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Biomass production from the U.S. forest and agriculture sectors in support of a renewable electricity standard

Eric M. White [a,*], Greg Latta [a], Ralph J. Alig [b], Kenneth E. Skog [c], Darius M. Adams [a]

[a] Department of Forest Engineering, Resources and Management, 280 Peavy Hall, Oregon State University, Corvallis, OR 97331, USA
[b] USDA Forest Service Pacific Northwest Research Station (retired), 3200 Jefferson Way, Corvallis, OR 97331, USA
[c] USDA Forest Service Forest Products Laboratory, 1 Gifford Pinchot Drive, Madison, WI 53726, USA

HIGHLIGHTS

- We model the response of forest and agriculture to increased bioelectricity demand.
- The agriculture sector, through energy crop production, is the key biomass provider.
- Increased land exchange is projected for the highest bioelectricity demands.
- Land exchange from forest to agriculture yield the greatest changes in GHG flux.
- Agriculture and forestry must be accounted for when considering bioenergy policy.

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ABSTRACT

Production of renewable energy from biomass has been promoted as means to improve greenhouse gas balance in energy production, improve energy security, and provide jobs and income. However, uncertainties remain as to how the agriculture and forest sectors might jointly respond to increased demand for bioelectricity feedstocks and the potential environmental consequences of increased biomass production. We use an economic model to examine how the agriculture and forest sectors might combine to respond to increased demands for bioelectricity under simulated future national-level renewable electricity standards. Both sectors are projected to contribute biomass, although energy crops, like switchgrass, produced on agriculture land are projected to be the primary feedstocks. At the highest targets for bioelectricity production, we project increased conversion of forest to agriculture land in support of agriculture biomass production. Although land conversion takes place in response to renewable electricity mandates, we project only minor increases in forest and agriculture emissions. Similarly, crop prices were projected to generally be stable in the face of increased bioelectricity demand and displacement of traditional agriculture crops.

1. Introduction

Renewable energy produced from biomass and other sources has been the focus of much discussion of U.S. energy policy. Recently, much of the interest in renewable energy focuses on anticipated employment gains (e.g., Becker et al., 2009) and potential new sources of income for agriculture and forest landowners. Many of the arguments for renewable energy have focused on the use of biomass from U.S. forest and agriculture sectors (e.g., Galik et al., 2009; Perez-Verdin et al., 2008). In addition to jobs, renewable energy production also has been highlighted as a means to improve U.S. "energy security" by using available U.S. resources to meet energy needs. Further, movement from fossil-fuel based energy production to renewable energy has been a central focus of environmental efforts. Use of biomass from agriculture and forestry operations in the U.S. is expected to be a key component in the transition away from fossil fuels (e.g., Sullivan et al., 2009).

Although there are several seeming positives from bioenergy production, concerns pertain to the sustainability of producing bioenergy feedstocks (e.g., Niven, 2005; Solomon, 2010; Verdonk et al., 2007), the unanticipated creation of adverse environmental conditions (e.g., Marland and Obersteiner, 2008; Walmsley et al., 2009), and the potential implications for production of other goods and services resulting from increased demand for biomass feedstock (e.g., Abt et al., 2010; Johansson and Azar, 2007).

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[*] Corresponding author. Tel.: +1 541 738 6785; fax: +1 541 737 4316.
E-mail address: eric.white@oregonstate.edu (E.M. White).

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Additionally, an inconsistency in current projections involves how the forest and agriculture sectors individually might benefit from increased demand for bioenergy feedstocks. Much of that inconsistency traces to the number of studies that have been completed examining bioenergy feedstock supply from one of those sectors mostly, or entirely, in isolation (e.g., English et al., 2006; De la Torre Ugarte et al., 2009; Johansson and Azar, 2007; Khanna et al., 2011; Galik et al., 2009; Gan and Smith, 2006; Perez-Verdin et al., 2008). Other studies have considered both sectors but not fully accounted for potential land movement between sectors or substitutable products produced by the sectors (e.g., BRDB, 2008).

National-level mandates for use of renewable biofuels in the U.S. have been in place for several years and there has been a wealth of related research. Since the establishment of a renewable fuels standard (RFS) in the U.S. Energy Independence and Security Act of 2005, significant research efforts have examined the environmental and market implications of that mandated renewable energy policy. Whether the replacement of gasoline with ethanol has positive or negative greenhouse gas (GHG) implications has been the source of particularly extensive debate. Aside from a definitive answer to that question, the debate has shown the complexity and importance of carbon accounting and consideration of both direct and indirect land use changes in bioenergy production. Additionally, the impacts on agriculture commodity prices from the establishment of targets for first-generation biofuels have been heavily studied. Increased commodity prices resulting from the conservation-oriented biofuel policy have led to concern over potential intensification of agriculture land use, including new production on land presently enrolled in the U.S. Conservation Reserve Program.

First-generation ethanol production relies on a limited number of feedstocks and requires significant infrastructure for production and dispensing. Conversely, renewable electricity could be produced from a variety of biomass feedstocks in locations across the U.S. using modified existing electrical sector production infrastructure and existing distribution systems. Currently, relatively little national-level research has examined the joint response of the forest and agriculture sectors to significant expansion in bioelectricity production (see McCarl et al., 2000 as an exception). In this analysis, we use an economic model to project how the U.S. forest and agriculture sectors might respond to the establishment of national-level renewable electricity standards. The specific objectives of this research are to project: (1) the types and regional distribution of feedstock use, (2) national and regional intensification and changes in land use, and (3) changes in GHG flux in the forest and agriculture sectors resulting from bioelectricity feedstock use.

2. Literature context

Quantifying the relative amounts of biomass feedstocks that might be supplied from the agriculture and forest sectors is of much interest (e.g., U.S. Department of Energy, 2011). Landowners and some producers in both sectors have the potential for welfare gains from increased demands for bioenergy feedstocks. The agriculture sector has been estimated to have the capacity to produce about 290 million additional dry tonnes of residues and energy crops per year by 2022 at moderate feedstock prices (U.S. Department of Energy, 2011). From the forest sector, logging residues, material from hazard fuel reduction, mill wastes, and urban wood wastes amount to about 84 million dry tonnes of available biomass per year by 2022 at moderate feedstock prices (U.S. Department of Energy, 2011). Forest and agriculture sector residues and wastes are expected to be used to meet early feedstock demands and at relatively low feedstock prices. As prices rise, and over time, energy crops are projected to become increasingly important (U.S. Department of Energy, 2011).

Multiple agriculture and forest sector feedstocks can be used for bioenergy and as feedstock prices rise, a variety of feedstocks in the agriculture and forest sectors would likely contribute to bioenergy production. Walsh et al. (2000) estimated biomass supply curves for every U.S. state. At moderate feedstock prices ($36/tonne delivered), the North Central and South Central regions were projected to supply the greatest volumes of feedstock—mostly energy crops and agriculture residues. At $45/tonne delivered, Walsh et al. (2000) projected that the Great Plains region would also begin supplying feedstock from agriculture residues and energy crops. In a study of potential agriculture feedstock supply, Gallagher et al. (2003) estimated about 142 million tonnes of agriculture residue feedstocks would be available at regional roadside feedstock prices that ranged from about $23/tonne in the Corn Belt to about $45/tonne in the Great Plains and Western regions. As in other studies, the Corn Belt was projected to be the primary provider of agriculture feedstocks (2/3 of total supply).

