Journal of Forest Economics, 2019, 34: 7–45

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

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ABSTRACT

This paper presents a series of narratives that can be used to define possible future trends in the global forest sector across the Shared Socioeconomic Pathways (SSPs), which we refer to as Forest Sector Pathways (FSPs). SSPs are part of a new scenario framework established by the climate change research community that facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The SSPs are based on five narratives describing alternative socio-economic pathways, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development. The long-term demographic and economic projections of the SSPs depict a wide uncertainty range consistent with the scenario literature. However,

*We thank the participants of the Forest Sector Modelling workshop at IIASA in March 2017 for their valuable input. A portion of this research was supported by the USDA National Institute of Food and Agriculture, McIntire-Stennis (project number ME041825), through the Maine Agricultural & Forest Experiment Station, the U.S. Environmental Protection

ISSN 1104-6899; DOI 10.1561/112.00000441

the literature on sector-specific narratives outside of the energy and industrial sectors is currently limited, and this paper seeks to build upon existing SSP storylines by elaborating on the potential implications of SSP-related variables on forest resource management, forest product markets, wood-based bioenergy expansion, and other relevant trends in global forestry. The global forestry pathway narratives presented in this paper build on alternative futures research and multi-model inter-comparisons by further developing recent narratives with additional detail on specific issues related to the development and use of our world's forests.

Keywords: Land use policy, forest carbon, bioenergy, consumption, technological change, modelling

JEL Codes: Q23, Q27, Q28, Q54, Q56

1 Introduction

Over the past century, forests in the northern hemisphere have become a large carbon sink, sequestering around 2.4 gigatonnes of CO_2 equivalent ($GtCO_2e$) per year in recent years (IPCC, 2013; Pan *et al.*, 2011). Most of this sequestration has occurred as forests have reverted from agriculture to forest lands and forests have aged (Mather, 1992; Kauppi *et al.*, 2006; Birdsey *et al.*, 2006). Looking forward, however, there is concern that the accumulation of carbon in this land-based sink may slow, and recent literature indicates that this slowdown is already occurring (Nabuurs *et al.*, 2013; Coulston *et al.*, 2015). Furthermore, the trend of net forest carbon emissions in the southern hemisphere could continue as global population and per capita income increase and place additional pressure on land use.

There is uncertainty over what land use and carbon emissions will indeed be in the future, which can be influenced by a number of major socioeconomic, demographic, technological, lifestyle, policy, and institutional trends. As a result, the global change research community has developed a set of narratives known as shared socioeconomic pathways (SSPs). These SSPs have been developed to clearly, consistently, and logically present trends for five distinctly different pathways about future socioeconomic developments as they might

Agency (EPA) (Contract EP-BPA-16-H-002, Call Order #EP-B16H-00176), the USDA Forest Service Southern Forest Research Station (16-JV-11330143-039), and the USDA National Institute of Food and Agriculture, McIntire-Stennis (project number WIS01899) at the University of Wisconsin- Madison. The views and opinions expressed in this paper are those of the authors alone and do not necessarily state or reflect those of the EPA, and no official endorsement should be inferred.

unfold in the absence of *explicit* policies and measures to limit climate forcing or to enhance adaptive capacity (Riahi *et al.*, 2017; O'Neill *et al.*, 2017). Previous work has looked at the impact of SSPs on global land use, however the focus has typically used integrated assessment models (IAM) with relatively crude representation of the forest sector, with results aggregated across regions and forest type (Riahi *et al.*, 2017; Popp *et al.*, 2017). To elaborate specifically the forest sector development, this paper develops detailed narratives for how the global forest sector could vary across the five different SSPs, through the development of Forest Sector Pathways (FSPs). Key impacts include forest area, timberland management intensity, carbon sequestration, and consumption of forest products. Furthermore, we present a detailed set of narratives for several forest-specific outputs as well as methods used to translate these narratives into quantitative model parameters.

The future of the forest sector, particularly forest area, harvest levels, and carbon sequestration potential remains highly uncertain. Income levels are expected to rise (Dellink *et al.*, 2016), as is population to at least 2050 (KC and Lutz, 2017), leading to increased competition for land use from agriculture (Bodirsky *et al.*, 2015). Rising income levels and demand for forest products and other forest ecosystem services can drive investment in forest resources, resulting in greater terrestrial carbon storage (Tian *et al.*, 2018). At the same time, higher levels of income and population could also place additional pressure on land remaining as forest to be more productive and/or be harvested, which could have an ambiguous effect on total carbon storage. Furthermore, there is uncertainty in how the demand for forest products will evolve in the future, which may lead to different harvest patterns and land use dynamics over time (Popp *et al.*, 2017). Undoubtedly, societal factors like population, income, and trade, will influence the carbon sequestration potential of the forest sector, and there is a growing literature that seeks to understand how market and policy forces may drive forest carbon trajectories, even at local scales (e.g., Latta *et al.*, 2018).

Consistent sector-specific SSP storylines are particularly desirable for forestry as the global forestry sector is expected to play a key role in achieving long term climate stabilization targets and other sustainable development goals (Forsell *et al.*, 2016; Grassi *et al.*, 2017). However, even with the emphasis on forestry and other land use mitigation sources in recent IAM projections, little work to date has focused on developing SSP storylines in the context of forest resource utilization, forest product markets, and forest-based industries. SSP narratives developed with a forest sector focus can highlight potential important interactions between macroeconomic growth, policy drivers, forest product markets, biophysical attributes of the forest resource system (including yield growth), harvest dynamics, and other relevant forest management decisions. Ignoring these interactions or not accounting for heterogeneity of the forest resource base across regions can potentially over-or under-state the global forest sector's potential role in mitigating climate change.

This paper does not represent the first attempt to catalog possible developments in the land use sectors across alternative SSP scenarios, though we do attempt to build on previous efforts that offer a more aggregate perspective of variables and policy- and market-oriented trends that are relevant to forestry. Nearly all IAM analyses have handled forest resource management and product markets in an aggregate fashion and typically offer a detailed suite of mitigation technologies and associated costs, but lack significant details for how specific elements of the forest sector were accounted for, nor how they may be able to adapt under these alternative pathways. Furthermore, recent advances in forest economic modeling and policy analysis offers significant additional detail relative to IAM studies, but lack stylized scenario inputs and policy assumptions to consistently inform different modeling efforts.

Given the relative importance of forests globally in contributing to long-term climate stabilization and other sustainable development goals, developing SSP narratives with sufficient forest sector detail can improve both integrated assessment and land use sector modeling efforts that rely on the basic SSPs to inform future macroeconomic and policy scenario inputs. In addition to offering additional detail on how different SSP assumptions might influence the forest sector, this paper also adds to a growing literature that uses general SSP assumptions to develop detailed narratives regarding future trends for sectors of the economy or resource bases that could be greatly impacted by long-term macroeconomic, policy, and environmental changes. For comparison, a similar approach was recently undertaken to develop oceanic system pathways (OSP) for oceanic resources and fisheries (Maury *et al.*, 2017).

The paper is organized as follows. The next section provides an overview of the methods used to develop the global SSPs and FSPs. The following section presents the results of the five FSP narratives, including details on how key elements of the forest sector could be impacted under the various FSPs. Section four discusses some implications of the FSPs and how they could be used for policy analysis. The final section provides a brief conclusion and suggestions for future research.

2 Methodology

2.1 Shared Socioeconomic Pathways

Global level SSPs have been developed to specify five distinct pathways on the development of socioeconomic futures as they might unfold in absence of any *explicit* assumptions or policies to limit climate change or enhance adaptive capacity, nor do they account for the potential impacts of climate change[1] (Riahi *et al.*, 2017; O'Neill *et al.*, 2017). The intentional exclusion of climate policy and climate change is consistent with the notion that these broad pathways should be used in subsequent studies on mitigation and adaptation without over-constraining the structure of the analysis (O'Neill *et al.*, 2017). While these SSPs are relatively new, the concept of developing a set of alternative futures has a long track record of helping to inform global environmental assessments (see Meadows *et al.*, 1972; Gallopin *et al.*, 1997; Nakicenovic *et al.*, 2000). Furthermore, while the SSPs are primarily intended to enable climate change-focused research and policy analysis, the broad perspective and set of indicators means that they can also be used for non-climate related scenarios (O'Neill *et al.*, 2014).

