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economics

Projected Market Competition for Wood Biomass between Traditional Products and Energy: A Simulated Interaction of US Regional, National, and Global Forest Product Markets

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Using a partial market equilibrium framework, this study evaluated the US regional timber and wood products market impacts of a projected national level expansion in wood biomass consumption for energy. By restricting logging residue use, we focus on the impacts on timber harvests and paper production from increased pulpwood consumption and focus on the impacts on lumber production from increased mill residue consumption. Analyses showed that increased consumption of wood for energy led to diversion of about 37 million m^3 of pulpwood away from pulpwood-using traditional products (e.g., panels and paper), reducing production and net exports of paper and paperboard by up to 3 million tonnes. Increased wood energy consumption also led to increased timber harvests (up to 40 million m^3 or 8 percent), increased prices (up to 31 percent), and increased lumber production and net exports by up to 9 million m^3. The South was projected to supply the majority of the energy feedstock (47 m^3 or 77 percent) and to experience the resultant effects on forests and wood products sectors. The findings highlight the importance of market linkages at local, national, and global levels in evaluating the impacts of increased wood energy consumption and the importance of identifying feedstock sources.

Keywords: timber, final products, mill residues, logging residues, wood energy, market competition

An increase in future consumption of wood energy, potentially driven by national and international policies and programs, has the potential to affect wood products markets and the use and management of forests. A large body of literature has broadened our understanding about the magnitude of forest and wood products sector impacts of a hypothetical expansion in wood energy (Sedjo 1997, Galik et al. 2009, Buongiorno et al. 2011, Ince et al. 2011a, Abt et al. 2012, Daigneault et al. 2012, Sedjo and Tian 2012, Ince and Nepal 2012, Latta et al. 2013, White et al. 2013, Abt et al. 2014, Miner et al. 2014, Moiseyev et al. 2014, Galik et al. 2015, Johnston and van Kooten 2016, Baker et al. 2018, Latta et al. 2018). These studies have used different forest sector models, covered different geographical areas (regional, national or global), employed different optimization methods (intertemporal or dynamic recursive), and made different assumptions about the timber and wood products sectors. These studies found that increased demand for wood energy leads to effects on both timber markets and final product markets. In addition, the increased demand has impacts on standing forest inventory and forestland area. The magnitude of these modeled effects is contingent, in part, on whether land is allowed to shift between agriculture and forestry uses and whether logging residues are used to meet the feedstock demands for energy (e.g., Latta et al. 2013).

Galik et al. (2015) provided an improved understanding of linkages between national and local markets by using a hierarchal approach, where the outcomes from a national forest sector model (Forest and Agriculture Sector Optimization Model with Greenhouse Gases) and the Sub-Regional Timber Supply Model

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(SRTS) were used to evaluate the local and the national environmental and economic effects of regional bioenergy policy in the southeastern United States. Their study, however, did not evaluate the impacts on final products markets. While some other studies evaluated impacts of national or global increases in wood energy demand on final products markets (e.g. Buongiorno et al. 2011, Ince et al. 2011a), they did not report how US regional wood products markets would unfold under those hypothetical increases in wood energy demand. Johnston and van Kooten (2016) evaluated the global wood products market impacts of an assumed doubling of wood energy demand in Europe, but their study ignored the linkage between the US regional timber markets (sawtimber and nonsawtimber harvest and prices) and US national and global wood products markets. They showed that wood energy–induced changes in world price altered individual countries' comparative advantages with resulting gains in welfare for timber-rich countries such as the United States and Canada and welfare losses in other countries, with overall welfare gains in the wood products sector.

Most studies have shown that expanded wood energy production leads to increased timber harvests (e.g., Ince et al. 2011a, Latta et al. 2013, Johnston and van Kooten 2016). However, the degree and magnitude of such increases will depend on the level of wood energy demand and the ability to use logging and mill residues (Abt et al. 2012, Latta et al. 2013, Abt et al. 2014). The potential for bioenergy to be met using non-wood biomass from agricultural crops and residues is also a crucial factor in determining the impact on forests and wood products sectors. Latta et al. (2013) found that agricultural biomass is preferred in scenarios where both agricultural and forestry biomass were modeled. Latta et al. (2018) evaluated wood energy demand using a model that includes both softwood and hardwood timber, as well as detailed mill-level demands and FIA plot-level supply analyses. Several studies investigated impacts of a regional bioenergy policy on timber supply and timber resources in the US South using the SRTS model, which focuses on timber markets and does not address final product markets (e.g., Galik et al. 2009, Abt et al. 2012, Chudy et al. 2013, Duden et al. 2017).

While these studies have improved our understanding of the likely forest and wood products sector impacts of increased wood energy at an aggregate national level for the United States or for a single US region, less is understood about the degree and magnitude of competition between wood for energy and traditional products and the associated effects on timber harvest and price and final and by-product production and prices across all US regions. Because each US region competes with other regions in supplying raw materials (timber) to meet product demands for domestic and foreign consumers, an evaluation of the effects of increasing national level wood energy demand requires modeling the dynamics of timber and wood products production across regions. This sort of finer scale market modeling can provide a more complete picture of the likely effects of the wood energy sector on both landowners and wood product manufacturers.

Restrictions on logging residue use could arise because of ecological reasons (e.g., need to preserve nutrient cycling), economic reasons (e.g., too costly to recover), or biophysical reasons (e.g., not enough supply in perpetuity). This has consequences for the wood products industries that use pulpwood and mill fiber residues in manufacturing paper and composite products (Ince et al. 2011a, Latta et al. 2013, Moiseyev et al. 2014, Johnston and van Kooten 2016). Baker et al. (2018) evaluated the impact of increased wood energy demand using only logging residues and concluded that logging residues could meet much of wood energy demand, with lower greenhouse gas (GHG) impacts, if only logging residues were used. Our study evaluated the impacts of increased wood energy demand on forests and wood products sectors under the assumption that there are significant limitations on logging residue use.

Our study fills a gap in our understanding of regional US effects of expanded wood energy production by evaluating and reporting how the increased consumption of wood for energy would impact timber and final products and by-products markets, including production, consumption, prices, and trade at US regional levels. We used a partial market equilibrium framework to project market prices and quantities of timber and final and by-products for two scenarios: a baseline scenario and a high wood energy scenario. In the baseline scenario, wood energy consumption was determined based on an estimated historical relationship with gross domestic product (GDP) and price (Buongiorno et al. 2012). In the high wood energy scenario, wood energy consumption was increased exogenously as projected in the High Economic Growth scenario of the Annual Energy Outlook of the US Energy Information Administration (US DOE, EIA 2018). Finally, we compared and contrasted our results with related studies and discuss the implications of our findings for management of forest resources and the economic well-being of the wood products sector in three US regions—North, South and West.

Methods

Raw materials evaluated in this study are the timber products. Delivered wood/fiber products included sawlogs, pulpwood, logging residues, firewood, and other industrial roundwood. Final

Management and Policy Implications

The findings of this study, which evaluated US forest and wood products sector impacts of projected national level expansion in wood energy consumption, suggest notable changes in timber markets including increases in regional timber harvests (up to 40 million m^3 or 8 percent higher), timber prices (up to 31 percent higher), timberland area (up to 5 million ha, or 1 percent higher), and timber inventory (up to 0.35 billion m^3 or 2 percent higher). The projected increased consumption of pulpwood for wood energy led to higher pulpwood prices (up to 42 percent higher than the baseline prices), leading to a 3 million tonne decline in production and net exports in pulpwood-using traditional wood products industries. At the same time, increasing pulpwood consumption for energy led to increased lumber production and gains in the net exports of lumber by up to 9 million m^3, with consumption holding steady. By increasing associated future forest rents, wood energy–induced increases in timber prices could help prevent forest conversion to other land uses. At the same time, timber price increases can serve as an economic incentive for landowners to invest in new plantations or intensified management activities, which would further work toward offsetting potential reduction in timber inventory. Wood energy–induced increases in timber harvests, timber inventory, and production of long-lived products suggest increases in forest and wood products carbon sequestration that can play a role in climate change mitigation efforts. A long-run effect of increased timber harvests and prices could be increased forest area and inventory, which could lower the competition between wood for energy and traditional products, moderating the associated economic impacts in the pulpwood-consuming wood products industry.