A variety of national-level renewable electricity standards (RES) have been proposed by the U.S. legislators. Sullivan et al. (2009) used a linear programming model to examine how the electrical sector might respond with increased production in a broad suite of renewable electricity technologies to three proposed RES policies. Those authors considered RES policies in the context of GHG flux, regional energy production patterns, and energy prices. Peak renewable electricity production among the three programs considered ranged from about 12% to about 22% and occurred in the 2020s. Relative to baseline projections, CO_2 emissions under an RES were projected to decline by between 95 and 435 million tonnes (Sullivan et al., 2009). The largest reduction in CO_2 from increasing renewable electricity consumption coincided with an assumed 15% reduction in consumed power. The Western states were projected to easily meet their RES requirement through use of wind and solar energy. The Southeast states were projected to rely primarily on the use of biomass energy and the purchase of renewable energy certificates from other regions. Consumer electricity prices were projected to generally be unresponsive to the establishment of an RES program. Under an RES, average state-level price increases above the baseline were about 1% and no increase was more than 5%.

Woody biomass from forest materials is projected to be an important contributor to bioenergy production. At low feedstock prices, forest material is generally expected to be mill waste and readily accessible forest-based residues. However, as available residue and waste material is consumed and feedstock prices rise, there is concern that feedstock demand may draw roundwood material that might otherwise be used for pulp production (Galik et al., 2009, Abt et al., 2010). Forest landowners have been found to be willing to sell material for wood energy use (Conrad et al., 2011). In their study focused on North Carolina, Abt et al. (2010) projected an approximate doubling of pulpwood prices, relative to business as usual, by the mid-2020s when a state renewable portfolio standard was in place. However, pulpwood harvesting was projected to increase only slightly because of price inelastic supply and projected near-term inventory declines in the baseline (Abt et al., 2010). In turn, increased prices under the renewable energy scenario initiated increased planting for pulpwood production. Although sawtimber material was not projected to be used for bioenergy, increased harvesting of small diameter material for pulp and bioenergy production was projected to result in slight decreases in sawtimber inventories over the long term.

Ince et al. (2011) use the U.S. Forest Products Model (USFPM) to examine how the forest sector might respond to increased demands for forest biomass resulting from a range of national-level renewable electricity standards. They use the Global Forest Products Model scenario A1B as presented in Raunikar et al. (2010) as the basis for international trade in forest products. Those authors assumed that wood served as biomass to support 1/3 of the simulated increase in bioelectricity; the agriculture sector provided the remainder. Because logging residues and mill residues were projected to be the greatest source of biomass feedstock in each of the considered scenarios, Ince et al. (2011) found very limited impacts to timber product consumption or prices, little change to forest inventories, and minor trade changes in response to renewable electricity standards. Increasing the share of forest feedstock used to meet bioelectricity demand resulted in more substantive impacts to the forest sector and timber product markets. In the present research, a key extension from Ince et al. (2011) is combined modeling of both the forest and agriculture sectors. This treatment allows for endogenous determination of the relative contributions of the two sectors in meeting feedstock demand, varying those shares over time, and conversion of land between the two sectors in response to new biomass markets. We also extend the previous work by running our model until 2080—allowing time for at least one full timber harvest rotation cycle to be completed on any newly planted forest stands.

3. Methods

3.1. Model description

To complete this research, we rely on the Forest and Agriculture Sector Optimization Model—Greenhouse Gases. Updated, comprehensive, model documentation for FASOM-GHG is available online in Beach et al. (2010). FASOM-GHG is a dynamic, nonlinear programming model of the U.S. agriculture and forest, sectors that includes representation of bioenergy production. The model uses an inter-temporal dynamic optimization approach to simulate markets for numerous agriculture and forest products (Adams et al., 1996; Alig et al., 1998; Beach et al., 2010), including feedstocks to support biofuel and bioelectricity production. The model solves by simultaneously determining the optimal allocation of resources and management effort in the agriculture and forest sectors that maximizes the aggregate benefits to producers and consumers in all time periods.

Because they are linked, the forest and agriculture sectors compete (1) for the use of private lands that can produce either agriculture or forest products, and (2) to supply substitutable products including sequestered carbon and biomass energy feedstocks. Agriculture producers can switch crops and convert lands to other agriculture uses (e.g., pasture) or timberland in each period. Upon final harvest, forest sector producers can convert lands to agriculture use or change tree species and management regimes (as allowed within the region). Conversion from agriculture to timberland incurs planting and site preparation costs; conversion from timberland to agriculture incurs land clearing costs (see Beach et al., 2010). Only a limited share of agriculture land and timberland are assumed to have capacity to be converted to a different land use. Public and private-owned rangelands and silvipasture land uses are represented in the model. However, those land uses are not discussed here because we assume they do not have the capacity to produce bioenergy feedstocks or be eligible for conversion to agriculture land or timberland.

In this analysis, the model was run for years 2000–2080 represented in five-year timesteps, although we focus primarily on the results between 2010 and 2035. A long model run ensures that forest management investments during the policy period come to fruition within the modeling time horizon. At points in the results, we describe the 2010–2025 period as being the “short-term” and 2025–2035 as the “long term” of the policy period. An exogenously determined amount of agriculture and timberland is assumed to convert to development in each period.

FASOM-GHG and its component models have been used for a variety of policy analyses involving traditional markets for forest and agriculture products (e.g., Alig et al., 2000; Chen and McCarl, 2009), new markets for GHG offsets (e.g., Alig et al., 2010; Baker et al., 2010; Latta et al., 2011), and bioenergy (e.g., McCarl et al., 2000; Szulczyk and McCarl, 2010). In analyzing alternative policy formulations, FASOM-GHG depicts what could be achieved when operators make optimal decisions about resource allocations. Contrasts are made across policy formulations assuming that operators make optimal decisions under each formulation. Output from FASOM-GHG is extensive and includes a variety of conditions for agriculture and forest resources across 11 U.S. regions (see Tables 2–7 in Beach et al. (2010) for a description of the FASOM regions). FASOM-GHG also includes full accounting for GHG emissions and carbon sequestration in the forest and agriculture sectors (see Beach et al., 2010 for a full description). Agriculture GHG emissions recognized in FASOM-GHG include those from livestock production and manure management, soil disturbance, fertilizer application, and the use of fossil fuels in agriculture production. Within FASOM-GHG, emissions of N_2O from agriculture lands under specific cropping practices are accounted for using parameters estimated from the DAYCENT model. Within the forest sector, GHG emissions occur from the use of fossil fuels in management, deforestation, and the burning of residues. Carbon sequestration is accounted for through biomass accumulation in forest ecosystems as well as storage in wood products.

Current and expected future technologies create opportunities to produce bioenergy from a variety of agriculture and forestry feedstocks. We consider the production of 21 bioenergy feedstocks, including energy crops, residues available from agriculture and forestry operations, and production wastes and byproducts (Table 1). In many cases, bioelectricity feedstocks can be produced, in a complementary process, to existing, traditional agriculture and forest sector products. Residues from agriculture production (e.g., wheat and corn residues) can be collected (less than 100% of residue material) from area planted in those crops. Similarly, a portion of the logging residues generated from harvesting activities can be collected for biomass feedstock. Within the agriculture sector, the production of energy crops like switchgrass can displace land that might otherwise be idled, be used to produce traditional crops, or committed to a different land use. Finally, the use of feedstocks (e.g., pulp and milling residues or corn residue) to produce bioelectricity might compete with traditional or biofuel use of those feedstocks.

