Published in final edited form as:

For Policy Econ. 2022 December 28; 147: 1–17. doi:10.1016/j.forpol.2022.102898.

Projecting U.S. forest management, market, and carbon sequestration responses to a high-impact climate scenario

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Abstract

The impact of climate change on forest ecosystems remains uncertain, with wide variation in potential climate impacts across different radiative forcing scenarios and global circulation models, as well as potential variation in forest productivity impacts across species and regions. This study uses an empirical forest composition model to estimate the impact of climate factors (temperature and precipitation) and other environmental parameters on forest productivity for 94 forest species across the conterminous United States. The composition model is linked to a dynamic optimization model of the U.S. forestry sector to quantify economic impacts of a high warming scenario (Representative Concentration Pathway 8.5) under six alternative climate

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CRediT authorship contribution statement

Justin S. Baker: Conceptualization, Methodology, Formal analysis, Writing – original draft, Supervision, Funding acquisition, Visualization. **George Van Houtven:** Conceptualization, Methodology, Data curation, Funding acquisition, Project administration, Writing – review & editing. **Jennifer Phelan:** Methodology, Data curation, Funding acquisition, Writing – review & editing. **Gregory Latta:** Conceptualization, Methodology, Formal analysis, Visualization, Data curation, Writing – review & editing. **Christopher M. Clark:** Methodology, Writing – review & editing. **Kemen Austin:** Data curation, Conceptualization, Writing – review & editing. **Olakunle Sodiya:** Visualization, Writing – review & editing. **Sara B. Ohrel:** Methodology, Writing – review & editing. **John Buckley:** Data curation. **Lauren E. Gentile:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition. **Jeremy Martinich:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2022.102898.

projections and two socioeconomic scenarios. Results suggest that forest market impacts and consumer impacts could range from relatively large losses (−$2.6 billion) to moderate gain ($0.2 billion) per year across climate scenarios. Temperature-induced higher mortality and lower productivity for some forest types and scenarios, coupled with increasing economic demands for forest products, result in forest inventory losses by end of century relative to the current climate baseline (3%–23%). Lower inventories and reduced carbon sequestration capacity result in additional economic losses of up to approximately $4.1 billion per year. However, our results also highlight important adaptation mechanisms, such forest type changes and shifts in regional mill capacity that could reduce the impact of high impact climate scenarios.

Keywords

Forest productivity; Forest management; Climate change adaptation; Mill capacity

1. Introduction

There is growing need to understand how climate change could affect ecosystems and economic production capacity in natural resource-intensive systems such as agriculture and forestry. The productivity of the global land use sectors is susceptible to changes in average temperatures and regional precipitation patterns (IPCC, 2018), which will be especially challenging as they continue to face rising global demands for food, fiber, energy, and natural climate solutions (Riahi et al., 2017). Continued efforts to understand how climate change will interact with socioeconomic and environmental demands for land resources can inform mitigation and land use policy design and adaptation planning. There is substantial literature devoted to agricultural sector climate impact assessments using different methods, including bottom-up empirical techniques (Lafferty et al., 2021; Schlenker and Roberts, 2009) or top-down integrated systems modeling (Baker et al., 2018; Beach et al., 2015; Janssens et al., 2020). Recent multi-model assessments developed by the Agricultural Model Inter-Comparison Project (AgMIP) (Valin et al., 2014) have contributed significantly to this domain, and more recent efforts are linking agricultural climate impact scenarios with mitigation policy assessments (Fujimori et al., 2019; Frank et al., 2021).

However, considerably less attention has been devoted to quantifying potential future impacts of climate change on the global forestry sector. Forests have an outsized influence on terrestrial carbon storage levels and local climate systems relative to the economic contribution of the sector (Daigneault et al., 2022). The net effects of changing climate conditions on the forest sector include both market implications (e.g., how changes in productivity affect harvest levels and forest product markets) and forest management implications (e.g., how management changes to adapt to climate change affect ecosystem and climate services such as forest carbon sequestration). Given the heterogeneity in forest management techniques and in growth rates for different tree species, assessing potential impacts from climate change decades in the future requires a dynamic approach that links management decisions under different (climate-driven) productivity change scenarios to socioeconomic systems. That is, quantifying the impacts of climate change on the forest sector should include accounting for exogenous climate-driven productivity changes for different forest types as well as endogenous adaptation responses to changing productivity regimes.

Further, impact assessments should evaluate how climate-induced changes in forest productivity and regional adaptation responses could also shift forest inventories and carbon sequestration rates. Adaptation responses can limit economic damages to the sector by maintaining production and consumption levels over time for scenarios that adversely affect forest productivity. However, without complementary policies to protect standing inventories[1] or carbon stocks, such scenarios could result in lower carbon sequestration rates. Reduced sequestration would then reinforce negative climate feedback effects, similar to those associated with growing forest fire risks.

1.1. Objectives and study contributions

This study builds on previous literature evaluating potential climate change impacts in the U.S. forest sector. We develop structural dynamic simulations of climate scenarios using the forestry component of the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOM-GHG, Beach et al., 2010), coupled with a forest growth model based on empirical relationships for individual tree species (Van Houtven et al., 2019; Horn et al., 2018). We show how anticipated changes in forest productivity affect management and harvest dynamics in key domestic timber-producing regions. We compare market, management, and carbon sequestration projections across scenarios and then quantify estimated net economic impacts of high-impact climate scenarios. We discuss potential adaptation responses to temperature and precipitation changes in the U.S. forestry sector, which could include shifting the spatiotemporal distribution of harvests, changing forest types, increasing management intensity, and expanding or contracting regional mill capacity.

Specifically, this study links empirically derived tree-species-specific growth and survival equations to estimate how climate inputs (mean annual temperature and total annual precipitation) affect plot-level species composition and yields (Horn et al., 2018; Van Houtven et al., 2019). This approach deviates from the economic modeling literature on forest climate impacts, as most studies use process-model projections to adjust productivity of forest ecosystems over time (e.g., Tian et al., 2016). Instead, we apply our empirical technique to adjust the growth and yield tables for different forest types included in FASOM-GHG. Our analysis makes several contributions to the literature.

First, to simulate long-term economic and forest ecosystem impacts of extreme temperature and precipitation changes, we apply the yield-adjusted FASOM-GHG dynamic optimization model of the U.S. forest sector under a climate change scenario (Representative Concentration Pathway [RCP] 8.5) represented by six different general circulation model (GCM) projections. Although all GCM outputs used in this analysis link to the RCP8.5 scenario, for the purposes of this manuscript, we refer to each GCM model run as a separate “climate scenario,” as these represent a range of temperature or precipitation conditions that could positively or negatively impact forest productivity.

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[1] In this analysis we use the term “inventory” to represent aboveground living forest biomass. A positive change in forest inventories is thus an increase in standing forest biomass.

We apply FASOM-GHG to project potential management and market implications of alternative climate futures using a dynamic framework. We run intertemporal (dynamic) simulations to project the spatiotemporal distribution of harvest patterns and inventory changes for alternative expected climate and socioeconomic futures. This approach allows us to assess adaptation responses to changing temperature and precipitation inputs assuming full information (via the intertemporal function of the model) on future growth and yield dynamics under climate change.

Second, our analytical approach recognizes that manufacturing capacity in the forest products sector is not fixed over time. Mill capacity can contract or expand within a region depending on relative cost advantages and standing forest inventories at or near harvest age. Under climate change, regional mill capacity could migrate as an adaptation mechanism, reflecting how climate-driven changes in forest productivity and inventory could affect the flow of capital investments in the sector. Previous U.S. forest sector climate impact assessments have not incorporated the potential role of mill capacity expansion/contraction as an adaptation response.

Finally, similar to other previous studies (Henderson et al., 2020; Tian et al., 2016), we find that U.S. forest markets as a whole are fairly resilient to high warming scenarios, at least through the end of century (though longer-term impacts could be more substantial). That is, net economic welfare changes, measured as the sum of simulated consumer and producer surplus changes, are <2 % across all climate scenarios. However, our results also show that regional inventory changes, mill capacity utilization, and carbon sequestration could vary dramatically across scenarios. These results suggests that while forest *markets* may be fairly resilient to climate change in aggregate, losses in carbon sequestration capacity and forest inventories may require complementary policies to address these impacts. We find negative impacts on the sector under most scenarios, maxing out at approximately $2.6 billion per year in damages. However, near-term damages from reduced carbon sequestration capacity (estimated using the social cost of carbon), are more than 50% greater than consumer and producer losses across many of our modeled scenarios.

In the following sections, we provide an overview of recent economic modeling literature on forests and climate change, describe our empirical and structural modeling approach, and discuss key results and policy takeaways. Our concluding section highlights limitations of our approach and identifies areas for future research.

1.2. Literature review

Analyses of climate change impacts on forest growth and productivity—There is a significant and growing literature that has assessed climate change impacts on forests using a variety of techniques – empirical and modeling – to assess the influence of climate inputs on forest productivity or to simulate changes in net primary productivity (NPP) of ecosystems, or forest growth, under future climate conditions (Romeiro et al., 2022). The following review synthesizes recent forest climate impact analyses, with a particular focus on the temperate region and studies that link empirical or process model estimates with economic frameworks.

Some empirical work in the U.S. has focused on plantation or productive regional timber supply systems using experimental or survey plot data coupled with climate variables (Farjat et al., 2015; Latta et al., 2010). Horn et al. (2018), which provides the empirical foundation for the forest composition model used in this study, estimated tree species-specific growth and mortality responses to a variety of factors, including climate variables and nitrogen and sulfur deposition. Other empirical work has evaluated climate's influence on forest mortality (e.g., Gustafson and Sturtevant, 2013) or has been linked with growth models to simulate productivity changes (Klesse et al., 2020; Burkhart et al., 2018; Huang et al., 2011), but such studies are typically restricted to select regions and forest types. Other empirical efforts have focused on behavioral or management responses to climate change (Fischer, 2019; Thomas et al., 2022), as well as future species distribution (Thurm et al., 2018). Gustafson and Sturtevant (2013) simulate how management might adapt to climate change. One common issue with these empirical and simulation studies is that they are often local in scope or do not account for feedback between markets and managed forest systems.

Another common technique for simulating future climate impacts is the use of Dynamic Global Vegetation Models (DGVM) or stand-level process models, which can simulate above- and below-ground ecosystem productivity under different future scenarios by spatially varying input assumptions such as climate or nutrient inputs. Common DGVM and process models that have been applied in conjunction with economic models include MC2 (Kim et al., 2017), LPX-Bern (Favero et al., 2018), Biome-BGC (Running and Hunt, 1993; Ueyama et al., 2009) BIOME3 (Sohngen et al., 2001), and 3PG (Landsberg and Waring, 1997; West et al., 2021).

Using BIOME3 to estimate climate-induced changes in the distribution of timber species and their productivity globally, Sohngen et al. (2001) found that under two different climate and economic scenarios, there are likely to be large conversions from one forest type to another, large conversions of non-forest land to forestland, and higher NPP. West et al. (2021) simulated the forest productivity responses to climate change with 3PG and found that stand volumes at harvest were most sensitive to precipitation and available soil water content and varied substantially across the six climate model projections under four RCPs. Kim et al. (2017) applied the DGVM MC2 to project changes in NPP in major forestry regions. Results of this study suggest that forests may be more productive in the future, even with a high warming scenario such as RCP 8.5, due to CO_2 fertilization.