The core component of the SSPs is detailed narratives designed to span climate change mitigation and adaptation challenges (Figure 1). The current set of SSPs range from a 'sustainable' world that is highly adaptive and faces relatively low socio-economic challenges (SSP1, Sustain ability) to one that is quite fragmented with relatively weak global institutions and faces high population growth (SSP3, Regional Rivalry), thereby potentially creating relatively high challenges. There are also two asymmetric scenarios that assume high adaptation but low mitigation challenges (SSP4, Inequality), and vice versa (SSP5, Fossil-Fueled Development). A fifth narrative (SSP2, Middle of the Road) describes moderate challenges of both with the intent to describe a future pathway where development trends are not extreme in any dimension and hence follow a middle-of-the road pathway relative to the other SSPs. SSP2 is often referred to as the 'business as usual' pathway as many of the indicators closely follow historical trends through 2100.

A summary of the characterization of the global SSPs based on O'Neill *et al.*'s (2017) key elements is listed in Table 1, which highlights the diverging nature of the different pathways. In addition, there are two key aspects of this table that we use to guide the FSP development. First, nearly all of the elements have a socio-economic or land use element (e.g., trade, consumption, and environmental policy), and thus will have an effect on the forest sector. Second, most terminology used to describe how each element relates to a specific SSP is highly qualitative (e.g., medium, rapid, and uneven). We chose to use similar qualitative terminology when developing the SSPs to be as consistent as possible with the prior literature.

In addition to not including any explicit climate policies, the basic SSP narratives do not extend to out comes such as emissions and land use that are often estimated through integrated assessment models (O'Neill *et al.*, 2014).

[1] N.B., although the general SSPs do not include explicit climate policies, some applications have included a more defined component to account for climate mitigation in their analysis. For example, Popp *et al.* (2017) include explicit information on when and what land use emissions face a carbon price (e.g., all land use emissions in SSP1 are priced at the level of carbon prices in the energy sector after 2020).

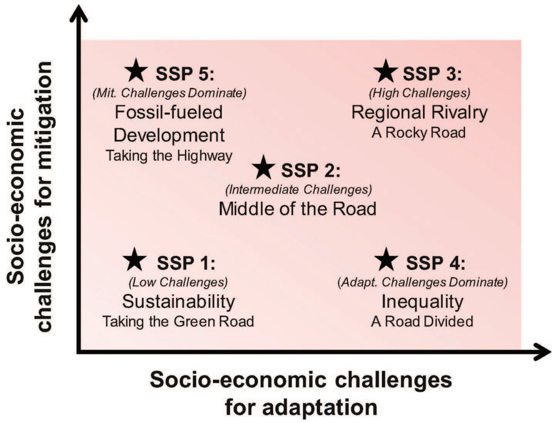

Figure 1: Overview of Shared socioeconomic pathways (SSPs) representing combinations of challenges to mitigation and adaptation (from O'Neill *et al.* (2017)).

This approach is intentional, so that the global modelling community has flexibility in how they SSPs are implemented as a suite of 'scenarios' in which SSPs are combined with other pathways such as the Relative Concentration Pathways (RCPs) that focus on greenhouse gas (GHG) emissions and climate projections absent of any socioeconomic assumptions. As a result, the comparison between SSP and RCP emissions trajectories are likely to vary across models and analyses, and it is difficult to align each SSP to a given RCP. For example, Riahi *et al.* (2017) found that radiative forcing was relatively aligned for the combinations of RCP8.5/SSP5 and RCP6.0/SSP1, but none of the SSPs closely followed RCP4.5 or 2.6.

2.2 Forest Sector Pathways

This paper follows similar methods used to create the global SSPs to develop a set of consistent and comprehensive narratives for the forest sector, which we refer to as FSPs. These FSPs build upon the SSP storylines and provide additional details concerning relevant forest resource management and forest product market variables including forest management, regional forest area, ecological sustainability, technological change, forest carbon, forest bioenergy expansion, and forest product consumption. Like the previous literature, these provide guidance concerning the development of the forest sector, with the potential to inform multi-model comparative analysis.

The methodology used to develop the FSP narratives is strongly aligned with the methods employed by O'Neill *et al.* (2014) and Maury *et al.* (2017) to develop the respective SSPs and OSPs. That is, we use a logical set of steps specified by Alcamo (2008) to guide expert elicitation for defining key

Table 1: O'Neill *et al.* (2017) characterization of the SSPs in terms of major global issues.

SSP element	SSP1	SSP2	SSP3	SSP4	SSP5
Population growth	Relatively Low	Medium	Low in OECD, high in other countries	Low in OECD, relatively high in other countries	High in OECD, low in other countries
Economic growth	High in LICs, MICs; medium in HICs*	Medium, uneven	Slow	Low in LICs, medium in other countries	High
International trade	Moderate	Moderate	Strongly constrained	Moderate	High, with regional specialization in production
Globalization	Connected markets, regional production	Semi-open globalized economy	De-globalizing, regional security	Globally connected elites	Strongly globalized, increasingly connected
Consumption & diet	Low growth in material consumption, low-meat diets, first in HICs	Material-intensive consumption, medium meat consumption	Material-intensive consumption	Elites: high consumption lifestyles; Rest: low consumption, low mobility	Materialism, status consumption, tourism, mobility, meat-rich diets
International cooperation	Effective	Relatively weak	Weak, uneven	Effective for globally connected economy, not for vulnerable populations	Effective in pursuit of development goals, more limited for environmental goals
Environmental policy	Improved management of local and global issues; tighter regulation of pollutants	Concern for local pollutants but only moderate success in implementation	Low priority for environmental issues	Focus on local environment in MICs, HICs; little attention to vulnerable areas or global issues	Focus on local environment with obvious benefits to well-being, little concern with global problems
Policy orientation	Toward sustainable development	Weak focus on sustainability	Oriented toward security	Toward the benefit of the political and business elite	Toward development, free markets, human capital
Institutions	Effective at national and international levels	Uneven, modest effectiveness	Weak global institutions/natl. govts. dominate societal decision-making	Effective for political and business elite, not for rest of society	Increasingly effective, oriented toward fostering competitive markets
Technology development	Rapid	Medium, uneven	Slow	Rapid in high-tech economies and sectors; slow in others	Rapid
Environment	Improving conditions over time	Continued degradation	Serious degradation	Highly managed and improved near high/middle-income living areas, degraded otherwise	Highly engineered approaches, successful management of local issues

*LIC = low income country; MIC = middle income country; HIC = high income country.

elements of change in the global forest sector through 2100. These steps include: establishing a narrative development panel; identifying FSP specific elements sensitive to the basic SSP assumptions; developing qualitative narratives for each FSP that build upon the SSP narratives from O'Neill *et al.* (2017), Riahi *et al.* (2017), and Popp *et al.* (2017); and reviewing, comparing, and contrasting the qualitative description of elements for each scenario to form a consistent set of qualitative narratives.

This iterative methodology resulted in the development of five FSPs that are relatively aligned with the respective SSPs, but with a set of elements of particular importance to the global forest sector. Van Ruijven *et al.* (2014) and Ebi (2014) refer to this approach as developing "extended SSPs" that use assumptions consistent with the basic SSPs but can also support specific modeling efforts that require input beyond the general narratives (O'Neill *et al.*, 2017). This is apparent in the fact that the FSPs provide explicit information on when, where, and what types of forest carbon sequestration would likely to be 'priced' under each FSP, which closely follows the recommendation of Popp *et al.*'s (2017) global land use sector SSP analysis.

