incentivize forest carbon sequestration and those that stimulate demand for woody biomass for energy can be complementary [53,54].

5. Conclusion

We model a total of 81 future socioeconomic and climate policy scenarios across three FSMs to assess future forest climate mitigation investments and policy design. Our results demonstrate the importance of including detailed representation of the global forestry and forest market systems in mitigation analyses such as in integrated assessments of climate stabilization pathways to more accurately reflect forest market dynamics, forest management contributions to the terrestrial carbon cycle, and regional heterogeneity in forest types and policy responsiveness. Overall, we find a consistent positive trend in forest carbon stocks and timber supply through 2100, even in some scenarios with projected forest area loss, thereby highlighting the importance of carbon dynamics on existing forests and the potential gains that can be captured through forest management. In response, we suggest that future IAM-based climate policy assessments should better represent forest product markets and management dynamics, and that forest climate mitigation policies should be complemented by incentives to enhance demand for forest products and biomass.

There are several limitations of this analysis that will be addressed in subsequent research efforts. First, we do not directly address forest productivity changes under radiative forcing scenarios (e.g., 44, 46). Second, more coordinated analysis with the IAM community is needed to directly compare the forest-specific outcomes of mitigation policies and to offer explicit recommendations on how assessments of climate stabilization and deep decarbonization can better reflect the critical role of forests, including forest management in existing systems. Third, we do not explicitly account for the recent trends in wildfire and pest outbreaks, which could diminish forest health and carbon stocks. Finally, there are several national- and subnational-scale modeling tools with spatially detailed representations of forestry systems that we do not represent in this assessment. Subsequent analyses will focus on regional comparison efforts and improving methods for downscaling global narratives and forest sector projections to local scales.

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Supplementary Material for:

How the future of the global forest sink depends on timber demand, forest management, and carbon policies

1. Forest sector shared socioeconomic pathways

Global level SSPs specify five distinct pathways for the development of socioeconomic futures as they might unfold in absence of any explicit measures or policies to limit climate change or enhance adaptive capacity (Riahi et al., 2017; O'Neill et al., 2017). While the specific pathways are relatively new, the concept of developing a set of alternative futures has informed global environmental assessments for decades (see Meadows et al., 1972, Gallopin et al., 1997; Nakicenovich et al., 2000). Furthermore, although the SSPs are primarily intended to enable climate change-focused research and policy analysis, the broad perspective and set of indicators mean that they can also be used for non-climate related scenarios such as economic and/or sustainable development (O'Neill et al 2014).

The pathways range from a 'sustainable' world that is highly adaptive and faces relatively low socio-economic challenges (SSP1) to one that is fragmented with relatively weak global institutions and faces high population growth (SSP3). SSP4 assumes that there will be increasing inequality in global development, while SSP5 features rapid development that is driven by fossil fuels and technological change. A fifth narrative (SSP2) describes moderate challenges of both adaptation and mitigation with the intent to describe a future pathway where development trends are not extreme in any dimension and hence follow a middle-of-the road pathway relative to the other SSPs and it is often referred to as the 'business as usual' pathway because many indicators closely follow historical trends.

This paper builds off of specific aspects of the five global SSP narratives published in the literature (e.g., O'Neill et al 2014, Ebi et al 2014, O'Neill et al 2017), by expanding on how the global forest sector could be affected by each pathway (Daigneault et al., 2019). The elements that are important to the sector include economic and population growth, international trade, technological change, product demand, land use regulations, and forest management intensity and are assumed to vary across each SSP (Table S1). To isolate the socio-economic impacts from climate policy, this study uses only the baseline cases for all the SSPs; that is, SSPs scenarios without a climate mitigation policy implemented.

Several components of the SSP-RCP scenarios are implemented in each forest sector model as exogenous parameters (Table S2). Most of the SSP-RCP scenario parameters are taken from SSP-database, which is publicly available through IIASA (Riahi et al., 2017). The core SSP scenario parameters included in each model are global population and GDP (Figure S1). The core RCP parameters include total bioenergy demand and carbon prices (Figure S2).

Total bioenergy is derived from a mix of woody biomass, other biomass and energy crops. Other biomass consists of agricultural residues and waste. affects forest sector by increasing woody biomass use for energy. As such, global woody biomass demand was derived from total bioenergy demand following methods in Lauri et al. (2019), using the MESSAGE-GLOBIOM model. Energy crops are woody or non-woody biomass that is grown in dedicated energy crops plantations. [1] Total bioenergy demand is measured in terms of primary energy. Volumes of biomass are converted to energy units using factor 1 GJ=7.2 m^3 based on average density of 0.45 m^3/t and heating value 16 GJ/t (Lauri et al. 2014). Modern bioenergy consists of forest industry by-products (bark, sawdust, woodchips, black liquor, recycled wood) [2], logging residues and roundwood. All models in this analysis were calibrated to follow the respective woody biomass demand schedules for each SSP-RCP combination.

2. ForMIP Model Descriptions

2.1 Global Timber Model

This analysis uses a variant of the Global Timber Model (GTM), a dynamic optimization forest management model originally developed by Sedjo and Lyon (1990) and subsequently was updated by Sohngen et al., (1999), Daigneault et al (2012), Favero et al., (2017), and Tian et al (2018). The model relies on forward-looking behavior and solves all time periods at the same time. This "dynamic optimization" approach means that when landowners make decisions today about forest management, they do so by considering the implications of their actions today on forests in the future. For example, when forests are regenerated, the amount of money spent regenerating forests is determined consistent with future expectations about timber prices. In addition, when forests are harvested, forestland owners consider the marginal benefits and costs of waiting additional periods to harvest their trees.

In this model, sawtimber and pulpwood are drawn from the same forest resource base, which is allocated to either product after harvest. Forest resources are differentiated in several different ways, either by ecological productivity or by management and cost characteristics. To account for differences in ecological productivity, different land classes in different regions of the world will have different yield functions for timber. Data inputs used to differentiate forests by productivity are discussed below.

Furthermore, forests are broken into different types of management classes. One type is moderately valued forests (denoted by the subscript "i" below). These forests are managed in rotations and located primarily in temperate regions. A second type of management is inaccessible forest, located in regions that are costly to access. These types are denoted by the subscript "j" below. A third type is low-value forests that are lightly managed, if they are managed at all. These types are denoted by the subscript "k" in the temperate and boreal zones. These low-value lands in temperate and boreal zones are linked to inaccessible types directly, such that when inaccessible forests are harvested in boreal and temperate zones they are converted to semi-accessible forests, that is, when

[1] First generation biofuels (food crops) are considered as agricultural residues and included in other biomass instead of energy crops.
[2] Recycled wood is not forest industry by-product. It is included to by-products for simplicity.

harvested, types in “j” convert to “k.” Inaccessible forests are harvested only when the value of accessing the land exceeds the marginal access costs.