Another group of studies has developed hybrid approaches that link observational data with process modeling. For example, Thomas et al. (2017) offers a broader perspective on factors influencing planted pine (loblolly and slash) productivity in the Southern U.S. (e.g., precipitation and nitrogen inputs). The Pine Integrated Network: Education, Mitigation, and Adaptation Project (PINEMAP)[2] is another relevant regional example that links inventory data, field-level observations (including Free-standing Aerial Carbon Enrichment [FACE] sites), and process modeling to project yields of southern U.S. loblolly pine systems.

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[2] http://pinemap.org/reports/PINEMAP_FinalReport_reduced_size.pdf

Therefore, despite the growing body of empirical work focused on forest growth and mortality modeling, these models have thus far not been linked to dynamic forest sector economic models requiring comprehensive coverage of forests at national and global scales to conduct climate change impact assessments.

1.3. Integrated economic and ecological modeling of climate change impacts on forestry

With recent research indicating that arid and temperate forests are becoming less resilient, there is a need to better understand the mechanisms that increase tree mortality and make forests less resilient to future change, including temperature and precipitation thresholds (Forzieri et al., 2022). While there have been significant advancements in economic modeling of forest resource systems and forest product markets (Baker et al., 2019), most modeling applications focus on the implications of alternative policies or socioeconomic change, with much less emphasis on the implications of future climate change. This is in part due to the difficulty in empirically identifying the causal linkages between changes in climate inputs or CO_2 fertilization on forest productivity over long harvest cycles, as well as separating these effects from other environmental factors (e.g., nitrogen deposition) and management techniques (e.g., fertilizer use or genetic improvement). Many contemporary models of the U.S. forest resource base have relied on empirical growth curves developed from detailed inventory data to represent different forest types (Wear and Coulston, 2019; Latta et al., 2018; Wade et al., 2019a, 2019b; Daigneault and Favero, 2021). Adjusting these growth functions to account for different precipitation and temperature inputs requires either directly estimated species-specific marginal effects or modeled system-wide NPP changes.

Many previous applications of economic modeling to evaluate climate change impacts on forests linked economic models to DGVM or process model simulations. DGVMs are commonly used as inputs into economic simulation frameworks, as spatially explicit projections of NPP change can be used to shift growth assumptions for forest systems represented in economic systems models. Favero et al. (2018) provides an overview of research in this domain. Tian et al. (2016) studied the effects of climate change on timber production, timber prices, and carbon sequestration globally by integrating the MC2 model with the Global Timber Model (GTM), and results suggest that climate change will cause forest outputs to increase by approximately 30% over the century. Favero et al. (2018) similarly linked the GTM with a separate DGVM, LPX-Bern, to examine implications of extreme climate scenarios over 200 years and approximately 11° C of warming. Results suggest that forest productivity, particularly for planted/managed systems, could continue to expand in the future, but that high warming scenarios would induce loss of natural forestland. Other global studies (e.g., Reilly et al., 2007; Buongiorno, 2015) have shown similar results, with forest productivity generally increasing with climate change.

U.S.-focused studies have taken a similar approach for linking DGVMs and economic models, yielding a wide range of results. Haim et al. (2011) used an empirical framework to project forest growth and land use dynamics under three alternative climate scenarios. Their results suggest that productivity shifts under climate change are not as important as demand-side changes and urbanization in shifting forest land use dynamics. Beach et al. (2015) applied an earlier version of the FASOM model linked with the DGVM MC2, and their results suggest that the productivity gains from CO_2 fertilization boost the sector and increase economic welfare overall. Henderson et al. (2020) applied a regional timber supply model linked with the DGVM 3PG (using results from Thomas et al., 2017). They projected large gains in Southern U.S. forest inventories and carbon stocks, which put downward pressure on market prices, thus offsetting some of the economic benefits of the productivity gains. Other regional studies provide a different perspective on climate change impacts to the forest sector, including projected economic losses in Europe (Hanewinkel et al., 2013) and Canada (Lantz et al., 2022)

One common thread between forest climate impact analyses in the U. S. and globally is the potential importance of CO_2 fertilization. Despite different outlooks, there is growing scientific evidence of that CO_2 fertilization increases photosynthesis and boosts ecosystem productivity, suggesting potential benefits of elevated CO_2 to forest ecosystems. Chen et al. (2022) suggests that CO_2 fertilization has contributed 4.4 gC m^{-2} yr^{-2} to gross primary production globally since the early 2000s. Recent econometric analysis in the U.S. estimates a significant productivity boost for many U.S. forest types between 1970 and 2010, even in systems that have experienced some loss in productivity due to disturbance (Davis et al., 2022).

DGVMs typically show CO_2 fertilization to be a large driver of future biomass growth, which can help offset increased mortality and boost forest yields (and hence carbon sequestration) in some regions (Beach et al., 2015; Tian et al., 2016; Henderson et al., 2020). In most economic modeling applications that apply DGVM projections of NPP change, simulation results suggest that some (or most) forests will be more productive under higher atmospheric CO_2 concentrations, even with higher temperatures and shifting precipitation patterns. This productivity boost can result in a net welfare gain for the forest sector (Beach et al., 2015), but it could also put downward pressure on market prices for roundwood long-term as inventories increase.

However, uncertainties remain regarding the strength and efficacy of the CO_2 fertilization effect, including how photosynthesis rates may vary in the future with a combination of higher CO_2 concentrations in the atmosphere, warmer temperatures, and shifting water availability. Results from Gower (2003) and Lauriks et al. (2021) suggest that the CO_2 fertilization effect on NPP may fade over time in the absence of other silvicultural treatments, as forest systems age and become nutrient or water limited. Girardin et al. (2016) show no positive growth effect of warming and CO_2 fertilization in Canadian boreal forests. Results in Wang et al. (2020) also suggest that the CO_2 fertilization effect has declined over time due to reductions in nutrient and water availability. Similarly, Cunha et al. (2022) indicates that soil phosphorus limitations can limit the CO_2 fertilization effect. Baig et al. (2015) found that the interaction between temperature change and CO_2 fertilization is uncertain. Finally, CO_2 responses have traditionally been modeled using experimental data from FACE experiments or elevated CO_2 chambers (Thomas et al., 2017), and these studies are limited to select geographies, forest types, and limited time horizons. Further, we currently lack empirical estimates at the landscape or regional level on how CO_2 fertilization interacts with other management interventions (silviculture, rotational considerations, etc.).

Given these uncertainties, it is also important to consider climate impacts on the forestry sector separate from the future CO_2 fertilization response, which is the approach we take in this manuscript by focusing on temperature and precipitation impacts on forest productivity. We also build on previous literature by integrating empirical modeling of forest growth dynamics with a dynamic economic model of the U.S forestry system using recent climate scenarios from the most recent CMIP archives. This is the first study, to our knowledge, that links species-level empirical estimates of forest climate impacts in the U.S. with a structural economic model to quantify the potential nation-wide impacts of temperature and precipitation changes on the forest sector where temperature and precipitation impacts are decomposed from full climate impacts (including potential CO_2 fertilization).

2. Methods

We combine bottom-up estimates of forest productivity responses to climate inputs with dynamic economic modeling of the U.S. forest sector using the FASOM-GHG intertemporal dynamic optimization model of the U.S. land use sectors (forestry and agriculture). The model maximizes consumer and producer surplus measures for a variety of primary and secondary products while also representing physical resource constraints and heterogeneity in forest productivity by site class, forest type, and region. For this application, we apply only the forest sector component of the model. Using 5-year time steps for up to 100 years, the model yields a dynamic simulation of prices, production, management, consumption, GHG effects, and other environmental and economic indicators within the sector, under chosen policy scenarios. The following sections outline the general approach, including the development of forest growth adjustment factors and yield projections, structural modeling, and scenario design.

2.1. Climate scenarios

To compare outcomes under alternative climate futures for U.S. forests, we define baseline conditions as a “constant climate scenario,” which is represented using PRISM 30-year (1981–2010) mean annual temperature and precipitation 4-km resolution data.[3] Conditions with future climate change are represented using a high-emissions RCP 8.5 scenario[4] applied to the following six global climate general circulation models (GCMs) to simulate future temperatures and precipitation: CanESM2, CCSM4, GISS-E2-R, HadGEM2-ES, MIROCS, and GFDL-CM3.[5] The use of RCP8.5 (under multiple GCM-based scenarios), in addition to a no climate change baseline, allows for analysis of the widest potential temperature range while limiting the number of total scenarios necessary for running through the broader approach. An RCP with considerably lower forcing may not reach higher levels of warming, therefore leading to data gaps on forest response to plausible levels of change this century. Further, at the time of this writing, the only publicly available spatially downscaled climate projections for the U.S. in the CMIP6 archives correspond

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[3] PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004

[4] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[5] For each GCM, we acquired statistically downscaled Localized Constructed Analogs (LOCA) data for the continental U.S. for the period 2015–2100, using the USGS Geo Data Portal.

to higher radiative forcing scenarios, which necessarily limits the scenario scope of this analysis.

It is important to note that the selection of RCP 8.5 does not imply a judgment regarding the likelihood of that scenario. Recent research, such as Christensen et al. (2018), suggests that even in the absence of any global climate policy, RCP 8.5 has a higher forcing than the most likely future concentration pathway. However, while we acknowledge that RCP 8.5 may no longer be the most likely future from a forcing perspective, radiative forcing levels consistent with an RCP 8.5 world are still plausible, especially with strong carbon cycle feedback (e.g., methane emissions from tundra). Further, climate sensitivity on the high end of GCM projections could result in temperature and precipitation changes similar to the scenarios included in this study. By focusing on RCP 8.5, we exploit the variation in spatiotemporal temperature and precipitation change projections across GCMs to present a wide range of climate scenarios that range from moderate (or relatively optimistic) to extreme (pessimistic). While we do not consider lower radiative forcing scenarios, we do note that previous applications of the forest composition model (Phelan et al., 2021) applying CMIP5 climate projections resulted in lower levels of projected forest biomass loss for RCP 4.5 (1.6% by 2100 relative to a no climate change baseline) compared to RCP 8.5 projections (losses ranging 3.0%–8.6%).

2.2. Socioeconomic scenarios

In addition to multiple climate scenarios, we consider two alternative socioeconomic futures to reflect future potential differences in forest product demand driven by socioeconomic developments (e.g., population and income growth). Specifically, we model two alternative socioeconomic baselines that align with the Shared Socioeconomic Pathways (O’Neill et al., 2016): SSP2 (Business as usual) and SSP5 (Fossil-fueled development). Each scenario represents different demand growth trajectories for forest products, as described in Wade et al. (2019a, 2019b). SSP5 represents conditions with higher income and population growth, and therefore substantially higher demands for softwood lumber (due to higher housing starts). Each socioeconomic scenario is first simulated assuming no climate change (historical temperature and precipitation) and then simulated for the six alternative climate change projections.

