

Forest Model Intercomparison Project (ForMIP)

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**Forestry & Agriculture Greenhouse
Gas Modeling Forum**



ForMIP Highlights

- 3 global forest sector model inter-comparison of 81 future scenarios.
- Socioeconomic drivers strongly influence forest sector model estimates.
- Global forests could sequester 1.2–5.8 GtCO₂e/yr over the next century.
- Forest management can increase carbon *and* harvests w/out expanding area.
- Integrated assessments could improve representation of forest markets and management dynamics.

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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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Climate change mitigation
Shared socioeconomic pathways
Shared policy analysis

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 always 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 uses multiple global forest sector models to project forest carbon impacts across 81 shared socioeconomic (SSP) and climate mitigation pathway scenarios. We illustrate the importance of modeling management decisions in existing forests in response to changing demands for land resources, wood products and carbon. Although the models vary in key attributes, there is general agreement across a majority of scenarios that the global forest sector could remain a carbon sink in the future, sequestering 1.2–5.8 GtCO₂e/yr over the next century. Carbon fluxes in the baseline scenarios that exclude climate mitigation policy ranged from –0.8 to 4.9 GtCO₂e/yr, highlighting the strong influence of SSPs on forest sector model estimates. Improved forest management can jointly increase carbon stocks and harvests without expanding forest area, suggesting that carbon fluxes from managed forests systems deserve more careful consideration by the climate policy community.

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 (IPCC, 2018; Lauri et al., 2017; Grassi et al., 2017; Roe et al., 2019; Canadell and Raupach, 2008; Friedlingstein et al., 2019; Domke et al., 2020). Natural climate solutions such as avoided deforestation (Kindermann et al., 2008), afforestation (Bastin et al., 2019; Busch et al., 2019), forest restoration (Lewis et al., 2019), and improved forest management (Griscom et al., 2017; Austin et al., 2020) 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 (Forsell et al., 2016; Popp et al., 2017). Key gaps include the role of timber demand on carbon flux, the influence of climate change policies on forest management and timber production, and the regional variation in carbon and wood product harvest outcomes.

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 (Houghton and Nassikas, 2017) or project impacts from discrete land use change (LUC) decisions via integrated assessment models (IAM) (Popp et al., 2017; Roe et al., 2019) that often assume all global forests are unmanaged or hold forest

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ForMIP Evolution

- 2017-18: Forest Sector Pathway (FSP) development
- 2019-21: Initial ForMIP modeling + individual model publications
- 2022: First ForMIP paper published in GEC
- 2023+: Regional/downscaled modeling, climate change impacts, refined analyses

Developing Detailed Shared Socioeconomic Pathway (SSP) Narratives for the Global Forest Sector

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ABSTRACT

This paper presents a series of possible future trends in Socioeconomic Pathways (FSPs). SSPs established by the climate adaptation, and mitigation strategies describing alternative sustainable development, demographic and economic uncertainty range consist

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Global forest management, carbon sequestration and bioenergy supply under alternative shared socioeconomic pathways

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 SSPs

1. Introduction

The forest sector is recognized as a key player in the scientific community (Lauri & Raupach, 2008) as well as at the policy level. Countries have explicitly included forest in their Nationally Determined Contributions (NDCs) (Grassi et al., 2017). While there are forests that contribute to near- and long-term natural climate solutions such as afforestation and forest restoration (Lewis et al., 2019), forest management (Ortizco et al., 2017), many have expected changes in future emissions (IPCC, 2016). Incorporating future socioeconomic, lifestyle, policy, and institutional trends is a fundamental task to address the uncertainty



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

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1. Introduction

The global forest sector is widely recognized by policy communities for its contribution to the climate change mitigation (IPCC, 2016; Lauri et al., 2017; Roe et al., 2019; Canadell and Raupach et al., 2019; Donike et al., 2020). Natural climate avoided deforestation (Kundermann et al., 2009 et al., 2019; Busch et al., 2019), forest restoration and improved forest management (Ortizco et al., 2017) are important components of climate change mitigation. Despite this noted importance, knowledge gaps

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Climate and socioeconomic impacts on Maine's forests under alternative future pathways

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Keywords:
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 Fiber supply

1. Introduction

Forests are a critical component of the global carbon cycle because they take up and store carbon in vegetation biomass (Fahey et al., 2010). In the United States, net forest sequestration reached 173 Tg C per year, offsetting about 10% of greenhouse gas (GHG) emissions from transportation and energy sectors (Weiss and Goodwin, 2015). In 2022, the estimated carbon dioxide equivalent (CO₂e) sink derived from land use, land-use change, and forestry (LULUCF) activities was estimated to be 754 million metric tons (EPA, 2023). Ongoing global warming is projected to significantly affect carbon uptake and release rates in forest ecosystems, either by directly modifying photosynthesis and ecosystem respiration or by indirectly introducing disturbances such as fire, storm, and insect outbreaks (Chen et al., 2019; Wei et al., 2019), although overall impacts can vary by region, forest type, and management response (Favero et al., 2021).

ABSTRACT
 This study investigates the combined effects of climate and socioeconomic change on fiber supply and forest carbon in Maine, USA, for broad alternative futures. We conduct an econometric analysis to project forest resource use over the next 90 years under a range of shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs). Results show that continued forest successional dynamics – without any harvesting – contribute the most to Maine's aboveground carbon (AGC) accumulation, with 2100 AGC potentially increasing by 40% compared to 2020. On this basis, climate change could result in 2.44–2.64 times greater AGC in 2100 compared to today. Harvest activities are major drivers of forest C dynamics, resulting in 2100 AGC being only 16% >2020. Socioeconomic factors (SSPs) had much larger effects on total harvest and carbon stocks than climate change (RCPs). Harvest volume were projected to increase by 9–29% between 2020 and 2100 for favorable socioeconomic development scenarios (SSP1/SSP2/SSP5) and decrease by 9–20% for unfavorable socioeconomic development scenarios (SSP3/SSP4). Overall, Maine's forest C pools were projected to increase by end-century for RCPs x SSP1/SSP2. This study offers valuable insight on possible methods for region-specific socioeconomic and climate change assessments, particularly in areas with extensive and diverse working forests with mixed ownership.