The elements of each FSP include the specification of key drives for the forest sector, including:

1. Land-use regulation
2. Forest productivity growth
3. Environmental impact of forestry activities
4. International trade of forest products
5. Forest-specific mitigation policies
6. Efficiency of timber processing and wood use
7. Consumption of primary and secondary forest products
8. Forest carbon pricing and mitigation

This broad list was subsequently expanded upon with a set of sub-elements and presented using a series of tables and 2-axis figures that specify how key elements of the FSPs may be related. To account for possible deviations within a given FSP, this process also developed a plausible range of uncertainty around each point. For example, Figure 2 illustrates how income equality and macroeconomic growth are likely to compare across the five FSPs. Scenarios with high macro growth – typically represented by changes in GDP per capita – across both low and high medium countries (i.e., FSPs 1 and 5) will fall in the upper-right quadrant while those with low and/or diverging growth (i.e., FSPs 3 and 4) will fall in the lower-left one. The quadrants in this study

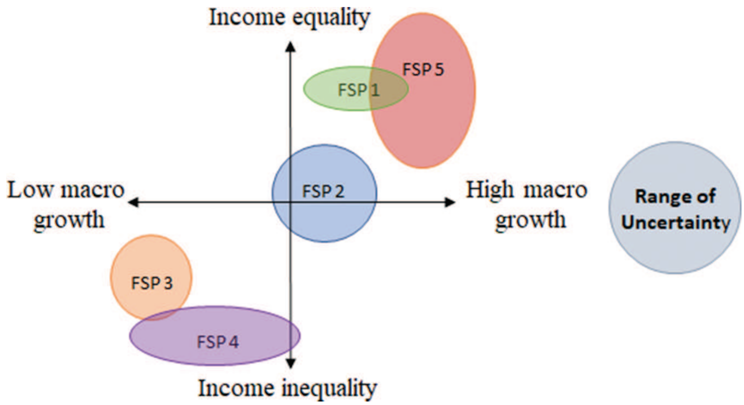

Figure 2: Range of potential FSP income equality and macro growth elements.

focused on key elements such as forest area use and management; forest sector productivity; forest carbon; and forest product demand.

A final point to note in developing and interpreting these scenarios is the need to follow a consistent set of definitions. As a result, the definitions of forest types, uses, and products discussed in this paper follow the Food and Agricultural Organization's specifications (FAO, 2012), unless explicitly stated otherwise. For example, 'plantation' forests are defined as planted forests composed of trees established through planting and/or through deliberate seeding of native or introduced species, where establishment is either through afforestation on land which has not carried forest within living memory or by reforestation of previously forested land. On the contrary, the FAO defines 'natural' forests as both primary forests that have not been disturbed by human activities as well as naturally regenerated forests that have clearly visible indications of human activities (i.e., all non-plantation forests).

3 Results

3.1 Forest Sector Pathways

We use the basic global SSP narratives as a foundation for developing detailed narratives for five FSPs. Table 2 provides a detail of how we extended the SSP elements relevant to the forest and land use sectors into FSP specific elements. This table provides a basis for linking general SSP narratives with the more detailed forestry specific discussion offered through the remainder of this manuscript. Some of the elements in Table 2 are adopted directly from Popp *et al.* (2017), (e.g., including land use change regulation), while other elements have been created directly for the purposes of this study (e.g., forest

Table 2: Overview of key elements of FSPs for each corresponding Shared socioeconomic pathways (SSPs).

Element	FSP 1	FSP 2	FSP 3	FSP 4	FSP 5
Land-use change regulation*	Strong regulation to avoid damages to the environment	Medium regulation; focused on reducing of deforestation	Limited regulation; continued deforestation	Highly regulated in MICs and HICs; lack of regulation in LICs lead to high deforestation rates	Medium regulation; slow decline in the rate of deforestation
Forest productivity growth	High improvements in forest plantation productivity and forest management; rapid diffusion of best practices	Medium increase of productivity in managed forests and plantations	Very low productivity development	Forest productivity high in HICs, low in LICs	Highly managed, resource-intensive; rapid increase in productivity
Environmental impact of forestry activities	Reduced harvest intensity in non-plantation forests, emphasis on conservation of environmental values. Increased areas set aside from forestry activities	Medium environmental impacts from forestry activities	Intensive harvests increase the stress on biodiversity and other environmental values	HICs: strong regulation ensures adequate set-asides and environmental considerations; MICs and LICs: negative impacts on the environment through poor control	Intensive harvests cause more stress to the environment, but moderate level of regulation and set-asides reduces the harmful impacts
International Trade*	Moderate	Moderate	Strongly constrained	Moderate	High, with regional specialization in production
Globalization*	Connected markets, regional production	Semi-open globalized economy	De-globalizing, regional security	Globally connected elites	Strongly globalized
Land-based mitigation policies*	No delay in international cooperation for climate change mitigation. Full participation of the land use sector	Delayed international cooperation for climate change mitigation. Partial participation of the land use sector	Heavily delayed international cooperation for climate change mitigation. Limited participation of the land use sector	No delay in international cooperation for climate change mitigation. Partial participation of the land use sector	Delayed international cooperation for climate change mitigation. Full participation of the land use sector
Efficiency of wood use (cascading, recycling, new materials, technical development)	High, with rapid development of new technologies for bio-based materials	Medium	Low, with primary focus on local technology	Medium-high in HICs; Low in LICs	High, with rapid development of new technologies, and regional specialization. Medium cascading and recycling
Forest Product Consumption	Decreased overall consumption, with a high share of wood-based materials	Medium, following historical trends	High total consumption, emphasis on conventional products	Medium, following historical trends with LICs relying heavily on firewood as an energy source	High overall consumption, with moderate share of wood-based materials and fuel

*as in *Popp* et al. *(2017)*

productivity growth). The remainder of Section 3.1 presents the general FSP narratives for scenario development. We then expand upon the key aspects of the FSPs in the Sections 3.2.

3.1.1 FSP for SSP 1 - Taking the Green Road

Forest use is heavily regulated, and tropical and old growth deforestation rates are strongly reduced. Agricultural crop yields increase rapidly in low- and medium-income countries, thereby reducing the impact on forests and other natural areas through less pressure from deforestation. Forest plantation yields are also rapidly increasing across the globe because of better and more intensive management. In non-plantation forests (i.e., not plantations but potentially affected heavily by human interventions), the harvest intensity is reduced, and preservation of ecological values is emphasized. Overall consumption is decreased, and societies are characterized by low forest product consumption growth and lower resource and energy intensity. Substitution of fossil-based raw materials leads to increased use of wood in construction, and the development of novel bio-based products is rapid, while the consumption of conventional paper and paperboard decreases at a more rapid rate than observed in the first two decades of the 2000s. Increased efficiency in the industrial wood use and new technologies permitting high recycling rates are rapidly diffused around the world and thereby reduce the demand for virgin wood for paper and board production. There is increased demand for especially 'sustainably' produced timber and non-timber forest products and forest-based amenities, with emphasis on wood sourced legally from forests under internationally recognized certification regimes. Carbon pricing and land use regulations are used to prevent loss of natural forests to competing land uses, and a rising share of timber products is provided by intensively managed planted forests. Low energy consumption rates contribute to a relatively small increase in the demand for woody biomass-based electricity and transport; however, the share of bio-based fuels increases relatively within total energy consumption. A global climate change mitigation policy starts in 2020 and includes active participation by most countries. GHG emission pricing and incentives for forest carbon sequestration through afforestation, improved forest management, and reduced emissions from deforestation and degradation (REDD) are readily traded in a global carbon market.

3.1.2 FSP for SSP 2 – Middle of the Road

The world follows a path in which social, economic, and technological trends continue to follow historical patterns. Forest use is incompletely regulated, and tropical and old growth deforestation follow historical trajectories. Forest plantation yields increase, but at a decreasing rate, in certain parts of the globe as a result of more intensive management. Crop yields also increase to some degree, particularly in certain low- and medium-income countries, but not enough to minimize the effect of the need to expand agricultural land at the expense of forests and other natural areas. Resource consumption and energy intensity increase at a decreasing rate, and as a result there is still ample demand for ‘traditional’ forest products, which are generally traded in regional markets. Current trends toward reduced consumption of graphics papers (newsprint, printing, and writing paper) are maintained, while demand for paper-based packaging continues to expand. Medium energy consumption demand results in a steady demand for woody biomass-based electricity and transport. Most developed countries start implementing a global climate change mitigation policy in 2020, with developing countries entering the market by 2040. Payments for forest carbon sequestration via afforestation and avoided deforestation are priced from 2030 onwards.