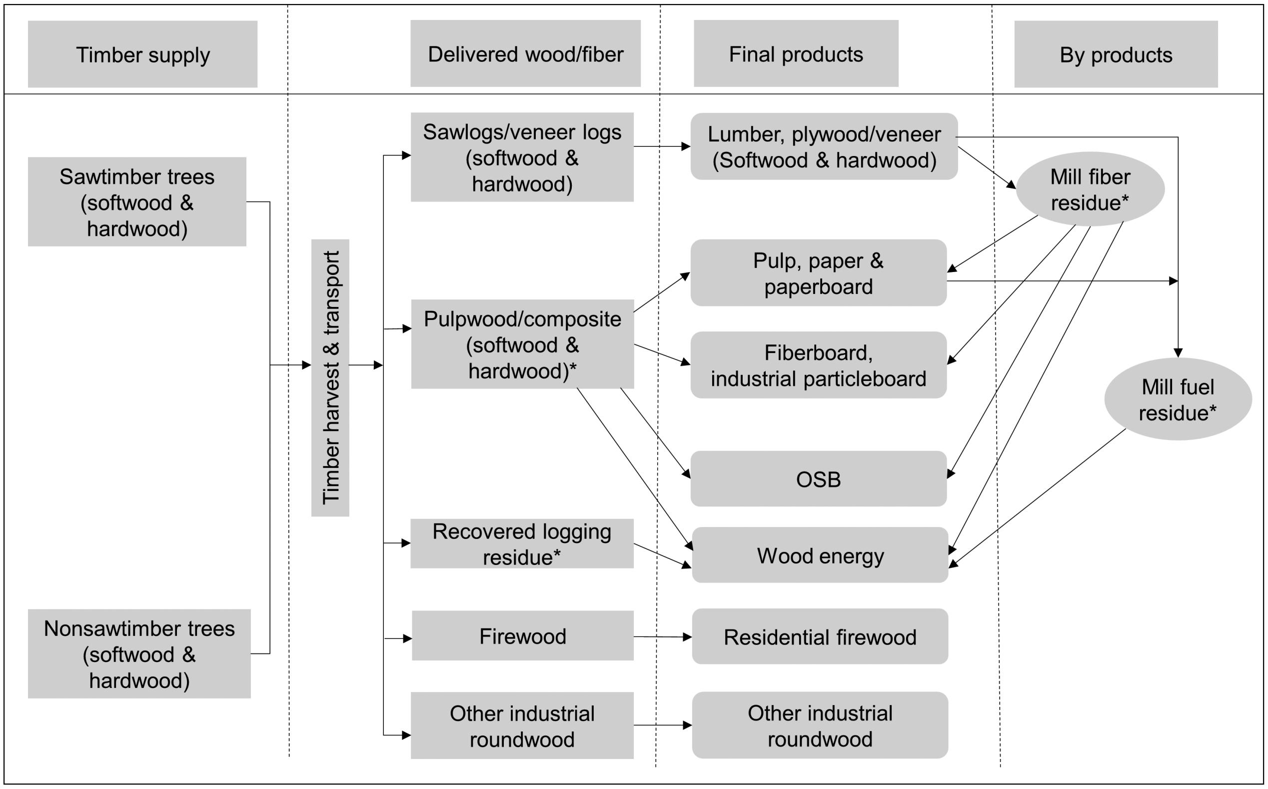

Figure 1. Wood flow structure (process and connection among timber, delivered, intermediate, and final products markets) as modeled in the USFPM/GFPM, adapted from Ince et al. (2011b). The asterisks represent the fuel feedstock.

products included lumber, structural panels, nonstructural panels, paper and paperboard, and wood energy. By-products included mill fiber and mill fuel residues (Figure 1). In the economic modeling framework used in this study, increased wood energy demand can be met by using forest-based wood biomass from three sources: 1) logging residues, 2) mill residues (fiber and fuel residues), and 3) pulpwood that is provided from softwood and hardwood nonsawtimber[1] and sawtimber[2] harvest. The economic model chooses the least-cost sources to provide wood energy, although we chose to evaluate conditions where logging residues were not used and increased the cost of providing logging residues. Currently, logging residues comprise less than 5 percent of delivered wood demands for pellet production (Forisk Consulting 2018).

Projected market equilibrium prices and quantities were obtained by maximizing the sum of consumer and producer surplus of the entire forest sector, based on theory and methods provided by Samuelson (1952) and Takamaya and Judge (1971). We used the updated US Forest Products Module (USFPM, Ince et al. 2011b), which operates within the broader Global Forest Products Model (GFPM, Buongiorno et al. 2003), jointly referred to as USFPM/GFPM. The USFPM provides a detailed representation of US wood products markets, with enhanced capability to simulate US timber markets and logging and mill residue production and use, which are not available in the standalone GFPM. This study utilized the 2016 version of standalone GFPM, with 2012 as the base year (Buongiorno and Zhu 2016). The USFPM/GFPM was calibrated not only for the base year (2012) but also for the next projection year (2015), so that the model solutions closely replicated observed values for 2012 and 2015 for timber harvests and intermediate and final wood products. The model structure and parameters of USFPM/GFPM and the standalone GFPM have been well described in past literature (e.g., Buongiorno et al. 2003, Ince et al. 2011b, Ince et al. 2011a, 2011b, Ince and Nepal 2012, Nepal et al. 2013, Nepal et al. 2015, Nepal et al. 2016).

Drivers of Timber Supply and Wood Products Demand and Trade

Tables 1 and 2 summarize supply and demand elasticities, respectively, used in the updated USFPM/GFPM. In USFPM/GFPM, US regional timber supply (Table 1) is a function of timber inventory (supply shifter) by softwood and hardwood categories and respective timber prices. Direct demand curves for these timber products are not specified in the model. However, their derived demand is driven by the projected US national demand for final products, including demands for lumber, structural panels, nonstructural panels, paper and paperboard, and wood energy. Sawtimber and nonsawtimber are converted into sawlogs, pulpwood, other industrial roundwood, fuelwood, and logging residues, with all conversions based on historical input-output coefficients by species group. Sawlog and pulpwood quantities are used as inputs to produce demanded quantities of final products. For the rest of the world, industrial roundwood supply is modeled instead of timber supply, which is directly converted to intermediate and final products, without the additional species information.

US aggregate demands (Table 2) for softwood lumber and structural panels (softwood plywood/veneer and OSB) are driven by exogenously specified growth in GDP and total housing starts. The updated USFPM/GFPM uses revised US housing and softwood lumber demand equations estimated by Prestemon et al. (2017). The revised US softwood lumber demand model suggests a more elastic demand with respect to GDP and total housing starts compared with

Table 1. US regional and the rest of the world supply elasticities specified in USFPM/GFPM.

Region	Supply commodity	US regional supply elasticity with respect to		Rest of the world supply elasticity with respect to	
		Price[1]	Inventory[1]	Price[2]	Inventory[2]
North	Softwood sawtimber	0.45	1.00	-	-
North	Softwood nonsawtimber	0.50	1.00	-	-
North	Hardwood sawtimber	0.55	1.00	-	-
North	Hardwood nonsawtimber	0.60	1.00	-	-
South	Softwood sawtimber	0.45	1.00	-	-
South	Softwood nonsawtimber	0.50	1.00	-	-
South	Hardwood sawtimber	0.55	1.00	-	-
South	Hardwood nonsawtimber	0.80	1.00	-	-
West	Softwood sawtimber	0.65	1.00	-	-
West	Softwood nonsawtimber	0.90	1.00	-	-
West	Hardwood sawtimber	0.65	1.00	-	-
West	Hardwood nonsawtimber	0.71	1.00	-	-
Rest of the world	Industrial roundwood	-	-	1.31	1.10
Rest of the world	Other industrial roundwood	-	-	1.31	1.10

[1]Specified US regional supply elasticities with respect to price and inventory are consistent with existing literature suggesting inelastic supply price and unitary supply inventory elasticities (e.g., Abt et al. 2009). The specified elasticities represent adjusted elasticities needed for the model to closely replicate observed harvests and prices.
[2]Supply elasticities for the rest of the world are from Buongiorno and Zhu (2016).