We use SSP-specific projections of income, population, housing starts, and access to internet to drive changes in forest product demand in the U.S., as described in Latta et al. (2018), Jones et al. (2019), and Wade et al. (2019a, 2019b). Table 2 shows the difference in average annual demand growth rates for forest product categories between 2015 and 2100. There is a large difference in these growth rates between SSP2 and SSP5, where the latter sees substantial demand growth for some forest products (e.g., softwood lumber and panels).

2.3. Forest growth adjustment factors

To incorporate the spatially and temporally varying effects of future climate change on forest biomass growth into FASOM-GHG, we develop growth adjustment factors that are applied to the model’s baseline (constant climate) forest yield curves. We estimate these factors using a spatially disaggregated forest cohort composition model (Van Houtven et al., 2019), which is based on annual growth rate and decadal survival rate estimates (Horn et al., 2018) for 94 tree species and applied to the entire conterminous U.S. (CONUS). Each species-specific empirical growth and survival equation is a function of mean annual temperature and precipitation, as well as nitrogen (N) and sulfur (S) deposition, tree size, and stand competition.

The forest composition model uses the U.S. Forest Services (USFS) Forest Inventory and Analysis (FIA) 2000–2016 tree plot database to represent the starting cohort of mixed-age and -species forest stands in 2015. The 94 modeled species are found on 120,159 of the 124,731 FIA plots (96.3%) in the FIA dataset and, on average, represented 93.2% of plot basal area nationally. For each of these species and plots, the model applies the Horn et al. (2018) growth and survival functions to simulate the evolution of species composition and total above-ground tree biomass under alternative future climate (and deposition) scenarios in 10-year increments.

To specify future temperatures and precipitation across the CONUS for each climate scenario (i.e., GCM), we use statistically downscaled Localized Constructed Analogs (LOCA) (Pierce and Cayan, 2016)[6] data for the CONUS for the period 2015–2100. We processed these data to estimate annual average temperature (°Kelvin [K]) and precipitation (decimeters) at each FIA plot over the study period. These annual average values were then used to scale temperature and precipitation changes from 2015 to 2095 *relative to the constant/baseline climate scenario*, for each GCM, plot, and year. For temperature, the scaling factor is the degree (K) change in average annual temperature, and for precipitation, it is the percentage change in average annual precipitation. The scaling factors were applied to the PRISM baseline temperature and precipitation dataset to produce six scaled temperature and precipitation trajectories for each plot from 2015 to 2095, each starting from the same level in 2015. To correspond with the tree growth and survival, which are modeled in 10-year increments, the baseline and scaled temperatures and precipitation estimates for each plot and scenario are converted into 10-year averages for the decadal periods 2016–2025, 2026–2035, …,2086–2095. These 10-year temperature and precipitation averages serve as input data for the forest cohort composition model.

The growth adjustment factors are developed in two steps. In the first step, we run the forest composition model for all plots and scenarios from 2015 to 2095. These model runs are designed to simulate "natural" forest growth (i.e., with no harvest or replanting of existing forest stands included) under alternative conditions. By focusing on specific cohorts of trees, it is important to note that these natural growth simulations do not include recruitment, management interventions (such as forest type change post-harvest) or in-growth of new trees. In the second step, we calculate adjustment factors by comparing estimates of biomass growth at each plot and for each time increment between the baseline (constant climate) scenario and the six GCM-based climate scenarios.

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[6] Pierce, D.W., Cayan, D.R. and Dehann, L., 2016. Creating climate projections to support the 4th California climate assessment. University of California at San Diego, Scripps Institution of Oceanography: La Jolla, CA, USA.

Results of the first step are summarized for the entire CONUS (all plots combined) in Fig. 1. By 2095, with no harvest or replanting of existing forest stands, biomass for the modeled initial cohort of trees under the baseline constant climate scenario is projected to grow by 95% compared to 2015. In comparison, growth is projected to be lower than the baseline under all six climate scenarios. It ranges from 66.5% under the HadGEM2-ES GCM scenario, which is the model with the highest projected temperature increases for the CONUS, to 85.7% under the GISS-E2-R GCM, which has the lowest temperature increase projection.

For the second step, at each plot, time-period, and climate scenario, the growth adjustment factor is calculated as:

$$\mathrm{F}_{ijt} = \left[\mathrm{RB}_{it}^{j} \big/ \mathrm{RB}_{it}^{0}\right]$$

where

RB_{it}^{j}: forest cohort composition model estimate of total biomass on plot *i*, at the end of 5-year period *t*, under climate scenario *j* (where *j* = 0 is the constant/baseline climate scenario).

2.4. FASOM-GHG Integration

Plot-level projections of total biomass from the forest cohort composition exercise was then aggregated to produce forest yield tables for the fourteen primary forest types included in the FASOM-GHG model.[7] For each combination of forest type, FIA site class (1–5),[8] and FASOM region,[9] we apply the growth adjustment factors to build separate yield tables for each climate scenario. These tables provide information on potential biomass accumulation (growth rates) for different forest types, net of mortality. Because FASOM-GHG includes the option to harvest forest plots, separate climate-adjusted yield curves were developed for existing age classes, as well as for newly planted or naturally regenerated forests. For each individual model simulation, the model applies the corresponding set of forest yield tables as scenario-specific model parameters. Table ST1 in the supplement provides a direct mapping between FIA forest types and FASOM forest type combinations for different regions of the U.S.

Importantly, all forest types (existing, and new forest after harvest) adopt the scenario-specific yields beginning in the base period (2015), so the discrete climate futures and associated productivity curves are realized in the initial period, meaning the trajectory and related effects of the specific climate futures start manifesting after that point in time. Using an initial age-class distribution that aligns with the FIA in 2017 and alternative scenario-specific forest yield assumptions, our approach affects both near-term and long-term forest productivity, carbon sequestration, and economic harvest rules. Unlike static

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[7] Aspen, Douglas Fir (naturally regenerated and planted), Hardwood, Juniper, Maple, Oak, Oak-Pine (naturally regenerated and planted), Pine (naturally regenerated and planted), Softwood (naturally regenerated and planted).

[8] FIA site classes are a measure of land productivity, with higher productivity forests corresponding to higher site class values.

[9] Regions include: Corn Belt, Great Plains, Lake States, Northeast, Pac. Northwest (East), Pac. Northwest (West), Pac. South, Rocky Mountains, South Central, Southeast, Southwest. Figure S2 in the supplement provides a map of FASOM regions.

impact assessments, our modeling framework uses intertemporal optimization, which allows us to assess instantaneous and longer-term management responses to the alternative forest growth projections.

We use a recently updated version of the FASOM-GHG model for this analysis, with key updates documented in Wade et al. (2019a, 2019b) and Jones et al. (2019). One key development from Wade et al. (2019a, 2019b) is a new method for allowing endogenous forest type change, post-harvest. Here, a forest can change from one classification to another, within a given region and site class if that transition was observed in the FIA dataset since 2000. This method allows us to directly reflect intensive margin expansion in forest management post-harvest (e.g., a shift from natural regeneration to planted systems).

This analysis uses single-sector (forest only) simulations to focus on intensive margin management responses (i.e., changes in forest types, harvest age and management intensity) to climate change on the resource base and at the mill level (including capacity expansion for a given product within a region). Our simulations also capture market adaptation effects, including changes in supply and consumption of particular forest products. Notably, we do not account for a full range of potential climate change impacts from a transition to a RCP 8.5 forcing scenario. Specifically, we focus on market and management responses to projected changes in precipitation, temperature, and forest productivity across different climate scenarios, but we do not capture changes in disturbance regimes (fire, hurricanes, pests, etc.) or CO_2 fertilization. Further, we do not simulate alternative technology developments (e.g., improved forest genetics for planted systems) across SSP scenarios.

3. Results

Overall, we show that precipitation- and temperature-induced changes in tree mortality and productivity results in differences in national-scale market outputs (i.e., harvest levels, prices, and economic welfare) across simulation scenarios. We show that markets are fairly resilient in aggregate to projected changes in climate inputs (that is, price effects are relatively small), but changes in regional product output range from modest to large, with larger changes occurring over the longer term. Further, we find relatively large changes in regional inventories and carbon flux projections, as summarized in the following sections.

3.1. Spatiotemporal harvest pattern and inventory changes

Baseline (no additional climate change) projections of national log harvests for SSP2 and SSP5 have starting 2015 values of around 310 and 390 Mft^3, respectively, and each socioeconomic scenario shows increasing national harvest levels over time, driven by rising demands for forest products (Fig. 2) associated with growing income levels. Greater long-term growth in demand under SSP5 is driven by a steep rise in lumber demand, after an initial decline in pulp and paper products that causes a brief dip in harvests. SSP2 shows modest but consistent growth in harvest levels of about 0.5% per year.

Across climate scenarios, projected total harvest volumes reveal minimal impacts. Fig. 3 shows the net change in cumulative harvests relative to baseline at two different points in time (mid-century and end-of-century). For SSP2, total harvest levels are closely aligned to the baseline scenario, with cumulative harvests decreasing <1% for all climate scenarios. By the end of the century, total harvest reductions across climate scenarios are generally larger under SSP5 than SSP2, as greater demand growth raises harvest levels early in the simulation horizon, resulting in increased resource scarcity longer-term. This scarcity manifests in lower overall harvest levels toward end-of-century under climate scenarios that result in higher mortality and lower productivity than the baseline. The greatest (negative) impact on total harvests occurs by 2095, with cumulative harvests declining 6% and 3%, respectively, under the HadGEM2-ES and MIROC5 climate projections (i.e., those with the highest projected rate of temperature increase). Under SSP5, half (i.e., 3 of 6) of the climate scenarios show a slight increase in cumulative harvests by mid-century, followed by a long-term net decrease relative to the baseline for all but one scenario.

Projections using GFDL-CM3 consistently show an increase in total harvests, driven in part by the relatively high rates of future precipitation projected by this model coupled with high temperature changes that boost productivity in northern latitude forests. CanESM2 projects the largest increase in precipitation and relatively high temperature changes; however, this combination results in lower productivity by end-of-century relative to GFDL-CM3 due to the different spatial distribution of these impacts. The largest reduction in harvest by 2050 and 2095 are projected to occur under HadGEM2-ES, which projects much warmer temperatures but reduction in precipitation in the summer months, which drives tree mortality.[10]

Increasing harvest levels over time and urban development pressures[11] result in lower forest inventories over the long-term, both with and without climate change. For baseline conditions, Fig. 4 shows total forest inventory (standing live tree volume) across all forest types and ownership classes for the two SSPs. SSP2 shows increasing projected inventories until approximately 2050, when annual harvest levels start to exceed biomass growth on the landscape. SSP5 shows flat or declining inventory projections throughout the simulation horizon due to higher resource demands. By the 2095 period, SSP2 inventories fall approximately 9% relative to the initial period (2015) while SSP5 inventories fall approximately 30%.