Timber harvesting, the major human introduced forest disturbance, can laterally remove the carbon from forest ecosystems and either immediately release it into the atmosphere or store it within harvested wood products (HWPs)—such as paper, furniture, and construction materials—thereby constituting an additional forest carbon pool. By using historical records, Johnston and Radtke (2019) revealed that the carbon sequestered within global end-use HWPs represented a net sink of 90 Tg C in 2015. Similarly, Zhang et al. (2020) found that the average annual carbon sink in global end-use HWPs was 122 Tg C during the period of 1992–2015, accounting for 3.2–6.1% of the annual carbon sink within the global forest sector (2400 ± 400 Tg C per year) (Pan et al., 2011). In addition, Eggers (2002) reported that carbon stored in the HWP pool constituted 13% in Australia, 6% in Finland, 13% in Germany, 6% in Norway, and 26% in Portugal across the entire forestry sector and all wood products. Smith and Heath (2008) updated this fraction to 10% in the USA, while Dewar and Cannell (1992) reported a

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ForMIP scenario development and simulation

- **Forest Sector Models (FSM):** 3 global forest sector models (GFPM, GTM, GLOBIOM) that account for timber harvest, forest area, and carbon sequestration for alternative socioeconomic and climate change mitigation pathways.
- **Shared Socioeconomic Pathways (SSP):** 5 pathways that vary degrees of global macroeconomic and socioeconomic change, including demographics, economic growth, technological change, and policy orientations.
- **Relative Concentration Pathways (RCP):** 6 pathways of global greenhouse gas emissions over time. In this paper, RCPs designate global climate change mitigation targets and do not account for the physical impacts of climate change.
- **Shared Policy Assumptions (SPA):** 2 consistent model assumptions used to achieve climate change mitigation targets. In this paper, mitigation pathways are simulated in each FSM through specific carbon price and bioenergy demand pathways for each SSP-RCP combination.

Key ForMIP Forest Sector Model Elements

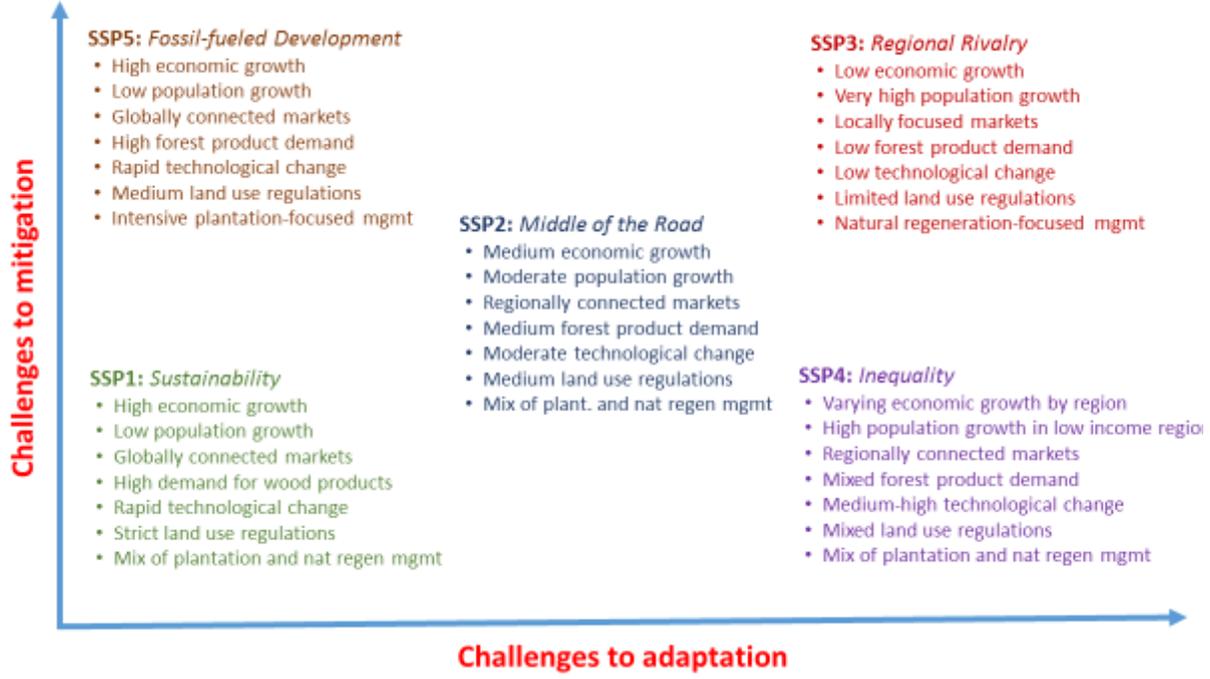
Element	GTM	GFPM	GLOBIOM
Economic Regions	16	180	59
Resolution	regional	country	0.5°-2° grid
Sectors	Sawtimber, pulpwood, bioenergy	forest product industry	Forest industry, forestry, bioenergy, agriculture
Forest types [^]	302	1	6
Climate effect on forests	no	no	no
Forest products*	3	14	35
Forest products 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 to 2016	Model calibrated to FAOSTAT and FRA data from 2000 to 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
Model documentation	https://u.osu.edu/forest/code-repository/	https://buongiorno.russell.wisc.edu/gfpm/	https://iiasa.github.io/GLOBIOM/index.html

[^] e.g., PNW Douglas fir, coniferous, deciduous, etc.).

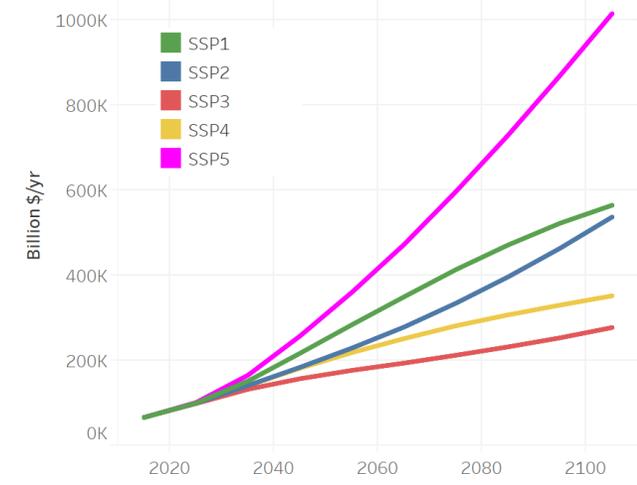
* (e.g., sawlogs, pulp, etc.).

