A multi-sector intertemporal optimization approach to assess the GHG implications of U.S. forest and agricultural biomass electricity expansion

Latta, Gregory S.[1], Baker, Justin S.[2], Beach, Robert H.[2], Rose, Steven K.[3], and McCarl, Bruce A.[4]*

1: Oregon State University
Department of Forest Engineering, Resources and Management,
Corvallis OR 97331, USA

2: Research Triangle Institute,
Agricultural, Resource, and Energy Economics & Policy Program
Research Triangle Park, NC 27709, USA

3: Electric Power Research Institute,
Energy and Environmental Analysis Research Group
2000 L Street NW, Suite 805; Washington, DC 20036, USA

4: Texas A&M University,
Department of Agricultural Economics,
College Station, TX 77843, USA

**corresponding author: e-mail: greg.latta@oregonstate.edu;*
phone: + 1-541-737-6264

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Introduction

With rising concern over future energy security and the environmental footprint of the global energy system (including climate change concerns), energy policy is moving towards efforts that encourage or require that a larger proportion of energy generation be derived from renewable sources. In the U.S., there are examples of such policies at both the national and state levels. Nationally, the U.S. currently has the Renewable Fuels Standard (RFS2; enacted under the Energy Independence and Security Act (EISA) of 2007 to expand the original RFS program created under the Energy Policy Act of 2005), which imposes stringent mandates on first and second generation biofuel production. In addition to increasing renewable fuel volume requirements and establishing new categories of renewable fuel (biomass-based diesel, cellulosic biofuel, and advanced biofuel in addition to traditional renewable fuel), RFS2 requires that each category of renewable fuel has specific minimum percentage GHG reductions relative to the petroleum fuels being replaced. However, there currently is not an analogous comprehensive federal plan on renewable electricity.

At the state level, existing mandatory and voluntary programs include a wide range of utilization requirements and other incentives encouraging the adoption of renewable energy sources. Such energy sources include solar, wind, biomass, hydroelectric, geothermal, hydrogen, waste and waste-based gases, and ocean-based heat and energy. Some existing policies favor investment in specific renewable sources, and are currently seen in a number of states; these include tax credits, grants, loan guarantees and other price incentives (a detailed discussion of existing policies is found in Aguilar, Song, and Shifley, 2011). Other policy efforts simply establish portfolio standards and let the market determine the optimal generation mix. For example, the state of Oregon established a renewable portfolio standard (RPS) for electric utilities and retail electricity suppliers, mandating the use of a variety of renewables sources for different reduction targets depending on a utility's size. The Massachusetts RPS requires all retail electricity suppliers to provide a certain percentage of annual kWh sales from certain classes of renewable sources. California's RPS requires that 33 percent of the state's energy comes from certified renewable sources, including biomass, by 2020. The California policy also contains a cap and trade program that includes compliance offset protocols for GHG emission reductions or sequestered carbon (from, for example, tillage change, afforestation or improved forest management) that may be used by regulated entities to meet a percentage of compliance obligations.

With many states already having renewable targets and depending on how federal renewable goals unfold, biomass could play a predominant role in the portfolio-based electricity policy. The rationale for promoting renewable electricity sources is that utilization of such energies in lieu of fossil fuels yields numerous potential benefits, including GHG emissions reductions and future climate change mitigation, local air and water quality improvements, energy security (for states without abundant fossil fuel resources), and rural economic development, including employment, and farm and forest income opportunities.

Of particular note is the potential role of electricity derived from the combustion of biomass (henceforth referred to as biopower) to meet policy-driven renewable energy demands. In addition to being derived from renewable resources, biopower offers a relatively low-cost renewable electricity source (Brown and Baek, 2010, Touš et. al., 2011). While biomass feedstocks are higher cost than conventional fossil fuels on an energy equivalent basis, biomass can often be co-fired directly with coal at existing facilities with low to no up-front technological investment. This can make biopower a cost-competitive source of renewable energy in the short-term relative to renewables that require significant capital investments for both generation and distribution (e.g., wind, concentrated solar thermal, solar photovoltaic, tidal). Other studies have shown that biopower offers greater GHG mitigation potential than biofuel production using the same feedstock (Thomson et al., 2009, Farine et al., 2012, Soimakallio et al., 2009, and Campbell et al., 2009). In addition, Baker et al., 2010, showed that renewable energy and climate mitigation policies in the U.S. could lead to large income benefits for U.S. farmers and foresters.

However, while there is general agreement in the literature that replacing electricity generated using fossil fuels with biopower will often reduce GHG emissions; there is a lack of consensus on the level of this reduction. Some biomass energy policies assume a priori that biopower is 'carbon neutral', meaning that the combustion of biomass does not contribute to atmospheric GHG concentrations. More recent research has questioned the carbon neutrality of biopower, suggesting that without an equivalent increase in the terrestrial carbon stock, harvesting woody biomass for biopower can result in a net emissions increase (e.g., Searchinger et al., 2009). Certainly this can be true when evaluating GHG impacts of biomass harvested at small scales (e.g. from individual forest stands)—harvests today for fossil fuel replacement can result in large carbon debts and lengthy payback periods (Walker et. al., 2010; McKechnie et al., 2011). However, this is not necessarily the case when viewing the net impacts at a larger geographic scale (Galik and Abt, 2012; Rose et al., forthcoming). Given the importance of understanding the net GHG effects of biopower for policy development, there is a pressing need for better characterization and analysis of the net GHG implications of expanding biopower use under a variety of feedstock, region, and policy combinations.

Additionally, some policies acknowledge that the use of different bioenergy feedstocks have different impacts. Currently the U.S. Environmental Protection Agency is studying the scientific and technical issues associated with accounting for emissions of biomass combustion at stationary sources, and developing possible methods to account for those emissions. In 2012, Massachusetts finalized new requirements that define the types of biomass that qualify as eligible for the state's RPS, acknowledging that different forms of biomass fuels have different emissions impacts and should be treated differently[1]. In particular, the regulations require biomass plants using woody biomass as fuel to rely on harvest residues and materials from thinning rather than whole trees.

Numerous studies have investigated the impacts of increased consumption of biofuels and biopower from various perspectives, focusing on different feedstocks and/or specific regions. This study takes a more holistic viewpoint and evaluates systematic changes in land use, production, and GHG emissions patterns resulting from U.S. biomass energy expansion. We focus on biopower and the role of land use competition and product substitution potential

[1] http://www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/biomass/renewable-portfolio-standard-biomass-policy.html

between the forest and agricultural sectors in affecting these trends. We utilize an intertemporal partial equilibrium (PE) model of the U.S. forest and agriculture sectors to evaluate the degree to which increased production of biopower from different feedstock groups alter projections of GHG emissions from the terrestrial system. This model is unique in its inclusion of both detailed agricultural and forest management options and the endogenous linkage between the two sectors as they compete for the land resource and provide substitutable commodities. Simulated scenarios are developed for first an open market with no artificial or policy limitations, and then for a suite of scenarios developed to explore not just the extremes in imaginable policy, but also represent constraints present in past modeling analyses. By constraining our model to mimic the systematic constraints of these past studies, we aim to provide important context for their findings relative to a model that is less restrictive of land use and product allocation, but that assumes decision-makers have perfect foresight of future policy shocks and market conditions. In each of our policy scenarios biopower demand is exogenously increased relative to expected business-as-usual market and policy conditions.