Table 2. US aggregate and rest of the world demand elasticities specified in USFPM/GFPM.

Commodity	US demand elasticity with respect to				Rest of the world demand elasticity with respect to	
Demand commodity	Price	GDP	2nd shifter	3rd shifter	Price	GDP
Softwood lumber[1]	−0.42	1.09	0.55	−0.02	-	-
Hardwood lumber[2]	−0.10	0.22	-	-	-	-
Sawnwood[3]	-	-	-	-	−0.17	0.24
Softwood veneer/plywood[4]	−0.65	0.55	0.69	-	-	-
Hardwood veneer/plywood[2]	−0.29	0.41	-	-	-	-
Veneer/plywood[3]	-	-	-	-	−0.33	0.72
Oriented strand board[4]	−0.65	0.55	0.69	-	-	-
Industrial particleboard[2]	−0.29	0.54	-	-	-	-
Particleboard[3]	-	-	-	-	−0.51	0.59
Fuel feedstock[5]	−0.50	0.22	-	-	-	-
Fuelwood[3]	-	-	-	-	−0.12	−0.14
Other industrial roundwood[6]	−0.50	−0.58	-	-	−0.12	−0.03
Fiberboard[6]	−0.46	0.35	-	-	−0.54	0.92
Newsprint[7]	−0.68	0.77	1.35	−1.00	−0.25	0.42
Printing and writing paper[7]	−0.42	0.60	1.00	−0.55	−0.53	0.59
Other paper and paperboard[6]	−0.23	0.43	-	-	−0.45	0.40

[1]Prestemon et al. (2017), the 2nd shifter is total housing starts (single plus multi-family), and the 3rd shifter is trend variable; [2]Ince et al. (2011b); [3]Buongiorno (2015); [4] Ince et al. (2011b), 2nd shifter is single-family housing starts; [5]Buongiorno et al. (2012); [6]Ince et al. (2011b) for US elasticities, and Buongiorno (2015) for the rest of the world elasticities; [7]Ince et al. (2011b) for US elasticities, and Buongiorno (2015) for the rest of the world elasticities; 2nd shifter is advertising spending in print media, and the 3rd shifter is advertising spending in electronic media.

previously estimated elasticities for GDP and single-family housing starts (Ince et al. 2011b). The revised housing projection model takes into account US total housing starts (single + multi-family), unlike the previous version of USFPM/GFPM, which used only single-family housing starts as a shifter of the US softwood lumber and structure panel demand (discussed further in the scenario section).

In the United States, consumption of newsprint and printing and writing paper are driven by projected exogenous growth in expenditures in print and electronic media, in addition to GDP growth (Table 2). For the rest of the world, demands for lumber, panels, and paper products are driven by GDP growth only, consistent with the standalone GFPM structure. We acknowledge that not accounting for the effects of electronic media use in predicting demand for newsprint and printing and writing paper for other countries could result in an upward bias in projected consumption of those products globally, as suggested by Johnston (2016).

Fuel feedstock consumption for energy in the United States (Buongiorno et al. 2012) and fuelwood consumption in the rest of the world (Buongiorno 2015) are modeled using a demand equation that is a function of its own price and GDP. Note that the model version used does not allow residential fuelwood to trade off with commercial and industrial uses of fuel feedstock, which is only modeled for the United States. Figure 1 shows wood flow pathways (processes and connections among timber, delivered/intermediate, final and by-products markets), as modeled in the USFPM/GFPM.

Following the GFPM structure, wood products trade in the USFPM/GFPM is modeled between individual countries and the rest of the world. Trade in a product is driven by the competitive advantage of a country or a region in producing and shipping each product. For instance, a country or a region can have better production and trade competitiveness (i.e., higher net exports) if it has a relatively more cost-effective technology (lower input requirement or lower manufacturing costs, compared with another country or region). We use the term "competitive advantage" to refer to any case where production costs in any US region may be lower than production costs in other US regions or other countries. The updated USFPM/GFPM does not use currency exchange rate as a trade driver, as was done in earlier versions (e.g., Ince and Nepal 2012). Many authors suggest that changes in the exchange rate have little or no effect on wood products trade (e.g., Bolkesjø and Buongiorno 2006). Without the impact of the currency exchange rate, we expect less rapid growth in projected US net export quantities compared with Ince and Nepal (2012).

Wood Energy Scenarios

To evaluate the US regional timber and wood products market impacts of a hypothetical nationwide expansion in wood energy demand, the study used two scenarios: a baseline scenario and a high wood energy scenario. For the baseline scenario, US wood energy consumption increased 15 percent between 2015 and 2050, from 56 to 64 million m^3 (Figure 2a). Target wood energy consumption for the high energy scenario was achieved exogenously (and iteratively) by shifting the wood energy demand curves outwards until the specified target wood biomass quantities for energy were satisfied. US consumption of wood biomass for energy in the high energy scenario was assumed to increase by 121 percent in 2050, relative to the 2015 level, which resulted in an increase in wood energy consumption from 56 million m^3 in 2015 to 125 million m^3 in 2050 (Figure 2b). This increase was 95 percent higher than the increase for the baseline case.

Both scenarios included the same assumed increases in GDP and population, consistent with the IPCC's "middle of the road" or Shared Socioeconomic Pathway 2 (SSP2, Riahi et al. 2017), the same level of increases in US total housing starts (Prestemon et al. 2017), and an assumed rent-based timberland area response to changes in timber prices (Hardie et al. 2000). The SSP2 represents a future world economy that is not too different from the recent past (Riahi et al. 2017). In SSP2, the projected US average annual GDP growth rate over the 2015–75 period was 1.7 percent (IIASA 2017), and this was used in both scenarios. The projected housing start quantities in this study represent the long-run equilibrium US total housing starts of about 1.1 million starts, as projected by Prestemon et al. (2017), using the GDP and population growth trajectories from SSP2.

Timber Growth, Inventory and Forest Area Projection

Projected forest inventory, which shifts timber supply for US regions and industrial roundwood supply for the rest of the world, depends on the most recent period's forest inventory and the current period's forest inventory growth, harvests, and forest area. Forest inventory growth was endogenously projected (before harvests) for three US regions and for individual countries in the rest of the world using separate models that are nonlinear functions of forest stock density (forest inventory divided by forest area), as described by Nepal et al. (2012) for three US regions and by Turner et al. (2006) for the rest of the world.