A fourth type of forests includes low-value timberland in inaccessible (“l”) and semi-accessible (“m”) regions of the tropical zones. Inaccessible forests in this class are harvested only when the value of accessing the land exceeds the marginal access costs. They may be converted to agriculture or returned to forestry after harvesting, depending on the opportunity costs of land and the value of future timber harvests. If the lands return to forestry, they do so in a type in m that corresponds to a similar ecological productivity level in l. The key difference between the conversions of land from inaccessible to accessible but low-value land in the temperate/boreal zones and the tropics is that lands in the temperate/boreal regions are assumed to have no opportunity costs so they remain in forestry. In contrast, opportunity costs may be greater than 0 in the tropics and inaccessible or low-value accessible lands may convert to agriculture now or in the future.

A final type is the high-valued timber plantation (“n”) type that is managed intensively. These high-value forest types can be located anywhere in the world, but at present they are principally found in subtropical regions of the United States (e.g., loblolly pine plantations), South America, southern Africa, the Iberian Peninsula, Indonesia, and Oceania including Australia and New Zealand. There are numerous types of fast-growing plantations globally with various rotation ages. Southern pines in the United States have rotation ages of approximately 30 years, while pines in other parts of the world (South America, Central America, Australia, South Africa) have rotation ages of 20 years. Eucalypts have rotation ages of around 10 years. Douglas fir has a longer rotation age, of 40 years, and teak plantations have rotations of 50 or so years. The new dedicated bioenergy plantation types in the United States are placed in this category because they are assumed to be managed similarly in 10-year rotation ages.

The model maximizes total welfare in timber markets over time across approximately 350 world timber supply regions by managing forest stand ages, compositions, management intensity, and acreage given production and land rental costs over 200 years. The supply side of the model consists of forestland with various biological yield rates that can be modified by changes in investment and management levels as well as land use changes. Superimposed on this system is a demand side that anticipates changes in demand levels for industrial sawtimber, pulpwood, and biomass though time, primarily through exogenous changes in population, per capita income, consumer preferences for wood products, and technology. The timber supply model involves the incorporation of a forward-looking forest management projections approach that is used increasingly in forestry (e.g., Sohngen et al., 1999; Adams et al., 1996). The model uses a discrete time, nonlinear, optimization approach to maximize the net present value of net surplus in timber markets.

The model’s optimization problem is formally written as:

$$max \sum_0^\infty \rho^t \left\{ \begin{array}{c} \int_0^{Q_{t,SSP}^{tot}} \left\{ D\left(Q_{t,SSP}^{ind}, Z_{t,SSP}\right) + D\left(Q_{t,SSP}^{wbio}\right) - C_{H,SSP}^i \left(Q_{t,SSP}^{tot}\right) \right\} dQ_{t,SSP}^{tot} - \\ \sum_i C_{G,SSP}^i\left(m_t^i, G_t^i\right) - \sum_i C_{N,SSP}^i\left(m_{t,SSP}^i, N_t^i\right) - \sum_i R_{t,SSP}^i\left(\sum_a X_{a,t}^{i,j,k}\right) \end{array} \right\} \quad \textbf{(S1)}$$

$$Q_{t,SSP}^{tot} = Q_{t,SSP}^{ind} + Q_{t,SSP}^{wbio} \quad \textbf{(S2)}$$

$$\boldsymbol{Q^{ind}_{t,SSP} = \pi^{pulp}_{SSP} Q^{ind}_{t,SSP} + \pi^{saw}_{SSP} Q^{ind}_{t,SSP}} \quad \textbf{(S3)}$$
$$\boldsymbol{Q^{wbio}_{t,SSP} = \pi^{wbio}_{SSP} Q^{bio}_{t,SSP}} \quad \textbf{(S4)}$$

where ρ^t is a discount factor, $D\left(Q^{ind}_{t,SSP}, Z_{t,SSP}\right)$ is a global demand function for industrial wood products given the quantity of wood $Q^{ind}_{t,SSP}$ and average global consumption per capita $Z_{t,SSP}$ for each *SSP*, $Q^{wbio}_{t,SSP}$ is the woody biomass demand for bioenergy production, C^i_H is the cost of harvesting and transporting timber to the mill.

Total supply is affected by several management and land costs: where C^i_G is the cost of managing G_t hectares of forest type *i* (e.g., plantation, regenerating, natural), at varying intensities *m*, C^i_N is the cost of new forestland *N* at time *t*, and $R^i_t\left(\sum_a X^i_{a,t}\right)$ is the opportunity cost of land area *X* in age class *a* at time *t*. The objective function in Eq. 1 is nonlinear, and the model assumes that management intensity is determined at the moment of planting, and planting costs vary depending upon management intensity.

Timber demand follows the functional form $Q^{ind}_{wood,t,SSP} = A_t\left(Z_{t,SSP}\right)^{\theta} P^{\omega}_{wood,t}$, where A_t is a constant, θ is income elasticity, $P_{wood,t}$ is the timber price, ω is price elasticity, and *wood* represents the type of roundwood demanded (sawtimber or pulpwood). The global demand function is for industrial roundwood, which is itself an input into products like lumber, paper, plywood, and other manufactured wood products. Total industrial demand incorporates separate demand functions for sawtimber and pulpwood. Each log harvested in the model is used proportionally in the supply of wood to sawtimber or pulpwood markets, though the proportions change endogenously over time. Demand for woody bioenergy production $Q^{wbio}_{t,SSP}$ is estimated by adjusting the total bioenergy consumption in the IIASA SSP database (Riahi et al., 2017) with the proportion of global biomass energy produced from wood by following similar assumptions in Lauri et al., (2017). Moreover, we assume different preferences for different wood products (π) according to the SSP. For example, the sustainable SSP1 scenario is likely to favor more durable timber products (sawtimber) and more sustainable bioenergy feedstocks (woody biomass) than the other SSPs. Table 2 describes the values assumed for each parameter and each SSP in the study.

GTM assumes there is an international market for timber that leads to a global market clearing price. As the price of wood for bioenergy rises to compete with industrial timber, both timber and bioenergy are traded internationally (Favero and Massetti 2014). Competition for supply equilibrates their prices.

The assumptions of each SSP impacts both the demand and supply of forest products. In particular, input costs and the rates of technological change for forest management, harvesting, and timber processing change to be in line with the future socio-economic scenarios. To account for these effects, we vary the model parameters for management intensity, forest management costs, agricultural land rental functions, and rates of technological change for harvesting and processing timber products:

$$\boldsymbol{Q^{tot}_{t,SSP} = \sum_i\left(\sum_a H^i_{a,t} V^i_{a,t}\left(\varphi^i_t, m^i_{t0,SSP}\right)\right)} \quad \textbf{(S5)}$$

where the total quantity of wood depends upon the area of each age class a harvested $H_{a,t}^{i}$ in a given period and the yield function $V_{a,t}^{i}$, which is itself a function of ecological forest productivity $\varphi_{t}^{i}$and management intensity $m_{t0,SSP}^{i}$. Moreover, the intensity of management is chosen at the time stands are established (t_0) and continues with the stand throughout its life. The management intensity for each SSP incorporates different assumptions.