In the context of being fired to produce bioelectricity, the feedstocks differ in the amounts of energy released per unit of material and in their assumed moisture contents. Some feedstocks represented in FASOM-GHG, such as production wastes and byproducts, require few additional inputs to produce and can be obtained at relatively low cost. Other feedstocks, such as energy crops, require land and other agriculture inputs and are available at higher cost. Production yields for energy crops and agriculture and forest residues are region specific and differ by crop or forest type. The ultimate delivery of feedstocks to bioenergy production is determined endogenously, dependent on the optimal allocation of resources in the sectors.

Within FASOM-GHG, bioelectricity can be produced from agriculture and forest sector feedstocks in dedicated biomass electricity plants or via co-firing with coal. Dedicated biomass plants are assumed to be 100 megawatts (MW) in size and require

Table 1
Annual feedstock requirements (wet tonnes) in the Forest and Agriculture Sector Optimization Model for 100 MW dedicated and co-fired bioelectricity plants operating 75% of the year.

Feedstock	Direct fired	Co-fired with coal			
		5%	10%	15%	20%
Agriculture residues					
Barley residue	560,633	21,192	43,729	67,724	93,289
Corn residue	904,433	34,188	70,546	109,256	150,498
Oats residue	560,633	21,192	43,729	67,724	93,289
Rice residue	751,127	28,393	58,588	90,736	124,988
Sorghum residue	700,185	26,467	54,614	84,582	116,511
Wheat residue	554,230	20,950	43,230	66,951	92,224
Energy crops					
Energy sorghum	606,877	22,940	47,336	73,311	100,984
Switchgrass	606,877	22,940	47,336	73,311	100,984
Bagasse	811,980	30,693	63,334	98,087	135,114
Pulpwood/milling residues					
Hardwood pulpwood	782,289	29,571	61,019	94,501	130,173
Softwood pulpwood	695,369	26,285	54,239	84,001	115,709
Hardwood milling residues	782,289	29,571	61,019	94,501	130,173
Softwood milling residues	695,369	26,285	54,239	84,001	115,709
Logging residues					
Hardwood logging residues	782,289	29,571	61,019	94,501	130,173
Softwood logging residues	695,369	26,285	54,239	84,001	115,709
Short-rotation woody crops					
Willow	589,546	22,285	45,985	71,217	98,100
Hybrid poplar	726,090	27,446	56,635	87,712	120,821
Other residues					
Lignin, nonforest	457,931	17,310	35,719	55,318	76,200
Lignin, hardwood	392,864	14,850	30,643	47,458	65,373
Lignin, softwood	367,920	13,907	28,698	44,445	61,222
Sweet sorghum pulp	731,569	27,653	57,062	88,374	121,733

9704 terajoules of input per year. The amount of biomass feedstock required to fire dedicated and co-fired biomass plants depends on the commonly accepted higher heating values (see Beach et al., 2010) and moisture contents of the feedstock. Co-firing is assumed to occur at coal-fired electricity plants that achieve 5, 10, 15, or 20% of their required energy input from biomass. The types of plants, any co-firing rates, and the biomass feedstock used at each plant are determined endogenously. Biomass feedstock is assumed to burn more fully when co-fired with coal and that improved efficiency results in a slightly lower mass of required feedstock relative to what would be consumed in a dedicated plant. Both dedicated and co-fired plants are assumed to operate 75% of the time.

In the context of biomass feedstock production, we account for GHGs in the generation of biomass and in changes in conditions on the forest and agriculture land base. Biomass harvested for electricity production is withdrawn from the carbon stocks in the forest and agriculture sectors. Changes in the amount of sequestered carbon and management-related emissions are calculated for scenarios with and without renewable electricity targets. Because FASOM-GHG solves for the optimal use of resources and management actions over time, changes in GHG status between scenarios with and without an RES can be attributed to the presence of renewable electricity targets. For example, deforestation, timber harvest, or, alternately, afforestation in an RES scenario over and above that projected when no RES is present, would be attributed to the presence of increased demand for bioelectricity.

In the generation of bioelectricity, we track avoided fossil carbon emissions that would have occurred had the same amount of electricity been produced using a different energy source—typically coal. In the U.S., coal is the largest source of energy to produce electricity and we assume that 88.56 kg of CO_2e are emitted per 1 gigajoule of energy generated from coal. With our assumed technologies, higher heating values, and plant downtime, a dedicated 100 MW bioelectricity plant would annually offset 625,515 t of CO_2e that would have been emitted using coal at the plant to produce the same amount of electricity. Similarly, an electrical plant co-firing with 10% biomass would annually offset approximately 62,552 t of CO_2e that would have been emitted using coal. In addition to accounting for carbon, FASOM-GHG accounts for the net increase in methane and nitrous oxide emissions from producing bioelectricity relative to what would have been emitted had coal been used. Finally, we account for carbon emitted from burning fossil fuels to transport and process biomass for use in bioenergy production.

3.2. *Scenarios*

We considered baseline renewable electricity consumption plus two alternative national-level RES scenarios. The national-level targets for renewable electricity were assumed to be met by a known mix of technologies, including solar, wind, and bioelectricity. Our scenarios were a subset, the lowest and highest targets, of the renewable electricity scenarios adopted by Ince et al. (2011). The national-level renewable electricity targets in our scenarios were consistent with the targets established in the RES legislation modeled in Sullivan et al. (2009). Consistent with that analysis, hydroelectricity did not count towards meeting RES targets in our scenarios. The baseline scenario followed the AEO 2010 reference scenario projection of the amount of consumed power in the electricity sector produced from biomass for the period 2010–2030 (AEO, 2009a). In our alternative scenarios, a simulated national RES resulted in an increased share of consumed electricity being generated from renewable sources (Fig. 1). We considered RES scenarios of both 10% and 20%. As is the case currently, we assume biomass meets only a portion of renewable electricity production. Wind and photovoltaics are assumed to also contribute to renewable energy production targets and do so with the same relative shares found in the baseline projection. National-level targets for the biomass portion of renewable electricity production under baseline and alternate scenarios were entered within FASOM-GHG as constraints that must be met. Renewable electricity consumption was assumed to reach the RES target by 2020 with a linear increase in consumption between the AEO observed consumption in 2010 and the 2020 target. Post-2030, we assumed that biomass and renewable energy consumption remained fixed at 2030 levels.

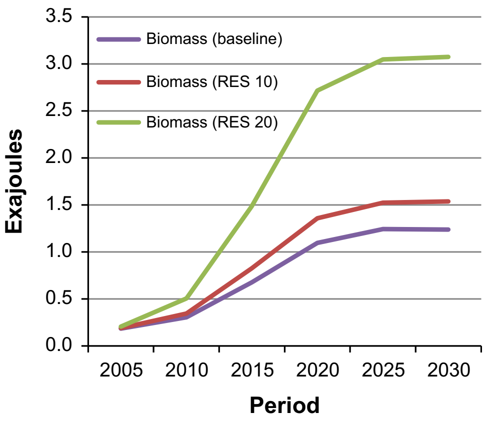

Fig. 1. Electricity production from biomass under a baseline and two alternate renewable electricity scenarios.