A general decrease in forest productivity and higher mortality under RCP8.5 reduces inventories further relative to each respective SSP baseline (Fig. 5) over the long-term, ranging from moderate differences (<5%) to large inventory declines (>24% for the HadGEM2-ES scenario under SSP2). Under the climate scenarios, inventory loss as a percentage of baseline levels is generally smaller under SSP5 than SSP2. This occurs for two reasons. First, as shown in Fig. 3, in the long-term SSP5 harvests decline by more relative to baseline than SSP2 harvests. These lower harvests contribute to less inventory loss. Second, higher demand for forest products under SSP5 throughout the simulation horizon raises market prices and stimulates investment in the form of forest type change (e.g., switching to planted/managed forest types and shorter rotations in some regions [see Wade et al., 2019a,

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[10] Figures SM1 and SM2 in the supplemental material show relative changes in precipitation and temperature across an ensemble of climate projections, including the six scenarios used in this manuscript.

[11] Urban development causes an exogenous loss of forests regionally by 2050 for SSP2 and SSP5, respectively. See Wade et al. (2022) for a description of our urban development projections.

2019b for additional discussion]), and these management responses ameliorate longer-term inventory losses. Consistent with these management responses, SSP5 shows a discernible bump beginning in the 2080 simulation period driven by intertemporal adjustments and forest rotations under the high demand scenarios. That is, the temporary improvement in inventory projections under SSP5 relative to the SSP2 inventory loss projections is driven by rotational considerations and management investments made under SSP5 long-term demand growth.

Regionally, we project a mix of inventory growth and loss under climate scenarios and relative to the SSP baselines (Supplement Table ST1). In some regions, we project long-term gains in inventory under most climate scenarios (e.g., Rocky Mountains, Pacific Southwest). This is due to two main factors. First, higher mortality of some species under climate change incentivizes harvest, which is followed by changes to forest types that are better suited to a changing climate, either early on or in later periods in the simulation horizon. This type of change represents a potentially important adaptation response by the forest sector to climate change. For example, there is a shift in the Rocky Mountain region from some softwood forest typess (e.g., natural pine) to the more heat tolerant juniper. Second, some forest types, including juniper, experience higher growth rates in these regions due to projected increased average precipitation in some climate scenarios (e.g., the GFDL-CM3 scenario, which predicts higher precipitation in the Western U.S. under RCP 8.5). Other regions see moderate growth or declines in inventory early on, but large decreases by 2095 (e.g., the Corn Belt and Northeast regions). This positive change occurs in part due to harvest reallocations from regions such as the Southeast and South Central to these regions, which become more economically competitive under climate scenarios.

Consistently, the largest inventory losses occur in the Southeast and South-Central regions. These are two out of the three most productive timber supply regions in the U.S. currently. Results indicate that both the Southeast and South-Central regions could see a loss in total forest inventory of up to 40% or 24% by 2095 relative to the SSP2 and SSP5 baselines, respectively. Our framework identifies higher temperatures as an important factor driving productivity declines in currently highly productive southern forest types such as planted loblolly pine, slash pine, and longleaf pine. Thus, in our simulations, southern forest inventories and management are found to be particularly sensitive to projected long-term temperature increases. The warmest scenarios (HadGEM2-ES and MIROC5) result in a net loss in inventory and a slight change in the regional comparative advantage of timber production in the southern U.S. However, it is noteworthy that these projected inventory declines in that region are different from other recent studies (e. g., Thomas et al., 2017; Henderson et al., 2020), which show increased productivity to southern U.S. pine systems due to elevated CO_2 and changes in other management inputs (e.g., nitrogen fertilizer).

3.2. Economic surplus, prices, and mill capacity utilization

The projected change in total economic surplus relative to the no climate change baseline (i.e., the change in the net present value of consumer plus producer surplus) ranges from modest to significant across the climate scenarios. Table 1 shows the net change in economic welfare across our climate scenarios relative to each respective SSP baseline.

Here, we compute the full net present value of consumer and producer surplus for the full simulation horizon (the objective function value) and calculate the difference relative to the SSP baselines for each climate scenario. These differences are averaged over the 85-year simulation horizon to compute an average annual net present value impact metric for each corresponding scenario. Impact values range from highly negative ($2.6 billion per year in damages under SSP5, HadGEM2) to slightly positive ($200 million per year in benefits under GFDL-CM3, SSP5).

The magnitude of the impact increases from SSP2 to SSP5 given the higher market demand for forest products and associated market prices in SSP5. These market conditions increase the scarcity value of the resource, drive up costs, and result in larger negative consumer surplus impacts from higher prices with climate change. While the model responds to higher prices through intensive margin adaptation and investments, these investments are not enough to compensate for reduced productivity and higher mortality. At the extreme end, damages of $2.6 billion per year equate to approximately 2.5% of the economic value of the U.S. forest products industry (as a proportion of current U.S. gross domestic product (GDP)). Under high impact scenarios (HadGEM2-ES and MIROC5), damages are driven by consumer-side impacts due to higher prices. Restricted supply (inventories) under these scenarios reduces total production costs for the sector, but high price changes negatively impact consumers.

For most scenarios, however, impacts are relatively modest relative to the economic contribution of the forest sector as a whole (less than $1 billion per year). Modest impacts to consumer and producer surplus measures are consistent with projected changes in output prices in our climate scenarios relative to each baseline, which are <5% for most forest products throughout the simulation horizon. One notable exception for price effects is softwood lumber, which increases up to 32% and 28% for SSP2 and SSP5 (respectively) by mid-century under the HadGEM2-ES relative to the baseline, with price deviations continuing through end of century. Products such as oriented strand board (OSB) and panels also show larger deviations in price relative to the baseline.

Another adaptation response that facilitates this modest change in economic output is climate-driven changes in mill capacity. For example, Fig. 6 shows relative changes in mill capacity for softwood lumber, a key product class, for different regions of the U.S. The “Southern U.S.” represents the Southeast and South-Central regions in the FASOM-GHG model (Jones et al., 2019), while the “Rest of U.S.” represents all other agroforestry regions. Fig. 6 shows growth in softwood lumber mill capacity over time relative to the index period (2015). With no climate change, production of softwood lumber increases nationally, and southern mill capacity increases by 85% and 140% for SSP2 and SSP5, respectively, by 2095. For SSP5, there is a drop in mill capacity use in the South around 2080 driven by intertemporal adjustments in harvest and regional production patterns. Under the climate scenarios, however, the growth rate in southern mill capacity slows precipitously, particularly for HadGEM2-ES. Mill capacity and capacity utilization (and hence production) continues to expand in these regions under the climate scenarios, but this expansion slows under more extreme climate scenarios. This slower growth is due in part to lower productivity in planted pine systems under warming temperatures.

In contrast to the southern region, expansion in softwood lumber mill capacity utilization in other regions is lowest under the no climate change baselines. This difference occurs because the climate scenarios induce greater expansion in mill capacity in other regions to make up for lower productivity, declining inventories, and higher relative production costs in the southern U.S. forest sector. Thus, mill capacity expansion shows a slight migration to other regions – particularly to the Rocky Mountains and Pacific Northwest – in lieu of continued expansion in the Southeastern and South-Central U.S.

3.3. Projected carbon sequestration changes

Differences in forest growth and mortality, spatiotemporal shifts in harvests, and forest type changes also affect carbon sequestration capacity of U.S. forests. Fig. 7 shows annual forest carbon sequestration for aboveground carbon in atmospheric terms (e.g., negative values indicate net terrestrial sequestration while positive values indicate net emissions from forest growth, management, harvests, and mortality). Similar to other studies applying FASOM-GHG (Jones et al., 2019; Wade et al., 2019a, 2019b), we project forests will continue sequestering carbon over the next few decades, but in the longer term (and under all scenarios) the sector could revert from sink to source as demand growth and harvest removals outpace growing stock inventory. For SSP2, projected carbon sequestration is lower relative to the baseline for all scenarios, aside from the moderate impacts scenario GISS-E2-R. Starting from the initial model period (2015), this decline is driven by higher mortality and lower productivity under most climate scenarios. Results are similar for SSP5.

The estimated long-term effects of climate change on carbon sequestration vary across scenarios. Fig. 8 shows the average annual change in U.S. forest carbon sequestration in 2050 and 2095 (in $\mathrm{MtCO_2e}$) for each climate scenario relative to its respective SSP2 baseline. Carbon sequestration trends generally align with projected inventory changes, with a key difference being that carbon projections include various aboveground pools (e.g., litter and understory) not included in the standing inventory totals. Most climate scenarios show a negative net change in carbon sequestration over time. Under SSP2, the potential change in carbon sequestration ranges −129 to 63 $\mathrm{MtCO_2e}$ by 2050 and −102 to 63 $\mathrm{MtCO_2e}$ by 2095. Under SSP5, the potential changes in carbon storage range −120 to 57 $\mathrm{GtCO_2e}$ by 2050 and −64 to 74 $\mathrm{GtCO_2e}$ by 2095. For context, reductions in carbon sequestration by 2050 for the highest impact scenario are approximately 129 $\mathrm{MtCO_2e}$ yr-1, which is close to the low end of the potential mitigation range from U. S. agriculture and forestry reported in the 2021 U.S. Nationally Determined Contribution (United Nations Framework Convention on Climate Change (UNFCCC, 2021). Gains in carbon storage are driven by spatiotemporal differences in forest harvest, replanting, and regeneration trends relative to the baseline. Thus, there is considerable uncertainty in the long-term carbon storage implications of climate change, as carbon sequestration projections are sensitive to socioeconomic assumptions, assumed productivity parameters, and adaptation responses to environmental change.

Although market impacts are found to be modest, the economic costs (or benefits) of long-term ecosystem service provision could be substantial. To illustrate this point, we quantify the socioeconomic value of carbon stock changes by quantifying the net present value of sequestration changes over time using the social cost of carbon (Interagency Working Group on the Social Cost of Greenhouse Gases (IWG), 2021). That is, we convert projected U.S. forest carbon stock changes across scenarios to a net present value using the social cost of carbon (\$ per tCO_2e) to compare the benefits (costs) of sequestration (emissions) changes across scenarios.[12] We find high variation in the present value of changes in carbon storage relative to each SSP baseline, ranging from −\$4.1 to \$2.0 billion in 2050 and −\$32.5 to \$1.4 billion in 2095 (Fig. 9). To compute this impact metric, we multiplied the change in projected carbon sequestration in each time step by five (number of years) and the social cost of carbon at that point. We then calculate the net present value of sequestration changes using a 3% discount rate for each climate scenario.

Thus, for the highest impact climate scenarios, damages from lost carbon sequestration capacity in the near-term more are more than 50% greater than damages from consumer and producer surplus losses. Some of this lost sequestration capacity occurs due to lower simulated productivity and higher mortality of southern plantation pine systems, the most economically important monoculture production forestry system in the U.S. While this result differs from simulated yield growth in other analyses (which assume strong fertilization effects), it is important to note that potential temperature sensitivity in plantation pine systems could result in a reallocation of resources to other regions or a northern migration of plantation systems in the absence of improved climate resilience.