The cost functions for harvesting and transporting roundwood and forest residues, $C_{H,SSP}^{i}$, are structured such that marginal costs generally increase with volume supplied to the mill or plant. Costs of managing forests, $C_{G,SSP}^{i}$, also follow a similar functional form. Both of these respective costs are assumed to vary by SSP ($\gamma_{t,SSP}^{i}$, $\beta_{t,SSP}^{i}$) to reflect differences in technology and efficiency over the different pathways.

Competition of land for crop and livestock is represented in the model using a land rental approach (Kim et al., 2018). The rental supply function is restricted to agricultural land that is naturally suitable for forests. It presumes that crop and pasture land with the lowest marginal value (or economic rents) and the ability to grow forests will be converted first and that rental rates increase as more land is converted and thus becomes scarcer. We adjust the scale of the regional rental supply functions ($\alpha_{t,SSP}^{i}$) for each SSP to reflect the relative change in demand for agricultural land under the different SSPs. For example, SSP1 (sustainability) is assumed to have strict environmental and land use policies and thus would place a relatively high value on maintaining or even increasing both managed and naturally regenerating forest area. The same pathway is also expected to have high technological change across all sectors of the economy, including food production. These two factors will result in a relatively low opportunity cost for agriculture across the globe. On the contrary, SSP3 (divided) will have the opposite effect due to high population growth, low technological change, and limited land use policies.

The key components and parameters specific to GTM that are modified to represent the five SSPs are summarized in Table S3, with other assumptions listed in Table S2. The primarily demand-side components include GDP per capita, wood product preferences, and share of total bioenergy from wood. Major supply-side influences include forest management, harvest, processing costs, and shifts in annual agricultural land rents. We also adjust the forest management intensity response parameter (i.e., biomass yield increases from investment), which is used to represent technological change.

2.2 Global Forest Products Model (GFPM)

The GFPM is a recursive dynamic forest sector model that tracks 14 wood product groups across 180 individual countries. The model is calibrated to the most recent data reported by FAOSTAT by estimating input-output coefficients, and costs associated with manufacturing transportation - the GFPM solution for 2015 closely replicated the observations for the same year on production, consumption, prices, and net trade according to FAOSTAT. The GFPM is solved by calculating successive yearly market equilibriums by maximizing a quasi-welfare function, as given by the sum of consumer and producer surpluses net of transaction costs:

$$Z=\sum_{ik}\int_0^{D_{ik}} P_{ik}(D_{ik})\,dD_{ik} - \sum_{ik}\int_0^{S_{ik}} P_{ik}(S_{ik})\,dS_{ik} - \sum_{ik}\int_0^{Y_{ik}} m_{ik}(y_{ik})\,dY_{ik} - \sum_{ijk} c_{ijk}T_{ijk}$$

(S6)

where *i* and *j* refer to countries, with *k* wood product markets of price *P* as determined through end product demand *D* and wood supply *S*. The manufactured quantity of wood is denoted by *Y* at marginal cost *m*, and the quantity traded *T* at transaction cost (including tariffs) *c*. In other words, the first portion of equation (S6) is the area under the demand curve for consuming end products, while the second and third components measure the cost of production and manufacturing respectively. Finally, the last portion of equation (S6) measures the total cost of shipments. The model computes the market equilibrium subject to a number of economic and biophysical constraints, including a market clearing condition which states the sum of imports, production, and manufactured supply of a given product in a given country must equal the sum of end product consumption, exports and demand for inputs in downstream manufacturing:

$$\sum_j T_{jik} + S_{ik} + Y_{ik} = D_{ik} + \sum_n a_{ikn}Y_{in} + \sum_j T_{ijk}, \quad \text{(S7)}$$

where a_{ikn} is the input of upstream product *k* required in the manufacture of a given unit of downstream product *n*. Changes in resource efficiency are operationalized through changes in the input-output coefficients, and evolve exogenous over time according to:

$$a_{ikn,t} = a_{ikn,t-1}(1-\eta_{ikn,t}) \quad \text{(S8)}$$

where $\Delta a_{ikn,t}$ is the periodic rate of change in input-output coefficient.
The demand in country *i* for final product *k* is assumed to follow a constant elasticity of substitution:

$$D_{ik,t} = D^*_{ik,t}\left(\frac{P_{ik,t}}{P_{ik,t-1}}\right)^{\delta_{ik}} \quad \text{(S9)}$$

where $P_{ik,t-1}$:; is last periods price, δ"ik is the price elasticity of demand for product *k* in region *i*, and current consumption at last periods price is given by:

$$D^*_{ik,t} = D_{ik,t-1}(1+\alpha_{iy}g_{iy,t}+\alpha_{i0}) \quad \text{(S10)}$$

which is a function of last periods demand, the growth rate of GDP at time *t*, g"I,9, the elasticity of demand with respect to GDP, α_{iy}, and a period trend, α_{i0}.

The cost of shipping product *k* from region *i* to region *j* in any given year is assumed to be a constant elasticity of substitution form:

$$c_{ijk,t} = c^*_{ijk,t}\left(\frac{T_{ik,t}}{T_{ik,t-1}}\right)^{\tau_{ik}} \quad \text{(S11)}$$

where $T_{ik,t-1}$ is last periods quantity traded, and τ_{ik} is the elasticity of transport costs with respect to quantity traded. The base period transaction cost $c_{ijk,t}$ is calibrated to estimated freight costs, observed export taxes and import ad-valorem tariffs, and endogenously determined product prices.

Supply is also described through a constant elasticity of substitution supply curve:

$$S_{ik,t} = S^*_{ik,t}\left(\frac{P_{ik,t}}{P_{ik,t-1}}\right)^{\lambda_{ik}}, \quad \text{(S12)}$$

where λ_{ik} is the price elasticity of supply for product *k* in region *i*, and current production at last periods price is given by:

$$S^*_{ik,t} = S_{ik,t-1}(1 + \beta_{iI} g^I_{it} + \beta_{ia} g^a_{it}), \quad \text{(S13)}$$

where $g^I_{,it}$ is the periodic rate of change of forest stock in region *i* at time *t*, $g^a_{,it}$ is the periodic rate of change of forest area, and β′*s* indicated respective elasticities.

Land use change enters the model through changes to forest area; assumed to be a function of evolving demographics and economic growth. An environmental Kuznets curve (EKC) relationship associates changes in income per capita (Y/N) to the forest area annual growth rate, $g^a_{,it}$:

$$g^a_{it} = (\alpha_{i0} + \alpha_1 (Y/N)_{it}) e^{\alpha_2 (Y/N)_{it}}.\ \alpha_1>0 \text{ and } \alpha_2<0. \quad \text{(S14)}$$

With parameter estimates of α_1, and α_2 estimated from historical data, and α_{i0} calibrated such that in the base year (2015) equation (S9) predicted the observed forest area growth rate, $g^a_{,it}$, given the observed level of income per capita, $(Y/N)_{it}$. Equation (S9) predicts negative growth rates of forest area for low income countries, which increase and become positive at higher income, and decrease progressively to zero at the highest income levels. The annual rate of change of biomass stock due to tree growth and mortality is inversely related to the forest density (residual stock level, S_{it}, per unit area, A_{it}).