In this analysis, US timberland area was exogenously specified for initial model runs, based on declining timberland area trends projected for three US regions under A1B scenario in the USDA Forest Service 2010 Resource Planning Act (RPA) assessment studies (USDA Forest Service 2012). In subsequent model runs, area was allowed to respond to changes in the softwood sawtimber price projected in previous runs, based on an assumed elasticity of timberland area with respect to softwood sawtimber price (0.2), as reported by Hardie et al. (2000). While the elasticity estimates provided by Hardie et al. (2000) provide the measure of market response for the US South only, we apply the same response in the North and the West, as we lack better information regarding the responses of timberland to timber prices in these regions. Projected timberland area from other simulation models such as FASOMGHG are available for the West, but they are not based on statistical tests, are subject to the assumptions made for each of those models, and are not appropriate for use in an empirically based simulation model like USFPM/GFPM. We opted to use the model developed from Southern data so that sawtimber prices would influence the amount of timberland. We acknowledge that our baseline shows an unlikely level of increase in timberland area in the West, as Latta et al. (2016) showed that land conversions in Oregon, at least, were primarily for building and that conversions to and from agriculture were historically small. Our concern here is the evaluation of changes between the baseline and the high wood energy scenario and not the precise prediction of the future. For each scenario, the projected percentage changes in US softwood sawtimber price over the projection periods, obtained from the first run, were used in the second run

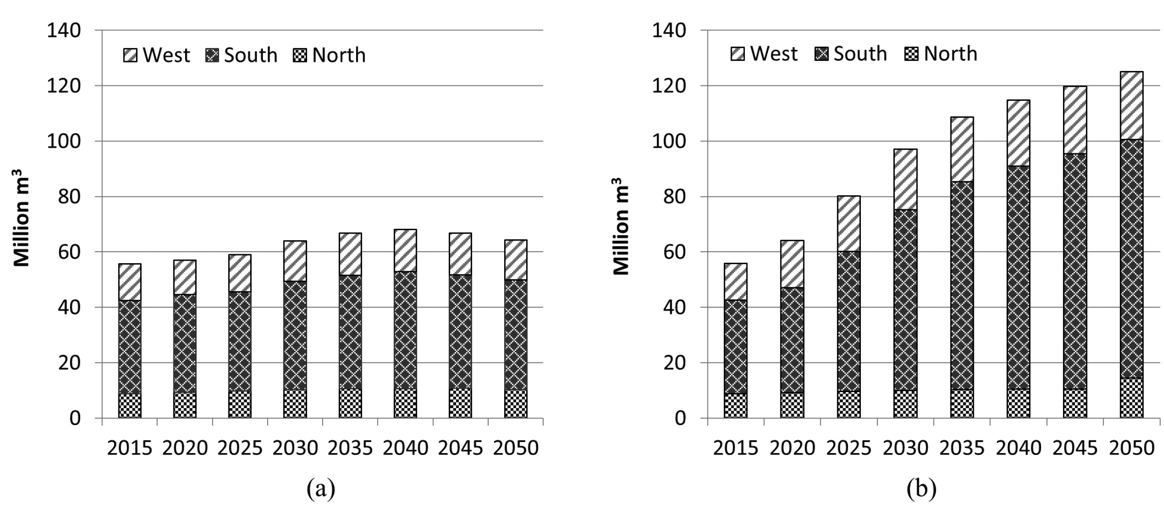

Figure 2. Projected supply of wood energy biomass by US regions for the (a) baseline scenario and (b) high wood energy scenario.

and in later runs to determine the changes in timberland area so that a 1 percent change in softwood sawtimber price would induce a 0.2 percent change in timberland area. This iterative process was repeated until projected timber price and timberland area did not change. For the rest of the world, forestland area was projected based on the Environmental Kuznets Curve, modeled as a quadratic function of GDP, as described in Turner et al. (2006).

Results

The analysis indicated varying effects on key US forest and wood product variables, deriving from projected US expansion in wood consumed to produce energy and from assumed constraints on the use of logging residues. The results for the baseline and the high wood energy scenarios are presented in Tables 3 through 10 and Figure 2. We begin by describing the quantities and types of wood biomass feedstock produced in each region to meet the expanded, nationwide consumption of wood energy. We then describe the changes in timber harvests, prices, timberland area, inventory, and final products at regional and US aggregate levels. Finally, we describe US consumption and net exports.

Price and Quantity of Wood Biomass Feedstock

The relative contribution of each region in meeting the total national consumption of wood for energy remained largely unchanged between the baseline and high energy scenarios, with the South providing 68 percent and the West and North providing 20 percent and 12 percent, respectively, of total wood energy consumption in 2050. Table 4 shows that all prices for fuel feedstocks increased except for hardwood pulpwood in the West, which is a small component of fuel feedstock.

While nearly all (99.9 percent) of the wood energy consumed in the baseline scenario in 2050 was met by mill residues (not shown in the table), most of the increased wood consumed in the high energy scenario in 2050 was met from pulpwood (92 percent), primarily softwood pulpwood (66 percent) (Table 3). This led to an increase in the price of pulpwood (Table 4) and a reduction in the amount of pulpwood used in traditional industries such as paper and paperboard manufacturing and panels (Table 3). Increased harvests provided 34 percent of the increased pulpwood use for energy, while the remainder came from the diversion of pulpwood away from use by traditional products (Table 3). Mill fuel residues (5 percent), which are not used to produce other wood products, and mill fiber residues (3 percent), which are used to produce paper and panel products, provided the remainder of the increased fuel feedstock. Of the pulpwood

Table 3. Changes in US regional and aggregate quantities produced and quantities used to meet wood energy need (high wood energy minus baseline scenario).

Production/Use	Region	2015	2020	2025	2030	2035	2040	2045	2050
		change, in million cubic meters, between high wood energy and baseline[1]							
Total pulpwood produced	North	−0.01	−0.28	−0.34	−0.55	−0.37	−0.31	−0.33	0.61
	South	0.06	1.77	6.72	11.48	12.81	15.30	17.29	17.91
	West	0.00	0.00	0.02	−0.12	0.01	0.15	0.37	0.49
	US	0.05	1.50	6.40	10.81	12.46	15.14	17.33	19.00
Pulpwood used for manufacturing traditional products	North	−0.01	−0.28	−0.34	−0.55	−0.37	−0.31	−0.33	−3.51
	South	0.00	−0.33	−6.92	−12.83	−19.13	−20.35	−23.27	−24.96
	West	0.00	−4.58	−6.60	−7.53	−7.88	−7.99	−8.39	−8.76
	US	−0.01	−5.20	−13.86	−20.92	−27.37	−28.65	−31.99	−37.23
Pulpwood used for energy	North	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.12
	South	0.06	2.11	13.63	24.31	31.93	35.65	40.56	42.87
	West	0.00	4.58	6.62	7.41	7.89	8.15	8.76	9.24
	US	0.06	6.69	20.26	31.72	39.82	43.79	49.31	56.23
Total mill residue produced	North	0.00	−0.06	−0.13	−0.25	−0.27	−0.23	−0.20	−0.02
	South	0.01	0.46	2.11	3.60	3.99	4.70	5.20	5.15
	West	0.02	0.16	0.19	−0.16	0.28	0.74	1.18	1.58
	US	0.03	0.56	2.17	3.19	4.00	5.21	6.18	6.72
Mill residue used for manufacturing traditional products	North	0.00	0.00	0.00	−0.01	0.00	0.02	0.04	0.06
	South	0.00	0.05	1.05	1.79	1.83	1.96	1.92	1.38
	West	−0.13	0.10	0.11	−0.09	0.15	0.40	0.60	0.80
	US	−0.13	0.15	1.17	1.69	1.99	2.38	2.57	2.24
Mill residue used for energy	North	0.00	−0.07	−0.13	−0.24	−0.28	−0.25	−0.25	−0.08
	South	0.01	0.41	1.05	1.81	2.16	2.73	3.28	3.78
	West	0.14	0.06	0.08	−0.07	0.13	0.34	0.58	0.77
	US	0.16	0.41	1.00	1.50	2.01	2.83	3.61	4.47
Logging residue produced[2]	North	−0.01	−0.19	−0.23	−0.35	−0.24	−0.21	−0.22	0.42
	South	0.04	0.97	2.36	3.81	4.14	4.95	5.75	6.58
	West	0.01	0.05	0.07	−0.11	0.08	0.28	0.53	0.75
	US	0.04	0.83	2.20	3.35	3.98	5.03	6.06	7.74
Logging residue[3] used for energy	North	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	South	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	West	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	US	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Total wood biomass used for energy	North	0.00	−0.07	−0.13	−0.24	−0.28	−0.25	−0.25	4.05
	South	0.08	2.52	14.69	26.12	34.09	38.38	43.83	46.65
	West	0.14	4.64	6.70	7.34	8.02	8.49	9.33	10.02
	US	0.22	7.10	21.26	33.23	41.83	46.62	52.92	60.71

[1] The US aggregate values may not match with the sum of regional values because of rounding; [2] These are potentially recoverable amounts, representing 60 percent of total residues generated from timber harvests; [3] zero or negligible contributions from logging residues were because of assumed restriction on logging residue use in this study and were obtained by increasing the cost of providing logging residues.