This paper makes several unique contributions. First, we show the optimal allocation of land and resources required to meet the growing demand needs on a Renewable Electricity Standard (RES) policy. Next we show that the net GHG performance of biopower can change depending on the types of feedstocks eligible to participate in the market, and the extent to which GHG emissions could vary depending on assumptions of land use change and product substitution potential. A less flexible (and less realistic) forestry and agriculture system in which land use change and product substitution face excessively high transactions costs or are prohibited by policy can lead to less GHG-efficient biopower. In addition, we illustrate the importance of dynamic considerations in modeling the effects of biopower expansion efforts. We isolate average GHG effects over the short-term (2010-2025) and long-term (2025-2040) to illustrate the value of intertemporal optimization procedures in characterizing landowner behavior. Land use decisions in each period depend on expectations of future market and policy conditions, which can lead to biopower production and emission projections that vary greatly over time as land use decisions are made in anticipation of future returns. Ultimately, such expectations can lead to a feedstock portfolio and emissions effects that change over time. As recently enacted or proposed renewable energy policies are dynamic in nature, increasing in stringency over time, we argue that the influence of intertemporal decision-making should not be ignored in assessments of the economic and physical impacts of biopower policies.

We continue with a review of relevant literature and brief introduction to prior studies using forest sector PE model to analyze U.S. bioenergy expansion. We then introduce the model and describe the scenarios. The next section presents the results and is followed by a discussion of our results and an in depth comparison with the PE models analyses briefly introduced earlier. We conclude by reemphasizing our key findings as well as study limitations and point out topic for future research.

Literature Review

While policy governing biopower use is evolving quickly, research on the effectiveness of different policy mechanisms has lagged behind. The majority of previous research and economic modeling efforts in the broad area of bioenergy have primarily focused on first and second generation liquid biofuels for transportation. A number of computable general equilibrium (CGE) and PE models have been applied to examine the economic, land use, and GHG emissions implications of biofuel expansion (an excellent review is provided by Kretschmer and Peterson, 2010). However, there are few examples of similar systems-based assessments of biopower expansion, in part because there are fewer existing policies to evaluate relative to biofuels.

Some studies have evaluated biomass indirectly, using partial equilibrium models to analyze increases in U.S. renewable energy, including all renewable sources. Examples include Palmer et al. (2011), which applied the Haiku electricity market model, or Brown and Baek (2010), which used the National Energy Modeling System (NEMS) and focused on forest products and the forest products industry. While these studies allow for exploration of tradeoffs among renewable sources as well as changes in overall demand, they include coarse representation of the forest and agriculture sectors and do not explicitly account for forest carbon stocks or the GHG emissions associated with biomass production pathways. Such details are critical for accurate assessments of the net emissions impact of biopower expansion. Forest sector partial equilibrium models have the ability to incorporate carbon markets, future energy prices, land use competition, and explicit GHG accounting. Thus a great deal of focus has been placed in recent years on using forest sector PE models in biomass energy policy analysis.

Recent work has focused either regionally on Europe (Moiseyev et al., 2011; Lauri et al., 2012), or nationally on Norway (Bolkesjø et al., 2006; Sjølie et al., 2010; Trømborg and Solberg, 2010), Finland (Kallio et al., 2011), and France (Lecocq et al., 2011). In Norway, Bolkesjø et al., (2006) used the Norwegian Trade Model II (NTM II) to evaluate the biopower impacts of varying future energy price scenarios on not only forest industrial biopower production and consumption, but also on the changes in wood stove and district heating use. Sjølie et al., (2010) looks at incentives to invest in district heating as well as a carbon tax in Norway and reports avoided GHG emissions as a result of the policies, but failed to report forest industrial changes or forest stock impacts. Trømborg and Solberg, (2010) revisit the NTM II analysis of Bolkesjø et al., (2006) again modeling an increase in Norwegian energy prices. They disaggregate the energy production representation to the county level and present impacts for both forest industrial production and employment. Moiseyev et al., (2011) uses the European Forest Institutes Global Trade Model (EFI-GTM) to evaluate the impacts of a range of wood biomass price increases ranging from 25 – 120 €/m^3 for the A1 and B2 Intergovernmental Panel on Climate Change (IPCC) SRES 4. They report forest biomass supply and forest products impacts as well whether the biomass is derived from residues, complementary fellings, competitive use of wood, or trade yet do not report GHG implications.

Studies that have evaluated bioenergy policy impacts for the U.S. forest sector have utilized a diversity of methods in solution technique, geographic representation, and products considered. Perhaps most important here is the distinction in how the different models handle dynamics and land use change. To capture long time horizons consistent with forest rotations, forest sector models are typically presented as recursive dynamic or intertemporal. Both techniques can offer valuable insight, but differences in dynamic structures could have implications for overall results.

Recursive Dynamic Models

While partial equilibrium models typically solve the classic Samuelson, (1952) net social surplus maximization, they do differ in the way they implement its maximization through time. A recursive dynamic solution technique solves each time period's net social surplus maximization independently, typically updating key parameters such as forest stock and manufacturing capacity between solutions of adjacent periods. Such solutions have imperfect foresight regarding future impacts of policy shocks. Models that have used this technique for U.S. bioenergy policy analysis include the Global Forest Products Model (GFPM), the U.S. Forest Products Model (USFPM), the Global Biomass Model (GLOBIOM), and the Subregional Timber Supply Model (SRTS). Raunikar et al., (2010) used GFPM to simulate the wood products market impacts of two IPCC scenarios of future population, income and energy demand. They find that the large increases in woody biomass for bioenergy production would lead to reduced inventory levels and a convergence in prices with biomass for energy production and industrial roundwood by the middle of their 60 year projection. Buongiorno et al., (2011) use GFPM and revisit the Raunikar et al., (2010) analysis this time focusing on the A1B scenario alone with two different fuelwood targets to isolate the impacts of the change in production. World demand for manufactured wood products falls with the largest production change being a 24 million m^3 drop in sawnwood production in the U.S. mitigated by increases in Canada, Europe and Asia.

Ince et al., (2011) also use the Raunikar et al., (2010) GFPM A1B scenario as a backdrop for their study in which they apply the USFPM. USFPM is essentially an expanded representation of the U.S. within the GFPM global model. They find that the expansion of regions and addition of logging and milling residues for fuelwood in the U.S. leads to an expansion of U.S. sawnwood production and expansion of forest stock. Land use change both models is exogenously determined with GFPM using scenario specific GDP and GDP per capita values and an environmental Kuznets curve approach (Turner et. al., 2006) while USFPM employs land use values from Alig et al., (2010a) in the U.S.

Other recursive dynamic models have been applied to assess the regional consequences of biomass energy use. Galik et al., (2009) utilize the Subregional Timber Supply System (SRTS) to investigate the potential stumpage market impacts of using logging residues for bioenergy in the Southeastern U.S. Guo et al., (2011) also use SRTS but narrow the geographic region to the state of Tennessee while expanding the biomass supply available to fuel a biorefinery to include both logging residues as well as roundwood. GHG implications of bioenergy have also been reported in SRTS based studies as Galik and Abt (2012) used SRTS to examine the impact of different biomass accounting techniques and assessment scales and Abt et.al., (2012) evaluate the supply impacts of varying logging recovery rates, forest growth, and plantation response to stumpage price changes. The SRTS model is an exception to the exogenous land use treatment of other recursive dynamic models in that it allows for changes in timberland area between annual surplus maximizations based on methods from Hardie et al., (2000). By basing land use change on not only predetermined agricultural rents and county populations but also the prior periods pine timber price, SRTS timberland areas are specific to the market values of each scenario.

Intertemporal Models

An intertemporal optimization solution technique solves all time periods simultaneously with what is often called 'perfect foresight' of the implications of policy shocks. Thus, land use and production decisions made in time period *t* are driven by market and policy conditions in not only *t* but also all subsequent time periods. Models that use this solution technique include the Timber Supply Model (TSM), and the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG). Daigneault et al., (2012) use TSM to evaluate the impacts of two different levels of increased U.S. forest biomass utilization for energy. They do this for multiple rates of GDP growth as well as with and without logging residue utilization or endogenous land use change. Results find that restricting land use change and residue utilization has a dramatic impact on the GHG emission associated with bioenergy policy implementation.