3.1.3 FSP for SSP 3 – A Rocky Road

The world becomes increasingly compartmentalized due to national concerns about competitiveness and security. Forest use has few regulations in most parts of the world, leading to intensive harvests of timber and forest residues, alongside with continued tropical and old growth deforestation and in some developing countries even an increased deforestation relative to historic rates. Forest plantation yields improvements are minimal due to lack of investment in management and less international trade. Crop yields also decline to some degree over time, particularly in certain low- and medium-income countries, thereby leading to a significant increase in agricultural land area at the expense of forests and other natural areas. Resource and energy consumption per capita are high in developed countries, but the large population living in the developing world do not increase their consumption at the same pace. Technological improvements are halted, with little development of new biomaterials. Productivity growth is slow and focused on local solutions. High energy consumption results in a steady demand for woody biomass-based fuels, but the emphasis is on solid biofuels, with little development of wood-based liquid biofuels. Most developed countries start implementing a national or regional climate change mitigation policy in 2020, with developing countries entering the market around 2030. Agricultural emissions are priced at the onset of the policy in 2020, but payments for forest carbon sequestration via afforestation and avoided deforestation are not priced until 2030 in developed countries, and 2050 in the developing world. Even when carbon prices are imposed on the forest sector, they tend to be heavily discounted relative to prices on energy- and industrial-based GHGs (Riahi *et al.*, 2017).

3.1.4 FSP for SSP 4 – A Road Divided

Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Forest use is heavily regulated in the developed world, while poor regulation in the low and middle income countries leads to increased degradation of forests, characterized by intensive harvesting and little attention to sustainable management or environmental consideration. Forest plantation yields and management improve in the high income countries, but the development elsewhere is minimal and limited to plantations producing raw material for the high income countries. Low crop yields in developing countries lead to a significant increase in agricultural land area, particularly near the tropics, contributing to high deforestation rates in tropical forests. Resource and energy consumption follow historical trends, with the developed world making a faster transition to lower-intensity use. This results in a steady demand for woody biomass-based electricity and transportation, where regulations limit this to 'sustainable' use/production in the developed world. In the low income countries, wood remains as a major fuel source. Most developed countries start to cooperate in regional climate change mitigation policy in 2020, with developing countries entering the market between 2030 and 2050. Payments for forest carbon sequestration via afforestation and avoided deforestation are priced from 2030 onwards, and only in some countries.

3.1.5 FSP for SSP 5 – Taking the Highway

This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. The sustainable management of forests is not consistently followed across the globe, and thus deforestation continues to occur, albeit at a decreasing rate. Forest plantation yields and management increase rapidly, driven by increased demand for forest products in a globally integrated marketplace, aided by rising investments in timber growing technology. Crop yields also increase across the globe, but a strong demand for animal products continues to put pressure on converting some forest to pasture. Resource and energy consumption grow faster than historical trends. Forest product markets are global, allowing countries to specialize and invest in new technologies and new products that are traded internationally. As a consequence, demands for packaging material and transportation fuels increase heavily. While fossil fuel demand dominates, there is also a steady increase in the production and consumption of woody biomass-based electricity and transportation fuels. There is strong interest in global climate change mitigation policy, but international cooperation is not fully achieved until 2040. Payments for forest carbon sequestration via afforestation and avoided deforestation are not priced until at least 2030.

3.2 Detailed FSP Elements

3.2.1 Forest area development, forest use and ecological sustainability

The change in total forest area and composition (i.e., managed and natural) could be highly variable under the different FSPs, and is strongly driven by elements related to establishing forest-set asides, plantation development, and regulation and enforcement of deforestation (Table 3). Deforestation is one of the most discussed elements related to forest area. Human activities are primarily the direct drivers of deforestation, typically through the form of clearing land to accommodate agriculture, mining and urban growth (FAO, 2016), which are related to macro-level interactions of demographic, economic, technological, social, cultural, and political factors (Kissinger *et al.*, 2012), all important elements of SSP/FSPs. As a result, deforestation varies significantly across the globe. Recent data from FAO (2016) indicates that commercial agriculture resulted in 70% of the deforestation in Latin America between 2000 and 2010, while small-scale agriculture is the primary cause in Africa. The rate of change in global population and income coupled with changes in consumer preferences and agriculture technology will have a strong effect on deforestation rates over the next century. This is reflected by the fact that 88 countries – most designated as high and mid-income – have experienced net gains in natural forest area between 1990 and 2015 (FAO, 2015). Thus, a world with large increases in income coupled with low population growth (i.e., FSP 1) may expect to see deforestation rates become close to zero by 2100, while a world that is expected to experience high population growth but minimal change in income and agricultural productivity could potentially see deforestation rates close to historical trends or higher.

Sustaining biodiversity is one of the cornerstones of sustainable development and sustainable forest management. It is identified as one of the Sustainable Development Goals of the United Nations (United Nations, 2017), and a key focus of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Ferrier *et al.*, 2016). Efforts to protect or enhance forest biodiversity also influence ecosystems services such as soil, water and air provisions, both through its role as a regulator of the processes, and as a final ecosystem service itself (Harrison *et al.*, 2014; Mace *et al.*, 2012). High biodiversity and the following diversity of different species and micro-organisms have a positive effect on the decomposition and nutrient cycling, production of biomass, as well as the stability of populations. There is also strong evidence that biodiversity increases the stability of forest ecosystem functions through time, and that for any single ecosystem pro-

Table 3: Summary of assumptions regarding managed and protected forest area development in the FSPs.

Element	FSP 1	FSP 2	FSP 3	FSP 4	FSP 5
Deforestation rates	Rapid decrease to almost none	Slow decrease	Medium increase	Slow decrease in MICs and HICs; Medium increase in LICs	Slow decrease
Set-aside or protected forest areas	High increase of set-aside forest areas for nature conservation and biodiversity	Medium increase of set-aside forest areas for nature conservation and biodiversity	Low increase of set-aside forest areas for nature conservation and biodiversity	High increase of set-asides in the HICs, Low development of set-asides in the MICs and LICs	Medium increase in set-asides for nature conservation and biodiversity
Natural forest area	High increase	Low decrease	High decreases	Low increase in HICs. Medium decreases in MIC and LICs	Low increase
Plantation forest area	Medium-high increase	Medium increase	Low increase	High increase in HICs. Medium increases in MIC and LICs	High increase

cesses, the changes accelerate as biodiversity loss increases (Cardinale *et al.*, 2012).

There are different views to the best strategies to preserve biodiversity in forest ecosystems: whether it is better to focus on preserving large continuous areas, many small areas, or a mixture of large and small areas (Heller and Zavaleta, 2009). In some ecosystems, it is also possible to provide different ecosystem services and use the natural resources without jeopardizing biodiversity, especially if the scope of the ecosystem services is wide and the intensity of their use is low (e.g., Nelson *et al.*, 2009). Together with climate change, socio-economic development is one of the main drivers reducing biodiversity in the world. For terrestrial ecosystems, land use and its change are identified as the main driver of biodiversity loss, while over exploitation is the biggest threat for marine ecosystems in the world (Pereira *et al.*, 2010). The general consensus is that in order to preserve global biodiversity, rapid actions are needed to protect more forestland (Heller and Zavaleta, 2009). Our five FSP scenarios cover a wide range of possible futures of forest land protections and utilization, which can have a direct effect on forest biodiversity and ecosystem services.

Newbold *et al.* (2016) show that urgent preservation of areas that still remain intact is required to slow or reverse the global loss of biodiversity, together with restoration of human-used lands to natural vegetation. Furthermore, Visconti *et al.* (2016) found that the current trends of economic development and relatively high consumption rates, comparable to FSP2, are likely to lead to increased rate of species extinction. To halt this development and instead turn towards sustainable production, they propose adoption of reduced impact logging, sustainable intensification of production on plantations, and strategically protecting areas where habitat loss poses the highest threat to biodiversity. FSP1 reflects this development, with strong regulation of land use and increased area of protected land. The other end of the spectrum is described in FSP3, where global deforestation continues and land use is very poorly regulated, and on the other hand strong population growth combined with poor education and economic growth levels contribute to more extensive and inefficient use of natural resources.

It is important to note that the impact of land use on biodiversity varies between different biomes. Grasslands are currently identified as being the most affected by human actions, while tundra and boreal forests are the least affected (Newbold *et al.*, 2016). Habitat loss in the tropical regions cannot either be fully compensated with gains in the temperate regions, as the species and areas they inhabit each have their own niche within global biodiversity (Pereira *et al.*, 2010). The different conditions in different parts of the world are likely to be highlighted even more in the world described by FSP4, where unequal development threatens to worsen the situation even further on the parts of the world that are already under the most stress. Similar threats are posed by FSP5, where the overall strong resource use is likely to reduce the global biodiversity. In FSP5, however, it is possible that the intensive use of land can be compensated to some extent by protecting other areas.