Table 4. Projected US regional pulpwood and aggregate fuel feedstock prices for the baseline and the high wood energy scenario.

Scenario	Region	Commodity	2015	2020	2025	2030	2035	2040	2045	2050
						\$2012/cubic meter				
Baseline	North	SW[1] pulpwood	26.9	26.6	26.7	26.7	26.6	26.5	26.5	26.4
		HW[2] pulpwood	28.4	30.8	31.2	30.4	29.7	28.6	29.2	30.2
	South	SW pulpwood	28.8	23.6	19.7	17.4	16.5	16.5	17.8	19.4
		HW pulpwood	20.3	20.2	19.7	19.8	19.9	19.8	19.8	19.8
	West	SW pulpwood	21.1	22.0	22.0	22.0	22.0	21.8	21.9	21.9
		HW pulpwood	29.7	30.3	30.3	30.4	30.3	30.0	30.0	30.0
	US aggregate	Fuel feedstock	17.6	17.6	17.2	15.1	14.3	14.4	15.5	16.9
						\$2012/cubic meter				
High wood energy scenario	North	SW[1] pulpwood	26.9	26.6	26.6	26.6	26.6	26.5	26.5	27.7
		HW[2] pulpwood	28.6	32.6	33.6	35.2	33.8	34.9	36.8	37.0
	South	SW pulpwood	28.8	23.6	23.1	24.2	22.9	24.2	26.2	27.7
		HW pulpwood	20.5	23.6	23.1	24.2	22.9	24.2	26.2	27.7
	West	SW pulpwood	21.1	23.6	23.1	24.2	22.9	24.2	26.2	27.7
		HW pulpwood	29.7	30.3	30.4	30.4	30.4	30.2	30.1	30.0
	US aggregate	Fuel feedstock	17.8	20.5	20.1	21.1	19.9	21.0	22.7	24.1

[1]Softwood; [2]Hardwood

consumed for energy in 2050, 76 percent was from the South, 17 percent from the West, and the remaining 7 percent from the North (Table 3). Our analysis did not show any contributions from logging residues in the high energy scenario because of an assumed restriction on logging residue use, which we implemented by increasing the logging residue recovery costs by about \$5 per m^3 in all regions.

Softwood pulpwood provided about 66 percent (40 million m^3) of the total increased national consumption of wood for energy in 2050, with the South supplying about two-thirds of that amount. Hardwood pulpwood provided 26 percent (16 million m^3) of the total increased national consumption of wood for energy in 2050, which all came from the South. The North and West did not provide any hardwood pulpwood for consumption as energy, mainly because it was too valuable for other uses, as shown by projected pulpwood and fuel feedstock prices in Table 4. The increasing diversion of pulpwood away from traditional products resulted in increased prices of both fuel feedstock and pulpwood, which were up 42 percent in 2050 compared with the baseline scenario (Table 4). This changed the profitability of supplying biomass feedstock and resulted in changes in timber harvest and other wood product production and trade in each region.

Timber Harvests and Prices

As expected, the nationwide expansion in wood energy led to increased timber harvests in all three regions (Table 5). The high wood energy scenario resulted in an increase in US aggregate harvests of 165 million m^3 by 2050, a 41 percent increase relative to the 2015 level and an 8 percent increase relative to the baseline level in 2050. The South supplied 84 percent of the new wood, where harvest was 12 percent higher than in the baseline in 2050 (Table 5). There were no changes in softwood harvests in the North nor any changes in hardwood harvests in the West. Softwood sawtimber provided almost half of the increases in 2050, in contrast to a one-third increase in the baseline scenario, indicating that sawtimber harvests increased as a result of increased wood energy demand. Softwood nonsawtimber harvests increased from 16 percent of total timber harvest in the baseline scenario to 24 percent in the high wood energy scenario.

The projected increases in timber harvests were mostly accompanied by increases in timber prices, although there were only small changes, except in the South (Table 6) where softwood prices increased 28–31 percent and hardwood prices increased 3–8 percent. Again, in softwoods in the North and hardwoods in the West, the negligible changes in harvest quantities are consistent with the negligible changes in timber prices.

Timberland Area and Timber Inventory

Assuming that a 1 percent change in softwood sawtimber price would induce 0.2 percent change in timberland area, based on the work of Hardie et al. (2000), our analysis suggested that that US aggregate timberland area would increase by about 1.6 million hectares (ha) between 2015 and 2050 for the high energy scenario, in contrast to a loss of 3.6 million hectares during the same period in the baseline scenario, thus representing an increase of 5.6 million hectares (2.5 percent) more than the baseline scenario in 2050 (Table 7). This is consistent with projected higher softwood sawtimber prices for the high energy scenario. Most of the projected increase in timberland area by 2050 occurred in the South (4.1 million ha), with small changes in the West (0.75 million ha) and the North (0.40 million ha).

The increases in timberland area under the high wood energy scenario, combined with the higher harvests in this scenario, led to only a slight reduction in softwood inventory in the South and gains in inventory in the other regions and timber types. Thus, the increased softwood sawtimber prices led to both increased harvest and increased timberland, resulting in a larger land base but a younger sawtimber inventory. Increases in timberland area helped offset reductions in timber inventory in the South. The softwood inventory in the South was higher in the high energy scenario until 2045 but lower than the baseline scenario in 2050, possibly implying a declining trend in later years. The greater accumulation of hardwood inventory in the South resulted from the relatively lower hardwood timber harvest levels compared with softwood timber harvests. The West and the North each showed an approximate 1 percent increase in inventories in the high energy scenario in 2050 compared with the baseline scenario (Table 8).

Traditional Wood Products Production, Consumption, and Trade

Our analyses indicated that a nationwide expansion in wood consumption for energy would lead to increases in the production of complementary products (such as lumber) and decreases in the production of products that compete for inputs (such as paper and

Table 5. Projected US regional and aggregate timber harvest quantities for the baseline and the high wood energy scenario.

Scenario	Timber products	Region	2015	2020	2025	2030	2035	2040	2045	2050
						million cubic meters[1]				
Baseline	Softwood sawtimber	North	14	14	15	17	18	19	19	19
		South	92	92	95	101	106	107	109	111
		West	65	66	72	78	83	84	85	84
		US	171	173	182	196	207	210	212	213
	Softwood nonsawtimber	North	7	8	8	9	10	10	10	10
		South	56	56	58	62	65	65	66	68
		West	19	19	20	22	24	24	24	24
		US	82	83	87	93	98	99	101	102
	Hardwood sawtimber	North	37	40	43	46	48	50	52	52
		South	42	44	46	49	52	55	58	59
		West	3	3	3	4	5	5	5	5
		US	82	87	93	99	105	110	115	116
	Hardwood nonsawtimber	North	42	45	48	51	54	56	59	59
		South	23	24	25	27	29	30	32	32
		West	2	2	2	3	3	4	4	4
		US	67	71	76	81	86	90	94	95
	Total timber	North	100	107	115	123	129	135	140	140
		South	213	217	226	239	252	258	265	270
		West	88	90	98	107	114	117	118	117
		US	401	414	438	468	496	510	523	527
						million cubic meters				
High wood energy	Softwood sawtimber	North	14	14	15	16	18	18	19	19
		South	92	93	102	112	119	122	125	126
		West	65	67	72	78	83	85	87	87
		US	171	174	189	206	220	226	231	233
	Softwood nonsawtimber	North	7	8	8	9	9	10	10	10
		South	56	57	62	68	72	75	77	77
		West	19	19	20	22	24	24	25	25
		US	82	83	91	99	106	109	112	113
	Hardwood sawtimber	North	37	40	42	45	48	50	52	53
		South	42	45	48	51	55	58	61	64
		West	3	3	3	4	4	5	5	5
		US	82	88	94	101	107	112	118	122
	Hardwood nonsawtimber	North	42	45	48	51	53	56	58	60
		South	23	25	26	28	30	32	34	35
		West	2	2	2	3	3	4	4	4
		US	67	71	76	82	87	91	96	99
	Total timber	North	100	106	113	121	128	134	139	142
		South	213	220	238	260	276	287	297	303
		West	88	91	98	107	115	118	121	121
		US	402	417	450	487	518	538	557	566

[1]The US aggregate values may not match with the sum of regional values because of rounding.

panels) (Table 9). Accordingly, prices for lumber declined slightly, and prices for paper and panels increased (Table 6). Regionally, the largest production gains were in Western nonstructural panels (16 percent), Southern lumber (13 percent), Northern structural panels (10 percent), and Western lumber (7 percent). The largest declines were in Southern and Western paper products (17 percent and 5 percent, respectively) and in both nonstructural and structural panels in the South (17 percent and 10 percent, respectively).