McCarl et al., (2000) use FASOMGHG to generate biopower supply curves for forest and agricultural biomass by meeting biopower targets ranging from 0 - 8,840 TBTUs/yr. with varying technology, wood yield, and growth in wood cost assumptions. Alig et al., (2010b) also use the FASOMGHG model allowing avoided fossil fuel emissions as a GHG reduction mechanism while analyzing a carbon tax/subsidy system finding an 8 fold increase in biopower at \$25/t CO_2 and an eleven fold increase at \$50/t CO_2. Other GHG mitigation analyses using FASOMGHG have biopower as part of a suite of mitigation options eligible to receive GHG reduction subsidies (Baker et al., 2010; Latta et al., 2011). In addition to intertemporal dynamics, FASOMGHG provides the distinct advantage of endogenously capturing agricultural production possibilities (and hence a larger suite of biopower feedstocks) and land use competition between the forest and agricultural sectors. Additionally, the multi-sector framework allows for inter-sectoral commodity substitution, where fiber produced on agricultural lands can be used to satisfy forestry sector demands.

Methods

For our simulations of the market impacts of increased levels of biopower we utilize the FASOMGHG model (Beach et al., 2010, Adams et al., 2008). FASOMGHG integrates the U.S. agriculture, forest, and bioenergy sectors using an inter-temporal dynamic optimization approach to simulate market equilibrium values for an array of agriculture and forest products, including biofuels and biopower markets (McCarl et al., 2000; Alig et al., 2010b) while providing comprehensive GHG accounting. The linkages between sectors allow for competition and substitution in the use of private lands for production of either agriculture or forest products as well as the supply of substitutable products including pulp and bioenergy feedstocks. The inter-temporal optimization approach allows the model to capture behavioral responses of agents to expected future outcomes of the simulated policy scenario, in this case an RES policy. This includes long term investment decisions related to existing forest silvicultural changes and land use change between sectors.

Forestry GHG accounting in the model includes standing live and dead tree biomass, down dead material and forest understory vegetation, organic litter on the forest floor, and forest soils (Smith et al. 2006). Fossil fuel emissions in harvesting and silviculture are represented and harvested wood products accounting is based on Skog and Nicholson, (2000). Agricultural sector GHG accounting includes emissions from livestock production and manure management, soil disturbance, fertilizer application, and use of fossil fuels in agricultural production. Emissions of N_2O for specific cropping practices are derived from the DAYCENT model (Parton et al. 2001) and CH_4 emissions per head of livestock include the handling of livestock manure as well as enteric fermentation. Fossil fuel emissions included those from use of gasoline and diesel in planting, management, and harvesting of agricultural products. Agricultural soil carbon accounting is based on the CENTURY agroecosystem model (Ogle et al., 2009) and was influenced by tillage practices, use of irrigation, land use (e.g., land in pasture), and planting of perennials (e.g., switchgrass). A full description of the FASOMGHG carbon accounting methodologies and assumptions can be found in Beach et al., (2010).

Biopower modeling in FASOMGHG involves the complex interaction of primary and secondary forest and agricultural products. To isolate the impacts of an expanded RES program we simplify the biofuels part of the model by constraining ethanol and biodiesel production levels to those projected by the U.S. Department of Energy in their Annual Energy Outlook for 2010[2]. These fixed levels of production are for aggregate volumes of domestic conventional and cellulosic ethanol and biodiesel, but do not constrain the feedstock sources utilized within those biofuel categories other than constraining the maximum amount of conventional ethanol produced from grains. Lignin recovered in the distillation of cellulosic ethanol is likewise not considered applicable to our simulated RES biopower targets. Table 1 presents a list of the available biomass feedstocks that FASOMGHG allows to be applied toward the RES targets along with the embodied assumptions of energy and moisture content for each feedstock. The Higher Heating Values (HHVs) provided in Table 1 reflect the energy output per metric tonne of the biomass and take into account the latent heat requirement for vaporization of the moisture content.

The model was also modified in its treatment of biopower generating capacity and potential for co-firing biomass with coal. We revised the FASOMGHG model structure to allow for greater detail in tracking regional biopower generating capacity throughout the model timeframe. Table 2 gives the existing national coal electrical production (excluding co-generation of heat and power) considered available for co-firing with biomass which effectively limits the tonnages of biomass that can be utilized at different co-firing percentages in FASOMGHG. This means that given current annual electrical generation of 1978 TWh from coal-fired plants (representing 47% of aggregate U.S. electrical production of 4188 TWh), displacing 5% of this power could use no more than 79 Mt of biomass and would displace 36 Mt of coal.[3] If more than 79 Mt of biomass is to be co-fired, 5% co-firing of all biomass utilized is not possible (i.e., some coal plants would have to be set up for 10% co-firing). Regional allocation of the coal

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[2] AEO 2010 projects biofuel levels through 2035. We hold biofuel production levels constant at these 2035 values through the remainder of the modeling time horizon. This study and its results differ from other recent FASOMGHG studies that utilize mandated RFS2 biofuel volumes.

[3] TWh is a terawatt hour and denotes 10^{12} watts of power expended for an hour and is equivalent to 3.6×10^{15} joules. The 1978 TWh is the sum of all non-combined heat and power plants that use coal as a primary feedstock and 4188 is the sum of all electrical power production (including combined heat and power) from eGRID2010 (Version 1.1., http://www.epa.gov/egrid). To produce 5% of the non-CHP coal electrical production (or 99 TWh) given a 5% cofiring heat rate of 11169 kJ/kwh (from Table 2) assuming softwood biomass with an HHV of 13951 kJ/kg (from Table 1) would require 99*11169/13951, or 79 Mt of biomass. The coal it would displace using 30228 kJ/kg as an HHV (from Table 1) is 99*11169/30228, or 36 Mt.

generating capacity also presents limitations in the eleven domestic FASOMGHG regions, as regions like the Pacific Southwest (California) have no coal based electricity that doesn't utilize the heat energy byproduct of combustion, and thus only have dedicated biomass plants with lower efficiencies as an option. In addition to the co-firing limitations, FASOMGHG's biopower facilities are constrained to use a single feedstock, so only the use of forest-based, agricultural residue, energy crop, or short rotation woody crop feedstocks is allowed for 100% firing in dedicated biomass energy plants.

The additions to the model controlling biopower generation are provided in the appendix. They include equations that control the period-to-period capacity dynamics, generation limitations, and cost considerations.

Scenarios

To examine the potential impacts of an RES policy we not only evaluate a free market solution in which resources and commodity are allocated optimally between forest and agriculture, but also a suite of hypothetical scenarios that vary by: biomass feedstocks allowed, land and commodity substitutability, and levels of biopower generation. We evaluate not just the individual impacts, but also the combined impacts of all three policy design elements.

There is considerable variation in the energy potential of biomass from different agricultural and forest feedstocks as shown in Table 1. Information regarding market, land-use, and GHG impacts of individual feedstock types in the event of increased biopower generation is important. In our simulations and results we aggregate these feedstocks into the six biomass feedstock groups as found in Table 1; energy crops, crop residues, short rotation woody crops (SRWC), logging residues, milling residues, and roundwood. Our free market scenario is:

All Biomass Sources – All sources of agricultural and forestry biomass included within the model are eligible for use towards meeting the RES target.

We isolate the potential impacts of policies aimed at increasing biopower into additional scenarios defined by feedstock eligibility and also lay out possible reasons such eligibility requirement could be part of an RES policy. While the limitations and rationale for policy-based exclusion of particular feedstocks may appear questionable they do represent omissions present in past studies of U.S. forest biomass energy expansion and thus provide important context for their findings. Our biomass eligibility scenarios are:

Only Agricultural Sources – All agricultural biomass is eligible for meeting the RES (including crop residues, short rotation woody crops and energy crops). One rationale for specifying a policy in this manner is that agricultural biomass feedstocks both sequester and release carbon within a relatively short time horizon. Forest biomass, on the other hand, is not considered due to potential issues related to the much longer periods required for forest carbon to be sequestered and long-term forest dynamics.