4. Discussion

4.1. Forest product markets could be more resilient to adverse impacts of climate change than carbon sequestration and related ecosystem services

Our analysis provides projections of U.S. forest markets, inventories, mill activity, and carbon storage under two socioeconomic scenarios. These socioeconomic scenarios are combined with alternative yield projections that correspond to historic climate and six projections of temperature and precipitation change for a single RCP (8.5) and alternative GCMs. We run simulations from 2015 to 2095 to quantify both near- and long-term impacts of alternative forest productivity assumptions.

An important takeaway from this analysis is that while the forest resource system could see dramatic changes under future climate scenarios, markets (economic systems) could be resilient to potential future productivity shifts. Given strong demand growth, the sector responds by shifting regional production, harvest and management patterns, and mill capacity utilization to achieve levels of national output for key forest products that are similar to the baseline. The greatest shifts in management are in 1) regions that see higher mortality or productivity declines coupled with high demand for wood (e.g., the South Central and Southeast, ST1 and ST2), and 2) region and climate scenario combinations that project relatively more precipitation in the future (including the Rocky Mountains and the Pacific Northwest). These spatiotemporal shifts result in adaptive management responses and market effects that limit changes to producer and consumer surplus measures.

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[12] We use 2021 social cost of carbon values beginning with a 3% discount rate. The initial SCC value in 2020 used in this analysis is \$42/tCO2e, rising over time.

4.2. Understanding climate change and carbon sequestration interactions is a critical area for future research

Our findings indicate a need for continued analysis of the interactions between changing climate inputs and the value of forest carbon sequestration capacity. For moderate climate impact scenarios analyzed for this study such as GFDL-CM3, which boosts productivity in some regions, the value of additional carbon sequestration capacity could be substantial. This result is consistent with findings in other research on forest climate impacts in the U.S. and globally that assume strong CO_2 fertilization effects under high radiative forcing scenarios (e. g., Tian et al., 2016; Beach et al., 2015). This suggests that under the right conditions, climate change could benefit the forest sector and associated ecosystem services, even in the absence of expanded CO_2 fertilization. However, most climate scenarios analyzed in this analysis result in a slight loss in carbon storage value over time, especially under SSP2. A relatively pessimistic climate projection in terms of temperature and water availability (HadGEM2-ES) results in the most substantial economic losses from reduced carbon storage, with much of this loss confined to the southern U.S.

While recent literature has addressed variation in carbon sequestration under alternative policy and socioeconomic futures (Tian et al., 2018; Wear and Coulston, 2015; Johnston et al., 2019), or under different model parameters (Johnston et al., 2019; Sohngen et al., 2001), economic modeling studies have not focused as much on interactions between climate change and forest carbon sequestration capacity of forests. Our analysis indicates that the effects of climate change on forest carbon in the U.S. vary substantially across the assumed future scenarios and across regions. Additional research is needed to better understand and decompose specific climate impacts on carbon sequestration as well as how adaptation responses, such as management intensification or forest type change, might ameliorate potential losses in carbon storage in the future.

4.3. A need for more comprehensive impact assessments in forestry

More research and analysis is needed that attempts to decompose climate change impacts on the forest sector into key components.[13] Fig. 10 presents a simple conceptual diagram of standing inventory over time for a representative forest type and uncertainty ranges of long-term climate impacts. The top figure shows illustrative and theoretical impact ranges from projected temperature and precipitation changes that, depending on forest type, location, and GCM projection, could result in increased or decreased inventory levels, ceteris paribus. Adding to this uncertainty would be the impact of fertilization that increases inventory (CO_2, atmospheric N deposition, or synthetic fertilizers), or disturbance that leads to higher mortality and hence lower inventory levels. Including fertilization and disturbance impacts expands the theoretical uncertainty range. The net impact of a given climate scenario would be the cumulative sum of these individual components (captured somewhere in the theoretical uncertainty range), and this would be further impacted by management changes that occur in response to market feedback (e.g., management intensification from higher prices as inventories decline).

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[13] Decomposition of potential climate impacts is lacking in the economic literature, though prominent examples such as the PINEMAP project exist in the silviculture and process modeling domains (e.g., Thomas et al., 2017).

The bottom figure shows added future uncertainty in the form of market feedback. If climate impacts induce a net negative effect on forest inventory over time, this would put upward pressure on prices, resulting in a near-term incentive to invest in management, thus negating a portion of the anticipated long-term decline in inventory. Alternatively, lower productivity could result in higher relative costs over time, contraction in regional mill capacity, and reduced investment in the resource base, which would further reduce inventory over time. If climate change significantly boosts productivity of a given forest type relative to others via fertilization, this could shift comparative advantage in favor of this forest type, which could increase relative harvests and decrease inventories. Alternatively, productivity boosts from fertilization could increase standing inventories over the long-term and suppress prices and management (see Henderson et al., 2020 for an example of this impact).

4.4. Anticipating productivity benefits from CO_2 fertilization could alter future management patterns

While we do not represent CO_2 fertilization in the forest composition model, we develop hypothetical scenarios to test the sensitivity of our market projections to scenarios that include a marginal productivity boost from rising CO_2 concentrations. Given the uncertainty in long-term CO_2 fertilization effects and interactions with other climate inputs, sensitivity scenario assumptions are based on recent empirical estimates on the effect of CO_2 fertilization on US forests (Davis et al., 2022). Hypothetical scenarios are analyzed relative to the HADGEM2-ES scenario, and include:

1. CO2_20: A 20% uniform increase in annual increments, consistent with the estimated CO_2 fertilization effect for all forest types age 1–25 years as reported in Davis et al. (2022).
2. CO2_40: A 40% increase in annual increments, presenting an optimistic CO_2 fertilization effect that recognizes higher CO_2 concentrations under RCP 8.5.
3. CO2_20–40: A split CO_2 fertilization effect of 40% for planted forests and 20% for all other forests, reflecting potential complementarities between CO_2 and other silvicultural decisions.

While these scenarios are illustrative, the CO_2 effects are in line with recent studies (Davis et al., 2022; Terrer et al., 2016). Results from sensitivity runs show modest market changes (slight decreases in prices) but no significant changes in projected inventory over time relative to the HADGEM2-ES scenario without CO_2 fertilization (<1% by 2100). This result occurs due to the relatively inelastic demand assumptions for forest products in the model and exogenous trade assumptions. Projections result in similar levels of total harvests and inventory change over time, even with accelerated levels of growth under the illustrative CO_2 fertilization scenarios.

However, results show that accelerated growth from CO_2 fertilization causes temporal tradeoffs in carbon sequestration services. Carbon sequestration increases near term with higher forest growth, but this effect diminishes over time, and net annual emissions increase with CO_2 fertilization relative to the base HADGEM2-ES scenario (Table 3). Higher emissions long-term are due to different management strategies over time – including reduced investment in new planted forests, which falls 1%–2.2% relative to the base HADGEM2-ES scenario. Anticipated productivity improvement from CO_2 reduces the economic incentive to increase management intensity and shifts spatiotemporal management strategies over time such that net emissions after mid-century increase with CO_2 fertilization relative to the base HADGEM2-ES case. With higher anticipated productivity for all forest types, the sector invests less in adaptation and forest production shifts toward inventory drawdown after mid-century. This result illustrates the importance of accounting for market feedback and potential management responses to anticipated productivity shifts in climate change projections.

More economic research is needed that integrates empirical or modeled assessments of climate change on forest productivity to decompose the various impact sources and to better understand how climate-induced changes in productivity could affect markets and alter regional management patterns. Our analysis attempts to do this by focusing on forest type and regionally-specific estimates of projected precipitation and temperature impacts on forest productivity and mortality and linking these estimates with a structural economic model of the U.S. forest sector. Future research will attempt to quantify a broader range of impacts and explore interactions between market changes and shocks on forest productivity and mortality.

4.5. Market-driven changes in management potentially more impactful than temperature and precipitation impacts on productivity

We show that the U.S. could experience moderate economic losses in the forest product sector and large losses in carbon sequestration capacity. Under the most pessimistic climate scenarios analyzed (HadGEM2-ES and MIROC5), some of the most productive timber-producing regions in the U.S. see diminished productivity and steep inventory declines, but adjustments in regional harvest patterns, forest investments and mill capacity utilization help to temper these effects (positive market feedback). In general, forest management trends, markets, and harvest patterns appear more sensitive to socioeconomic outlooks than reduced productivity from changing temperature and precipitation. For instance, inventory declines substantially under the SSP5 baseline under higher demand growth for forest productivity. By 2100, standing inventories are approximately 24% lower under SSP5 than SSP2, and the net forest C flux is also lower under SSP5 throughout the simulation horizon.

Notably, our analysis does not account for potential production reallocation to other regions of the world. If the U.S. were to experience diminished productivity for commercial forest types like southern pine, then markets could adjust by importing greater quantities of softwood logs and lumber. In our current analysis, imports/exports are fixed and exogenous. Thus to test whether our projected inventory and carbon stock changes are robust to international market adjustments, we explore sensitivities in imported softwood sawlog and softwood lumber by increasing these exogenous import projections by 50% for two of the highest impact scenarios (HadGEM2-ES and MIROC5). Results suggest that our standing forest inventory projections are fairly robust to these expanded import scenarios – national inventories expand slightly under HadGEM2-ES (3.3% by 2050 and 0.8% by 2100) and MIROC5 (−0.8% by 2050 and 1.4% by 2100) relative to the base model import assumptions.

However, increasing imports of softwood lumber and sawlogs reduces total harvests and increases carbon sequestration in the near term.

In summary, market assumptions are important drivers of long-term forest management and inventory changes, and future analyses should carefully consider interactions between socioeconomic, climate, and trade policy scenarios.

5. Conclusion

Our analysis is a first-of-its kind attempt to link a detailed forest cohort composition model with a structural dynamic optimization economic model of the U.S. forest sector. We apply spatially explicit and species-specific empirical estimates of forest yields under different climate scenarios to forest types, site classes, and regions in the FASOM-GHG model. With this combined framework, we conduct model simulation runs for two socioeconomic scenarios and six alternative GCM projections of RCP8.5 (a high warming future). Results show relatively modest impacts on economic welfare and markets, but large effects on regional inventories and carbon sequestration rates.

We provide examples of key adaptation responses such as forest type change and regional reallocation of harvests to climate scenarios and alternative productivity assumptions, including forest type change and regional mill capacity expansion/contraction. Finally, we show that while markets are simulated to be resilient to climate change, carbon sequestration capacity varies substantially, and warmer/dryer climate projections could result in significant economic damages from reduced terrestrial carbon storage. Most of our scenarios differ from the economic modeling literature, as these studies show large inventory changes in the future driven primarily by CO_2 fertilization.

There are important limitations of this study that warrant future research. Importantly, the climate changes incorporated in this analysis are those represented by changes in long-term trends in average annual temperatures and precipitation. In its current form, the model does not incorporate the potential additional effects associated with increased temperature or precipitation variability, changes in pest pressures, or other potential climate effects. Further, we are projecting productivity changes over the long-term, well outside the range of historic observation.

Second, the omission of CO_2 fertilization in the forest composition model is potentially important, but uncertainty around this effect and its lasting effect on forest yields warrants new empirical research and modeling that go beyond the scope of this study. Illustrative simulations of the most pessimistic climate scenario (HADGEM2-ES) with assumed CO_2 shifters show similar market trends as the base HADGEM2-ES case, but also indicate that anticipated productivity benefits from CO_2 can shift management regimes, reduce adaptation responses (forest planting), and result in tradeoffs in the provision of carbon sequestration over time.