The weighted average price of all categories of paper and paperboard (newsprint, printing and writing paper, and tissue and packaging paper) increased by 19 percent by 2050 in the high energy scenario compared with the baseline scenario (Table 6). Similarly, the projected national prices of industrial particleboard, OSB, and fiberboard were higher compared with price levels projected under the baseline scenario. In contrast, the weighted average price of lumber declined by 1 percent in 2050.

Because of assumed inelastic product demands with respect to prices, the previously mentioned price changes led to only small changes in US consumption of final products (Table 10). While US consumption of lumber, nonstructural panel and paper, and paperboard were approximately half a percent less in 2050, structural panel (mostly OSB) consumption was approximately 2 percent less.

Combined with the larger changes in production, the small changes in consumption imply that trade will absorb most of the impact of the wood energy sector on final products markets. US lumber net exports were projected at roughly 9 million m^3 more under the high energy scenario in 2050. For paper and paperboard, net exports were roughly 3 million tonnes lower in 2050, while nonstructural panel net exports were roughly one million m^3 less under the high energy scenario compared with the baseline scenario in 2050. No effect was observed on structural wood panel trade.

Discussion and Conclusions

The projections led to four broad findings that resulted from an increase in wood energy demand under our model and assumptions: (1) timber harvests and prices increased generally, (2) pulpwood was diverted from traditional pulpwood-using industries to meet wood energy demand, (3) lumber production increased, and lumber prices declined slightly, while lumber consumption stayed steady, and (4) the US South contributed 84 percent of the total wood to meet the increased wood energy demand. Key assumptions that drove our results were that (a) logging residues were not used to meet increased wood energy demand, (b) land use in all US regions responded to sawtimber prices, (c) coproduction of lumber with

Table 6. Projected US regional timber and aggregate final product prices (indexed, 2015=100) for the baseline scenario and the associated percentage changes for the high wood energy scenario.

Scenario	Region	Timber products	2015	2020	2025	2030	2035	2040	2045	2050
						2015=100				
Baseline	North	SW[1] sawtimber	100	93	97	103	108	106	103	100
		SW nonsawtimber	100	94	97	103	107	105	103	99
		HW[2] sawtimber	100	104	111	119	127	135	145	146
		HW nonsawtimber	100	104	110	118	125	131	141	141
	South	SW sawtimber	100	79	73	74	76	73	73	72
		SW nonsawtimber	100	81	75	76	77	75	75	74
		HW sawtimber	100	104	114	130	146	165	186	194
		HW nonsawtimber	100	104	113	127	142	158	176	182
	West	SW sawtimber	100	95	101	112	120	118	115	110
		SW nonsawtimber	100	96	101	112	119	117	115	113
		HW sawtimber	100	101	119	144	166	186	184	180
		HW nonsawtimber	100	106	130	170	210	243	243	236
	US aggregate	Lumber[3]	100	97	100	104	106	106	106	104
		OSB	100	97	96	95	94	94	94	94
		Industrial particleboard	100	100	100	99	99	99	99	100
		Fiberboard	100	100	100	100	100	99	99	99
		Paper and paperboard[4]	100	98	97	96	94	92	90	85
						percent change from the baseline				
High wood energy scenario	North	SW[1] sawtimber	0.0	0.0	-0.8	-3.3	-1.4	-1.0	-0.8	0.0
		SW nonsawtimber	0.0	0.0	-0.8	-3.0	-1.4	-1.5	-0.8	0.0
		HW[2] sawtimber	0.0	-1.5	-1.2	-1.1	-0.8	-0.9	-1.6	2.0
		HW nonsawtimber	0.0	-2.0	-1.9	-1.8	-1.7	-0.8	-1.5	2.2
	South	SW sawtimber	0.0	0.0	8.8	17.5	20.7	25.7	30.1	31.3
		SW nonsawtimber	0.0	0.0	7.4	15.6	19.0	24.1	27.1	28.3
		HW sawtimber	0.0	4.8	3.6	3.5	1.5	0.8	1.4	8.3
		HW nonsawtimber	0.0	3.3	3.9	3.4	1.2	1.1	1.0	7.7
	West	SW sawtimber	0.0	0.9	1.1	-0.7	0.9	2.4	3.8	5.4
		SW nonsawtimber	0.0	0.9	1.8	-0.8	0.7	2.2	4.6	5.5
		HW sawtimber	0.0	–6.4	–3.9	–6.1	–6.2	–6.0	–0.4	–1.3
		HW nonsawtimber	0.0	–9.1	–4.8	–9.7	–9.4	–8.1	–2.7	–2.8
	US aggregate	Lumber[3]	0.0	–0.6	–0.6	–2.2	–1.2	–1.7	–1.8	–1.1
		OSB	0.0	0.8	1.7	3.0	2.7	3.4	4.1	4.3
		Industrial particleboard	0.0	0.3	1.0	2.6	2.2	3.4	3.9	4.4
		Fiberboard	0.0	0.0	0.4	0.8	0.6	0.9	1.0	1.0
		Paper and paperboard[4]	0.0	2.33	4.73	7.13	9.73	12.3	14.5	18.8

[1]Softwood; [2]Hardwood; [3]Weighted average price of softwood and hardwood lumber; [4]Weighted average price of newsprint, printing and writing paper, and other paper and paperboard.

Table 7. Projected changes in US regional and aggregate timberland area (million hectares) for the baseline and the high wood energy scenarios.

Scenario	Region	2015	2020	2025	2030	2035	2040	2045	2050
					million hectares[1]				
Baseline	North	67.52	67.66	67.79	67.93	67.93	67.93	67.93	67.52
	South	84.56	82.88	81.24	79.63	79.51	79.39	79.27	79.83
	West	58.01	58.45	58.89	59.33	59.39	59.45	59.51	59.12
	US aggregate	210.09	208.99	207.92	206.89	206.83	206.77	206.71	206.47
					million hectares				
High wood energy	North	67.52	67.52	67.52	67.52	67.62	67.72	67.82	67.89
	South	84.56	83.75	82.96	82.17	82.62	83.07	83.53	83.91
	West	58.01	58.42	58.83	59.24	59.51	59.78	60.04	59.86
	US aggregate	210.09	209.69	209.31	208.93	209.75	210.57	211.40	211.66

[1] The US aggregate values may not match with the sum of regional values because of rounding.

mill residues was fixed, and (d) coproduction of logging residues with sawtimber and nonsawtimber was fixed. These results and the impact of the assumptions are discussed further.

We found that the increase in wood energy consumption, as projected by Annual Energy Outlook (US DOE, EIA 2018) in the High Economic Growth Scenario, led to increased timber harvests for both sawtimber and nonsawtimber in most years of the projection and for all three US regions. While Johnson and van Kooten (2016) estimated differences at one point in time in contrast to our projections from 2015–2050, they show similar harvest increases, with approximately 60 percent occurring in the US South. Our results indicate that the US South provided 84 percent of the timber harvest increase in 2050.

We found that roughly 92 percent of fuel feedstock consumed to make energy was met by pulpwood, while the remainder was met by mill fiber and fuel residues. By not including logging residues, we overstate the impacts of the increase on both pulpwood and mill residues. In a comparable scenario, Latta et al. (2013) found that roundwood met 50–66 percent of feedstock demand for power, while the remainder was met through logging residues. However, no distinction was made between sawtimber and nonsawtimber.