[#] HWP = harvested wood products

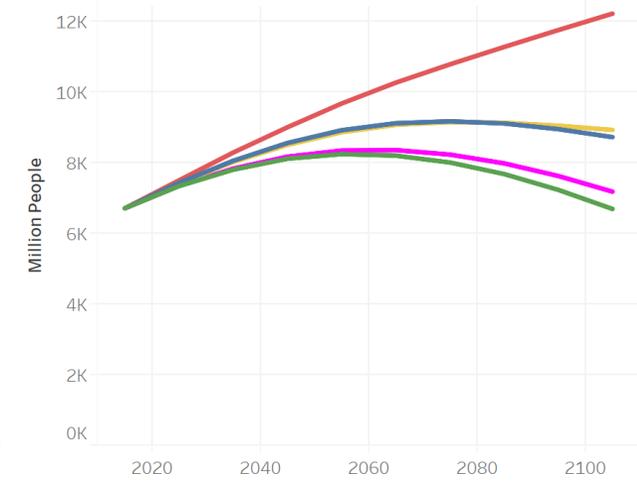
Key Global ForMIP Scenario SSP-RCP Elements



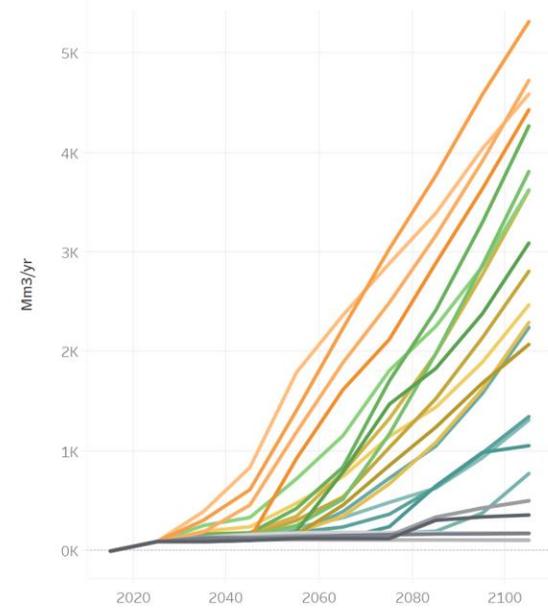
GDP



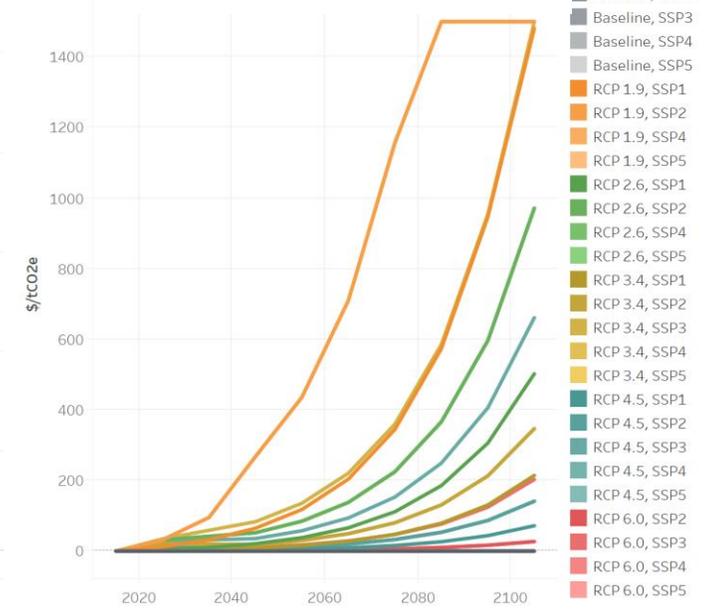