Only Forestry Sources – All forest based biomass can be used to meet the RES target, but no agricultural biomass (including short-rotation woody crops) is eligible. A rationale for this RES policy eligibility requirement could be that agricultural and energy crop biomass is not considered due to potential food security and indirect land-use change emissions issues related to conversion of cropland and other more carbon dense lands to energy feedstock production.

Only Forest Residues – Logging and milling residues, which are byproducts of harvest and manufacturing activities, are applied toward the RES target. A rationale for this policy specification could be concern over increasing competition for roundwood that may result in greater harvesting activity and net reductions in forest inventory as well as higher prices for roundwood, which would negatively impact the forest products sector.

Only Roundwood and Logging Residues – Only logging residues and roundwood (i.e., whole trees/logs) are eligible. This RES requirement could be to avoid potential negative impacts on forest products manufacturing processes that utilize milling residues.

Only Roundwood – Only logs are eligible, leaving the limbs and tops on site. This requirement could be due to concern over the long term soil nutrient implications of repeated removals of logging residues.

Another issue related to biopower policy is that of indirect land use change and commodity substitution. Limiting the ability of land to move between the forest and agriculture sectors provides useful policy-relevant information – the true impact of the policy without conflating factors such as changes in land owner behavior in response to the policy. Additionally, policymakers may also wish to limit potential food security and environmental impacts that could arise as a result of unexpected shifts in land use. To further investigate the forest and agricultural land base response to an RES policy we also limit commodity substitution between sectors in the form of woody biomass grown on agricultural land for the purpose of pulp and paper production. These scenarios with no substitution between sectors in land and commodities are evaluated only for the first three broad feedstock group policies; *All Biomass Sources*, *Only Agricultural Sources*, and *Only Forest Sources*.

The final consideration for our scenario analyses is the target level for biopower generation under the RES. The baseline assumes no biopower generation, thus can be interpreted as the optimal allocation of resources and products between the agriculture and forestry sectors under business as usual market and policy conditions, no biopower demand, and perfect foresight. We then consider nine national RES targets for biopower, ranging from 25 TWh/yr to 200 TWh/yr to be reached by 2035 and then maintained at that level thereafter. For the purposes of our analysis, the RES targets were all defined as quantities to be met by 2030 phased in with linear increases in required renewable generation beginning in 2010. The 200 TWh/yr target roughly corresponds to displacing 20% of the 1,978 TWh/yr coal power plant electricity production that could potentially be co-fired with biomass. This approach allows us to examine the GHG impacts of linear increases in bioenergy demand relative to a no bioenergy case.

The FASOMGHG model is used to simulate a market equilibrium in the forest and agricultural sectors by maximizing net social surplus over seventeen five-year periods (2000 – 2080), along with a terminal valuation, for a base solution with no biopower as well as for each of the scenarios of feedstock groups, substitutability, and RES target levels specified above.

Results

To facilitate interpretation we aggregate greenhouse gas impacts into three classifications; agriculture, afforestation, and the rest of forestry. The agricultural account includes all emissions and soil carbon sequestration from crop and livestock production practices, including additional soil C sequestration that results from cultivating dedicated energy crops such as switchgrass. The afforestation account captures all carbon gains on agricultural land planted in trees for the purpose of forest products or biopower. This does not include SRWC. Note that unlike previous FASOMGHG analyses where afforestation was incentivized through GHG subsidy payments, the only reason afforestation occurs in these simulations is to contribute to the overall biomass and forest product supply. The rest of forestry account (hereafter called forestry) includes emissions from forest product harvesting and carbon stored in current and future forests and manufactured wood products (which can also include feedstocks such as popular and willow that are grown on agricultural lands).

Feedstock Utilization

Total feedstock utilization levels are determined in large part by the level of demand and the time scales over which that demand exists. This makes short-run and longer-run responses to a hypothetical RES different. Figure 1 provides the proportion of feedstock supply in the short and long run for the various levels of biopower supply both with (Figures 1a and 1c) and without (Figures 1b and 1d) freely substitutable land and commodities between the forest and agriculture sectors. In the unconstrained land and commodity case, a biopower requirement of 25 TWh/yr is supplied primarily by energy crop and crop residues. Forest sources and SRWC provide up to half the supply at 50 and 75 TWh/yr, but then decline with energy crops dominating the supply choices at higher levels of biopower demand. In the longer-run with free land and commodity substitution, agricultural sources dominate the supply of biomass at all levels of biopower demand. The primary shift occurs within categories of agricultural feedstocks as the proportions of crop residues and SRWC decline and the share of energy crops increases as target levels of biopower are raised. In the 200 TWh/yr case, energy crops comprise roughly two thirds of biomass energy supply. With constraints on land use change and commodity substitution, agricultural energy crops emerge as a dominant feedstock source in both the short and longer-run at lower RES biopower targets[4]. Note that differences in feedstock storage and transportation requirements will likely affect the least-cost mix of biomass feedstocks supplied.

Biomass supply for the other feedstock availability scenarios are presented in Table 3. While agricultural feedstocks compose a large share of total biopower production for scenarios in which agriculture is allowed to participate, the different forestry-only scenarios provide key insight. With *Only Forest Sources* considered, substantial differences exist between feedstock sources utilized at low levels of biopower production. Roundwood comprises approximately

[4] While energy crops do constitute the majority of feedstock sources at the lowest target levels in the short run (Figure 1a) the volumes are small, declining, and do not increase in percentage until the 100 TWh/yr target level.

one third of the short-run biomass in the 25 TWh/yr case, yet becomes the dominant choice of feedstock in the longer-run supplying over half of the biomass for power generation. However, with land and commodity substitution restricted, logging residues dominate biopower feedstock supply at the 25 TWh/yr level while at higher RES target levels the forest feedstock choices vary little from the unrestricted case. When only forest residues can be used logging residues dominate at lower RES levels ceding to milling residues at higher RES target levels.

Land Use Change

Base scenario levels of land use changing from agricultural use to forestry average 256 thousand hectares per year over the 2010-2040 period. There is also an exogenous loss of 635 and 702 thousand hectares per year from forest and agricultural land respectively that occurs over this period both in the base and policy scenarios as land moves into developed uses. Table 4 presents the land use change results for the base case as well as for the 25, 100, and 200 TWh scenarios. Ultimately, in the short-run of all RES cases in which agricultural feedstocks are eligible (*All Biomass, Only Agriculture*), there is less afforestation on agricultural lands than in the base case. In the longer-run however, afforestation levels are higher than the base except in the *All Biomass* 200 TWh case. However, these long-term afforestation levels are less than the short-run reductions in afforestation, thus the net change in land use over the entire evaluation period results in more agricultural lands available for crop production than without these specific RES scenarios. The most dramatic changes in land use across all the simulated RES policies occur at high levels of biopower (200 TWh /year) and in the *Only Residues* scenario. When only forest residues are eligible, short-term afforestation is over three times as high as in the base with a 100 TWh/yr biopower target and more than six times as high with a 200 TWh/yr requirement. The impact is not quite as large in the longer-term, but we still see afforestation levels almost twice as high with a 100 TWh/yr target and over four times as high at 200 TWh/yr as in the base case. This is because the forest land base increases to provide harvests and their associated logging residues as returns to forestry are increased by the demand for logging residues to use in meeting biopower requirements. This increase in harvesting supports a substantial increase in manufacturing of forest products such as lumber and plywood, as well as leading to greater production of milling residues. These milling residues are also used in biopower generation.