Plantation forests are comprising an increasing share of the global forest area (Carle *et al.*, 2002; Siry *et al.*, 2005; FAO, 2011, 2015), garnering substantial investments (FAO, 2006; Carle and Holmgren, 2008) that are linked to industrial, economic, and ecological variables (Korhonen *et al.*, 2014). Plantations may take pressure off of natural forests by growing faster and by having a higher harvesting frequency, and supplying a greater proportion of the timber product markets (see section 3.3.2). The effects of plantation forestry biodiversity are complex and location dependent (Carnus *et al.*, 2006), and thus, that impact of increasing the share of industrial roundwood produced by planted forests may have an ambiguous effects on overall biodiversity and other ecosystem service outcomes. We discuss this aspect in more detail in Section 4.

3.3 Productivity and technological change

Forest, logging, and wood processing productivity are all key elements that have all improved historically due to improvements in management practices and technology. The degree of change for each of these elements is likely to vary by FSP, particularly under different assumptions about sustain ability and forest product demand (Table 4). For example, there has been significant investment in management of forest plantations over the past 30 years. Sohngen and Tian (2016) compare regional plantation estimates by Sedjo (1983) and Cubbage *et al.* (2010), showing that timber plantation yields have increased on average by 0.9% per year. The average is calculated across a limited set of countries (Brazil, Chile, New Zealand, South Africa, and the United States) and ranged from negligible decreases in New Zealand-grown *Pinus radiata* and South Africa-grown *P. patula* to a 2.1% per year increase for Brazil-grown *P. taeda*; *Eucalyptus grandis* yield changes were only available for Brazil, rising 1.6% per year. Such increases have been attributable to a variety of factors, including ambient atmospheric carbon fertilization but also technology advances, including the accumulated gains from genetic selection and improved management strategies. Ambient CO_2 concentrations increased about 15% between 1980 and 2010. Based on an estimated elasticity of net primary productivity with respect to CO_2 of about 0.6 (Norby *et al.*, 2005), a rough calculation would predict a 9% increase in timber yields over the 30 years due to increased CO_2 alone, one quarter of the 37% increase in plantation yields calculated by Sohngen and Tian (2016). Increased investments into genetics and management, perhaps as might occur in SSPs 1, 2, 4, and 5, could be consistent with greater yields over time on the order of 0.5% to 2% per year, depending on the pathway.

Harvesting productivity at the stand level is strongly influenced by average stem volume and extraction distance, which are constrained by stand characteristics and the available logging machine technology. The introduction of

Table 4: Summary of assumptions regarding productivity and technological change in the FSPs.

FSP element	FSP 1	FSP 2	FSP 3	FSP 4	FSP 5
Forest Plantations	High growth in forest plantation productivity and forest management; rapid diffusion of best practices	Medium increase of productivity in managed forests and plantations	Very low productivity development	Productivity high in HICs due to investment, low in LICs	Highly managed, resource-intensive; rapid increase in productivity
Timber Harvesting	High; more automation, sustainable and efficient logging techniques	Medium; Mix of labor and capital-intensive practices	Low; labor-intensive with emphasis on using equipment past typical life	Medium-high in LICs investing in automated capital intensive systems technology; Low in LICs that are labor intensive	Medium-high; capital intensive logging and low fuel costs
Wood Processing	High, with rapid development of automated process that maximize wood utilization	Medium	Very low due to low skilled labor and aging capital	Moderate in HICs as invest in new capital; poor efficiency of wood use in LICs	High, with rapid deployment of new fossil-dependent processing equipment

more efficient logging machinery and improved silvicultural techniques over the past 30 years have resulted in significant improvements in harvest productivity– measured as gross volume removed per working day – especially in the developed world. For example, Nordfjell *et al.* (2010) estimated that the average harvest productivity in Sweden roughly doubled between 1985 and 2003, although it has slightly declined since then due to maturing machine technology and stagnant practices. Similar observations have been made for the Nordic countries in general (Häggström and Lindroos, 2016). The development of new of machines and methods to facilitate more efficient harvesting practices is strongly influenced by market demand and organizational structure of the logging industry (Liden, 1995), which could vary considerably across the FSPs. For example, there is currently renewed interest in developing equipment capable of sustainably harvesting both roundwood and forest biomass for energy at the same time, which currently requires separate machines (Bergkvist, 2010). The development and adoption of such a technology will highly depend on whether how biomass energy policies and round wood markets evolve over time. Thus, we anticipate that the FSPs with high growth in demand for a wide-range of wood products (e.g., SSP1 and 5) are likely to induce greater harvest productivity gains than the other pathways.

An examination of recent data reveals gross trends in input uses per unit of output of wood processing that inform the level of changes that might be anticipated under each FSP. Wood processing technology has predominantly changed historically in the form of labor-saving. Toppinen and Kuuluvainen (2010) surveyed the more recent literature on technology change in the European forest products sector, noting labor-saving and energy-using biased technical change in the paper sector. For example, Lundmark (2005) found input cost-reducing technical change in Sweden's newsprint manufacturers of 0.7% to 1.4% per year. Stier and Bengston (1992) exhaustively reviewed the literature on technical change experienced in the North American forest products sector from the 1950s to the 1980s. Technical change across most studies was biased towards capital-using and labor-saving, with labor-saving rates approaching 3% per year in some industries. Studies examining total factor productivity found that productivity changes varied by study and by industry, from slightly negative to +4% per year. For example, Stier (1980) examined U.S. forest product manufacturers and found evidence of primarily labor-saving technical change, averaging 1–2% per year over 1958–1974. Buongiorno and Gilless (1980) found that technology change in the paper sector of OECD countries yielded output price reductions of 1.5% to 2.0% per year and that no technology change effect was found for the pulp sector, 1961–1976. Helvoigt and Adams (2009) identified both neutral and biased technological change in the sawmilling sector of the Pacific Northwest of the United States, favoring increased use of capital, at 1% per year and decreased use of labor at 0.6% per year, 1968–2002. While the U.S. experience may differ from that observed in the rest of the world, given technology diffusion (Stier and Bengston, 1992), we can expect that trends are similar across producers of forest products globally. A future of increased investment into labor-saving and capital-intensifying technologies in the forest products sector under FSP1 and FSP5 could yield lower labor and higher capital inputs than observed historically, lowered investment underFSP3 or SSP4 would lead to slowing of these trends, and FSP2 would continue to follow historical trends, which is characterized as following a medium growth trajectory.

3.4 Forest carbon sequestration and carbon-beneficial bioenergy pathways

The FSPs can have a strong influence on forest carbon and bioenergy pathways, which is driven by several elements ranging from global climate policy to regional biomass availability and trade (Table 5). Because forest management and human activities related to afforestation, deforestation, and post-harvest use of wood biomass play an important role in determining the concentration of CO_2 in the atmosphere, there is significant potential for carbon removals generated through the forest sector. Planting trees remove CO_2 from the atmosphere through photosynthesis and store it as carbon in living and dead biomass; thus, afforestation and reforestation are potential activities for removing atmospheric carbon that can improve a nations GHG emissions profile (IPCC 2000; 2006). Likewise, silvicultural activities (e.g., fertilization and hybridization) that enhance tree growth or otherwise increase the amount of carbon sequestered in a forest ecosystem could also contribute to the amount of carbon sequestration in the forest. Since deforestation releases significant amounts of CO_2 into the atmosphere, the preservation and conservation of forests (i.e., preventing degradation, conversion to other uses or simply delaying harvest) have been proposed as eligible means to obtain carbon offset credits (see van Kooten and Johnston, 2016). As society increasingly looks for strategies to mitigate climate change, the sequestration potential of the forest sector may lead to an expansion of forest area and stock, and increased consumption of harvested wood products. Placing value on carbon stored in trees may encourage longer rotations, greater levels of afforestation, and general intensive margin investments (van Kooten *et al.*, 1995; Baker *et al.*, 2017). However, uncertainties associated with natural disturbance can significantly affect forest planning (Kurz *et al.*, 2008; Lindroth *et al.*, 2009). Furthermore, placing value on forest carbon offsets may lead to altered long-term ecological outcomes of the forest (Johnston and Withey, 2017).