Population



Biomass Demand

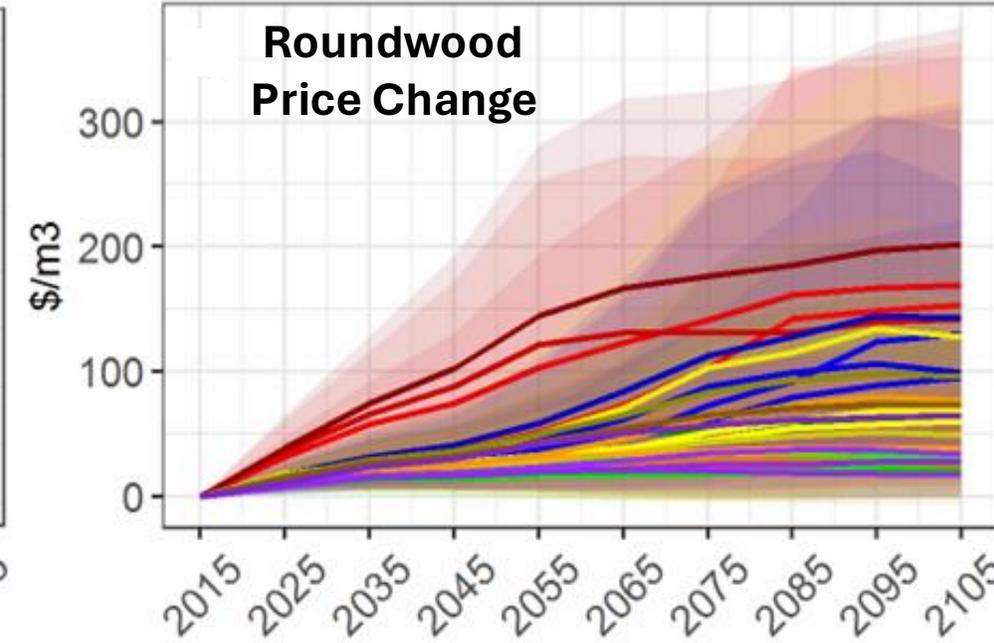
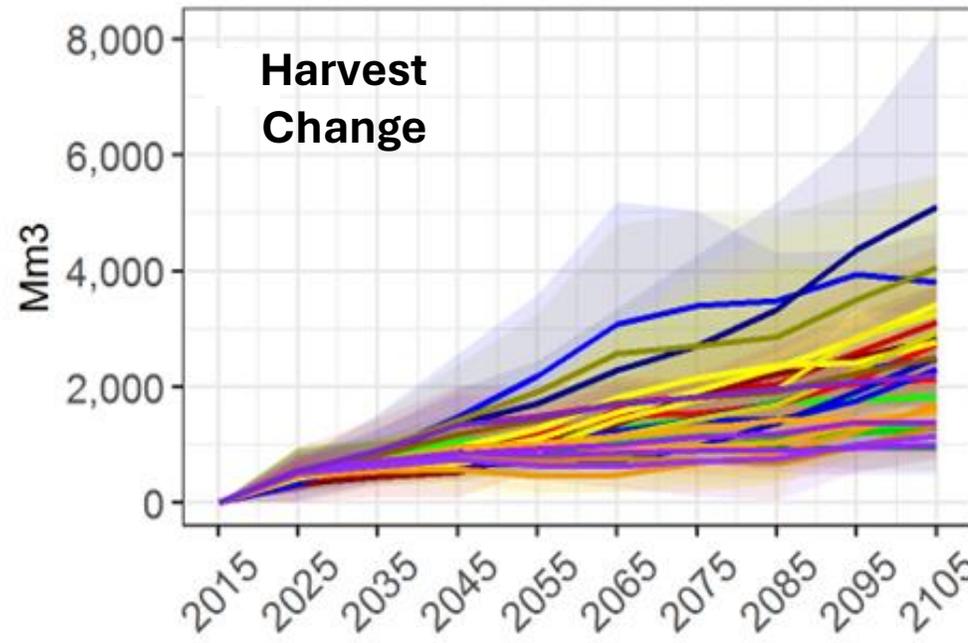
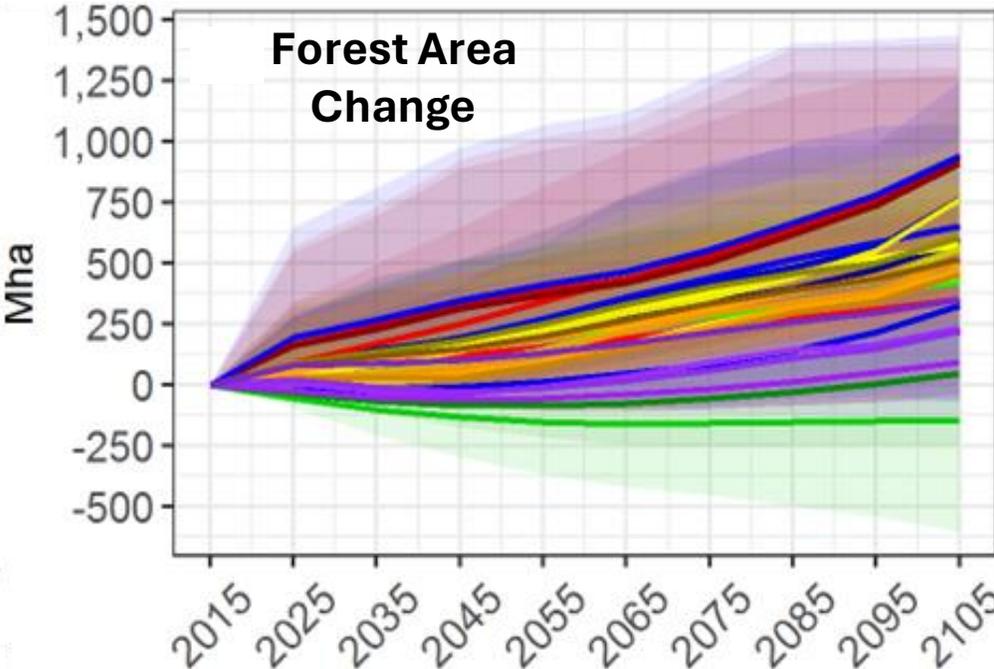
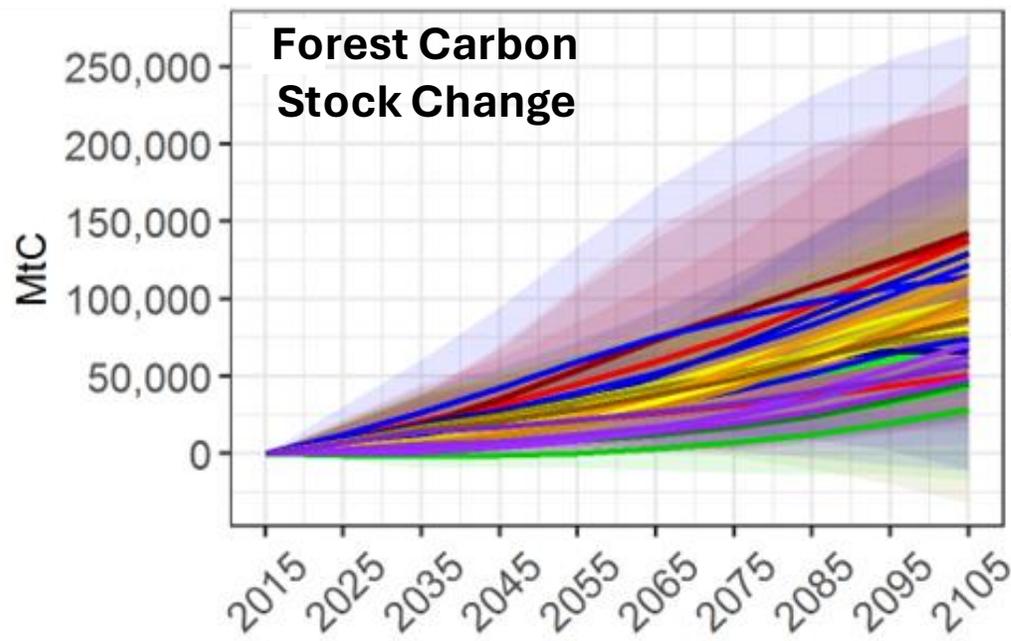