Third, we present a single-sector and U.S.-only perspective to isolate intensive margin adaptation responses in U.S. forestry, but this ignores potential extensive margin adjustments (e.g., afforestation) to climate change and resulting impacts on other sectors such as agriculture. Further, this U.S. focus ignores production and consumption responses in other regions of the world (recognizing the importance of the U.S. forest sector to global market). We address this limitation through sensitivity analysis of expanded import scenarios, finding consistent levels of inventory change but meaningful differences in forest management and carbon sequestration trends early in the simulation horizon.

Finally, we focus on a high emissions (and high impact) scenario, thus we only compare outcomes under business-as-usual climate and elevated CO_2 concentrations consistent with an RCP 8.5 future, which according to IPCC (2021) is potentially less likely to occur than in previous IPCC assessments. Despite these limitations, our analysis presents an approach for projecting the impact of long-term termperature and precipitation impacts on the forest sector.

Our results offer insight into potential adaptation responses to global change in important timber-producing regions. We also highlight the relative sensitivity of forest management and market projections to alternative climate and macroeconomic scenarios, showing that the combined impacts of high market demand growth and climate change-induced reductions in forest productivity could result in significant declines in carbon sequestration capacity and forest inventory. Our results fill an important research gap on how the U.S. forest sector might respond to extreme changes in temperature and precipitation and can help policy makers evaluate complementary policy incentives to maintain or increase forest productivity and carbon sequestration rates under different climate futures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This research was funded by the U.S. Environmental Protection Agency under contract #68HERH19D0030. The views expressed in this article are those of the authors and do not necessarily reflect those of their affiliated institutions, including the EPA.

Data availability

Data will be made available on request.

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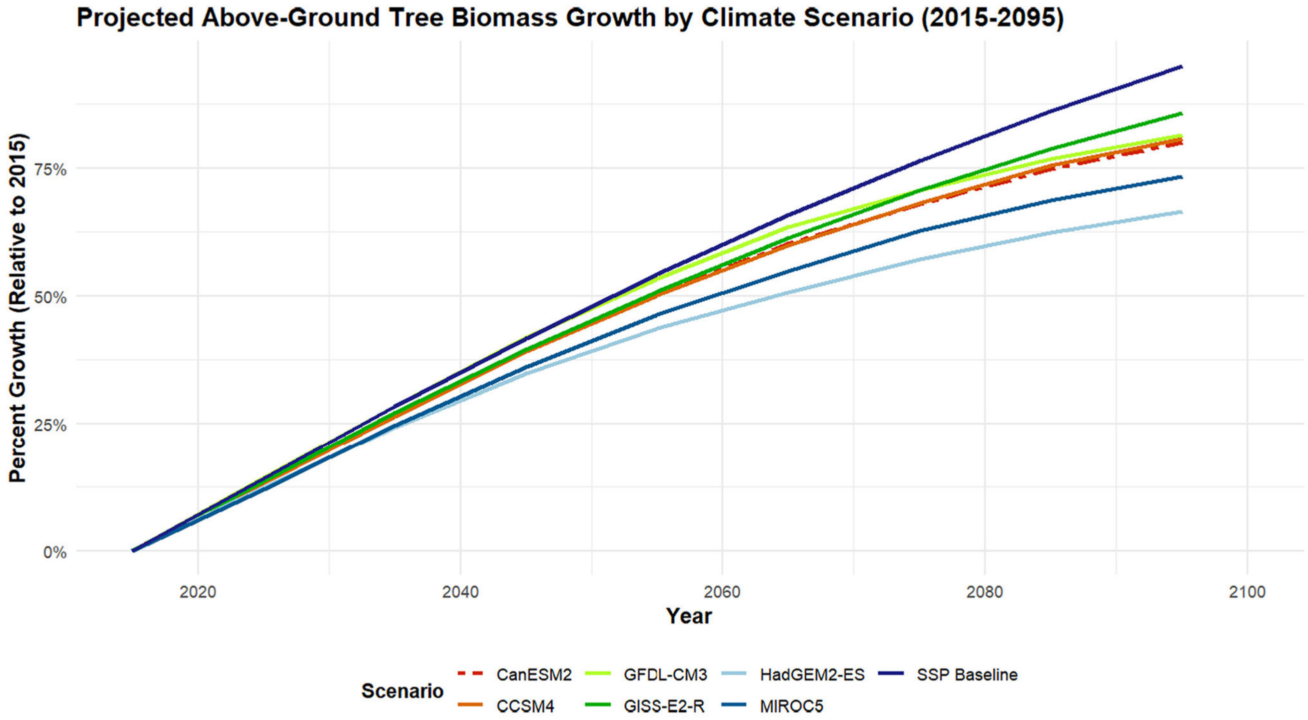

Fig. 1.

Projected aboveground tree biomass growth by climate scenario relative to the base period (2015).

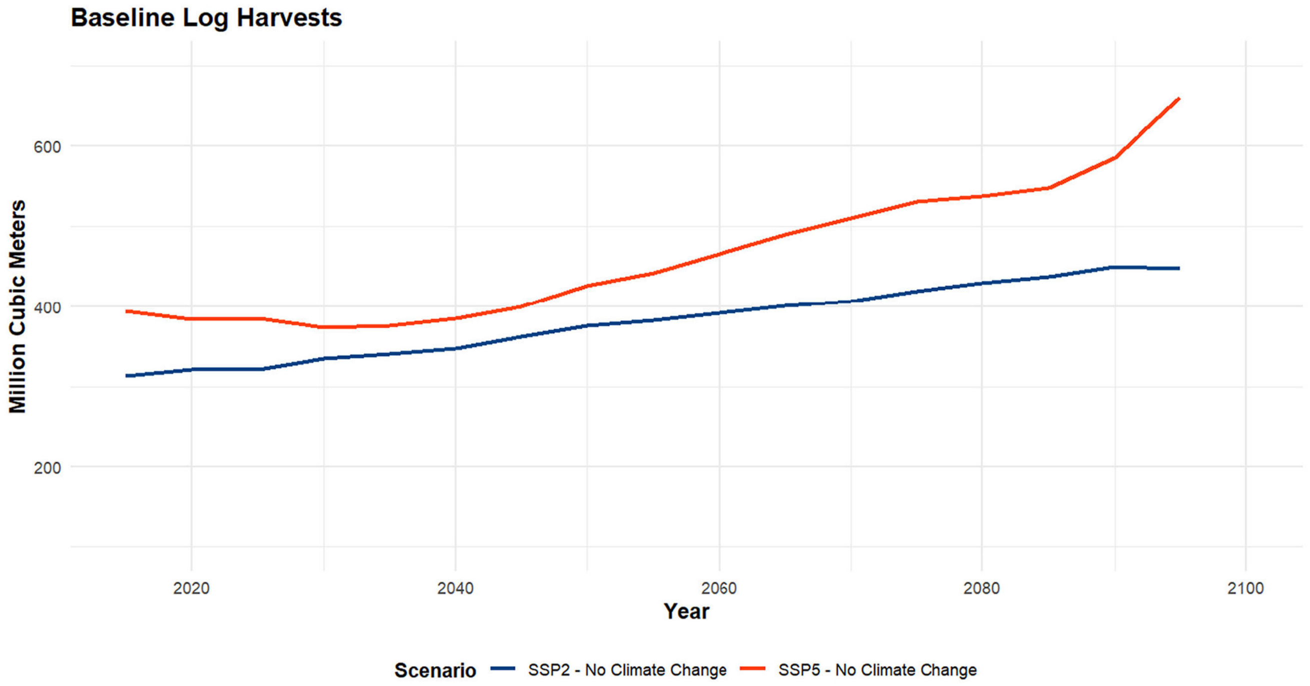

Fig. 2.

National log harvest totals (pulp and sawlogs) over time and for each respective SSP baseline in million cubic meters (no climate change).

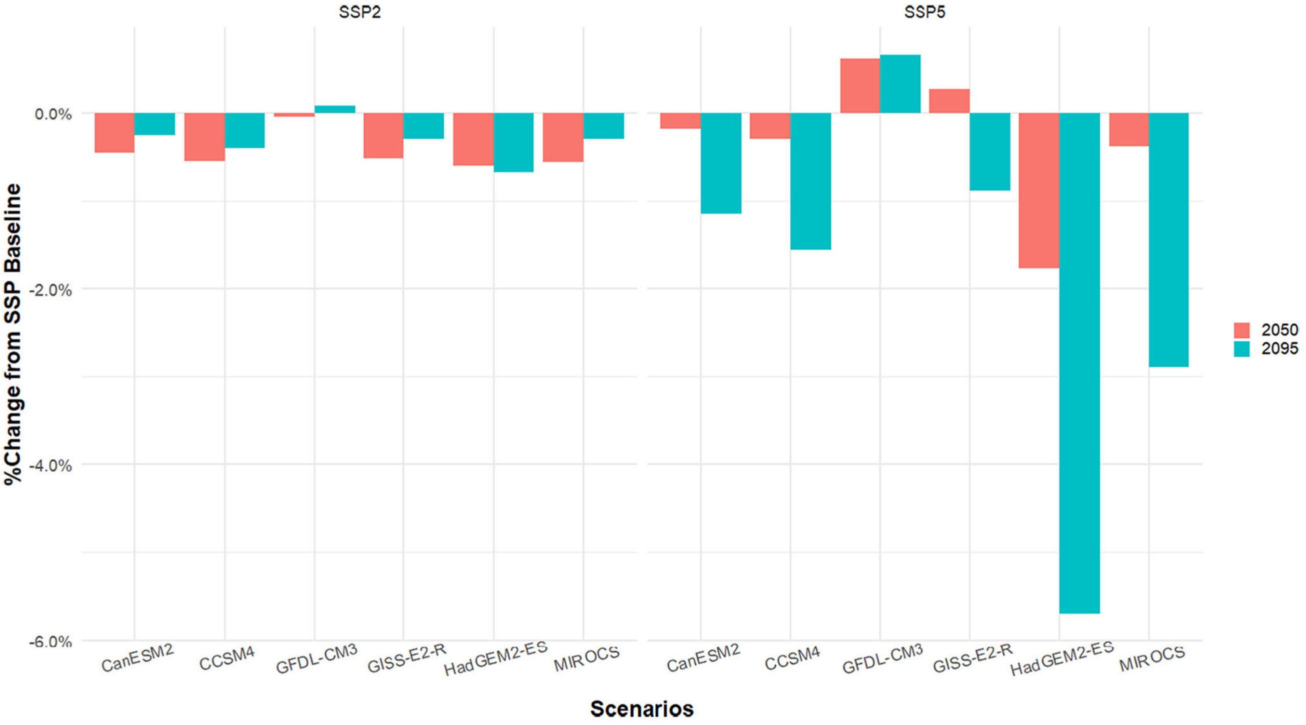

Fig. 3.

Percent change in cumulative log harvests (national) for each climate scenario relative to its respective SSP baseline.