SSP-RCP specific scenarios were modeled using a range of parameter assumptions, including changes in global GDP and population growth, international trade participation, resource efficiency, and wood-based bioenergy demand (Table S2). Region-specific land-use change for the different SSPs were modeled as a function of evolving demographics and economic growth represented through the EKC.

More detailed information on the model structure is provided in Buongiorno et al., (2003), including the formulations of constraints related to trade inertia, prices, manufacturing costs, transport costs, market dynamics, linear approximations of certain constraints, and annual allowable cut constraints.

2.3 Global Biosphere Model (GLOBIOM)

Global Biosphere Management Model (GLOBIOM) is a global spatially-explicit agricultural and forest sector model (Havlik et al. 2011, 2014). The forest sector representation includes forestry, forest industry and bioenergy modules (Lauri et al. 2014, 2017, 2019). The supply side of the model is solved in 0.5°-2° grid resolution while the demand and trade modelling is based on economic regions.

The model is solved recursively using biophysical data from Global Forest Model (G4M) (Kindermann et al. 2006, 2008, Gusti and Kindermann 2011) and Environmental Policy Integrated Climate Model (EPIC) (Williams 1995). Biophysical data from G4M includes biomass stocks and harvest potentials for each land use unit. Harvest potential is divided to different feedstocks (sawlogs, pulpwood, harvest loss, logging residues). G4M solves harvest potentials for GLOBIOM by assuming that all forest are normal forests. Normal forests have a uniform distribution of age-classes and in each period the oldest age-class is removed by harvesting or mortality. This is convenient from GLOBIOM recursive optimization perspective, because in normal forests harvest potentials are independent of harvest volumes and stay constant over time. Alternatively, G4M could solve harvest potential for GLOBIOM by actual age-class distribution of forests.

The model includes three forest types (primary forests, secondary forests, managed forests) and four forest management types (low intensity C/NC, high intensity C/NC). In addition to this, it is possible to exclude protected areas from production use and allocated them to primary or secondary forests. Primary forests are forestland that has not been used historically for production. Managed forests are forest land that is actively used for production while secondary forests are abandoned managed forests. Harvest volumes can be increased by increasing managed forest area (converting secondary and primary forests to managed forests) and by intensifying forest management (converting low intensity management to high intensity management).

The initial areas for different forest types are calibrated to match FRA (2020) country level data so that primary forests=FRA primary forests, managed forests =FRA production forests and secondary forests=FRA total forests-primary forests-production forests. Initial managed forest areas are allocated to low and high intensity management by using FRA planted forest data (FRA 2020) and FAOSTAT roundwood harvests data (FAO 2020). FRA planted forests are used as lower bound for high intensity management. The transition between different forest and management types is controlled by non-linear transition costs and transition constraints. Total forest area development over time is based on the SSP scenario data (IIASA 2020). Afforested areas are included into secondary forests and are not harvested under the policy assumption that these lands are planted for carbon stock preservation.

The spatial allocation of different forest and management types is based on the economic optimization, i.e., the model chooses optimal allocation of forest and management types by maximizing economic surplus given the spatially-explicit biophysical data from G4M, the country level area data from FRA and the country level biomass production data from FAOSTAT. The economic optimization typically allocates high intensity management to the most productive and easily accessible forest areas while low intensity management, primary forests and secondary forests are allocated to less productive and remote forest areas. On average, this leads a close match with the actual locations of different forest and management types. The outcome of the economic optimization can be visually assessed by using additional data on forest area use such as Nature Map Explorer (IIASA 2020b) and Word Database on Protected Areas (WDPA 2020).

The biomass demand for modern bioenergy is based on the SSP-RCP scenario data (IIASA 2020). The biomass demand for traditional bioenergy and material products are based on FAOSTAT data (FAO 2020) and shifted over time by SSP-specific GDP and population growth (IIASA 2020). Income and price elasticities for traditional bioenergy and material products are based on historical estimates, similar to Buongiorno et al. (2003) and Morland et al. (2018). Forest products bilateral trade volumes are calibrated to the BACI (Base pour I'analyse du commerce international) bilateral trade data (Gaulier and Zignago 2010) and FAOSTAT data (FAO 2020). Bilateral trade costs are based on constant elasticity functions, which are parametrized by reference volumes and costs. The trade of feedstocks and by-products is assumed to be less elastic than the trade of final products.

The forestry module includes 9 harvested products (C/NC pulpwood, C/NC sawlogs, C/NC other industrial roundwood, C/NC fuelwood, logging residues). The forest industry module includes 4 paper grades (newsprint, printing and writing papers, packaging materials, other papers), 6 pulp grades (C/NC chemical pulp, C/NC mechanical pulp, recycled pulp, other fiber pulp), 6 mechanical forest industry products (C/NC sawnwood, C/NC plywood, C/NC fiberboard), 6 forest industry by-products (C/NC woodchips, C/NC sawdust, bark, black liquor) and 2 recycled products (recycled paper, recycled wood). The bioenergy module includes 2 final products (traditional bioenergy, modern bioenergy) and one intermediate product (wood pellets).

The model's optimization problem for forest sector is formally written as:

$$\underset{x_{ik},y_{if},y_{iho},e_{ijk},z_{imno},I_{if}}{Max} W = \sum_{ik}\int_0^{x_{ik}} D_{ik}(x_{ik})\mathrm{d}x_{ik} - \sum_{iho} c_{iho}^{tran} y_{iho} - \sum_{iho} c_{iho}^{harv} y_{iho} - \sum_{if} c_{if}^{proc} y_{if}$$

$$- \sum_{if} c_{if}^{inv} I_{if} - \sum_{ijk}\int_0^{e_{ijk}} C_{ijk}^{trade}(e_{ijk}) de_{ijk} - \sum_{imn}\int_0^{z_{imn}} C_{imn}^{luc}(\sum_{o} z_{imno}) dz_{imn}$$

(S15)

subject to

$$x_{ik} - \sum_{f} a_{ifk} y_{if} - \sum_{ho} a_{ihk} y_{iho} - \sum_{j} (e_{ijk} - e_{jik}) \leq 0 \qquad \forall\ i,k \qquad \text{(S16)}$$

$$y_{iro} \leq \sum_{m} b_{irmo} L_{rmo} \qquad \forall\ i,r,o \qquad \text{(S17)}$$

$$y_{ilo} \leq \sum_{r} \phi_{irlo} d_{irlo} y_{iro} \qquad \forall\ i,l,o \qquad \text{(S18)}$$

$$y_{if} \leq K_{if} \qquad \forall\ i,f \qquad \text{(S19)}$$

$$K_{tif} = (1-\delta) K_{(t-1)if} + I_{tif} \qquad \forall\ i,f,t \qquad \text{(S20)}$$

$$L_{timo} = L_{(t-1)imo} + \sum_{n} z_{tinmo} - \sum_{n} z_{timno} \qquad \forall\ i,m,o,t \qquad \text{(S21)}$$

$$L_{imo} \leq \bar{L}_{imo} \qquad \forall\ i,m,o \qquad \text{(S22a)}$$

$$L_{imo} \geq \bar{L}_{imo} \qquad \forall\ i,m,o \qquad \text{(S22b)}$$

$$y_{if} \leq \sum_{k} \phi_{ifk} x_{ik} \qquad \forall\ i,f \qquad \text{(S23)}$$

where

i, j =economic regions
k= product
f=forest industry production activity
h=harvest activity
r=roundwood harvest activity ($r \subset h$)
l=logging residues harvest activity ($l \subset h$)
m,n= land-use/management types
o=land-use unit
t=time (not used if same for all variables of the equation)
W=welfare
x=consumption quantity
y=production quantity
e=trade quantity
z=area of land-use change