Carbon Price



Key 2015 Baseline Estimates by ForMIP Model



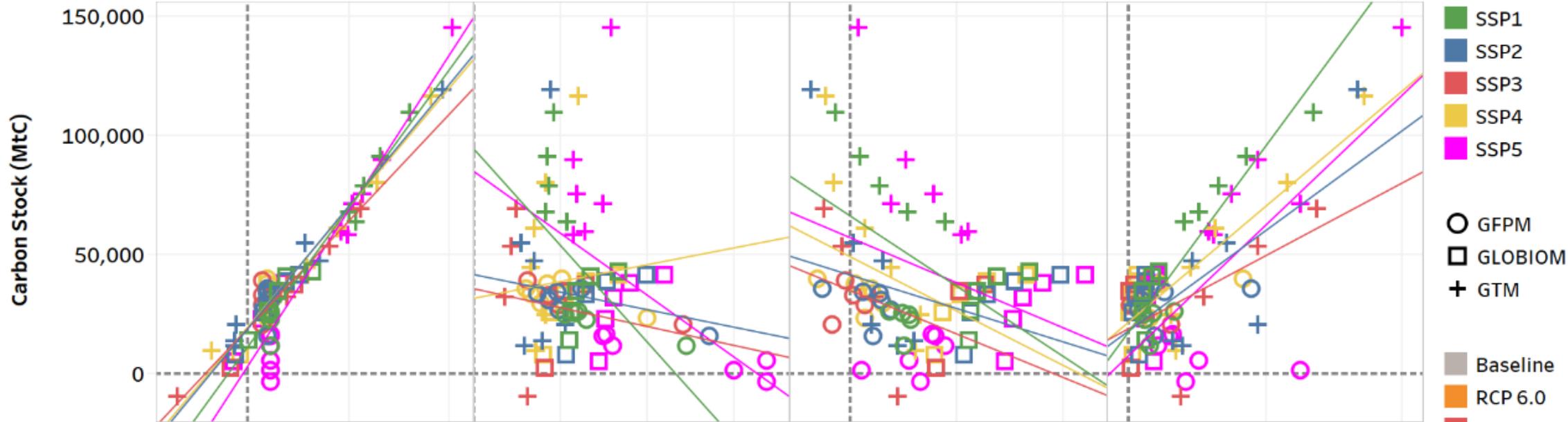


- Baseline-SSP1
- Baseline-SSP2
- Baseline-SSP3
- Baseline-SSP4
- Baseline-SSP5
- RCP 1.9-SSP1
- RCP 1.9-SSP2
- RCP 1.9-SSP4
- RCP 1.9-SSP5
- RCP 2.6-SSP1
- RCP 2.6-SSP2
- RCP 2.6-SSP4
- RCP 2.6-SSP5
- RCP 3.4-SSP1
- RCP 3.4-SSP2
- RCP 3.4-SSP3
- RCP 3.4-SSP4
- RCP 3.4-SSP5
- RCP 4.5-SSP1
- RCP 4.5-SSP2
- RCP 4.5-SSP3
- RCP 4.5-SSP4
- RCP 4.5-SSP5
- RCP 6.0-SSP2
- RCP 6.0-SSP3
- RCP 6.0-SSP4
- RCP 6.0-SSP5

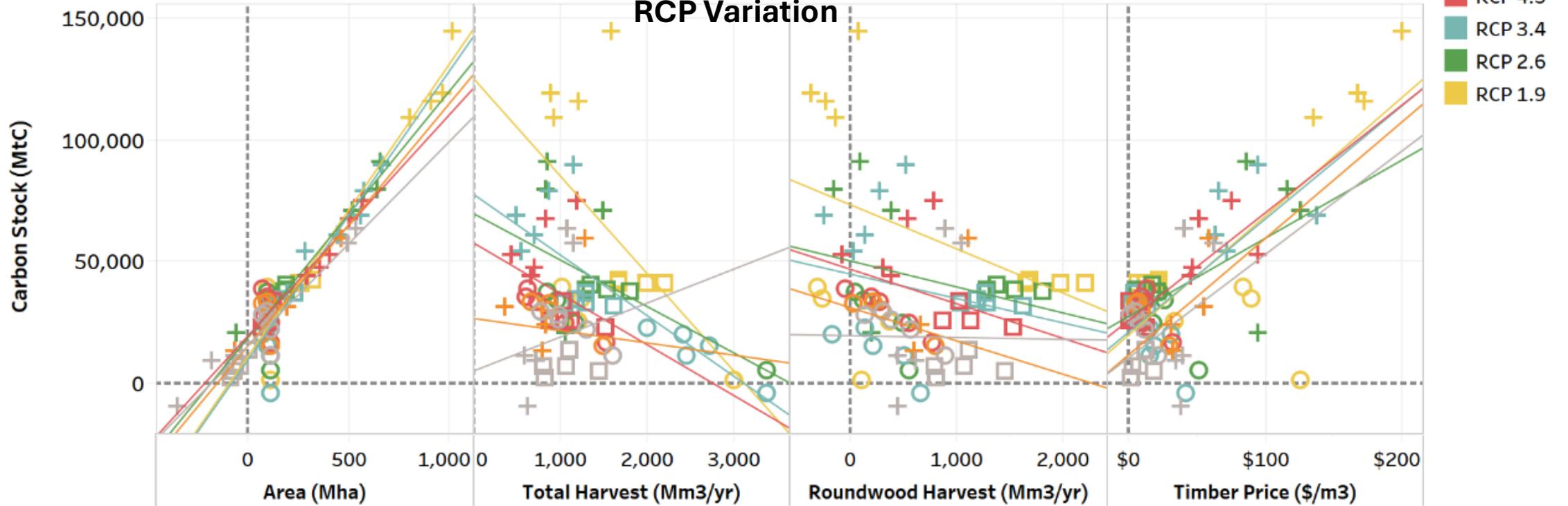
Mean change in global aboveground carbon stock (MtC), annual total wood harvest (Mm³), and annual industrial roundwood harvests (Mm³) from 2015 by RCP and SSP.