Table 8. Projected changes from 2015 to 2050 in US regional and aggregate timber inventory (billion cubic meters) for the baseline and the percent change under the high wood energy scenario.

Scenario	Region	Inventory	2015	2020	2025	2030	2035	2040	2045	2050
						billion cubic meters[1]				
Baseline	North	Softwood	1.74	1.87	2.00	2.11	2.22	2.31	2.40	2.47
		Hardwood	6.15	6.50	6.76	6.96	7.10	7.19	7.26	7.25
	South	Softwood	3.98	4.46	4.81	5.03	5.23	5.37	5.48	5.61
		Hardwood	5.21	5.37	5.44	5.44	5.48	5.48	5.45	5.44
	West	Softwood	10.42	10.89	11.35	11.77	12.08	12.35	12.60	12.75
		Hardwood	1.13	1.23	1.32	1.40	1.47	1.52	1.58	1.61
	US aggregate	Softwood	16.13	17.22	18.15	18.92	19.53	20.03	20.48	20.83
		Hardwood	12.50	13.10	13.52	13.81	14.05	14.20	14.29	14.30
						percent change from the baseline				
High wood energy scenario	North	Softwood	0.0	−0.2	−0.4	−0.5	−0.3	−0.1	0.0	0.7
		Hardwood	0.0	−0.2	−0.3	−0.5	−0.3	−0.2	0.0	0.7
	South	Softwood	0.0	0.9	1.9	2.3	1.9	1.5	1.1	−0.3
		Hardwood	0.0	1.0	1.9	2.8	3.5	4.3	5.0	4.8
	West	Softwood	0.0	0.0	−0.1	−0.2	0.2	0.5	0.8	1.1
		Hardwood	0.0	0.0	0.0	−0.1	0.3	0.7	1.1	1.4
	US aggregate	Softwood	0.0	0.2	0.4	0.4	0.6	0.7	0.8	0.7
		Hardwood	0.0	0.3	0.6	0.9	1.2	1.6	2.0	2.3

[1] The US aggregate values may not match with the sum of regional values because of rounding.

Table 9. Projected US regional and aggregate production of final products (million cubic meters) for the baseline and the high wood energy scenario.

Scenario	Region	Commodity	2015	2020	2025	2030	2035	2040	2045	2050
						million cubic meters[1]				
Baseline	North	Lumber	16.48	17.55	18.78	20.05	20.97	21.55	22.13	21.88
		Str. Panel[2]	3.36	4.52	5.32	6.10	6.83	7.98	9.32	10.35
		Nonstr. panel[3]	3.31	4.34	5.49	6.75	8.20	9.94	11.86	13.56
		Paper and paperboard	24.43	25.33	26.78	28.44	29.70	29.83	29.90	29.71
	South	Lumber	35.15	37.39	40.56	44.18	47.66	49.55	51.58	53.28
		Str. panel	13.69	13.84	14.59	15.85	16.96	17.86	18.67	18.61
		Nonstr. panel	6.10	6.41	6.97	7.58	8.21	8.57	8.73	8.38
		Paper and paperboard	43.96	42.85	42.01	41.11	39.88	38.56	37.28	35.54
	West	Lumber	24.49	23.72	25.18	27.75	29.36	29.19	28.45	26.90
		Str. panel	4.77	5.82	6.49	6.80	7.06	7.25	7.37	7.37
		Nonstr. panel	4.38	4.55	4.66	4.64	4.43	4.21	4.03	3.88
		Paper and paperboard	5.97	5.25	4.36	3.84	3.77	3.87	4.12	3.81
	US	Lumber	76.12	78.65	84.52	91.98	97.99	100.29	102.17	102.06
		Str. panel	21.82	24.18	26.41	28.74	30.85	33.09	35.36	36.33
		Nonstr. panel	13.79	15.30	17.12	18.98	20.84	22.72	24.63	25.82
		Paper and paperboard	74.36	73.43	73.15	73.39	73.35	72.25	71.29	69.07
						million cubic meters				
High wood energy scenario	North	Lumber	16.48	17.37	18.56	19.68	20.70	21.27	21.75	22.01
		Str. panel	3.35	4.43	5.41	6.40	7.38	8.51	9.84	11.43
		Nonstr. panel	3.31	4.27	5.42	6.72	8.19	9.90	11.77	13.45
		Paper and paperboard	24.43	25.20	26.49	27.91	29.17	29.65	29.71	29.53
	South	Lumber	35.17	38.00	43.03	48.47	52.55	55.47	58.33	60.30
		Str. panel	13.69	13.83	14.32	15.17	16.02	16.75	17.40	16.72
		Nonstr. panel	6.12	6.42	6.95	7.40	7.66	7.71	7.57	6.95
		Paper and paperboard	43.96	42.88	41.65	40.32	38.88	37.23	35.67	33.87
	West	Lumber	24.50	23.84	25.38	27.56	29.62	29.92	29.81	28.75
		Str. panel	4.77	5.82	6.47	6.79	7.06	7.26	7.39	7.41
		Nonstr. panel	4.36	4.50	4.63	4.70	4.70	4.63	4.60	4.51
		Paper and paperboard	5.95	5.24	4.35	3.70	3.54	3.49	3.57	3.17
	US	Lumber	76.15	79.22	86.97	95.72	102.86	106.65	109.89	111.06
		Str. panel	21.81	24.09	26.20	28.35	30.46	32.53	34.63	35.56
		Nonstr. panel	13.79	15.18	17.00	18.82	20.55	22.24	23.94	24.90
		Paper and paperboard	74.34	73.32	72.49	71.93	71.59	70.36	68.95	66.57

[1] The US aggregate values may not match with the sum of regional values because of rounding; [2]Structural panel; [3]Nonstructural panel

Contrary to findings from our study and the findings of Latta et al. (2013) and Ince et al. (2011a), Johnston and van Kooten (2016) found that US aggregate and US South sawnwood production declined slightly with increased demand for wood energy although they showed an approximate 3 percent increase in sawnwood production in the North. This may result in part because of Johnston and van Kooten's use of a single category of industrial roundwood with a single price. Our model evaluates four different timber types (e.g., softwood and hardwood sawtimber and nonsawtimber), which were allowed to vary independently according to individual demands, such that an increased demand for pulpwood had a positive effect on sawtimber production, thus increasing

Table 10. Projected US aggregate consumption and net exports of final products (million cubic meters) for the baseline scenario and the associated changes for the high wood energy scenario.

Variable	Scenario	Commodity	2015	2020	2025	2030	2035	2040	2045	2050
						million cubic meters				
Consumption	Baseline	Lumber	93.76	99.28	103.08	106.55	109.77	114.20	118.95	117.58
		Str. panel[1]	24.66	26.59	28.39	30.34	32.10	34.02	36.00	36.68
		Nonstr. panel[2]	17.91	19.02	20.24	21.55	22.77	24.07	25.42	26.07
		Paper and paperboard	71.08	68.92	66.81	64.94	63.03	61.44	59.97	57.38
	High wood energy	Lumber	93.78	99.40	103.23	107.30	110.12	114.63	119.37	117.85
		Str. panel	24.65	26.50	28.18	29.95	31.71	33.46	35.27	35.92
		Nonstr. panel	17.90	19.03	20.22	21.48	22.72	23.98	25.31	25.93
		Paper and paperboard	71.08	68.91	66.80	64.92	63.01	61.38	59.93	57.33
						million cubic meters				
Net export[3]	Baseline	Lumber	−17.63	−20.63	−18.56	−14.58	−11.78	−13.92	−16.78	−15.52
		Str. panel[1]	−2.84	−2.41	−1.99	−1.60	−1.25	−0.93	−0.64	−0.36
		Nonstr. panel[2]	−4.11	−3.72	−3.13	−2.58	−1.94	−1.35	−0.79	−0.25
		Paper and paperboard	−1.86	−2.46	−0.98	1.27	3.10	3.66	4.20	4.13
	High wood energy	Lumber	−17.63	−20.18	−16.26	−11.58	−7.26	−7.97	−9.49	−6.78
		Str. panel	−2.84	−2.41	−1.99	−1.60	−1.25	−0.93	−0.64	−0.36
		Nonstr. panel	−4.11	−3.85	−3.22	−2.66	−2.16	−1.74	−1.36	−1.02
		Paper and paperboard	−1.86	−2.51	−1.53	−0.05	1.32	1.83	1.78	1.41