K=capacity
I=investments
L=land area
c^{tran} *= transport costs*
c^{proc} *= process costs*
c^{harv} *= harvest costs*
c^{inv} *= investment costs*
δ*=depreciation rate*
a=input-output coefficient
b=increment per area
d=biomass expansion factor
ϕ*=recovery ratio*
D(x) = inverse demand function
$C^{trade}(e)$ *= trade cost function*
$C^{luc}(z)$*=land-use change cost function*

Equation (S15) is the sum of consumers' and producers' surpluses. The first term of equation (S15) is the area underneath the demand curve, which represents the value of final products consumption to the consumers. The remaining terms of equation (S15) are the areas underneath the marginal cost curves, which represent the compensations paid to the producers. The second term is the transport costs of woody biomass from forest to the mill gate within each region. The third term is the harvest costs of woody biomass. The fourth term is the process costs of woody biomass. The fifth term is the investment costs. The sixth term is the trade costs between the regions. The last term is the land-use change costs. Transport, harvest and land-use change costs are spatially-explicit, i.e., they are indexed with regions i and land-use units o. Process, investment and trade costs are not spatially-explicit, i.e., they are indexed with regions i (in case of trade costs or with import region i and export region j).

Equation (S16) is the material balance. It guarantees that products are not consumed or used as inputs in the production activities more than they are produced and traded. A production activity f uses product k as input if $a_{ifk}<0$ and produces product k as output if $a_{ifk}>0$. A harvest activity h produces just outputs, i.e., $a_{ihk}>0$.

Equations (S17) and (S18) determine the relationship between primary woody biomass supply and forest resources. Equation (S17) is the roundwood harvest constraint. This equation ensures that roundwood harvests volumes do not exceed their harvest potential for each land-use unit. The harvest potential is based on the increment and forest area data from G4M. Different forest managements are implemented in the model by assuming that harvest activities, i.e., managements, have different increments and feasible forest areas. Primary and secondary forests are not harvested, which is implemented in the model by assuming that these forest types have zero increments.

Equation (S18) is the logging residues harvest constraint. This equation connects logging residues harvest volumes to roundwood harvest volumes and limits logging residues extraction to some share of their total volume in each land-use unit. The total volume of logging residues is based on the biomass expansion factors while the share of logging residues that is allowed to be extracted on recovery ratio (Lauri et al. 2014). In the current version of the model the recovery ratio of logging residues is assumed to be 0.5 for all managements with positive increments. However, the recovery ratio of logging residues could be adapted according to management intensity and land-use units side conditions.

Equations (S19) and (S20) determine the relationship between production technologies and capital stock. Equation (S19) is the capacity constraint. Equation (S20) is capital accumulation constraint. Investments are undertaken as long as income of increasing capital stock is higher than the investment costs within each period. In the current version of the model the depreciation rate is assumed to be 0.3 in 10-year period and is same for all final products.

Equation (S21) is the land-use balance. Forestland decreases due to deforestation, i.e., changing forestland to cropland or grassland, and increases due to afforestation, i.e., changing cropland, grassland or other natural vegetation land to forestland. For sustainability reasons forestland is not allowed to be changed energy crops plantations. Within the forestland there are three forest types: primary forests, secondary forests and managed forests. For managed forests, the model chooses low intensity or high intensity management. If forest land is never used for biomass production, then it is allocated to primary forests. If the forestland is used for biomass production, then it is allocated to managed forest. If forest land is not actively use for production but has been disturbed by human activities, then it is allocated to secondary forests.

Equations (S22a) and (S22b) are additional spatially-explicit data, which is included to model to improve the outcome of economic optimization. The economic optimization typically allocates high intensity management to the most productive and easily accessible forest areas while low intensity management, primary forests and secondary forests are allocated to less productive and remote forest areas. On average, this leads a reasonably good match with the actual locations of different forest and management types, but in single cases it might fail due to additional institutional reasons to choose alternative locations.

Equation (S23) limits recycled paper supply to a certain fraction of paper and board consumption and recycled wood supply to a certain fraction of sawnwood, plywood and fiberboard consumption.

The one period social welfare maximization problem (S15)-(S23) is first calibrated and solved for the base years 2000-2020. Then it is solved repeatedly for the desired number of periods by assuming some exogenous or model history dependent changes in the state variables. The model period is 10 years. Because most of input data is annual data, the state variables of the model are adapted to correspond to one-year periods. Because the model is solved as a social welfare maximization problem, the objective function does not include any market prices or market clearing mechanism. Market prices for products k are obtained from the shadow prices of the material balance. From programming perspective, the model is solved using the GAMS programming language and linear programming. Non-linear functions are linearized by using the piecewise-linear approximation.

The key components of GLOBIOM that are modified to represent the five SSPs are summarized in Table S2. Contrary to GTM, the effect of SSP scenarios is restricted to factors that are quantitatively documented in the SSP database (economic growth, population growth, bioenergy demand, and carbon prices).

3. Additional Results

3.1 Model Specific Estimates & Comparison

Each forestry model used for this analysis has some specific parameters and assumptions (Tables S2-S4, Figure S5) likely to affect the results (Figure 4, Figures S3). Even with consistency in the response to socio-economic and policy scenarios, the magnitude of the responses and their timing can differ given the model structure and underlining parameters on technological change, land rents, and elasticity of the demand (Figure S5). For example, GTM is much more responsive to future expected demand and climate policy conditions than GLOBIOM and GFPM because of its forward-looking nature and ability to endogenously manage existing forests for improved productivity. Thus, forest area and land use responses are variable in GTM simulations (Figure S3), and the model's management response to market changes results in greater carbon gains than the other models included in this assessment. In contrast, GLOBIOM is a recursive dynamic framework, so simulation outputs are less responsive decade-by-decade, as there is no anticipation of future market conditions or policy incentives. Management decisions thus reflect changes in contemporary market conditions and are not driven by expectations of future demand growth and returns to forestry. As a result, intensive margin investments and associated carbon gains are smaller for GLOBIOM than for GTM. GLOBIOM is the only framework in this study that explicitly models agricultural land use and production possibilities in addition to forestry, and thus directly captures multi-sector trade-offs of mitigation investments and increased demand for woody biomass. GLOBIOM results are hence more consistent across scenarios. GFPM - also a recursive dynamic framework - shows similar results to GLOBIOM for forest area and carbon stock changes, but projected harvests are highly variable. This outcome occurs largely because GFPM demand growth for a wide range of forest products is empirically derived and projected, causing some non-linearity in projected harvest outcomes to meet long-term demand for wood products. High variability in long-term harvest patterns and forest area, coupled with policy responsiveness, results in highly variable timber price projections for GFPM and GTM. GFPM also models land use change (forest expansion) using a Kuznet's curve relationship, reflecting increased demand for forest area as incomes rise, even if there are other potential pressures to forest loss (Nepal et al., 2019).