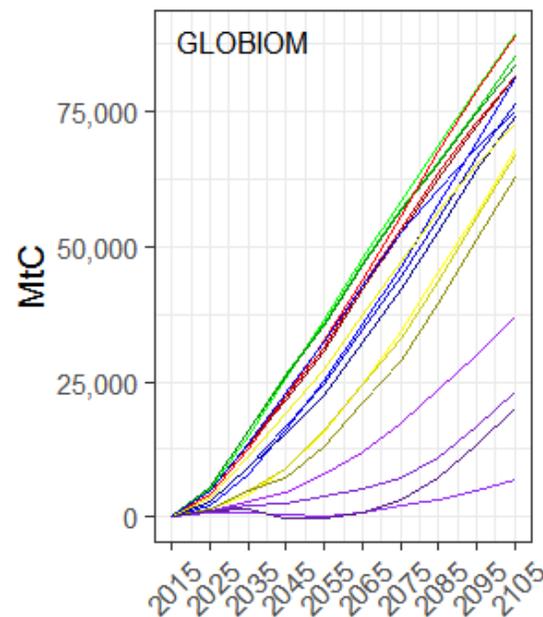
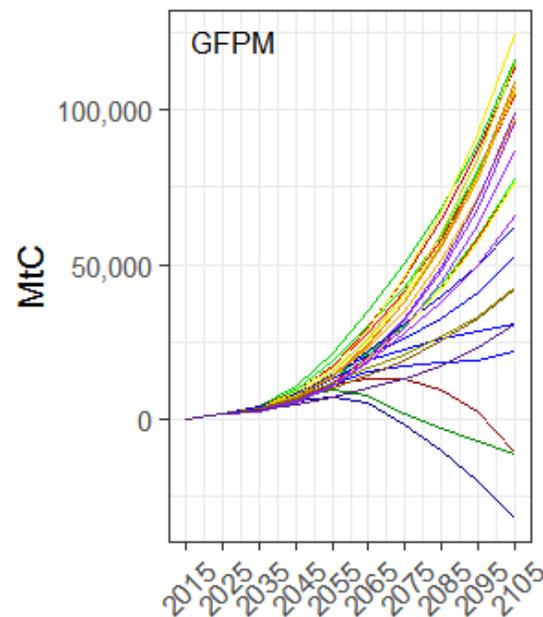
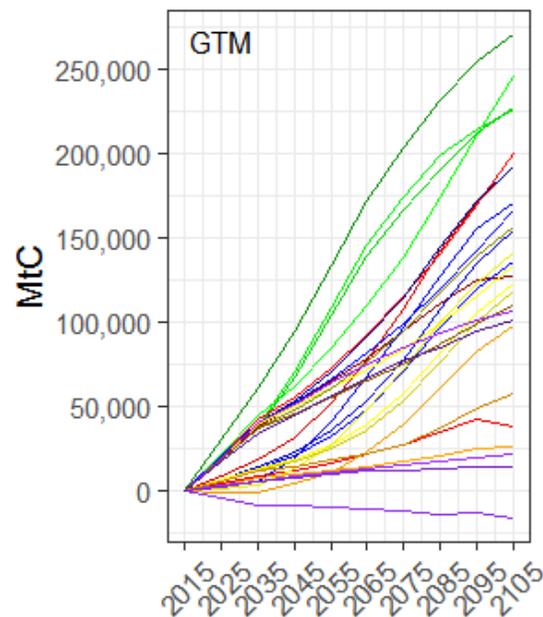
SSP Variation



RCP Variation



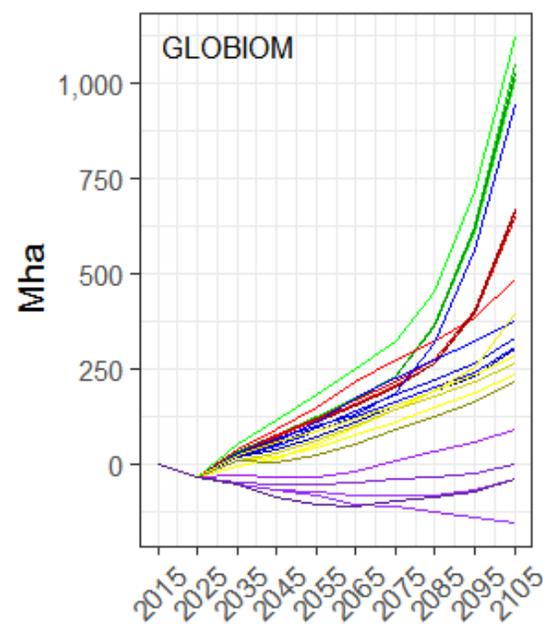
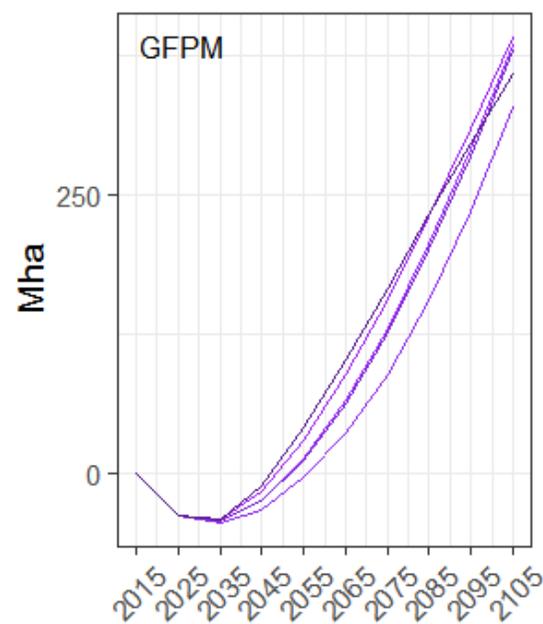
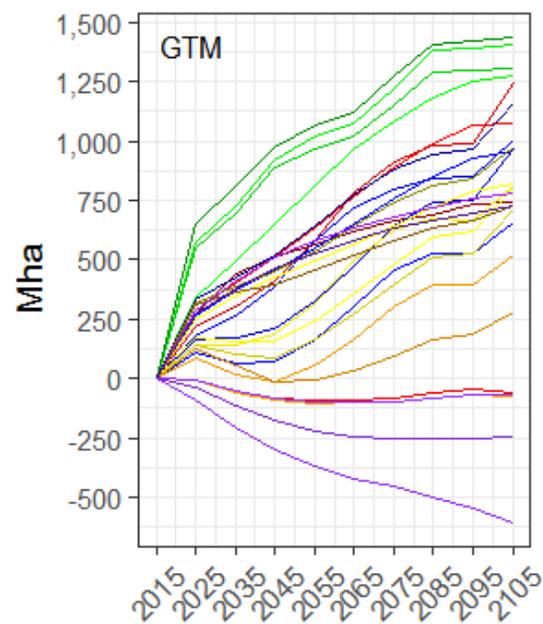
Forest Carbon Stock