Within FASOM-GHG, feedstocks produced from the agriculture and forest sectors can be used in the production of both biofuels and bioelectricity. In all scenarios, we assumed increasing biofuel production meeting the intent of the existing U.S. RFS. However, we employ the more moderate projections of ethanol, cellulosic ethanol, and biodiesel production from U.S. sources between 2010 and 2035, and fixed thereafter, from the 2010 AEO reference scenario (AEO, 2009b). Simulated ethanol production peaked at about 22.8 billion gallons (86.3 billion liters) in 2035; 17.7 billion gallons (70 billion liters) as first-generation ethanol. The volume of biofuels produced was static across the renewable electricity scenarios.

4. Results

4.1. Biomass supply

Under all scenarios, the forest sector is projected to be the greatest initial provider of bioelectricity feedstocks (Table 2). Logging residues contribute the largest initial quantities; milling residues and pulpwood are secondary forest sector sources. As time progresses and bioelectricity demand increases, the agriculture sector is projected to quickly transition to the primary provider of bioenergy feedstock. In all cases, the largest agriculture sector contribution is projected to be energy crops planted specifically for biomass production. Under the increased requirements for renewable electricity in the RES 10 and RES 20 scenarios, the use of agriculture feedstocks is projected to begin earlier and represent a larger total share of feedstock use. The amounts of logging and agriculture residues used for bioelectricity production are relatively similar between the base and RES 10 scenarios. Greater bioelectricity production in the RES 20 scenario is projected to primarily be achieved through increased reliance on energy crops and agriculture residues.

Annual feedstock consumption in the base case ranges from about 23 million tonnes in 2010 to about 81 million tonnes in 2025 (Table 2). Peak bioelectricity feedstock consumption is reached between 2025 and 2029 and ranges from 81 million tonnes in the base case to 202 million tonnes per year in the RES 20 scenario. In each scenario, energy crops are projected to account for the majority of feedstock consumed over the life of the projection; logging residues constitute a distant second in each case. Compared to the other feedstocks, the projected consumption of energy crops and agriculture residues increases substantially over time relative to that consumed in the initial period.

In all scenarios, wheat residue is projected to be the primary agriculture residue used in bioelectricity production. Barley and oat residues are used to produce a limited amount of bioelectricity in the RES 20 scenario. Switchgrass is the only energy crop relied on to produce bioelectricity. In the base and RES 10 scenarios, switchgrass is projected to produce about half of all consumed bioelectricity by 2035; in the RES 20 scenario, that figure increases to about 75%. From the forest sector, hardwood and softwood logging residues are used to produce bioelectricity, but hardwood residues are projected to be used to generate about twice the bioelectricity of softwood residues. The opposite pattern is found for milling residues and chips with softwood material being used at much greater rates than hardwood material. Only under the highest requirements for renewable electricity does use of hardwood milling residues and chips increase significantly.

In the baseline and RES 10 scenarios, the Southeast and Southcentral regions and Oklahoma and Texas (denoted as “SW”) are projected to generate more than 70% of bioelectricity in the short-term (Fig. 2). The Rocky Mountain region produces about 10% of short-term renewable electricity. Under the baseline scenario and in the short term, the Corn Belt produces less than 1% of the Nation’s bioelectricity. However, as renewable electricity requirements increase to 10% and then 20%, the Corn Belt becomes an increasingly important short-term producer of bioelectricity. Under the RES 20 scenario, the Corn Belt is projected to produce 9% of all bioelectricity in the short term.

Table 2
Projected annual bioelectricity feedstock consumption under baseline and two national-level renewable electricity scenarios (thousands of wet tonnes).

	2010	2015	2020	2025	2030
BASE					
Ag residues	950	2444	7212	8057	10,073
Pulp/Milling residues	5559	5645	6480	5424	4455
Logging residues	13,318	16,924	16,991	17,772	18,447
Energy crops	2818	21,965	39,242	47,381	45,869
SRWC[a]	–	–	3048	3038	2365
Sum	**22,644**	**46,978**	**72,974**	**81,672**	**81,209**
RES 10					
Ag residues	1601	3522	10,691	12,063	17,054
Pulp/Milling residues	5458	5702	6687	7059	4590
Logging residues	14,363	16,923	16,989	17,768	18,439
Energy crops	3898	29,990	51,701	59,424	56,936
SRWC[a]	–	–	3074	3056	2391
Sum	**25,320**	**56,137**	**89,142**	**99,371**	**99,023**
RES 20					
Ag residues	2766	8829	22,968	23,327	25,258
Pulp/Milling residues	5376	8615	11,611	11,018	9301
Logging residues	15,490	16,871	17,156	17,937	18,511
Energy crops	11,519	62,174	125,499	144,609	144,552
SRWC[a]	743	4373	5079	5002	3358
Sum	**35,894**	**100,862**	**182,313**	**201,893**	**200,980**

[a] *SRWC*=Short-rotation woody crops.

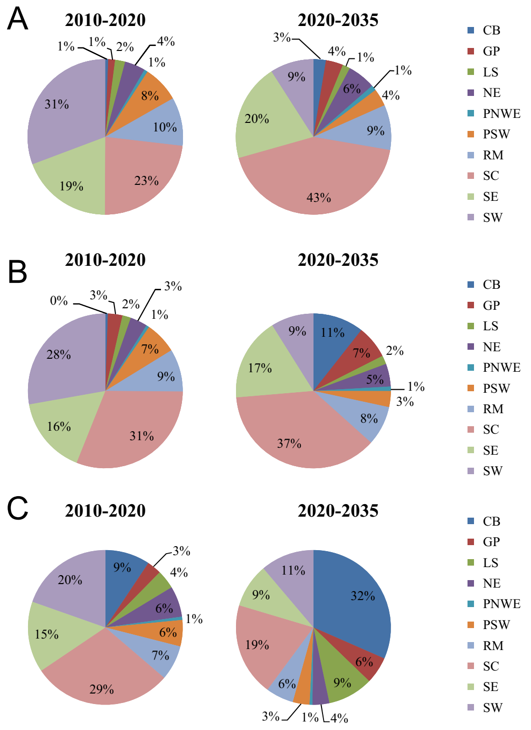

Fig. 2. Regional shares of renewable electricity production in short- and long-term periods under a baseline (A) and national-level renewable electricity standards of 10% (B) and 20% (C). Regions are Corn Belt, Great Plains, Lake States, Northeast, Pacific Northwest-Eastside, Pacific Southwest, Rocky Mountains, Southcentral, Southeast, and Southwest (Oklahoma and most of Texas).

In the long-term, in the baseline scenario, the South-central region is projected to produce 43% of the Nation's bioelectricity. Collectively, the South-central, Southeast, and Rocky Mountain regions produce more than 70% of the Nation's long-term bioelectricity in the baseline. As in the short-term, the importance of the Corn Belt as a long-term provider of biomass increases as greater amounts of bioelectricity are required. Under the RES 10 scenario, the Corn Belt produces 11% of the Nation's bioelectricity in the long-term period. That region is the single greatest producer (32%) of the Nation's bioelectricity in the long-term under the RES 20 scenario and combined with the South-central region produces 51% of all bioelectricity.