To better understand this complementarity effect, we evaluate changes in harvests and global forest carbon stocks both with and without climate policy drivers (as RCP 8.5. has no climate policy action). Specifically, we conducted a random forest analysis of the three models' variables, scenario parameters, and their relative influence on projected carbon stock changes (Figure S5. Random forest analysis of the relative importance of scenario parameters and endogenous model outcomes on projected carbon stock changes across scenarios for a) all models, b) GFPM, c) GTM, and d) GLOBIOM. Conducted using the RandomForest package in R.). According to this methodology, forest area (which is endogenously driven by both demand growth and carbon price) has the greatest relative influence on carbon outcomes in these models. Timber prices, time, and harvest levels (also endogenous variables) are next in line, followed by woody bioenergy demand and carbon price. Thus, forest area change is the key determinant of carbon changes across the models, though key drivers for forest area change differ per model (market demand and forest product price dynamics for GTM, the Environmental Kuznets Curve for GFPM, and carbon prices in GLOBIOM), and in this case, more significantly affect carbon changes than carbon price assumptions alone.

Area is a dominant variable in all three models, with the model year being an important variable for the recursive dynamic models (GFPM and GLOBIOM), while GDP/capita is a strong driver of timber market demand in GTM. In addition, biomass demand has a relatively strong influence on GTM and GLOBIOM but not GFPM, which is influenced more by total harvests (roundwood + biomass). These findings further highlight the uniqueness of each model framework in estimating impacts of socioeconomic and policy change on forest sector outputs. Identifying and understanding these important drivers of forest carbon stock changes and the relative significance to each other can help policy makers leverage different policy designs and market dynamics to bolster forest carbon accumulation as a natural climate solution.

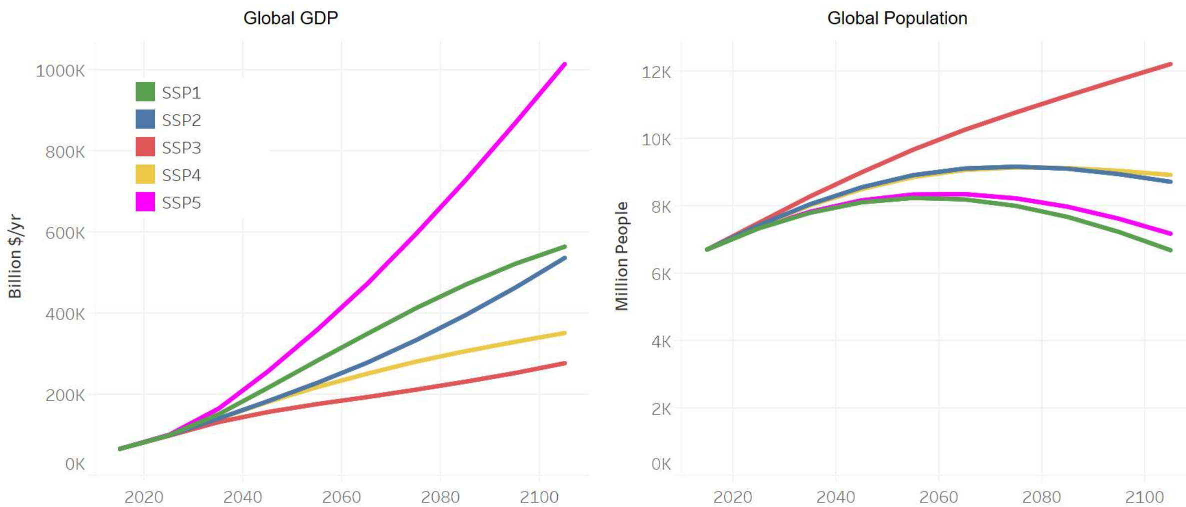

Figure S1. Global GDP and Population by SSP (Source: IIASA 2018)

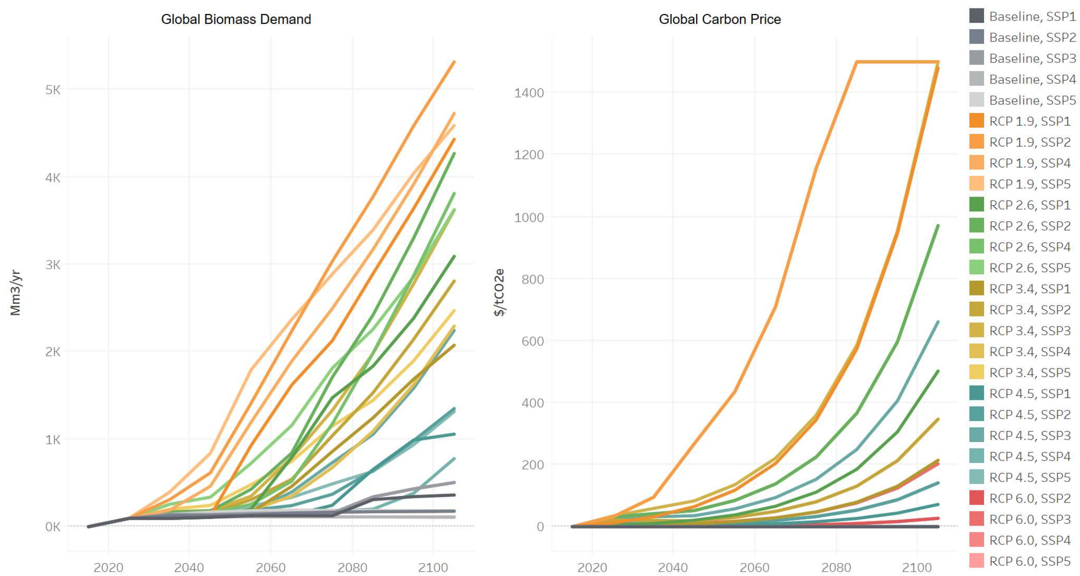

Figure S2. Total woody biomass demand and carbon prices used for SSP-RCP scenarios, as estimated by MESSAGE-GLOBIOM model (Source: IIASA 2018).