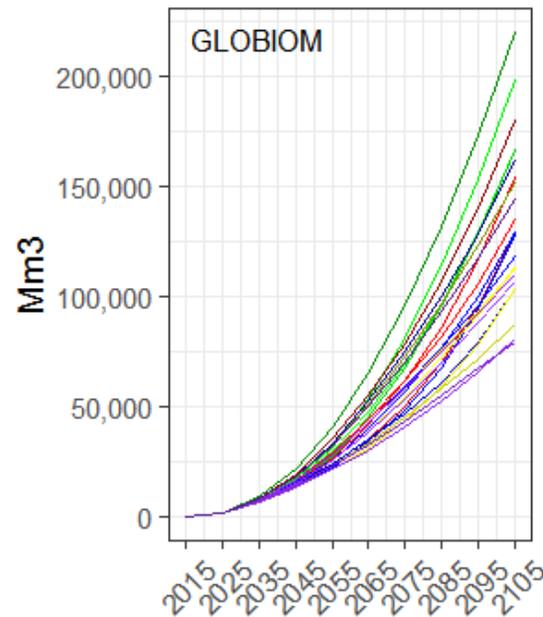
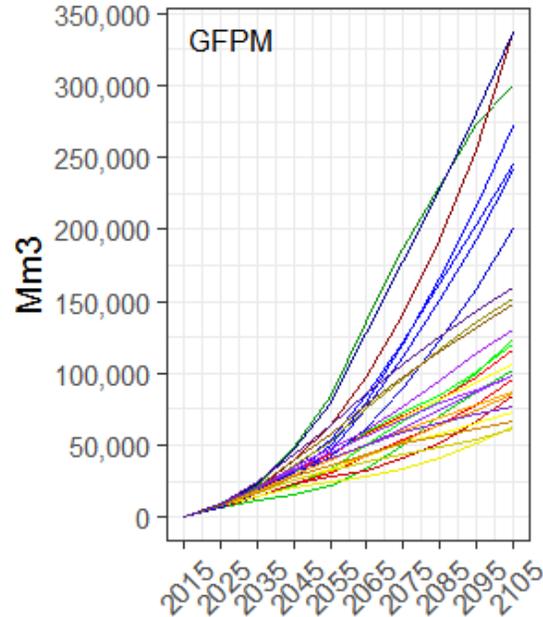
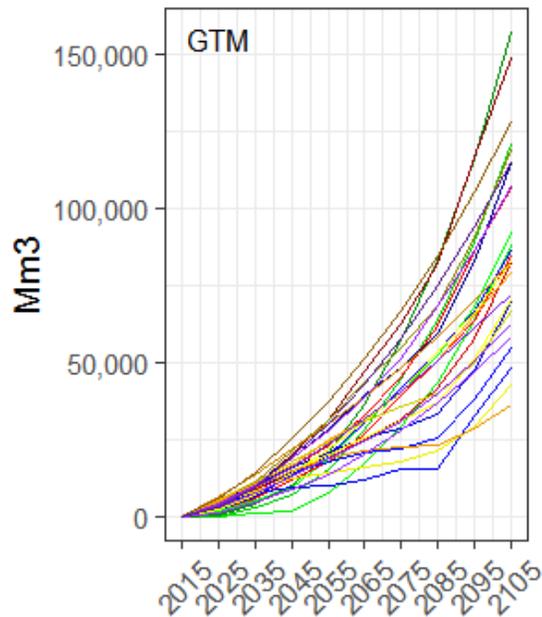
Scenario

- 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

Forest Area



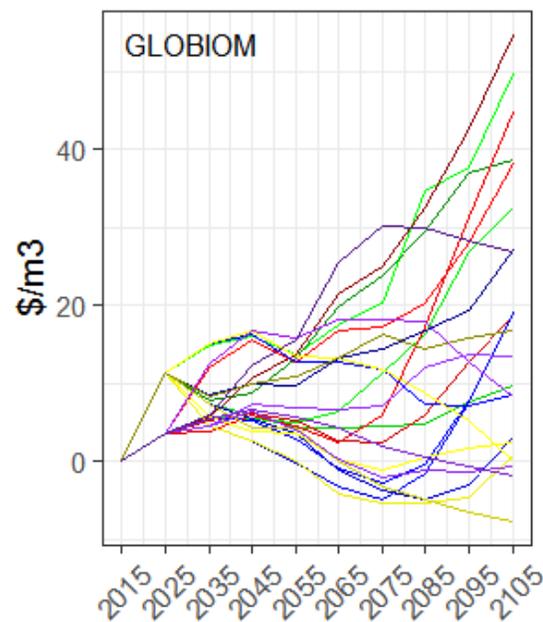
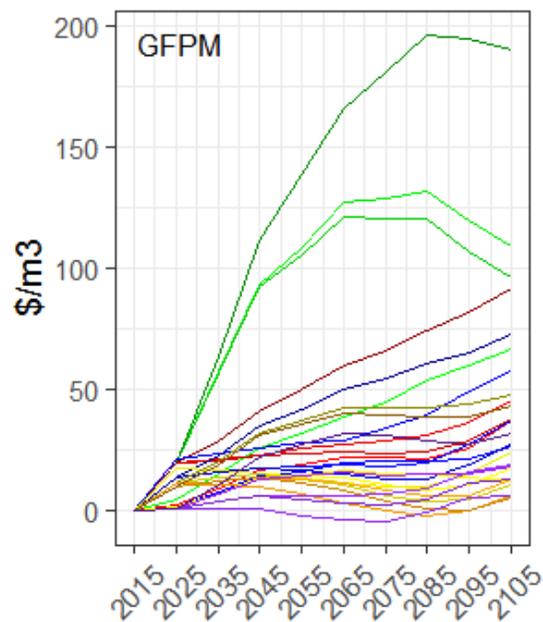
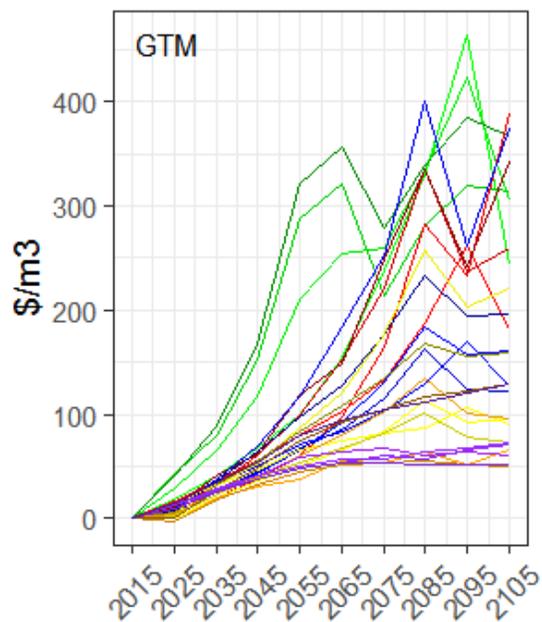
Cumulative Harvest