A variety of feedstocks are projected to be used within the regions represented in the FASOM-GHG model. Within the South-central, Southeast, Southwest (Oklahoma and most of Texas), and Corn Belt regions, energy crops are projected to be the primary bioelectricity feedstock in all the modeled scenarios (Table 3). Agriculture residues are the projected primary feedstock produced in the Great Plains region. From the forest sector, logging residues are projected to be an important feedstock in the South-central, Southeast, and Northeast regions. Short-rotation woody crops are a potentially important bioelectricity source and are projected to be produced within the Northeast region. The amount of bioelectricity produced from willow in the Northeast region increases as bioelectricity requirements increase from baseline projections to the RES 20 scenario.

4.2. Land use change

National-level increases in bioelectricity production are projected to yield a minor increase in the number of hectares in crop production. Under the RES 10 scenario, we project an additional 121,000 ha in crops in the short term and an additional 283,000 ha in crops in the long term relative to the baseline scenario—a 0.1% and 0.2% increase from initial cropland area. The RES 20 scenario is projected to result in cropland increases of 1.5 million hectares (a 1.3% increase) in the short term and 2.9 million hectares (a 2.3% increase) in the long term. Increases in cropland come about with concomitant reductions in the area of pasture and timberland (Table 4).

Cropland area expansion traces largely to projected increases in the area planted in switchgrass. In the RES 10 scenario, switchgrass area is projected to peak in 2020 and 2025 at 600,000 ha greater than in the baseline scenario. Under the RES 20 scenario, the additional area planted to switchgrass is projected to peak in 2025 at 4.8 million hectares. Nationally, increase in the area planted in switchgrass is projected to primarily be offset by decrease in areas planted to soybeans and wheat: up to 243,000 and 162,000 ha less in the RES 10 scenario and up to 1.1 million and 850,000 ha less in the RES 20 scenario. In the RES 20 scenario, because of the large increase in switchgrass production, the Corn Belt differs from that national pattern and is projected to have an offsetting reduction, to support switchgrass production, in the area planted in corn and soybeans. Relative to the baseline, under the RES 10 scenario,

Table 3
Projected bioelectricity feedstock consumption for select regions under baseline and two national-level renewable electricity standards, period 2010–2035 (thousand wet tonnes).

	SC	SE	SW	CB	GP	NE
BASE						
Ag residues	0	0	11,881	0	40,339	0
Pulp/milling residues	16,032	1	0	0	0	0
Logging residues	184,793	84,144	0	7665	0	43,485
Energy Crops	397,232	177,755	186,687	24,704	0	0
SRWC[a]	0	0	0	0	0	42,254
RES 10						
Ag residues	0	0	17,358	0	99,801	0
Pulp/milling residues	15,740	1	0	0	0	0
Logging residues	200,495	131,453	0	7637	0	43,502
Energy Crops	473,017	164,330	210,723	141,535	0	0
SRWC[a]	0	0	0	0	0	42,605
RES 20						
Ag residues	0	0	64,392	0	169,270	0
Pulp/milling residues	15,708	1	0	0	0	1
Logging residues	205,710	131,642	0	7240	0	43,483
Energy Crops	578,699	240,171	377,414	986,691	0	0
SRWC[a]	0	0	0	0	0	92,777

[a] *SRWC*=Short-rotation woody crops.

Table 4
Average annual projected area of cropland, pasture, and timberland under baseline and two national renewable electricity standards (million hectares).

			Difference from base			
	RES Base		**RES 10**		**RES 20**	
Land use	**2010–2025**	**2025–2035**	**2010–2025**	**2025–2035**	**2010–2025**	**2025–2035**
Cropland	121.4	121.0	0.1	0.3	1.5	2.9
Pasture	53.3	52.7	−0.1	−0.2	−1.4	−1.5
Timberland	138.9	134.7	0.0	−0.1	−0.1	−1.4

increases in the area of cropland in production are projected to occur primarily in the South-central region, peaking at 243,000 additional hectares in crop production after 2025. In the RES 20 scenario, up to an additional 1.3 million hectares are projected to be in crop production in both the South-central and Northeast regions after 2020. The RES 20 scenario is projected to also yield modest increases in cropland area in the Southeast, Rocky Mountain, and Corn Belt regions.

In the U.S., there is a lengthy history of land exchange between the agriculture and forest sectors and increased demands for bioelectricity feedstocks are projected to yield additional land exchanges. In the baseline scenario, by 2035, afforestation is projected to occur on 4.7 million hectares of agriculture land and deforestation to agriculture is projected on 4.5 million hectares of timberland (Table 5). Those gross changes in land use result in a net exchange toward timberland between the sectors. In the RES 10 scenario, an additional 241,000 ha are projected to be deforested to agriculture between 2010 and 2035, with all of the additional deforested land going to cropland. Concomitantly, projected afforestation of agriculture land during the same period is projected to increase by 134,000 ha. In the RES 10 scenario, the gross land exchange between agriculture and forestry still leads to a net exchange toward timberland of 107,000 ha.

The RES 20 scenario yields more substantive changes in land exchange relative to the baseline scenario. An additional 1.5 million hectares of timberland are projected to be converted to agriculture land between 2010 and 2035. All of the additional deforested land in the RES 20 scenario is projected to be converted to cropland. Afforestation on agriculture land remains roughly equivalent to that in the baseline scenario. Together, those gross exchanges yield a net reduction in timberland area of 1.3 million hectares under the RES 20 scenario.

Afforestation and deforestation for agriculture occur in every region, although the greatest land exchanges occur in the South-central, Lake States, and Corn Belt regions (Table 5). The RES 10 scenario yielded a small amount of additional deforestation to agriculture and almost all of that activity was projected for the South-central region. Under the RES 10 scenario, an additional 83,000 ha are afforested in the Corn Belt between 2010 and 2035. In the RES 20 scenario, almost all (1.4 million hectares) of the projected additional timberland deforestation occurs in the South-central and Southeast regions. In addition, projected deforestation between 2010 and 2035 in the Northeast increases by about 62,000 ha.

Table 5
Projected levels of afforestation and deforestation, in select FASOM-GHG regions, under baseline and two national renewable electricity standards, 2010–2035 (1000s hectares).

Deforestation	**Base**	Difference from base	
		RES 10	**RES 20**
Corn belt	483	0	−2
Lake states	988	0	0
Northeast	419	0	62
Rocky mountains	0	0	2
Pacific southwest	0	0	0
Pacific northwest-eastside	22	0	0
South-central	1979	243	991
Southeast	577	−2	441
Sum	**4468**	**241**	**1493**
Afforestation	**Base**	**RES 10**	**RES 20**
Corn belt	750	83	115
Lake states	53	0	0
Northeast	498	4	−13
Rocky mountains	996	30	40
Pacific southwest	65	−1	2
Pacific northwest-eastside	0	0	0
South-central	1654	19	−51
Southeast	647	0	−79
Sum	**4664**	**134**	**14**

4.3. *Greenhouse gas flux*

Electricity generated from biomass in the RES 10 scenario leads to a reduction in emissions from coal-fired electricity, net of emissions from biomass transportation and processing, of about 44 million tonnes CO_2e per year between 2010 and 2020 and about 111 million tonnes CO_2e annually between 2020 and 2035. Relative to the baseline scenario, the RES 10 scenario increases the avoided emissions from coal-fired electricity by about 7 million tonnes CO_2e per year in the short term and 21 million tonnes CO_2e in the long term (Fig. 3). With a substantially higher renewable electricity target, the RES 20 scenario creates total avoided emissions, net of transport and processing, of about 75 million tonnes CO_2e per year in the short term and 222 million tonnes CO_2e per year in the long term.