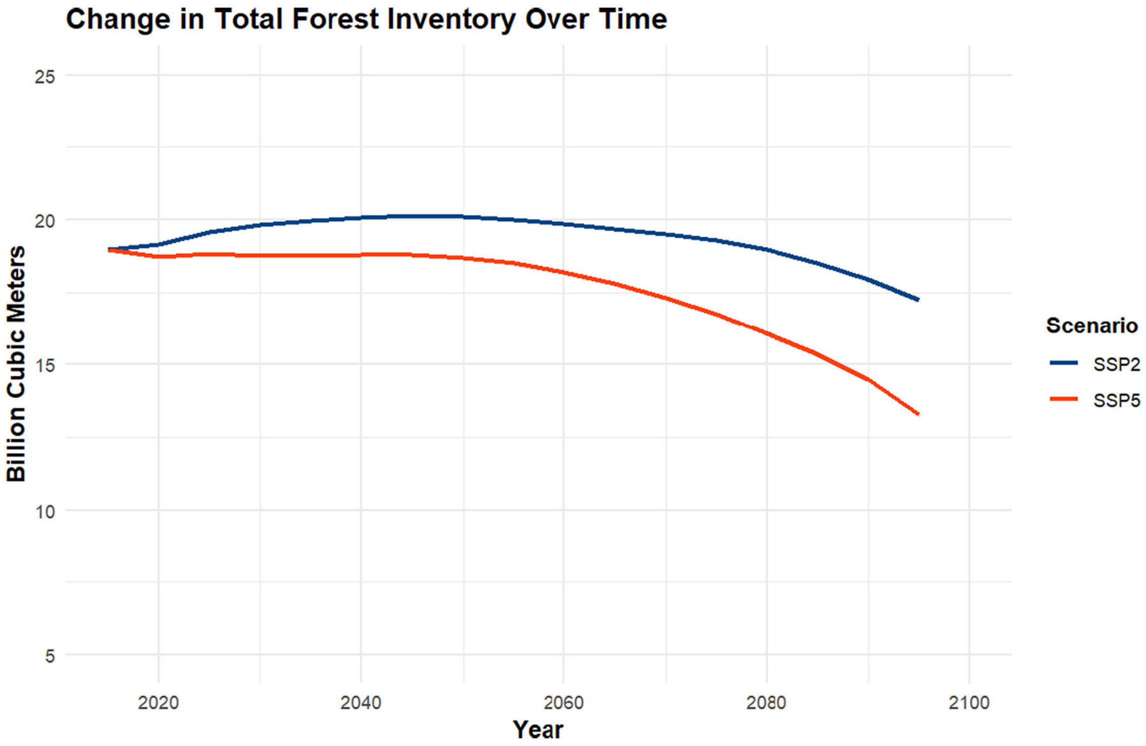

Fig. 4.
Change in total forest inventory over time under each SSP (no climate change) baseline simulation (Billion m^3).

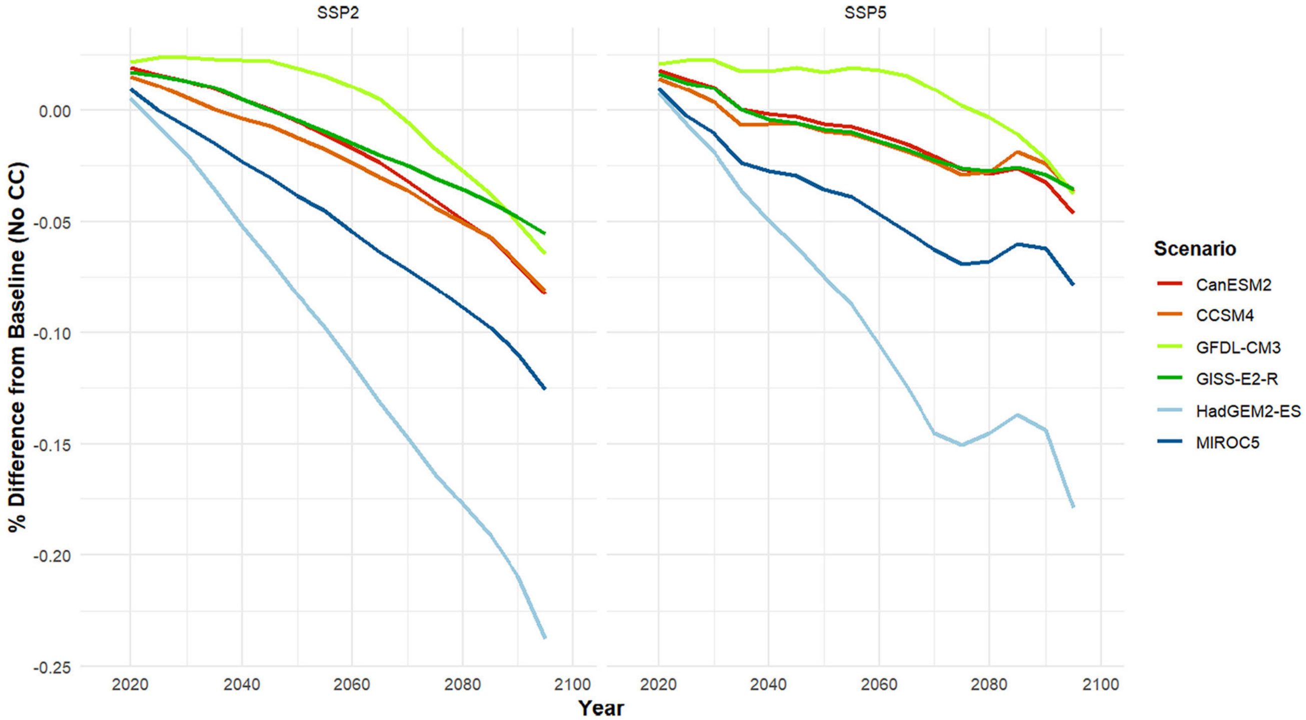

Fig. 5.

Inventory change over time under climate scenarios relative to each SSP baseline (decimal values represent percentage changes relative to the baseline).

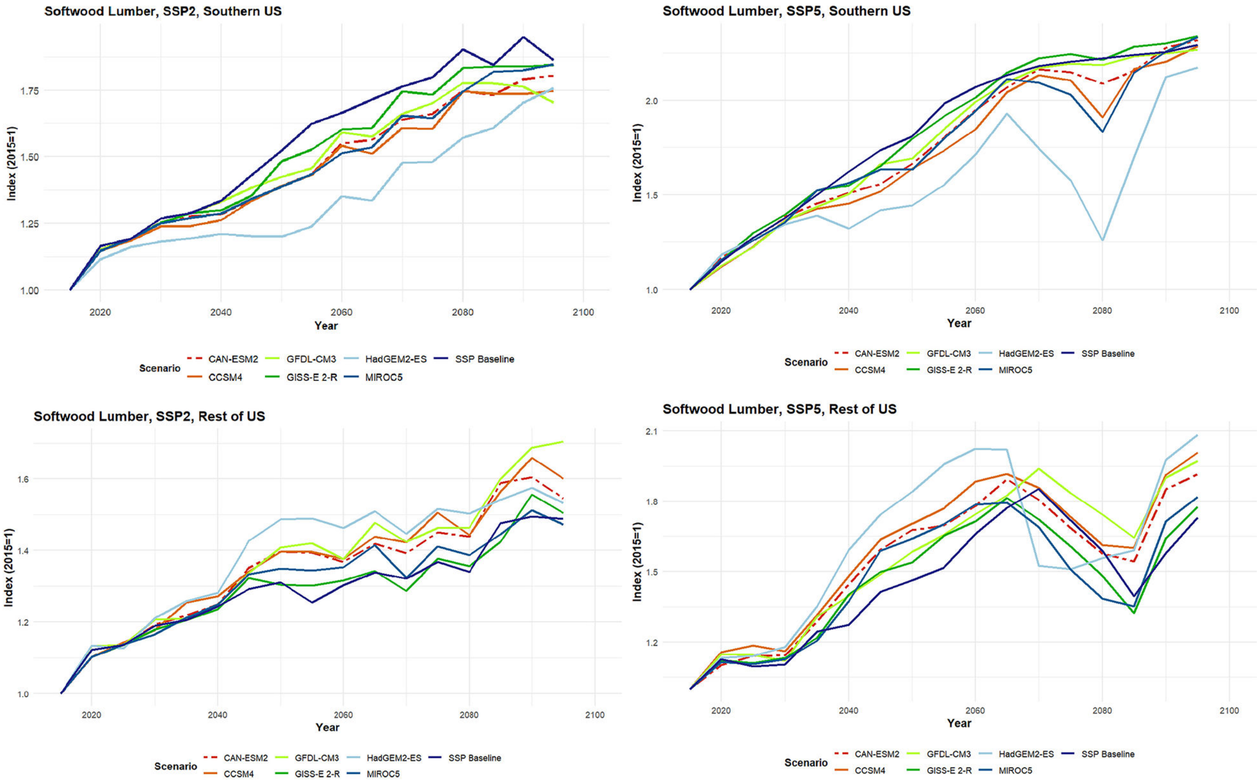

Fig. 6.

Regional mill capacity expansion for softwood lumber under alternative climate scenarios and SSPs.

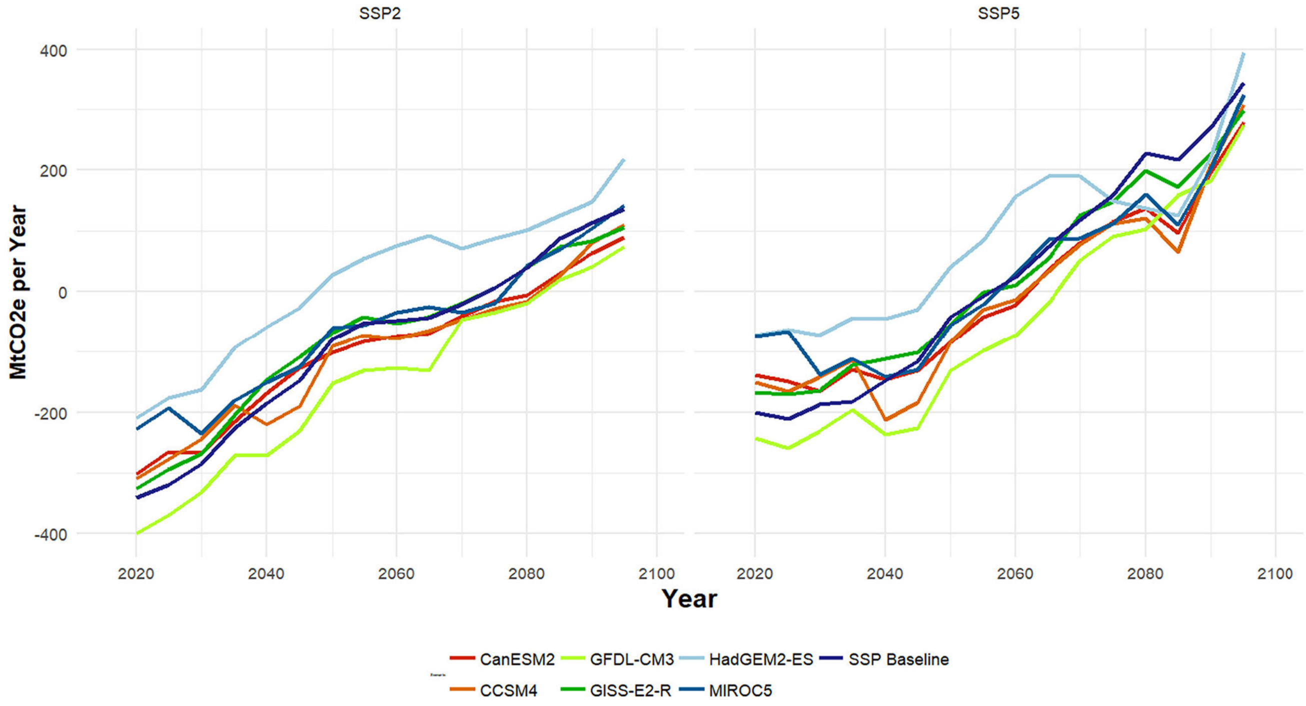

Fig. 7.