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
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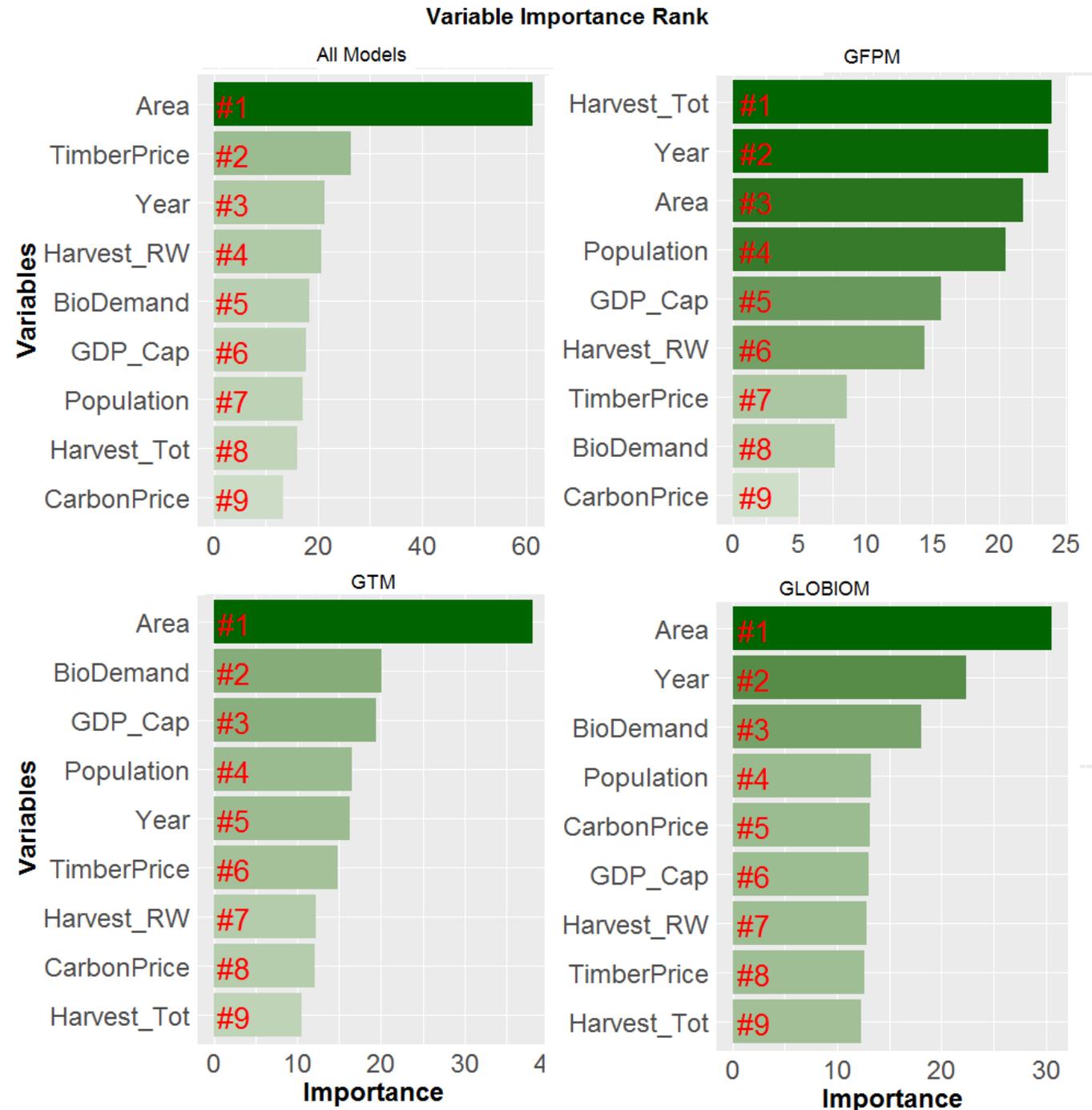
Timber Price



Relative importance of scenario parameters and endogenous model outcomes on projected carbon stock changes across scenarios & models

Variables:

- Area = forest area
- TimberPrice = timber price
- Year = model year
- Harvest_RW = roundwood harvest
- BioDemand = woody biomass demand
- GDP_Cap = GDP/capita
- Population = global population
- Harvest_tot = roundwood + biomass harvest
- CarbonPrice = carbon price



Summary

- ForMIP shows importance of modeling management responses to changing demands for land resources, wood products and carbon.
- 95% of scenarios had forest C stocks increasing through 2100 (1.2–5.8 GtCO₂e/yr)
- Carbon fluxes in the baseline scenarios excluding mitigation policy ranged from -0.8 to 4.9 GtCO₂e/yr
- Key influences of forest C change: Area, prices, roundwood + biomass demand
- Noticeable model variability in key estimates, but direction and overall outcomes consistent
- Global forests can jointly increase carbon stocks *and* timber harvests without necessarily expanding area
- Carbon fluxes from managed forests systems deserve more careful consideration by the climate policy community

Ongoing + Future Work

- Further evaluating impacts of harvests + harvested wood products on scenario outcomes
- Downscaling ForMIP scenarios for consistent regional analysis
- Incorporating climate change impacts into global models
- More direct use by national and regional policymakers

Want to know more & access data?

ForMIP paper published in *Global Environmental Change* (open access)

Key inputs and scenario estimates included as supplementary material

<https://www.sciencedirect.com/science/article/pii/S0959378022001200>

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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 always 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 uses multiple global forest sector models to project forest carbon impacts across 81 shared socioeconomic (SSP) and climate mitigation pathway scenarios. We illustrate the importance of modeling management decisions in existing forests in response to changing demands for land resources, wood products and carbon. Although the models vary in key attributes, there is general agreement across a majority of scenarios that the global forest sector could remain a carbon sink in the future, sequestering 1.2–5.8 GtCO₂e/yr over the next century. Carbon fluxes in the baseline scenarios that exclude climate mitigation policy ranged from –0.8 to 4.9 GtCO₂e/yr, highlighting the strong influence of SSPs on forest sector model estimates. Improved forest management can jointly increase carbon stocks and harvests without expanding forest area, suggesting that carbon fluxes from managed forests systems deserve more careful consideration by the climate policy community.

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 (IPCC, 2018; Lauri et al., 2017; Grassi et al., 2017; Roe et al., 2019; Canadell and Raupach, 2008; Friedlingstein et al., 2019; Domke et al., 2020). Natural climate solutions such as avoided deforestation (Kindermann et al., 2008), afforestation (Bastin et al., 2019; Busch et al., 2019), forest restoration (Lewis et al., 2019), and improved forest management (Griscom et al., 2017; Austin et al., 2020) 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 (Forsell et al., 2016; Popp et al., 2017). Key gaps include the role of timber demand on carbon flux, the influence of climate change policies on forest management and timber production, and the regional variation in carbon and wood product harvest outcomes.

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 (Houghton and Nassikas, 2017) or project impacts from discrete land use change (LUC) decisions via integrated assessment models (IAM) (Popp et al., 2017; Roe et al., 2019) that often assume all global forests are unmanaged or hold forest

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Additional Slides

ForMIP Scenarios

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

HIC: High-income countries; LIC: Low-income countries; Climate and woody biomass elements vary by RCP.

Regional Estimates