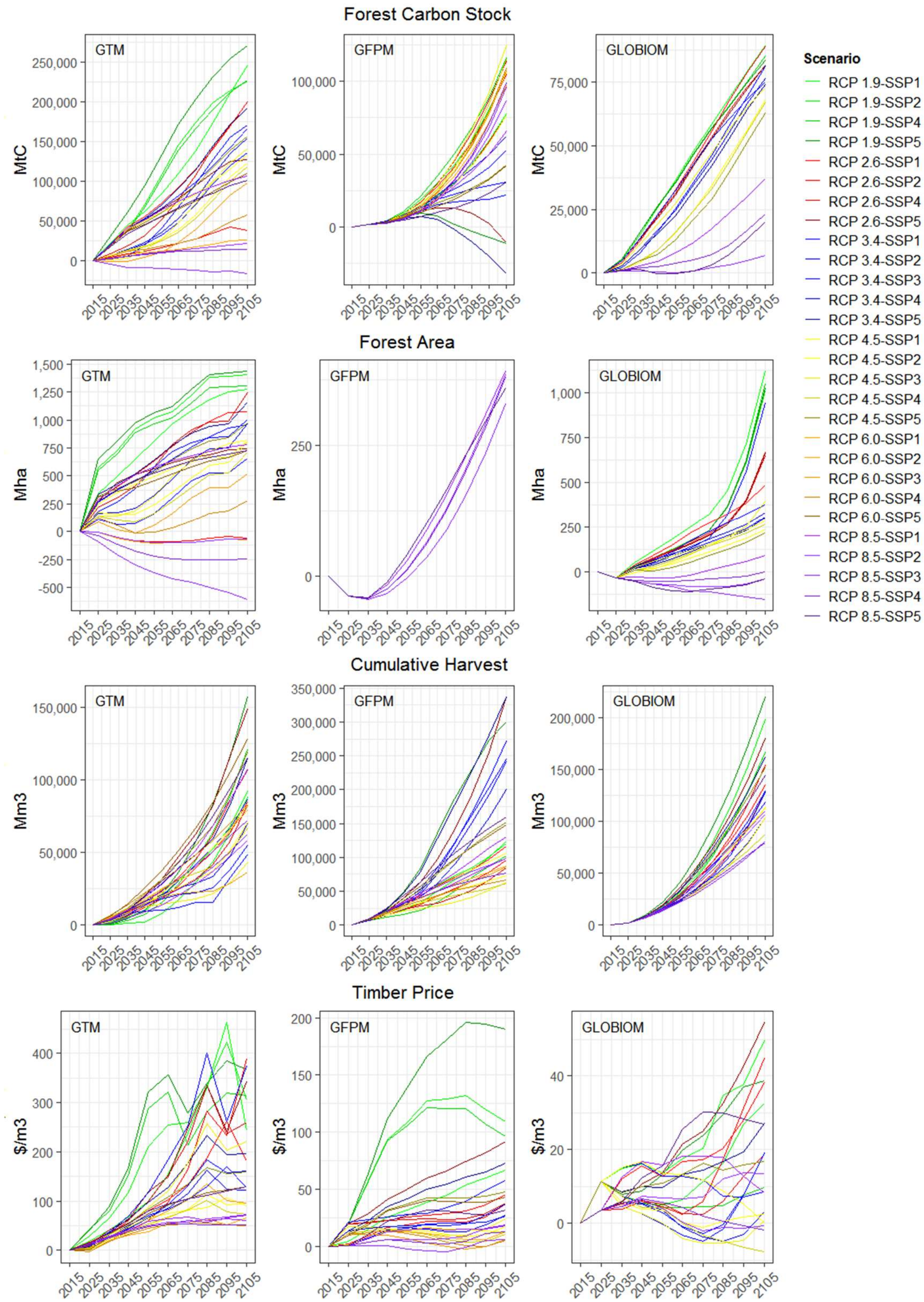
Forest Carbon Stock
Forest Area
Cumulative Harvest
Timber Price
GTM
GFPM
GLOBIOM
MtC
Mha
Mm3
$/m3
Scenario
RCP 1.9-SSP1
RCP 1.9-SSP2
RCP 1.9-SSP4
RCP 1.9-SSP5
RCP 2.6-SSP1
RCP 2.6-SSP2
RCP 2.6-SSP4
RCP 2.6-SSP5
RCP 3.4-SSP1
RCP 3.4-SSP2
RCP 3.4-SSP3
RCP 3.4-SSP4
RCP 3.4-SSP5
RCP 4.5-SSP1
RCP 4.5-SSP2
RCP 4.5-SSP3
RCP 4.5-SSP4
RCP 4.5-SSP5
RCP 6.0-SSP1
RCP 6.0-SSP2
RCP 6.0-SSP3
RCP 6.0-SSP4
RCP 6.0-SSP5
RCP 8.5-SSP1
RCP 8.5-SSP2
RCP 8.5-SSP3
RCP 8.5-SSP4
RCP 8.5-SSP5

Figure S3. Comparison of global forest sector model outputs for change in global forest area, carbon, harvest, and roundwood price from 2015.