The role of forest management in mitigating CO_2 extends beyond the forest as governments increasingly turn to wood biomass energy as a substitute for fossil-fuels (McDermott *et al.*, 2015). Although biomass includes agricultural crops and municipal waste, it is more commonly referring to all sources wood-

Table 5: Summary of assumptions regarding forest carbon sequestration and carbon-beneficial bioenergy elements of FSPs.

FSP element	FSP1	FSP2	FSP3	FSP4	FSP5
Forest carbon sequestration					
Global climate policy	Effective international cooperation, sustainable development, tighter regulations of local and global carbon emissions	Relatively weak cooperation, weak focus on sustainability, concern for local emissions with moderate success at abatement	Weak international cooperation, low priority for environmental issues, high level of nationalism and protectionism, weak global institutions	Effective cooperation among medium and high income countries, limited focus on global issues, pursuit of elite's interests	Limited environmental goals, pursuit of free and competitive markets, limited resources put towards global issues
Forestland protection	Strong regulations to avoid environmental tradeoffs	Medium regulations lead to slow decline in the rate of deforestation	Hardly any regulation; continued deforestation due to competition over land and rapid expansion of agriculture	Highly regulated in medium and high income countries; largely unmanaged in developing countries, leading to tropical deforestation	Medium regulations lead to slow decline in the rate of deforestation
Bioenergy deployment					
Energy tech change	Directed away from fossil fuels, toward efficiency and renewables, including biomass	Some investment in renewables but continued reliance on fossil fuels	Slow tech change, directed toward domestic energy sources	Diversified investments including efficiency and low-carbon sources	Directed toward fossil fuels; alternative sources not actively pursued
Fossil fuel constraints	Preferences shift away from fossil fuels	No reluctance to use unconventional resources	Unconventional resources for domestic supply	Anticipation of constraints drives up prices with high volatility	None
Woody biomass availability for bioenergy purposes					
Harvest and stump residue constraints	Strict limits on residue retention	Moderate limits	limited restrictions on residue removal from forest	Strong limits on residue retention in medium and high income countries	Moderate limits
Recovered wood and industrial by-products	High availability	Moderate	Low availability	High availability in HIC and low availability in LIC	Low availability
International trade of biomass	Moderate	Moderate	Strongly constrained	Moderate	High, with regional specialization in production

based energy, often in the form of sawchips, sawdust, bark, black liquor to be used in commercial electrical utilities or residential heating. From a carbon accounting perspective, the IPCC (2006) says the emissions and removals from biomass energy would be reported in the Agriculture, Forestry and Other Land-Use (AFOLU) sector at the time of harvest, and not the Energy sector when the wood is burned. Therefore, electrical utilities can reduce their reported CO_2 emissions in the energy sector by using woody biomass. Expanded reliance on bioenergy to reduce emissions may influence land use decisions away from marginal agriculture and towards managing lands for producing biomass for energy production (Ince *et al.*, 2011, 2012; Moiseyev *et al.*, 2011), and cause fuelwood and industrial roundwood prices to converge (Buongiorno *et al.*, 2011). Wood pellets themselves may complement the production of sawnwood and plywood, and compete for fiber with non-structural panel and pulp and paper industries (Johnston and van Kooten, 2014; Lauri *et al.* 2017). Further, government support for bioenergy may lead to increased trade volumes and prices of wood pellets to electricity generators, eroding the cost effectiveness of bioenergy to combat climate change (Johnston and van Kooten, 2015b, 2016). This is particularly true where stemwood, and not industrial by-products, are being used for the production of the wood pellets (Agostini *et al.*, 2014). Therefore, it would appear that the market effect of increased bioenergy is complicated, but should play a factor in determining how widespread it becomes as an effective strategy in the future.

Another factor that will inevitably influence the expansion of biomass energy in the future is the degree of net carbon benefits. Central to the 'zero carbon' argument for biomass energy is the idea that burning wood for energy is subsequently removed by the future regrowth of the harvested tree (Walker *et al.*, 2013). However, this regrowth may take many decades and can deteriorate the climate change mitigating benefits associated with bioenergy (Johnston and van Kooten, 2015a). Life cycle analysis of wood pellet production, which often takes a stand-level approach to GHG accounting, indicates the time taken to eliminate the carbon debt from biomass burning can take 38 years if standing timber were used; or 16 years if pellets are produced from forest residuals (McKechnie *et al.*, 2011). Meanwhile, Cherubini *et al.* (2011) show that while the global warming potential (GWP) of bioenergy is less than that for fossil-fuel alternatives, it may still contribute to the accumulation of atmospheric CO_2, contributing to global warming if terrestrial carbon uptake does not increase outside of the system boundaries of the biomass being removed from the landscape. Recent economic modeling studies suggest that supply-side responses to bioenergy policies that increase prices can result in net carbon gains on the landscape (e.g., Daigneault *et al.*, 2012; Latta *et al.*, 2013; Galik and Abt, 2015). This result is supported by Tian *et al.* (2018), which suggest that high levels of demand growth for forest biomass can stimulate intensive and extensive margin investments in forestry and hence higher levels of carbon sequestration.

Rather than focusing on bioenergy and forest activities that increase carbon storage on site, society may also consider the carbon sequestered in post-harvest wood product pools, and the CO_2 emissions avoided when wood replaces concrete and steel in construction. Carbon that is transferred from the living timber into wood products is considered an addition to the carbon that is stored as a result of forestry activities. Additional carbon savings between 0.3–3.3 tCO_2/m^3 could be counted if one included emissions avoided from using wood products in construction as opposed to relying on emission-intensive products like steel and concrete (Hennigar *et al.*, 2008). A comprehensive approach to forest management that takes account of carbon fluxes in all carbon pools may provide the greatest climate mitigation benefits provided by the forest sector (Lemprière *et al.*, 2013). Some have argued that commercial logging with timber processed into wood products is preferred to storing carbon in an unmanaged forest ecosystem (Smyth *et al.*, 2014). There may also be a greater carbon dividend if timber is processed into wood products as opposed to using wood biomass to produce energy (Kurz *et al.*, 2013). There remains significant potential for wood product sinks to expand, thereby storing carbon for extended periods, promoting an increase in wood product production (van Kooten *et al.*, 1999; Kurz *et al.*, 2013).

Since forests are capable of removing CO_2 from the atmosphere, SSPs envisioning a greener future could see forest activities take a central role in future climate change strategies. Recent studies of the Paris Agreement found that roughly 25% of the INDC emission reductions are expected to come from the LULUCF sector (Grassi *et al.*, 2017; Forsell *et al.*, 2016). However, determining the effect on the forest industry relies on the consideration of a myriad of effects. Placing value on the carbon offset potential of the forested ecosystem may create incentive to prolong harvests to store the carbon in trees, or alternatively, could encourage an increase in harvests to store carbon in wood products, offset emissions from steel and concrete, or offset fossil fuel energy production. It will come down to the degree with which society is willing to price the medley of activities that produce forest carbon offsets under the different SSPs.

3.5 Forest product consumption

Historically, production and consumption of timber has been divided between primary production of fuelwood, industrial roundwood (i.e., sawlogs and pulpwood) and the products that are derived from them. An important aspect of assessing the effect that each SSP may have on global forests over the next century is to identify the likely changes that would affect the consumption of various forest products, including sawnwood, plywood and other long-lived products, less durable consumables such as paper, newsprint, and packaging, energy sources such as fuelwood and biomass, and non-timber forest products (Table 6).

Table 6: Summary of assumptions regarding forest products consumption in the FSP's.