Projected carbon sequestration from U.S. forests across scenarios (MtCO$_2$e per year—represented in atmospheric accounting terms).

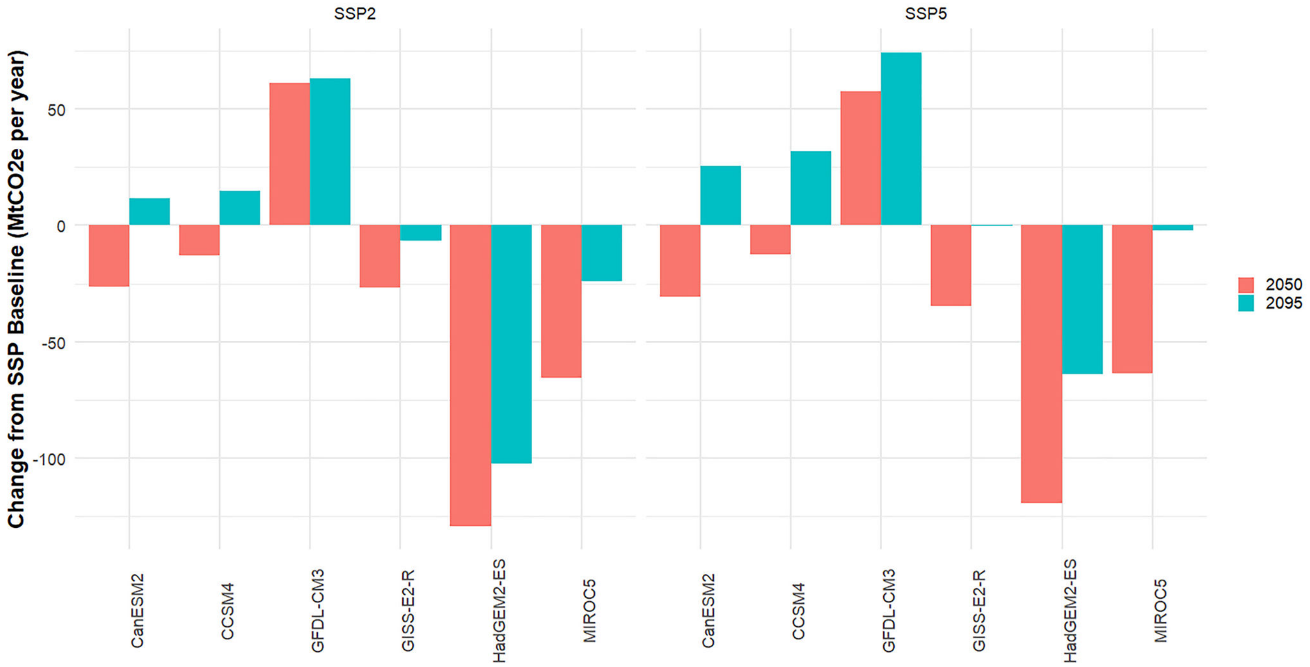

Fig. 8.

Change in average annual carbon sequestration over time under climate scenarios relative to each SSP baseline ($MtCO_2e$).

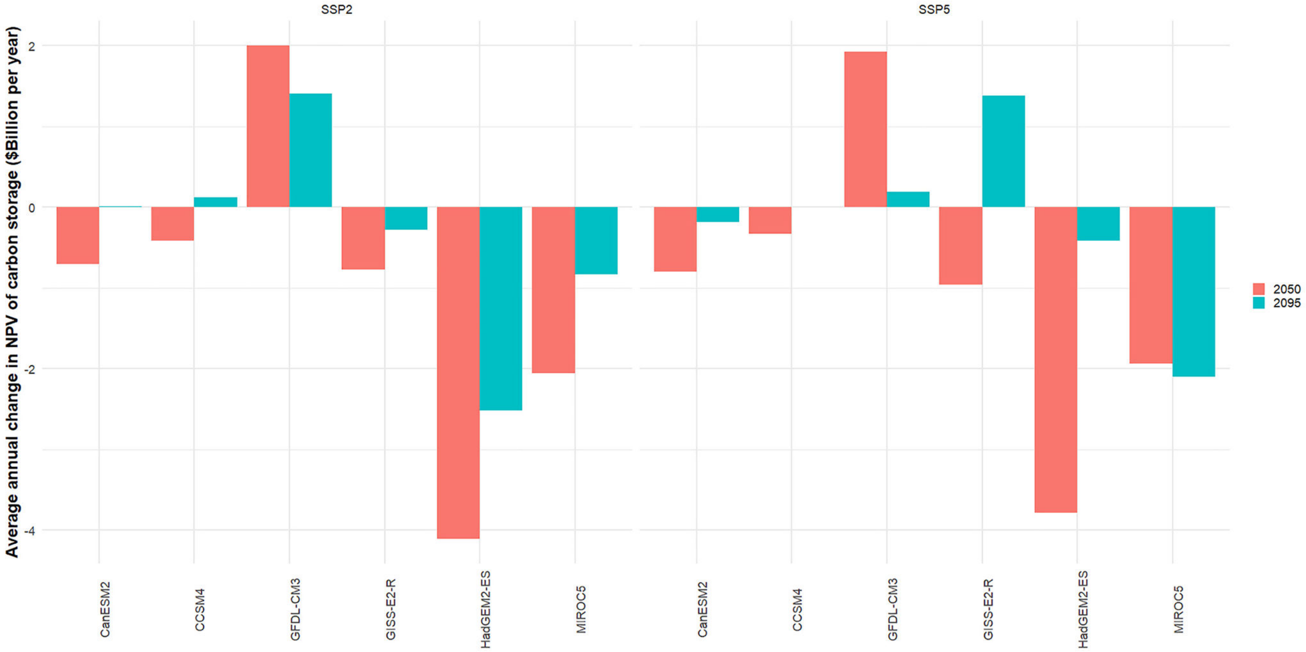

Fig. 9.

Change in the economic value of average annual carbon sequestration changes ($Billion per year).

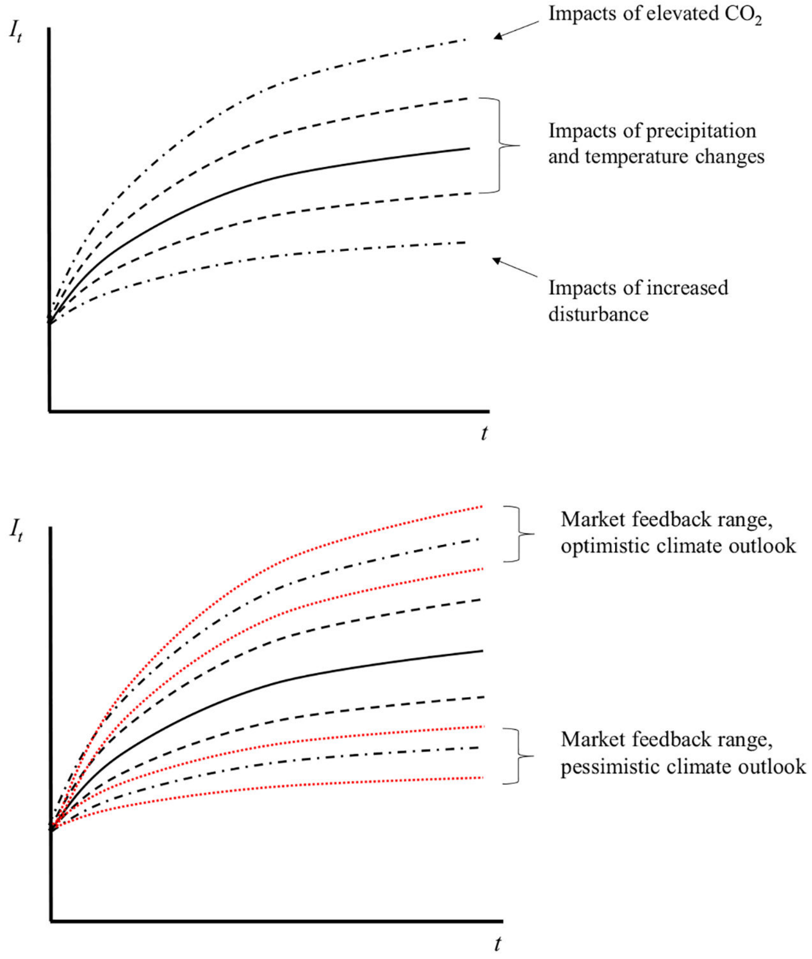

Fig. 10.

Hypothetical uncertainty range of potential climate change impacts on standing inventory of a representative forest type (I_t) over time (t), with and without market feedback and management responses.

Table 1

Average annual demand growth rates by SSP baseline for different forest product categories (2015–2100).

	SW_Lumber	HW_Lumber	SW_Plywood	HW_Plywood	OSB	OthPanels	MDF	Newsprint	P_W_Paper	Paperboard	Tissue
SSP2	0.9%	0.4%	0.7%	0.8%	1.8%	1.2%	1.2%	−1.1%	−1.0%	0.4%	0.4%
SSP5	2.9%	0.7%	3.7%	1.7%	6.4%	2.6%	2.6%	−1.2%	−1.1%	0.7%	0.7%

Table 2

Difference in consumer and producer surplus measures relative to each respective SSP baseline (Million USD per year average from 2020 to 2095).

	SSP2	**SSP5**
CAN-ESM2	−122	−556
CCSM4	−147	−632
GFDL-CM3	−12	201
GISS-E2-R	−127	−599
HadGEM2-ES	−509	−2604
MIROC5	−256	−1320

Table 3

Average annual net CO_2 flux from forest sector harvests and growth over two portions of the simulation horizon (Mt CO_2e yr^{-1}).

	HadGem2-ES	**HadGem2-ES: CO2_20**	**HadGem2-ES: CO2_40**	**HadGem2-ES: CO2_20–40**
Average Annual CO2 flux (2020–2050)	−54.5	−73.7	−94.1	−88.8
Average Annual CO2 flux (2050–2080)	135.6	156.1	175.3	150.3