The establishment of a national RES leads to relatively small changes in net GHG flux in the agriculture and forest sector land bases (Fig. 3). Annual changes in the short and long terms, relative to the baseline, are, in most cases, less than 5 million tonnes CO_2e. The agriculture sector is projected to experience relatively slight increases in annual emissions, relative to the base, in both the short term and long term. This change traces primarily to slightly less carbon sequestered in agriculture soils and slightly higher emissions from fertilizer applications. The largest projected change in agriculture emissions, 5.4 million tonnes CO_2e, is

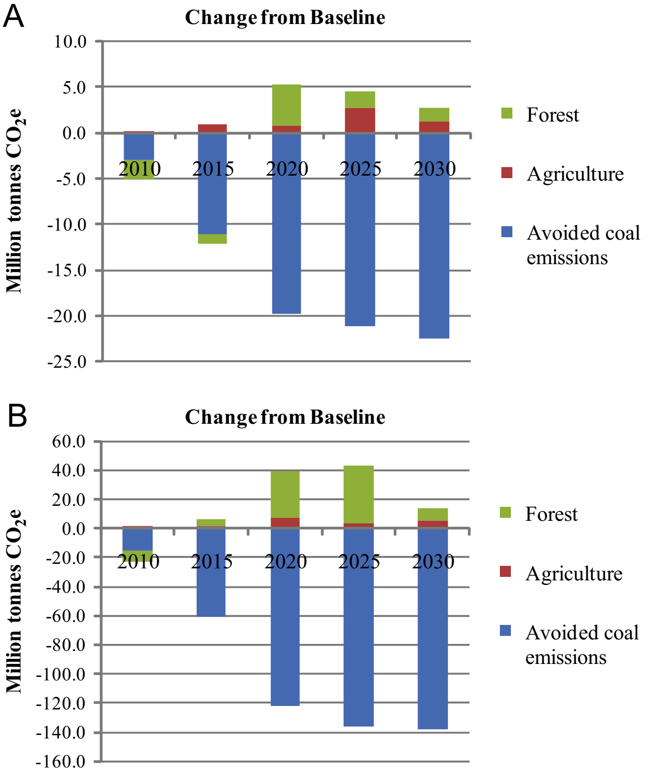

Fig. 3. Projected average annual greenhouse gas flux in the forest and agriculture sectors and avoided coal emissions associated with bioelectricity production under national-level renewable electricity standards of 10% (A) and 20% (B), relative to baseline projections (negative is an improvement).

projected in the RES 20 scenario post-2020. That change traces to increased emissions from agriculture fertilizer applications.

Improvements in GHG flux (sequestration), relative to the base, are projected for the forest sector in the short term for both RES scenarios. In the RES 10 scenario, that improvement traces to reduced emissions from forest management activities relative to the baseline. In the RES 20 scenario, greater amounts of sequestered carbon maintained in afforested stands leads to slightly improved carbon flux. In the long term, deteriorations in GHG flux in the forest sector are projected for both renewable electricity scenarios. In the RES 10 scenario, that deterioration is 2.5 million tonnes CO_2e annually and traces to lower amounts of sequestered carbon in forest soils and slightly higher emissions from forest management. The greatest projected change in flux (lower amounts of net sequestration) is in the RES 20 scenario, post-2020. That deterioration in flux, relative to the base case, of 27 million tonnes CO_2e annually, on average, traces to higher projected rates of deforestation beginning in 2020. That change represents about 16% of the net annual flux in the forest sector (sequestration) projected in the baseline post-2020.

5. Discussion

5.1. Greenhouse gas balance and avoided emissions

The burning of biomass to produce bioelectricity generates carbon emissions. Within FASOM-GHG, changes in forest-sector land-base carbon are determined by removal of biomass from the land to produce bioelectricity as well as the sequestration of atmospheric carbon in forests over time. In this study, for the forest sector, the projected amount of woody material burned for bioelectricity results in peak biomass energy emissions (in the 2020 decade) to the atmosphere of about 2.1 million tonnes CO_2e annually in the baseline and 3.6 million tonnes CO_2e annually in the RES 20 scenario. The length of time required to sequester the carbon emissions from forest biomass used to produce bioelectricity, and the land base considered in that calculation, has recently been of interest. Schlamadinger et al. (1995) proposed a calculation for a carbon neutrality factor ($CN(t)$) to gauge the net carbon balance, over time, of an increase in carbon emissions from biomass burning and associated change in carbon on the land. In Schlamadinger et al., 1995 $CN(t)$ value of zero indicates that an increase in cumulative emissions from biomass burning over a period from time zero to time t (comparing an alternate case to a base case) results in a difference in carbon on the land at time t, between the alternate case and base case, that is exactly equal to the change in cumulative emissions. Land carbon is decreased by the exact amount of the increase in cumulative biomass emissions. A $CN(t)$ value of one indicates that there is no change in land base carbon at time t even though there has been an increase in cumulative emissions—suggesting that carbon emissions associated with combusted biomass have been sequestered back to the land base over time t. Values between zero and one indicate a partial return of carbon emitted from burning biomass back to the land base over time t. Factor values of less than zero indicate that the carbon lost on the landscape is more than that emitted into the atmosphere from biomass combustion over time t; values greater than one reflect carbon gains on the landscape greater than carbon amounts emitted into the atmosphere from biomass combustion over time t.

$$CN(t) = 1 - [\Delta LC(t)/\Delta CE\text{fossil}(t)]$$

where $\Delta LC(t)$ is the carbon on the land in the base case at time t minus the carbon on the land in the alternate case at time t and $\Delta CE\text{fossil}(t)$ is the cumulative increase in fossil carbon emissions between a base case and an alternate case from time 0 to time t.

We compute CN for the case where we assume wood conversion efficiency equals fossil conversion efficiency so $\Delta CE\text{fossil}(t) = \Delta CE\text{wood}(t)$ = Cumulative increase in wood carbon emissions between a base case and an alternate case from time 0 to time t.

To the extent that wood conversion efficiency is lower than the fossil fuel it replaces, the ratio $[\Delta LC(t)/\Delta CE\text{fossil}(t)]$ will be larger than for our calculation and $CN(t)$ will be lower than we estimate. The degree of downward adjustment is larger to the degree that land carbon in the alternate (wood energy) case is lower than the base case. If the difference in land carbon is zero, $CN(t)$ equals 1 regardless of the ratio of conversion efficiencies.