FSP Element	FSP 1	FSP 2	FSP 3	FSP 4	FSP 5
Sawnwood, Plywood, and OSB/MDF*	High, driven by demand for renewable resources	Medium, following historical trends	Medium, driven by rapid population growth	Low, especially for LIC with limited income	High, driven by income effect and technological change
Paper and newsprint	Low, more emphasis on electronic-based information	Low, following historical trends	High, driven by population growth and consumption preferences	Low	Low
Paperboard and packaging	Low, income effect tempered by demand for locally produced goods	Medium	Low, driven by reduced trade and income growth	Low, especially for LICs	Medium
Fuelwood for heating and cooking	Low, driven by substitution to more efficient energy sources	Medium, following historical trends	Low, driven by substitution of fossil fuels	Medium, with most consumption in LICs	Low, driven by substitution of fossil fuels
Biomass for energy	Medium, demand for renewable resource tempered by concerns about sustainability	Medium, moderately regulated	Low, minimal regulations	Medium, with most consumption in HICs	Low, driven by demand for fossil-based energy
New forest products	High, substitution of fiber for fossil-based products (e.g., plastics) and clothing	Medium, new development of building and fiber-based products	Low, continue to consume existing suite of products	Medium for HICs, LICs consume existing products	Low, growth driven by complements of fossil-based products
Non-timber forest products (NTFP)	High, emphasis on efficient use of natural resources, biopharmaceuticals	Low	Medium, driven by low income and need to be resourceful	Medium, driven by LIC consumption needs and resource constraints	Medium, fossil fuel preferences dominate income effect
Overall Consumption	Decreased overall consumption, with a high share of wood-based materials	Medium, following historical trends	High total consumption, emphasis on conventional products	Medium, following historical trends with LICs relying heavily on firewood as an energy source	High overall consumption, with moderate share of wood-based materials and fuel

* OSB = oriented strand board; MDF = medium density fiberboard.

There are several elements that can impact the consumption of forest products globally. Jonsson (2011) has identified a broad list that includes patterns of globalization and economic development, technological change, information and communication technology development, environmental and land use policies, climate change impacts mitigation and adaptation, and material substitution. For this paper, we utilize information from both the global SSP and forest products literature to classify the main elements of forest product consumption as: GDP, population, trade, technological change, and consumer preferences (including that for sustainably produced *vs.* fossil fuel-based goods). These elements are likely to have various degrees of impacts on forest resources, and in some cases, will potentially offset each other. For example, the SSP3 scenario (i.e., 'Regional Rivalry') is specified to have a high increase in population through 2100, but with a relatively low trajectory of per capita income growth. The regionalized nature of the SSP3 economy is expected to result in less trade, slow technological change, and continued reliance on domestic fossil fuel resources (O'Neill *et al.*, 2017). Thus, a low GDP/capita growth rate coupled with reduced trade relative to historical trends is likely to dominate the population change effect, thereby resulting in relatively lower consumption of most forest products relative both to the historic trends as well as compared to other scenario pathways.

Historically, the global demand for products has steadily grown over time and is expected to continue to grow. The trend in consumption of forest products overall as well as the specific products demanded could vary regionally though due to changes in income and population (FAO, 2016). This trend is a strong driver of increased overall consumption in the SSP1 and SSP5 scenarios, which are likely to have high income growth.

Market-driven regional economies coupled with relatively low transportation costs have pushed the world to have a more globalized economy, thereby facilitating the creation and expansion of a global forest product market. The continued trend of globalization is expected to vary widely across the SSPs, with SSP5's strongly globalized and increasingly connected economy approach sitting on one end and the SSP3's de-globalized, regional security focus sitting on the other (O'Neill *et al.*, 2017). As a result, consumption of forest products in SSP3 is expected to see the least growth in overall forest product consumption.

The continued progression of the internet, social media, and other electronic information communication technology has had a noticeable impact on the consumption of newsprint, and printing and writing paper, which has declined by almost 20% globally over the past decade (FAO, 2017). This phenomenon has led some to conclude that the long-run income elasticity for newsprint in the US turned negative in the late 1980s (Hetemäki and Obersteiner, 2001) and others have argued that newsprint has transitioned into an inferior good; newsprint demand now declines with growth in income (Hetemäki, 2005).

In fact, Latta *et al.* (2015) provide evidence that the income elasticity for newsprint depends on the rate for which a countries population has adopted the Internet, and Johnston (2016) shows that a failure to account for future rates of Internet adoption will result in an upward bias on paper product market forecasts. At the same time, the continued growth in online commerce may continue to rely on paper-based packaging, but it is uncertain whether this is enough to compensate for the decline in other paper product markets. Therefore, we expect that the consumption of paper and newsprint will continue to be low or even decline in four of the five SSP scenarios. The only exception to this case is SSP3, where high population growth coupled with reduced globalization drives an increase in regional demand for what could be perceived as currently being an inferior good.

The demand for wood-based energy, both in the form of industrial-scale biomass and household-level fuel wood for traditional heating and cooking could have varying impacts on forest product consumption. These are driven by environmental policies, including climate change mitigation and relative concerns about the sustainable development and use of the forest sector. A strong preference for fossil fuel consumption, such as in SSPs 3 and 5, is likely to temper demand for wood-based energy, while a focus on producing energy from renewable and sustainable sources such as forests could result in a relative increase in consumption, particularly for biomass-based energy. There is still a relatively high level of uncertainty about the magnitude and trend of biomass consumption in our SSPs, as discussed in other sections of the paper.

Finally, forests can also provide a wide range of non-timber forest products (NTFP).[2] The consumption of NTFPs can vary widely, as can the subset of these types of goods that the forest can provide. For example, SSP1 is focused on 'sustainable' consumption and thus may place an emphasis on efficiently utilizing all the renewable materials that the forest has available and/or planting species that provide a wider range of goods and ecosystem services. On the other hand, the consumption of NTFPs in for SSP3 could still be relatively high as high population growth coupled with limited access to global markets could force people to take advantage of any local resources that they can find.

4 Discussion

The FSPs presented in this paper contain details on a number of important elements that range from an emphasis on forest protection and biodiversity to over-exploitation of natural resources and high consumption of forest products.

[2]FAO defines NTFP as being 'goods of biological origin other than wood derived from forests, other wooded land and trees outside forests'.

In some cases, these elements may have the opposite effect on the state of global forests, even under the same FSP. Furthermore, efforts to model these narratives in a quantitative sense will be strongly influenced by how these narratives can be translated into model parameters. As a result, we acknowledge that there is a degree of uncertainty in how the individual elements will collectively influence the future of the global forest sector. This section discusses some of these uncertainties and provides a framework to visualize and compare the interrelationships between some of the key elements of the five FSPs, which are aligned with the forest sector elements in Section 3.2. To facilitate this discussion, Figure 3 presents a series of 2-axis figures that specify how key elements of the FSPs may be related. The figures also attempt to account for potential uncertainty within and across the FSPs, which is represented by the shape and size of the bubbles.

Forest area is projected to expand under FSPs 1 and 5, but it is less certain how natural and plantation forest area may change under the other FSPs even though there has been an increase in the contribution of global plantations to timber supply over the past 30 years. In the United States, for example, planted forests provide nearly 40% of total harvests although they comprise only 5% of the country's managed forests. While some studies have shown benefits to natural forests from increased planted forests (Walters, 2004; Maclaren, 1996), others have found the opposite (e.g., Clapp, 2001). The effects on landscape-level biodiversity from increased reliance on planted forests are complex (Carnus *et al.*, 2006) because planted forests can add to landscape level biodiversity or subtract from it, depending on location. The prospect of having plantation forests reducing pressure from or even replacing natural forests for harvesting has been discussed by several authors, including Sedjo and Botkin (1997), Rudel (1998), and Carnus *et al.* (2006).

The quantities of ecosystem goods and services from planted forests can be enhanced if certain management practices are implemented (Namkoong, 1988; Hartley, 2002). Efforts by nations to increase the quantities of ecosystem goods and services overall therefore would have to carefully measure which ecosystem goods and services are desired, their spatial distributions, how management practices and other factors affect planted forest ecosystem goods and services. Furthermore the change in how plantations and natural forests are used (i.e., production *vs.* conservation) can also have a strong impact on ecosystem services. Hence, in the context of FSPs, envisioning a greener future could be consistent with increased investments in planted forests.