Commodity Substitution

Along with transferrable parts of the land base, the forest and agricultural sectors are linked in FASOMGHG through the substitutability of hybrid poplar and willow grown on agricultural lands with hardwood pulp logs from forest lands for the production of pulp and paper products. Policies that encourage the use of forestry feedstocks for biopower could draw fiber from pulp mills thus increasing their demand for SRWC fiber grown on agricultural lands. Table 4 provides model output for movements of agricultural fiber to pulp and paper mills in the base case as well as the RES policy scenarios. The smallest impacts on commodity substitution between sectors for pulp and paper production occur in the *All Biomass Sources* and *Only Agricultural Sources* cases involving agricultural biomass. The dominance of energy crop biomass in these cases minimizes the impacts on flows of SRWC fiber to the forest sector altering the volume by no more than half of the levels seen in the base case. In the forestry-based source cases, and

Only Roundwood in particular, we see dramatic increases in the use of SRWC at pulp and paper mills. In the short-run *Only Roundwood* 200 TWh/yr case we have 73.3 additional megatons of SRWC fiber moving from agriculture to pulp and paper products than in the base case and as shown in Table 3 we see forest roundwood biomass supplying 76.4 Mt/yr to biopower generators. This near one-for-one substitution of fiber to the pulp market decreases in the longer-run with only 55% of the forest biomass sent to the power sector being replaced by SRWC biomass.

Forest Harvest and Inventory

Projections of timber harvest and carbon stored in trees on U.S. private timberland for the base case and changes associated with the RES policy scenarios are given in Table 5. It is important to note that this analysis includes private timberland but not public lands. In general harvest levels increase when forest feedstocks are eligible under our simulated RES policies. When agricultural feedstocks are also eligible and land and commodity movements between sectors are allowed, these harvest level increases are less, and in some cases negative. The largest changes in harvest levels are in the 200 TWh/yr *Only Residues* scenario, in which aggregate U.S. timber harvest doubles in the longer run. The forestry cases involving roundwood sources have a much lower harvest impact than the *Only Residues* case as biopower could be produced from low grade pulp logs in addition to the residues associated with the conversion of higher grade sawlogs to solid wood products.

Additional carbon sequestered each year in trees on private U.S. timberland is also presented in Table 5. While one would assume that an increase in harvest would lead to a decrease in carbon uptake in trees, this was not always the case when agricultural biomass sources were also eligible. In the short-run *All Biomass Sources* 100 and 200 TWh/yr cases as well as the *Only Agricultural Sources* the 100 TWh/yr case harvest and tree carbon moved in the same direction (this also occurs in the short run *Only Residues* 100 TWh/yr case as well, discussed below). In the long-run only the *All Biomass Source* 100 TWh/yr case behaved as expected (i.e., an increase in harvest would lead to a decrease in tree carbon sequestration). While some of this could be explained by the differences in afforestation and agricultural fiber used in pulp and paper from Table 4, the *All Biomass Sources No Sub* scenario also has increases in harvest accompanied by increases in tree growth in the long-run without the land use and commodity substitution indicating a change in silvicultural management. This management change includes a lowering of the rotation age as an additional 50,000 ha/yr are harvested through 2035 leading to a slightly younger faster growing forest as well as changes in forest type such as the conversion of 100,000 ha of new pine plantation in the U.S. South.

One of the most interesting results is found in the *Only Residues* case in which the interacting effects of land use change, harvest levels, and expectations of future policy impacts lead to disparate results at the higher RES target levels. In the short-run 100 TWh/yr case tree carbon stocks increase by 18 Mt CO_2/yr (Table 5) due in part to a temporal shift in harvest patterns as landowners harvest less than the other forest biomass scenarios. They do this along with adding 737 Mha/yr (Table 4) to the productive forestland base in the short-run knowing that the *Only Residues* policy will require an additional harvest over 100 million m^3/yr (Table 5) higher than the *Only Forestry Sources* scenario in the longer run. It is this intertemporal shift in management actions along with an expanded forest land base that minimizes tree carbon growth losses to 150%[5] of *Only Forestry Sources* scenario in the long-run. In the 200 TWh/yr *Only Residues* case we see the opposite reaction as the short-run harvest increases are borne with a draw down in the tree carbon inventory of 474 Mt CO_2/yr (Table 5). Forest managers know that this draw down of the standing stock of trees coupled with an aggressive afforestation program adding 1862 Mha/yr (Table 4) in the short-run and 1007 Mha/yr (Table 4) in the longer-run will lead to increases in tree carbon sequestration rates that outpace the 370.6 million m^3/yr (Table 5) harvest levels over the longer term.

GHG Accounts

Table 6 presents additional emissions in comparison with the base case (with no biopower) in GHG accounts for agriculture, afforestation, and forestry and allow for comparison with the annual fossil fuel emissions avoided by displacing coal-based electricity production with biopower. These avoided coal emission values (in italics) are derived from the target RES level using an emissions factor of 88.2 kg CO_2/Gj[6] of coal heat input along with an average coal heat rate[7] from Table 2 of 10799 Kj/kwh. For *All Biomass Sources* in the short run, for example, the total amounts of net emissions above the base case GHG emissions from producing feedstocks to meet the three RES targets are 1, 24 and 10 mt/yr respectively. This can be compared with the fossil fuel emissions avoided in meeting the RES targets, which in this example are 10, 38, and 76 mt/yr respectively[8]. Three scenarios in the short run (*Only Forest Sources, Only Residues* and *Only Roundwood and Logging Residues)* and one scenario in the longer run (*Only Roundwood and Logging Residues*) emit more total emissions (compared to the base case GHG emissions) than avoided fossil fuel emissions in one or more of the targeted RES scenarios. These additional emissions associated with feedstock production under certain RES policy eligibility requirements exceed avoided fossil fuel emissions and hence fail to achieve the RES target of reduced emissions levels.

Limiting land conversion and commodity movements between sectors leads to different results with and without agricultural biomass allowed to participate in the RES. Limiting substitution leads to lower emissions in agriculture and little corresponding increase in forest sector emissions. Contrary to this, when looking at the *Only Forest Sources No Sub* scenario results we see increases in both agriculture and forestry and thus total emissions are substantially higher than avoided emissions in the 100 and 200 TWh/yr cases.

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[5] With changes in land use and silviculture in the longer-term, the tenfold increase in harvest as the *Residues Only* scenario requires 116.9 million m^3/yr compared to the 16.0 million m^3/yr *Only Forestry Sources* case leads to only a 150% change in tree carbon stock growth as the *Residues Only* scenario leads to a reduction of 75 Mt CO^2/yr compared to the reduction of 50.0 Mt CO^2/yr *Only Forestry Sources*

[6] eGRID2010 Version 1.1., http://www.epa.gov/egrid

[7] We assume the displaced coal is from the average facility. Either retiring or targeting co-firing efforts at less efficient capacity would yield additional ghg benefits.

[8] For example, the 76 mt/yr is determined using the average electricity displaced of 80 TWh/yr (40, 80, and 120 from the assumed linear increase in generation in the first three periods) along with the coal power plant heat rate of 10,799 kJ/kwh (from Table 2) and the 88.2 Kg CO_2/GJ coal emissions factor from eGRID2010. Therefore after dividing by one million to adjust for units, 76 = 80*10799*88.2/1000000.