We computed CN factors at ten points in time between 2015 and 2060. CN factors were computed comparing change in cumulative forest sector and both sector biomass emissions to (1) change only in forest land carbon (Fig. 4a) and (2) change in both forest and agricultural land carbon (Fig. 4b). For the forest sector only and in the RES10 case, when bioelectricity increases are relatively small, compared to the baseline case, the CN factor is between zero and one early in the projection before dropping below zero. Over time, the CN factor increases, reaching one by 2060 (Fig. 4a). Those CN factors indicate the forest sector land base is recovering less than 50% of the increase in cumulative carbon emission early in the period and 100% is recovered by 2060. When the bioelectricity demand increase is more pronounced in the RES20 case, and a large portion of biomass comes from agricultural crops, there is loss of forest carbon with conversion of more than 1.6 million hectares forest land to agriculture land and net afforestation declines in total. As a result, for the increase from the baseline case to the RES20 case, $CN(t)$ based on forest carbon change alone is highly negative and rises toward 0.0 by 2060. The

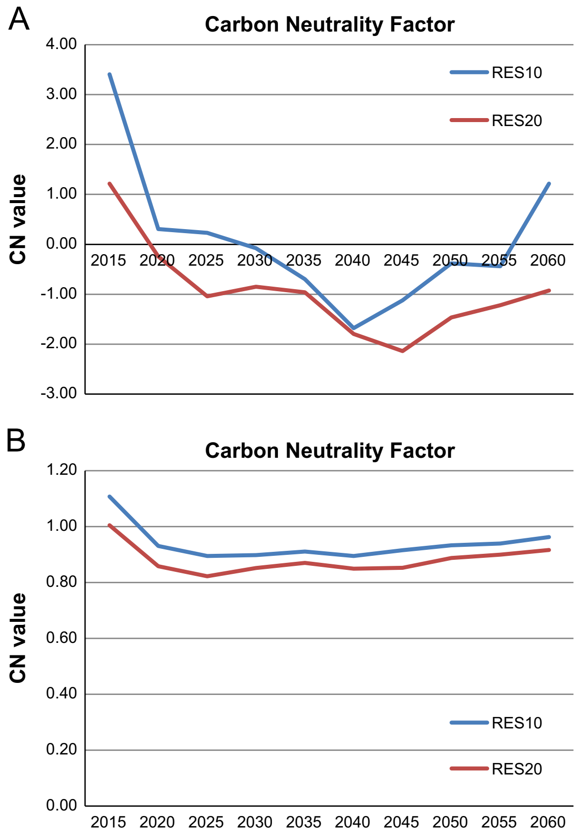

Fig. 4. The influence of considering only the forest sector (A) and the forest and agriculture sectors combined (B) on a calculation of a carbon neutrality factor (Schlamadinger et al., 1995) between biogenic emissions from bioelectricity and the land base.

increased biomass demand results in increased losses in the carbon sequestered in the forest land base over and above that associated with removed and burned forest biomass (Fig. 4a). Note that in 2015, the CN factors in both cases are greater than one due to early afforestation for the RES10 and RES20 cases compared to the baseline case in anticipation of increasing biomass demand. A key determinant in the CN factor, after 2020 for the forest sector, is the forest carbon loss due to conversion to agricultural land in support of agriculture biomass feedstock production.

The view of land carbon recovery of biomass emissions changes dramatically when we use total land carbon change (forest and agriculture) and compare it to total cumulative biomass emissions (forest and agriculture). For the RES10 and RES20 scenarios (compared to the base scenario), CN(t) is greater than zero for the entire projection period. The CN factor is above 0.9 for the entire RES 10 scenario (Fig. 4b). The CN factor in the RES 20 scenario is slightly lower and declines to near 0.8 by 2025 before reaching 0.9 by 2055. The forest and agriculture biomass CN factor is positive even though there is loss of forest carbon with timberland conversion to agriculture land. The carbon in agriculture soils and biomass productivity of the agriculture land offsets the loss of forest sector carbon. One reason land carbon recovery is rapid, (CN$\sim$ 0.9 in 45 years) is that—as modeled in FASOM-GHG—landowners make anticipatory investments in afforestation and herbaceous energy crops.

If we were to assume that new biomass energy plants would be replacing a natural gas alternative and the ratio of biomass to natural gas conversion efficiencies is 0.4—using modern wood and natural gas power cases from the Manomet Center for Conservation Sciences (2010, Exhibit 2−1)—then a CN(t) value of 0.6 in Fig. 4b would be adjusted downward to zero, 0.4 would be adjusted to −0.5 and a value of 0.9 would be adjusted to 0.75. So use of wood energy wood versus natural gas could result in 75% less net cumulative emissions over 55 years. However the decrease in radiative forcing over the period to 2060 due to an increase in biomass power use versus an increase in natural gas power use would be somewhat less than 75% because cumulative emission recovery is low to negative in early years.

Here, we report carbon recovery based on one calculation approach and dependent on the assumptions in our model. Alternate calculation approaches and the use of another model may lead to different recovery figures. Our primary impetus for calculating carbon recovery is to show the sensitivity of results to consideration of both the forest and agriculture land base. The estimates of carbon recovery over time suggest the following for life cycle assessment of biomass use for bioenergy. First, determining the impact of increased wood biomass use for energy cannot be done by modeling carbon dynamics at the forest stand level alone. Changes in land carbon will also be influenced by shifts in markets for wood and agricultural products and markets for land. Fully determining the impact of increased biomass energy use (and emissions) on land carbon will require either (1) full market modeling of scenarios that allow for (a) changes in agricultural and forest biomass supply and (b) tracking of land use change, or (2) partial market models (e.g., forest industry alone) with explicit assumptions about all sources of biomass supply and the effect of such biomass supply on land use change.

5.2. Implications for agriculture markets

The experience of increased corn prices in response to ethanol demands raises concerns about how bioelectricity feedstock production might influence agriculture commodity prices. In the case of bioelectricity, price increases might occur because land previously allocated to the production of traditional agriculture products is now used to produce biomass feedstock, especially energy crops. In this analysis, we project fairly limited displacement of traditional agriculture crops by biomass feedstocks. Of those crops affected, soybeans and wheat are projected to experience the greatest reductions in acreage under a renewable electricity standard. For corn, soybeans, and hard red winter wheat, the RES 10 scenario yields little change in projected crop prices (Fig. 5). However, at higher bioelectricity demands (under the RES 20 scenario) crop mixes adjust to provide more switchgrass and we project minor increases in corn, soybean, and wheat crop prices. Under the RES 20 scenario, the greatest price departures are in the 2020–2025 period, when biomass feedstock consumption is projected to be greatest. In that period, corn and soybean crop prices are projected to be about 4% greater and hard red winter wheat prices about 9% greater than baseline projections. Our model results indicate a strong reliance on energy crops to supply biomass feedstock needs. If energy crops end up a smaller component of future bioelectricity production, replaced perhaps with agriculture residues (e.g., BRDB, 2008), then fewer traditional crop hectares may be displaced likely leading to smaller crop price responses.