Forest sector productivity is likely to grow relatively fast for FSPs 1, 2, and 5, but less so for FSPs 3 and 4. In most scenarios, the growth in forest plantation and forest processing productivity is expected to be relatively correlated, but it is unclear whether the growth will be demand or supply-side driven across all FSPs. Technology change in the forest products sector is focused on increasing the value of forest products outputs relative to the costs

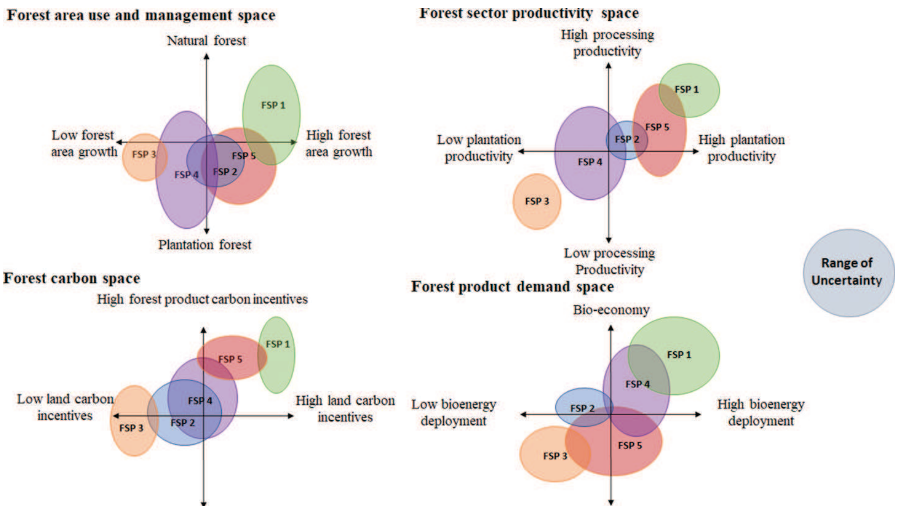

Figure 3: Relationship of key elements in Forest Sector Pathway (FSP) narratives.

of production inputs, which tends to shift the supply curve outward, allowing for greater total market equilibrium production, given prices. On the demand side, changing technologies can shift demand for particular forest products outward or inward at a given level of income, depending on how prices are changing across a set of potential substitutes and complements, including newly introduced substitutes and complements. Therefore, when technology change is considered to be happening across all sectors of an economy, conclusions about whether consumption and production of forest products will rise or fall is uncertain and dependent on market context. For example, the introduction of new and rapidly falling prices for electronic media has been shown and projected to bring future consumption of graphical papers downward over time (Zhang and Buongiorno, 1997; Chas-Amil and Buongiorno, 2000; Hetemäki and Hurmekoski, 2014; USDA Forest Service, 2016), with increasing rates of internet use reducing newsprint consumption (Johnston, 2016; Ochuodho *et al.*, 2017). It could be surmised, then, that continued technological advances in electronic media would put downward pressure on graphics paper consumption, even while overall incomes are rising.

Another example of the effects of changes in both supply and demand affecting production and consumption comes from two structural panel products used in construction in North America and elsewhere, softwood plywood and a relatively new technology, oriented strandboard (OSB), particularly in North America. Between 1982 and 2016, the share of OSB in the North American market has risen from 0% to 67% (APA, 2017). OSB is a cheap competitor to softwood plywood (Random Lengths, 2017), which explains part of the growth. Furthermore, the use of softwood plywood is affected by the lack of larger diameter timber in the Pacific Northwest due to reduced harvests from federal timberlands (Wear *et al.*, 2016), thereby increasing the consumption of smaller diameter trees in the eastern U.S. In another example, the use of wood per installed square foot of residential buildings in the U.S. has declined by about 0.2% per annum over the last five decades (Wear *et al.*, 2016; Skog *et al.*, 2012). Advances in building technology and the increased use of engineered wood products explain much of this decline (APA, 2017). There is also the potential for even more new uses of wood to become widely produced in the upcoming decades, including biomass that could be used to produce liquid biofuels, bioplastics, cross-laminated or mass timber, and nanocellulose-based composites, which will all be driven by a combination of technological development and consumer preferences (Jonsson, 2011). Furthermore, continued growth in Internet-based commerce will also increase the demand for paper-based packaging. As a result, there is a relatively wide range of uncertainty around what types of forest products will be produced under each FSP, perhaps with the exception of FSP2 which is assumed to closely follow historical trends.

The change in forest area, use, productivity, product demand can all impact the level of forest carbon sequestered under the alternative pathways. For example, SSP1 is likely to see a shift towards more productive forests that cover a greater area of the globe and contribute significantly to the bio-economy and bioenergy sectors. As a result, we would expect with some degree of certainty to store more carbon on the landscape as well as in long-lived forest products. In a pathway such as FSP4, where there is a greater deviation in how countries are assumed to manage forests and consume forest products, there is greater uncertainty about whether we will see an increase or decrease in total global forest carbon. On the other extreme, we are fairly confident that FSP 2 and 3 will lead to a general decline in forest carbon, particularly due to the lack of incentives to maintain or enhance forest stocks. Our expected outcome is generally aligned with the findings of model-based exercises that present impacts on forest cover and land-based carbon emissions under alternative forest product and demand assumptions, and land use policies, whether they are IAM (e.g., Riahi *et al.*, 2017; Popp *et al.*, 2017) or forest sector specific (e.g., Daigneault *et al.*, 2012; Tian *et al.*, 2018).

5 Conclusions

This paper develops FSP narratives that can be used to define possible future trends in the global forest sector across the SSPs. SSPs are used by the climate change research community to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The future of global forestry could change substantially under alternative scenarios of economic growth, environmental change, and policy assumptions. Thus, FSPs can benefit the modeling community by providing a consistent set of assumptions of how forests might evolve under alternative SSPs that can be adapted to a wide-range of modeling frameworks. The SSPs are based on five narratives describing alternative socio-economic pathways, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development. Specifically, this paper seeks to build upon existing SSP storylines by elaborating on the potential implications of SSP-related variables on forest resource management, forest product markets, wood-based bioenergy expansion, and other relevant trends in global forestry. The FSP narratives presented in this paper build on alternative futures research and multi-model inter-comparisons by further developing recent narratives with additional detail on specific issues related to the development and use of our world's forests.

This paper advances the literature by presenting detailed narratives that link specific SSP assumptions to key forest sector variables. These narratives can inform global forest sector modeling frameworks or improve the representations of forest resources and product markets in integrated assessment models. Furthermore, there are possibilities to downscale FSP narratives to the country or sub-national level for more refined region-scale analysis. Previous research has utilized global IPCC scenarios to inform global forest market projections modeling (Buongiorno *et al.*, 2011; Raunikar *et al.*, 2010), and results from the global analyses were then used to simulate U.S. forest harvests and product supply across alternative policy scenarios (Nepal *et al.*, 2012). More recent research uses U.S. focused projections of macroeconomic growth, housing starts, and woody biomass demand to project localized CO_2 emissions associated with forest growth and harvests (Latta *et al.*, 2018). However, these studies lack the level of detail presented in our FSPs, especially in terms of how income growth and SSP policy assumptions can influence technological change and forest management changes at the intensive and extensive margins. Other regional forest sector assessments, such as the ones recently done for Norway (Hu *et al.*, 2018) and New Zealand (Daigneault *et al.*, 2017), can be improved through downscaled FSP narratives instead of following the more generalized SSP assumptions.

There are a few key limitations of this analysis worth noting. First, keeping in line with the global SSP approach, we do not directly account for projected climate change impacts on forest growth and possible natural hazard risk. Additional analyses could to incorporate RCPs and associated emissions levels with the FSPs to account for possible changes in net primary productivity and carbon fertilization impacts, though this could require model comparison efforts for biophysical frameworks currently used to project forest productivity impacts of alternative climate scenarios (e.g., Kim *et al.*, 2015). Furthermore, our FSPs are not directly tied to existing social policy assumptions (SPAs, summarized in O'Neill *et al.*, 2017) and current nationally determined contributions commitments under the Paris Agreement that have pledged emissions reduction and adaptation/resilience activities in the forest sector (summarized in Forsell *et al.*, 2016). Third, our broad global-scale approach does not provide insight on how the narratives could change regionally beyond noting some possible differences between high and low income countries.

Regardless of whether modeling efforts are global or regional, apply detailed land use sector models or integrated assessment models, the FSPs presented in this analysis provide a consistent framework for calibrating assumptions of technological change and forest sector productivity, product demand, and other relevant aspects related to forest management. Consistency in underlying SSP assumptions applied to global forest sector can facilitate multi-model analyses and inter-model comparisons (e.g., Valin *et al.*, 2013). Comparative analyses that harmonize key FSP assumptions can result in more robust model comparison efforts by reducing discrepancies in forest sector assumptions (e.g., forest product demand growth), thereby focusing comparisons on differences in underlying model attributes, such as spatial and temporal scale and sectoral coverage.

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