While Table 6 provides an important breakdown of how the different feedstocks contribute to the change in total GHG emissions, the time profile of when these changes in emissions and sequestration occur is also important to consider. Figure 2 charts the annual and cumulative avoided coal combustion emissions along with the changes in GHG emissions associated with supplying the biomass for the *Only Forestry Sources* scenarios both with and without land and commodity substitution. There is a net increase in annual emissions when the biopower supply emissions exceed the avoided coal emissions. In the *Only Forest Sources* scenarios for the 25, 100, and 200 TWh/yr cases (2a, 2c, and 2e) the short term periodic impacts of the policy lead to an increase in emissions greater than the coal emissions displaced (e.g. the dashed black line is above the dashed grey line). These periodic emissions associated with the forest biomass production drop below the displaced coal values relatively soon after the policy is implemented leading to cumulative positive impact (solid black line below solid grey line) as early as 2015 in the 200 TWh/yr case and 2025 when the RES target is either 25 or 100 TWh/yr. The temporal dynamics of the GHG impacts in the *Only Forest Sources No Sub* scenario are quite different for higher RES targets with the initial policy impact leading to improved GHG emissions in the near term followed by a period of increased periodic GHG emissions that exceed the periodic avoided coal emissions. This leads to cumulative GHG impacts that remain above the cumulative coal emissions until 2055 in both the 100 and 200 TWh/yr cases. This is due to the long length of time it takes to see the benefits of altered forest management regimes when shifts in land use and commodity substitution from SRWC are not allowed. Though it has the same basic pattern as the higher RES cases, the 25 TWh/yr case does not have the negative GHG impacts for two basic reasons. First, due to its lower level of feedstock requirements, the short term biomass supply is dominated by logging residues while the higher feedstock demands of the 100 and 200 TWh/yr cases are dominated by roundwood and milling residues. Since the logging residues would have decayed on the forest floor anyway, the avoided coal emissions due to combustion for energy are almost entirely a GHG benefit. Secondly, in the longer term even the 25 Twh/yr RES target requires roundwood as feedstock and the annual emissions (dashed black line) exceeds the annual avoided coal emissions (dashed grey line) (Figure 2).

Discussion

Scenario analyses utilizing models rooted in basic economic theory such as the one presented here provide two general classes of information useful to discuss. The first of which is what the study tells us about the effectiveness of policy goals and possible impacts of various pathways to achieve those goals through modeled scenarios. The other is what it tells us about how results from different models based on the same fundamental economic theory can yield diverse results looking at similar policies.

Implications on Policy Effectiveness

Linkages between the agriculture and forest sectors present a number of challenges for policy makers in determining potential impacts and therefore the effectiveness of bioenergy policy. Of primary importance in determining these potential impacts is the definition of eligible biomass for which the policy is applicable, and the extent and ease with which land is able to move between agricultural and forest uses. Using results from a suite of scenarios reflecting limitations on feedstock eligibility along with the extremes of land flowing between sectors based on opportunity costs and no land transitions we can identify a range of potential outcomes and issues that may be encountered. One overriding outcome is that in general biopower has positive GHG impacts when displacing coal. Another fundamental result is that agricultural sources dominate the feedstock supply at high levels of biopower targets. Finally, the extent to which land can change influences the GHG mitigation potential with respect to biopower; we show that a system with low barrier costs and no policy restrictions on land use change can improve the GHG mitigation potential of biopower.

In general we find the GHG emissions associated with biomass feedstock production to be less than the GHGs that would have been emitted had that power come from coal combustion. Scenarios that included agricultural biomass tended to generate fewer emissions than the scenarios that focused on forest feedstocks. This is due in part to the higher yields associated with agricultural production as opposed to traditional forestry practices. In FASOMGHG, switchgrass yields of 12.1 t/ha provide an energy input of 193 million kj/ha/yr while a high productivity site softwood forest would produce 2.7 t/ha at culmination, which corresponds to a mean annual increment yielding 37 million kj/ha/yr of potential energy input. With more than five times the potential energy per unit of land for switchgrass relative to softwood, the impacts of biopower policy have less of a land resource footprint when relying on energy crops. Forest yields can be increased through changes in species composition and silvicultural intensity, but the resulting energy supply per unit of land remains far below the agricultural systems and the returns on silvicultural investment take years to realize, while agricultural systems provide feedstocks in the near-term.

Our results suggest that strategies for biopower sourcing depend not just on the eligibility of feedstocks, but also the target level of biopower production. An example of this can be seen in Figure 1 in the short-run results of the *All Biomass Sources* scenario which at the 25 TWh/yr target level biomass feedstocks are primarily energy crops and crop residues taking advantage of existing underutilized land and byproducts. Then as target levels increase additional supply sources are dominated by SRWC and forest sourced biomass. These increases in woody biomass begin to subside at the 75 TWh/yr level with additional demand being accommodated through crop residues. For biopower targets of 100 TWh/yr and higher supply is again dependent on energy crops, which comprise as much as 94% of the short term supply for the 175 TWh/yr and 200 TWh/yr cases.

An additional consideration is the cost of biomass. The price of delivered biomass is going to be very high in some of these scenarios, especially when feedstock options are limited, which raises questions of cost and economic viability of different policy constructs.

While there is most certainly land suitable for either forest or agricultural production, the extent to which that land would change uses as a result of a policy making the other use more profitable is unknown. We evaluate two cases of potential land use change. The first assumes land use decisions are based entirely on relative profitability, while the second does not allow land to transition between agriculture and forests or vice versa. We find that when land moves between sectors freely the resulting GHG impacts of our biopower policy are better when agricultural sources are allowed and worse when only forest sources are considered. This difference in the impact of restricting land use is due in large part to the fundamental difference in the underlying sectors' cultivation and production processes, and resulting GHG emissions. When you sever the linkages between sectors, biomass is produced by diverting agricultural resources from other GHG emitting uses thus reducing GHG emissions generated by those activities. With forests, biomass is produced by drawing down forest stock that was sequestering carbon and operating on shorter cutting cycles which carry less carbon in the standing stock of trees.

Implications on Prior Forest Partial Equilibrium Model Study Results

The scenario analysis approach conducted in this study provides meaningful insights with regards to the RES policy scenarios implemented, but also what we may discern from similar study policy interpretation results. It is therefore useful to discuss how differences in methodologies and applications of past studies fit within our findings regarding feedstock eligibility and land-use change flexibility.

Comparison of the results from the Buongiorno et al., (2011) study using GFPM and the Ince et al., (2011) study using USFPM provides an interesting case study because both utilize the Raunikar et al., (2010) A1B scenario as a basis but arrive at differing results for the US. Buongiorno et al., (2011) takes the Raunikar et al., (2010) A1B run and evaluates a doubling of bioenergy in all countries. For the U.S., lumber production, which is the largest use of logs, falls dramatically (24 million m3/yr, or 19%) by 2030 and forest stocks decline as well. Other countries such as Canada pick up the slack in global demand along with China and the European Union[9]. Ince et al., (2011), also employs the Raunikar et al., (2010) A1B scenario as its global backdrop, but uses the USFPM model which is essentially GFPM, with three U.S. regions and an expanded set of forest products including logging and milling residues and SRWC. They look at a 10 and 20% renewable electricity policy with a fixed proportion of it assigned to woody biomass. They find that U.S. lumber production doubles and forest stocks increase. These two prominent models[10] evaluate comparable policies and arrive at dramatically different results for the US.

It is possible that changes to one region in the form of increased detail could lead to a different reaction to the biopower increase. Another potential factor is the issue of model calibration. In both studies the authors point to the fact that the model has been calibrated to match the base year value exactly. However, it is possible that using calibration routines to adjust parameters ensuring base year precision could mask model parameterization issues which instead may surface in the sensitivity analysis.

Our results suggest that with the land use change limitations of these models, the divergence in policy impacts may be a function of the feedstock eligibility rather than an indication of potential modeling shortcomings in the models. Aside from the regional and product

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[9] GFPM does not have specific region-to-region trade instead excess supply from any country is used to satisfy global demand independent of transportation costs.