[1]Structural panel; [2]Nonstructural panel; [3]A positive value indicates that the US is a net exporter and a negative value indicates that the US is a net importer.

lumber production. With a single timber product, an increase in demand for timber for energy will raise the timber price and divert timber away from lumber production. Latta et al.'s model includes only softwood and hardwood roundwood but uses an alternative optimization other than that used in this study or in the Ince et al. (2011a) and Johnston and van Kooten (2016) studies, which may explain why Latta's results are consistent with ours, even in the absence of a more detailed specification of timber types. Consistent with our findings, Johnston and van Kooten (2016)'s findings showed lower US aggregate and regional particleboard, fiberboard, and wood pulp production, with corresponding increases in their prices, but with differences in projected magnitude of these changes (as expected), mostly resulting from differences in the amount of wood expansion for energy in the United States.

Our findings illustrate a situation where the use of logging residues is restricted because it is too costly, because future environmental restrictions do not allow their recovery, or because its biophysical availability is limited. Under such conditions, our results suggested that increasing consumption of wood biomass feedstock can be met by supplies of pulpwood, resulting in greater competition for pulpwood between energy and traditional wood products. While such competition proved to bring larger disruptions in pulpwood and pulpwood-consuming traditional wood products markets (pulp, paper, and panels), it also showed a complementary effect on timber harvests and the production of sawlog-consuming products (lumber and plywood/veneer). This finding implies that the wood pulp, paper, and panel industry—especially in the US South—might need to compete for increasingly expensive raw material (up to 42 percent higher pulpwood prices) under higher wood energy demand and restricted logging residue use. Such price competition could lead to reduced profitability and lower production and trade competitiveness. In contrast, increasing pulpwood use for energy raised timber harvests (up to 12 percent) and prices (up to 31 percent) in an assumed high wood energy scenario compared with a baseline scenario and increased production of lumber (up to 9 percent), with an associated increase in lumber net exports. A key insight is that advances in reducing the cost to recover logging residues or policies that encourage or allow logging residue use could result in a significantly different mix of sources of wood used for energy, with different market impacts.

We also assume that land use in all three US regions responds to sawtimber prices, as estimated in Hardie et al. (2000), although the Hardie et al. study focused exclusively on land use change in the US South. Economic theory implies that increases in timberland rents will, at the margin, increase timberland area. And in the absence of other empirical estimates that could be operationalized in the USFPM/GFPM model, we used the Hardie et al. estimates for all three US regions. Incorporating this assumption led to increased timberland area and over time increased inventory, as a result of increased sawtimber prices.

The imposition of fixed coproduction of mill residues with lumber and fixed coproduction of sawtimber with nonsawtimber, on top of the increased housing starts, led to those increases in sawtimber prices and harvest quantities, as well as increased production of lumber and lower lumber prices in the model results. Economic theory provides several alternative explanations for how increased demand for mill residues could lead to changes in lumber production and prices (e.g., directly through raising net revenues at the mill or indirectly through increasing the production of sawtimber). While these two factors (increased net revenue at the mill and increased sawtimber production) both lead to increased lumber production, the effect on lumber prices is less clear. Similarly, theory can explain how increased demand for pulpwood (and thus nonsawtimber) would lead to increased production of sawtimber. In most sawmilling, however, there are only small changes that can be made in production that would result in increased lumber production and decreased prices. For timber production, the fixed coproduction link is less viable because thinning harvests could be used to increase nonsawtimber production while increasing sawtimber less, though most thinning also results in the production of sawtimber. Our model makes only limited use of thinning as a harvest method.

Increases in forest rents that result from wood energy–induced timber price increases can help forest landowners keep their forests as forests, which otherwise would have been converted to agricultural or urban land uses in the absence of expanded wood energy use. At the same time, timber price increases can serve as economic incentives for landowners to invest in new plantations or intensified management activities, as evident from the projected expansion in pine plantation area of roughy 5 million hectares in the high wood energy scenario by 2050, the majority of which occurred in the US South. Increases in timberland area helped offset potential depletion in timber inventory, which would have experienced a greater loss in the absence of such price-induced increases in timberland area.

The findings that expanded wood energy use resulted in increases in timber harvests, timber prices, timberland area, and lumber production have implications for forest-based climate change mitigation efforts. For example, projected increases in US timber harvests and increased lumber production suggest a potential for increasing carbon accumulation in long-lived wood products, whereas an increased timberland area that helped increase the total US timber inventory base (up to 1.3 percent by 2050) suggests that US forests will continue to serve as a carbon sink for several decades. Projected continuous increases in timber harvests and inventory because of expansion in wood energy use, however, is expected to contribute to increasing availability of pulpwood with associated lower prices in the long run, which can help moderate the overall effects on US forest and wood products sector.

Finally, our analyses illustrate some distinct examples of an individual region specializing in producing a commodity where it has a comparative advantage. The fact that the US South was projected to supply the majority of increases in pulpwood use for energy is consistent with the relatively lower cost of timber harvests and pulpwood production coupled with an abundant resource base (inventory) in this region. Similarly, the outcome that the US North region demonstrated increased production of structural panels (mostly OSB) in the high wood energy scenario relative to the baseline scenario (no pulpwood was diverted away from production of OSB) shows that the North has a comparative advantage in producing OSB relative to other US regions. A similar example of specialization was shown for the US West region, where there was increased production of nonstructural panels (mostly industrial particleboard) in the high energy scenario.

Our findings indicate that while increased consumption of pulpwood for energy may divert pulpwood away from pulpwood-based products such as panels and paper, reducing their production and net exports, such a shift in pulpwood consumption can lead to complementary effects through increased timber harvests, lumber production, and lumber net exports. While the higher harvest and higher lumber output resulted in increased production of logging and mill residues, our findings highlight that the actual quantity and mix of wood biomass is determined by the relative comparative advantage that each region has in biomass feedstock production. These market linkages, combined with the quasifixed nature of timberland and timber inventory, imply that short-term market changes in wood energy consumption have the potential for creating long-term forest impacts that vary by region of the United States, with the South demonstrating the largest effects on traditional wood products.

The results of our study should be interpreted with caution because of inherent uncertainties associated with scenario development and limitations. First, future wood energy demand in the United States is uncertain, owing to declining fossil fuel prices and a lack of a dedicated domestic wood energy policy. To the extent that future wood energy demand is uncertain in the United States, our findings are also uncertain. Second, it is assumed that the growth in the demands for wood for energy in other countries will be the same across the scenarios. If such demands were to increase overseas, consistent with our scenarios that assume higher wood quantities are consumed to make energy in the United States, then there could be a shift to greater US net exports and higher prices for timber and wood fuel feedstock in the United States and globally. Despite these uncertainties and limitations, we believe that the study results are consistent with expected economic theory and offer useful insights into likely competition for wood resources for energy and traditional products. Future research could improve our understanding in this area, especially by estimating the net welfare effects on the US wood products sector from an increased dedication of wood to the production of energy.

Endnotes

1. Nonsawtimber is defined as trees between 12.70 and 22.86 cm (5 to 9 in.) dbh for the softwoods and between 12.70 and 27.94 cm (5 to 11 in.) dbh for hardwoods and includes all of the nongrowing-stock portion of both poletimber and sawtimber trees.
2. Sawtimber is defined as all live growing stock portion of trees above 27.94 cm (11 in.) dbh for hardwoods and trees above 22.86 cm (9 in.) dbh for softwoods.

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