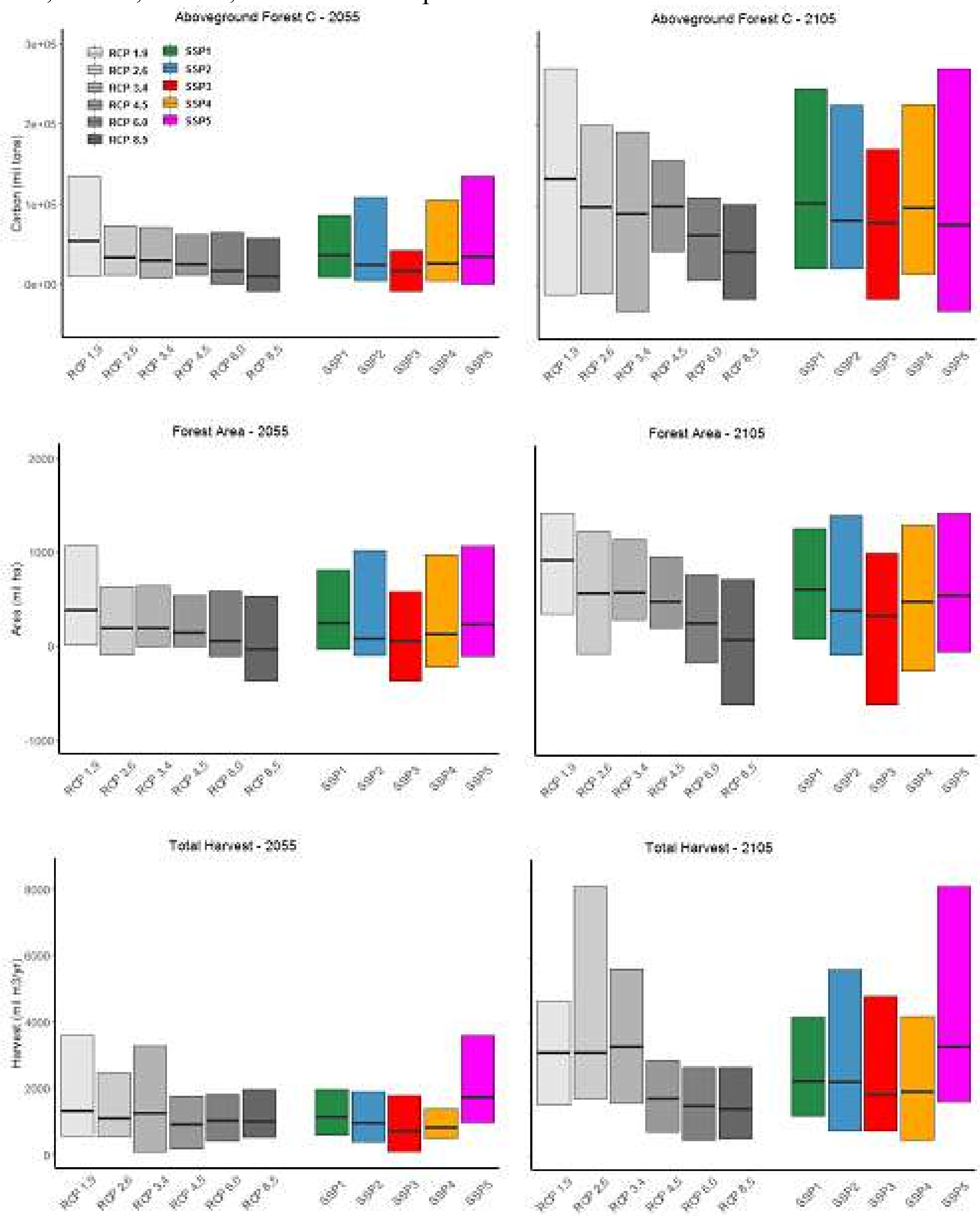

Figure S4. Mean (black bar), lower, and upper bound of changes in global forest carbon stock, forest area, and total wood harvest from 2015 by RCP and SSP.

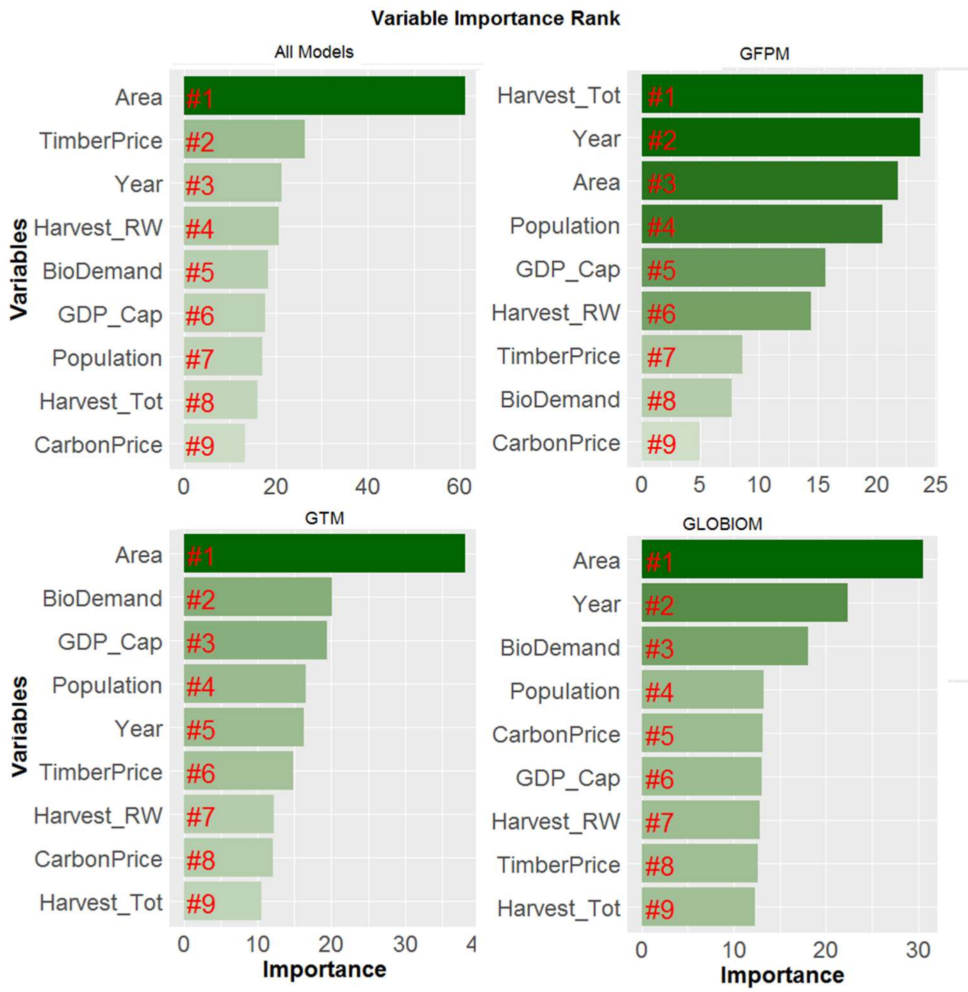

Figure S5. Random forest analysis of the relative importance of scenario parameters and endogenous model outcomes on projected carbon stock changes across scenarios for a) all models, b) GFPM, c) GTM, and d) GLOBIOM. Conducted using the RandomForest package in R.

Table S1. Source of model assumptions for SSP-RCP scenarios

Component	**SSP 1**	**SSP 2**	**SSP 3**	**SSP 4**	**SSP 5**
GDP	OECD GDP from SSP database				
POP	IIASA POP from SSP database				
Bioenergy demand	MESSAGE-GLOBIOM primary energy biomass from SSP database (*missing values for SSP4 and SSP5 replaced by SSP2 values*)				
Carbon price	MESSAGE-GLOBIOM carbon price from SSP database (*missing values for SSP4 and SSP5 replaced by SSP2 values*)				

Table S2. Overview of GTM model assumptions for SSP scenarios

Component	GTM Parameters	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
Global GDP per capita (annual change)	$\frac{Z_{t+1,SSP} - Z_{t,SSP}}{Z_{t,SSP}}$	OECD GDP and IIASA population from SSP database				
Wood product preference	π_{SSP}^{pulp} π_{SSP}^{saw}	0.15 0.85	0.2 0.8	0.22 0.78	0.18 0.82	0.2 0.8
Forest management intensity response (m)	$m_{t0,SSP}^{i,j,k}$	historical +10%	historical rate	historical -10%	HIC: hist +7.5% LIC: hist -7.5%	historical +7.5%
Forest management costs (% wrt t=0) $C_{G,t,SSP}^{i}(\cdot) = \beta_{SSP}^{i} C_{G,t=0}^{i}(\cdot)$	β_{SSP}^{i}	90%	100%	110%	HIC: 93% LIC: 110%	93%
Harvest & processing tech change (%/yr) $\gamma_{SSP}^{i} = \frac{C_{H,t+1,SSP} - C_{H,t,SSP}}{C_{H,t,SSP}}$	γ_{SSP}^{i}	1.5%	0.9%	0.5%	HIC: 1.2% LIC: 0.6%	1.25%
Agricultural Rents Shift (change w.r.t. to t=0) $R_{t,SSP}^{i}(\cdot) = \alpha_{SSP}^{i} R_{t=0}^{i}(\cdot)$	α_{SSP}^{i}	2.0 (all expand)	1.0 (varying. change)	1.0 (all contract)	HIC: 2 (expand) LIC: 1.5 (contract)	1.5 (all expand)

Note: HIC = high income countries, LIC = low income countries

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