[10] GFPM is used by the Food and Agriculture Organization of the United Nations (FAO) to produce supply and demand simulations for its periodic reviews of global forest product markets. USFPM is used by the U.S. Forest Service for the U.S. Renewable Resource Planning (RPA) Act periodic assessments of the U.S forest resource situation.

differentiation in the US, the largest difference between studies might be the addition of logging and milling residue biomass in USFPM which ends up being the primary feedstock source compared with the roundwood only approach in GFPM. Our *Only Forest Sources with No Substitution* scenario most closely resembles the Buongiorno et al., (2011) results with lower sawnwood production and forest stocks even though we allow both milling and logging residues. Our *Roundwood Only* scenario which closely matches the biomass eligibility in the GFPM studies has much higher sawnwood production and harvest levels. This perhaps suggests that land use change is a larger influence on policy impacts than feedstock eligibility in this case. The Ince et al., (2011) results are closest to our *Only Residues* scenario where we find a doubling in sawnwood production and a reversal of trade flows with Canada. This is despite the purported inclusion of roundwood and logging residues in USFPM that there may be some restrictions on their usage leading to the reliance on milling residues.

Recent studies focusing on the U.S. South stumpage market have used SRTS (Galik et al., 2009; Guo et al., 2011; Abt et al., 2012). While SRTS breaks supply down into log diameter classes which in turn influence potential conversion to products, this is accomplished through tracking logs by end-use (eg. sawtimber, pulp logs). Therefore, when Galik et al., (2009) and Guo et al., (2011) examine increases in bioenergy, they focus on the smaller logs. While their regional approach allows for much better representation of the transportation cost influence on biomass for bioenergy, the omission of the influence on larger logs through manufacturing residues is problematic. There is also a difference in the impact of price on logging and milling residues as well. Logging residues do not leave the woods unless the value exceeds the extraction costs causing the supply have a “kink” as that utilization threshold is met. Milling residues, however, are essentially treated as a part of the price received for finished products by lumber producers and have been modeled as such in econometric analyses of the industry[11] and would thus enter the market at a much lower price threshold and influence large log supply.

Daigneault et al., (2012) use the TSM to evaluate the impacts of expanded U.S. biopower. While their model includes logs and harvesting residues, it’s similarity with respect to land use change and endogeneity of silvicultural investment minimize the differences associated with the omission of milling residues. Nevertheless, when comparing the *Roundwood and Logging Residues* scenario of the current study with their *with residues* scenario they find higher levels of afforestation accompanied by an increase in imports and a lower level of GHG impacts associated with biomass production. When comparing scenarios including only roundwood in each study they find harvest levels decrease accompanied by a decrease in afforestation and a doubling of imports over their *with residues* case. Our results suggest that the ineligibility of logging residues would lead to higher harvest levels and an increase in afforestation as roundwood is combusted in generation facilities to fill the supply needs caused by the exclusion.

Prior studies with FASOMGHG have either looked at changes in biopower in response to a carbon tax in which avoided fossil fuel emissions were entitled to a payment (Alig et al., 2010b)

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[11] See for example Latta and Adams, (2000) for an econometric example of residues incorporated in lumber output price, or Constantino and Haley, (1988) for its explicit inclusion.

or were based on a prior version of the model that did not include forest product manufacturing (McCarl et al., 2000).

Comparing results with prior studies further validates our findings that the level of ease with which land can move between sector and uses will have a large impact on the effectiveness of biopower policy. It is also important to determine the extent to which biomass feedstocks will be included within the policy framework. Finally, given the interconnections between forests and agriculture in both the competition for the land resource base as well as the agricultural ability to generate woody biomass for use in the pulp and paper industry policies targeted at individual feedstocks or groups of feedstocks will have impacts both across sectors and commodity markets.

Conclusion

The analysis presented in this manuscript provides the results from a multi-sector partial equilibrium model investigating the GHG implications of U.S. biomass electricity expansion. We employ a suite of scenarios –ranging from more realistic policy designs to very unlikely but nonetheless illustrative scenarios – to explore the interrelationship between biomass feedstock eligibility in a biopower policy and the level to which adjustments to the flow of land and commodities between the agricultural and forest sectors affect overall policy impacts. The results highlight the differences in biomass feedstock sourcing both across levels of targeted biopower increase as well as across time as optimal supply strategies mature. The feedstock eligibility scenarios focus on how the utilization of different modeling approaches for similar policy constructs can yield significantly different results. This underscores the necessity to choose the most appropriate model type and assumptions to meet certain analytic goals.

Previous studies have provided key policy insight into the potential land use and GHG impacts of U.S. biopower expansion. This study synthesizes previous results and makes the case that understanding potential market dynamics is important for crafting meaningful energy policy; however, it is not by itself sufficient. Our analysis provides results that can aid decision-makers in assessing future policy proposals by better understanding potential market repercussions. We also provide new perspective on the results of past partial equilibrium analyses involving bioenergy in the forest sector. Ultimately, our results should be viewed collectively with other modeling efforts by policy makers seeking improved information on the direction and magnitude of land use and GHG emissions associated with U.S. biopower expansion.

The level of detail afforded by the partial equilibrium framework employed in this study comes at the expense of the breadth of the global economy as a whole. Sensitivities to changes in the macroeconomic outlook as well as interactions with similar renewable energy policies in other countries should be investigated as well. In addition, the intertemporal framework presented herein could over-estimate land use change in anticipation of future biopower incentives, as it does not account for risk preferences, or the impact of risk and uncertainty on long-term land use investment decisions. Recent work has shown more inertia in land use decisions with revenue/cost uncertainty relative to a perfect foresight approach that compare the net present value (NPV) of different land uses over a specified time interval (Song, Swinton, and Zhao, 2011). Unfortunately, given the size and complexity of FASOMGHG, uncertainty analysis for the combined agriculture and forestry sectors, aside from extensive sensitivity analyses, is not computationally feasible at this time.

Finally, future work should seek to build on the existing literature by better integrating not just forestry and forest products, but also attempting to encompass forest industry energy consumption as well. Certainly with the scale of energy use in certain industries, such as the pulp and paper industry, changes in production levels can lead to significant changes in biomass energy supply and demand, and related GHG emissions.

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Appendix. Additions to the FASOMGHG model controlling biopower generating capacity

To determine the extent to which existing coal-fired electrical generation facilities can be utilized for co-firing biomass with coal it is necessary to include a capital stock accounting framework with FASOMGHG. The ability to co-fire with lower biomass percentages allows for conversion to electricity at higher levels of efficiency (see Table 1). Equation A1-A4 provides the basic relationships incorporated within the linear programming optimization scheme controlling both the level of co-firing and overall capacity limitation dynamics through time. This includes a mechanism for tracking capital stock over time, a limit on overall biopower generation based on capital stock, a limit on co-firing with coal, and an equation calculating the cost of capital stock maintenance and expansion. Each equation is introduced below followed by a description and mathematical representation. Following the equations is a list of parameters, indexes and variables utilized.

Capital Stock Identity Equation – controls the period-to-period capital stock changes taking into account depreciation and expansion of capacity.

$$(1+\delta)^5 \cdot CAPACITY_{r,f,c,t-1} + EXPANSION_{r,f,c,t} = CAPACITY_{r,f,c,t} \qquad \forall\, r,f,c,t \qquad \text{(A1)}$$

Capital Stock Limit on Generation Equation – requires generation of biopower to be equal to or lower than capital capacity.

$$BIOPOWER_{r,f,c,t} \leq CAPACITY_{r,f,c,t} \qquad \forall\, r,f,c,t \qquad \text{(A2)}$$

Co-firing Limitation Equation – requires biopower capacity for co-firing to be less than or equal to the availability of coal power (non-cogen) capacity.

$$\sum_c \left(\frac{\sum_f \left(CAPACITY_{r,f,c,t}\right)}{COFIRE\%_c}\right) \leq CoalCapacity_r \qquad \forall\, r,t \qquad \text{(A3)}$$

Capital Stock Cost Accounting Equation – requires payments for one-time capital expansion and periodic maintenance of existing capital stock.