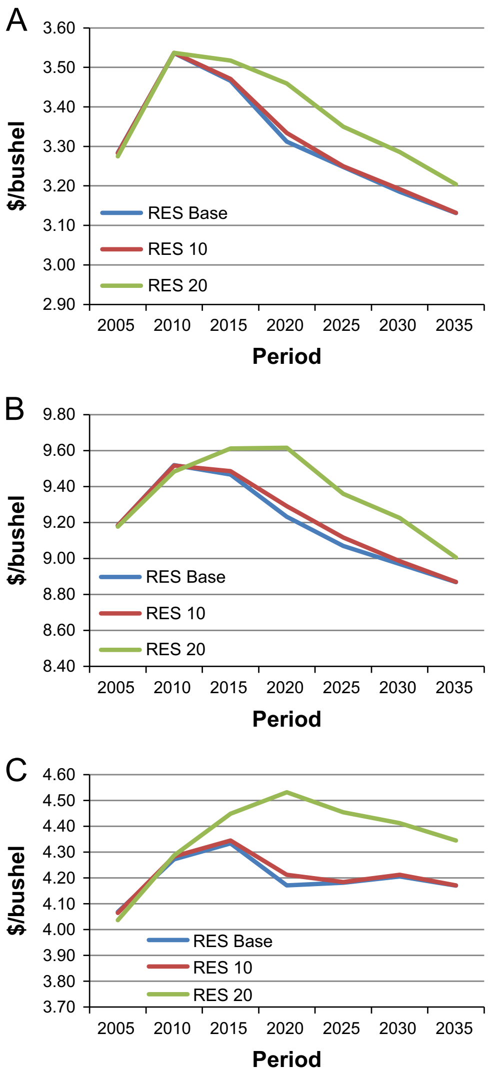

Fig. 5. Projected crop prices ($2004) for corn (A), soybeans (B), and wheat (C) under baseline and two renewable electricity standard scenarios.

5.3. Land use considerations

In this analysis, switchgrass is projected to be the greatest single biomass feedstock used to meet RES requirements. We project that our highest renewable electricity standard would result in up to 4.4 million additional hectares of switchgrass production. The land to support switchgrass production would come from a combination of cropland already in production, idle cropland, and land in other uses, such as timber production. Converting production agriculture hectares from annual crops to the perennial grass switchgrass has the potential to lead to environmental improvements, such as decreased soil erosion (Blanco-Canqui, 2010), decreases in nutrient leaching (Kovar and Claassen, 2009), increased carbon sequestration in agriculture soils (Purakayastha et al., 2008), and improved wildlife habitat (Murray et al., 2003; Roth et al., 2005). Additionally, switchgrass appears to be less prone to become invasive outside its natural range, even under climate change conditions (Barney and DiTomaso, 2010), than other energy crops such as miscanthus. The environmental co-benefits from converting active cropland to switchgrass might produce the types of conservation goals that could increase support among conservation groups (e.g., Stidham and Simon-Brown, 2011). However, we also project an additional 1.5 million hectares of deforestation of timberland to agriculture by 2035 under the RES 20 scenario. Most of those deforested hectares are projected for the South and to support increased switchgrass production. It seems unlikely that conservation groups would view such conversion as a positive aspect of bioelectricity production. Ultimately, the amount of deforestation from bioelectricity production is likely sensitive to the importance of agriculture energy crops. If those crops end up being a less-important feedstock, then deforestation to agriculture under a renewable electricity standard may be less extensive.

5.4. Regional considerations

The South-central, Southeast, and Southwest regions are projected to be integral in meeting short-term bioelectricity needs. Over the long term, or when renewable electricity demands were high, the Corn Belt is projected to become a key provider of bioelectricity. Each of those regions is projected to provide significant volumes of energy crops, switchgrass in this research. The South-central and Southeast regions are also projected to supply significant volumes of logging residues. Those regions that we project to be the most important providers of biomass for bioelectricity are consistent with the findings of other studies (Walsh et al., 2000; Gallagher et al., 2003; U.S. Department of Energy, 2011).

We assume that biomass is just one of several technologies used to meet our national-level renewable electricity targets. As is the case in other studies, different regions of the U.S. will likely rely on those renewable electricity technologies for which they have a comparative advantage. In an analysis that considered a full suite of technologies, Sullivan et al. (2009) projected that the western U.S. would likely rely on wind and photovoltaic sources to meet targets and the South would rely on a combination of bioenergy and purchases of electricity credits. Our results are consistent, projecting that the East, and South in particular, is the primary provider of bioelectricity. Policy formulations that reduce the role of biomass collectively, or some specific forms of biomass, or allow for the purchase of renewable electricity credits to meet targets would likely influence the regional distribution of renewable electricity generation. A national-level renewable electricity policy that limits the role of biomass may place greater onus on the Western U.S. for renewable electricity generation. From the standpoint of GHG mitigation, such a result is reasonable if system-wide GHG flux is improved—although maximum potential improvements may not be achieved. However, regions that have comparative advantage in producing bioelectricity might then not achieve important reductions in SO_2 emissions from coal power plants, potential environmental co-benefits from planting perennial grass feedstocks on cropland, and potential income to producers and employees.

6. Conclusions

The U.S. forest and agriculture sectors have the capacity to provide biomass feedstocks to contribute to renewable electricity standards meeting 10% and 20% of anticipated future U.S. electricity consumption. In our model, when the forest and agriculture sectors can compete to provide biomass and for land, both sectors contribute biomass to meet bioelectricity needs. Because of ready availability, we project that the forest sector would be the primary initial provider of biomass feedstock, mostly logging residues. Over time and with increased demands, we project that the agriculture sector would provide the majority of biomass feedstock via energy crops and some crop residues. The relative preference for agriculture sector feedstocks is consistent with (1) that sector's ability to produce higher biomass energy yields per unit of land area and (2) the shorter period of time for agriculture biomass crops to reach maturity.

The GHG implications of increased bioenergy production are a key concern. We project that moderate national-level renewable electricity standards result in small relative changes in GHG flux in the agriculture and forest sectors. Except for when bioelectricity demands were the highest, we project deteriorations in annual GHG flux for the forest and agriculture sectors that are less than 5 million tonnes CO_2e. Under the highest bioelectricity demand, in the 2020–2035 period, the forest sector is projected to have deterioration in annual GHG flux of about 27 million tonnes CO_2e.

In our model, lands that are suitable for both agriculture and timberland can convert between uses depending on values of the land in alternate production. At the highest levels of bioelectricity production considered, we project additional conversion of timberland to cropland of about 1.5 million hectares. The highest RES scenario resulted in a net exchange of land from timberland to agriculture of 1.4 million hectares in the South-central region and 450,000 ha in the Southeast region. Because energy crops mostly require cleared land for production, the amount of land exchange that might take place in response to a national bioelectricity standard is likely sensitive to the importance of energy crops as a biomass feedstock.

We use an economic model to project the behavior of agriculture and forest sector landowners in supplying feedstocks to meet increased demands for renewable electricity. As is required in our approach, we assume that landowners have perfect knowledge about future conditions and make optimal decisions. Our results depict what could be feasible under the conditions we model. As with similar modeling efforts, we are forced to make assumptions, including about production rates, technologies, and future market conditions, to complete this research. To the extent those assumptions differ from future conditions, our projections of feedstock production, and associated land use change, may depart from what is possible in the future.

In our analysis, increased bioelectricity production at the national-level can be achieved from the forest and agriculture sectors with relatively modest implications for GHG flux, land use change, and commodity prices. Energy crops are projected be the primary biomass feedstock. To the extent that perennial energy crops like switchgrass replace traditional agriculture crops, those energy crops may provide environmental co-benefits. Such environmental benefits may generate some support from conservation groups for bioelectricity production. However, increased deforestation to meet bioelectricity may somewhat offset any support created from taking marginal cropland out of traditional production to plant switchgrass.

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