$$\sum_{r,f,c}\left(ExpCost_c \cdot EXPANSION_{r,f,c,t} + MaintCost_c \cdot CAPACITY_{r,f,c,t}\right) = BIOELECCAPCOST_t \qquad \forall\, t \qquad \text{(A4)}$$

Where:

c	index of Co-firing % (5,10, 15, 20, 100)
f	index of feedstock types (forest, agricultural residues, energy crops, SRWC)
r	index of FASOM regions (CB,LS,NE,GP,SW,SE,SC,RM,PNWE,PNWW,PSW)
t	index of time period (period is 5 years)
δ	parameter for capital stock annual depreciation rate (2%)
$CoalCapacity_r$	parameter of regional coal capacity (non-cogen). See Table 1 for aggregate U.S. value
$ExpCost_c$	parameter for one time capital expansion cost by co-fire rate (0.20$/kwh for co-firing and 0.35$/kwh for dedicated capacity)
$MaintCost_c$	parameter for periodic capital maintenance costs by co-fire rate (0.004$/kwh for co-firing and 0.008$/kwh for dedicated capacity)
BIOELECCAPCOST_t	accounting variable representing bioelectric capacity costs in time period t.
$\text{BIOPOWER}_{r,f,c,t}$	variable representing bioelectric generation in region r, for feedstock type f, using co-fire level c, in time period t.
$\text{CAPACITY}_{r,f,c,t}$	variable representing bioelectric capital stock in region r, for feedstock type f, using co-fire level c, in time period t.
$\text{EXPANSION}_{r,f,c,t}$	variable representing bioelectric capital stock expansion in region r, for feedstock type f, using co-fire level c, in time period t.

Table 1. Biomass feedstock grouping, higher heating value (HHV) and moisture content utilized in the biopower sector of the model for this study.

Biomass Feedstock	Feedstock Group	HHV	Moisture
		(kJ/kg)	*%*
Corn Residues	Crop Residues	10,726	12.00%
Rice Residues	Crop Residues	12,916	15.00%
Sorghum Residues	Crop Residues	13,855	11.90%
Barley Residues	Crop Residues	17,304	10.30%
Oats Residues	Crop Residues	17,304	10.30%
Wheat Residues	Crop Residues	17,504	8.90%
Energy Sorghum	Energy Crop	15,986	12.00%
Switchgrass	Energy Crop	15,986	12.00%
Hardwood Logging Residues	Logging Residues	12,401	33.30%
Softwood Logging Residues	Logging Residues	13,951	33.30%
Hardwood Milling Residues	Milling Residues	12,401	33.30%
Softwood Milling Residues	Milling Residues	13,951	33.30%
Hardwood Roundwood	Roundwood	12,401	33.30%
Softwood Roundwood	Roundwood	13,951	33.30%
Hybrid Poplar	SRWC	13,361	31.00%
Willow	SRWC	16,456	33.30%
Coal	Fossil Fuel	30,228	

Note: From Table 5-19 in Beach et.al., (2010)

Table 2. Power plant technological assumptions

Power Plant Type	Efficiency	Heat Rate	Current Production	Feedstocks Required[1]	
				Coal	Biomass[2]
	%	*kJ/kwh*	*TWh*	------------- *Mt* -------------	
Coal Power Plant	33	10799	1978	707	0
Cofire Technologies					
5% Cofired Biomass	32	11169		671	79
10% Cofired Biomass	31	11517		636	163
15% Cofired Biomass	30	11890		601	253
20% Cofired Biomass	29	12285		565	348
Dedicated Biomass Plant	24	14770		0	2094

1 Feedstocks required determined by multiplying the current production by the heat rate and then dividing by the higher heating value of the feedstock.

2 Example biomass feedstock requirements based on softwood higher heating values in the model they vary by biomass feedstock.

Table 3. Biomass feedstock production in millions of metric tonnes by policy and feedstock group

Policy[1] Feedstock Group	Short-Run (2010-2025) 25	100	200	Longer-Run (2025-2040) 25	100	200
	---------------- *million metric tonnes per year* ----------------					
All Biomass Sources						
Energy Crop	4.6	7.2	55.7	3.8	29.8	99.9
Crop Residues	1.8	8.6	0.4	6.8	20.3	18.6
SRWC	-	5.6	3.1	5.2	9.0	10.2
Logging Residues	-	1.7	-	-	1.7	1.2
Milling Residues	0.5	4.5	-	0.6	3.0	2.8
Roundwood	-	2.6	-	-	2.4	8.6
Only Agricultural Sources						
Energy Crop	4.4	14.5	49.4	14.1	32.5	110.5
Crop Residues	1.1	2.8	9.9	2.0	11.0	20.6
SRWC	2.1	10.6	0.0	-	21.2	7.9
Only Forestry Sources						
Logging Residues	3.4	14.0	16.7	5.8	17.6	21.9
Milling Residues	2.7	8.0	19.6	3.9	14.7	31.0
Roundwood	2.7	14.5	38.4	11.5	53.9	122.0
Only Roundwood						
Roundwood	9.4	38.8	76.4	22.1	89.8	177.0
Only Residues						
Logging Residues	5.5	16.2	21.1	13.7	20.8	30.0
Milling Residues	3.1	19.9	49.1	6.7	60.3	90.3
Only Roundwood and Logging Residues						
Logging Residues	0.6	11.1	16.9	2.6	17.6	21.4
Roundwood	8.0	24.8	58.8	17.9	69.7	156.1
All Biomass Sources No Sub						
Energy Crop	1.8	23.6	51.9	5.0	48.3	88.3
Crop Residues	2.0	2.3	1.7	0.3	6.0	19.3
SRWC	-	-	-	8.4	7.7	20.4
Logging Residues	-	-	0.3	0.1	1.2	8.7
Milling Residues	2.9	2.3	3.3	2.7	2.3	4.6
Roundwood	0.9	-	2.0	-	-	0.4
Only Agricultural Sources No Sub						
Energy Crop	2.2	19.3	48.7	9.2	37.7	109.9
Crop Residues	3.1	7.8	3.4	3.6	18.6	11.5
SRWC	2.3	1.6	7.8	3.1	8.7	19.2
Only Forestry Sources No Sub						
Logging Residues	5.9	17.2	18.3	9.4	20.2	24.0
Milling Residues	2.1	8.4	13.0	6.2	19.7	30.8
Roundwood	0.8	11.6	43.5	4.8	46.9	115.3

Table 4. Annual average land use change and commodity substitutions with increases in biopower

Policy[1]	Afforestation			Agricultural Fiber to Pulp		
Base	*(1000 ha/yr)*			*(Mt/yr)*		
Short-term (2010-2025)	296			2.6		
Longer-term (2025-2040)	216			6.6		
Biolelectricity Target Levels	**25**	**100**	**200**	**25**	**100**	**200**
Short-term (2010-2025)	*difference from base (1000 ha/yr)*			*difference from Base (Mt/yr)*		
All Biomass Sources	(12)	(132)	(121)	(0.3)	(0.2)	(0.8)
Only Agricultural Sources	(25)	(25)	(175)	(0.1)	(0.9)	0.1
Only Forestry Sources	3	12	389	(0.8)	6.4	24.9
Only Residues	12	737	1862	(0.5)	6.9	13.8
Only Roundwood and Logging Residues	(3)	(145)	254	2.1	13.5	20.9
Only Roundwood	10	13	470	3.1	26.8	73.3
Longer-term (2025-2040)						
All Biomass Sources	42	49	(33)	0.3	(0.9)	(0.2)
Only Agricultural Sources	(0)	37	24	(1.2)	(1.5)	(3.3)
Only Forestry Sources	14	31	121	(1.2)	27.0	41.5
Only Residues	(19)	173	1007	1.8	6.5	(6.8)
Only Roundwood and Logging Residues	5	(22)	17	9.1	36.8	45.2
Only Roundwood	110	160	303	13.0	90.7	97.7

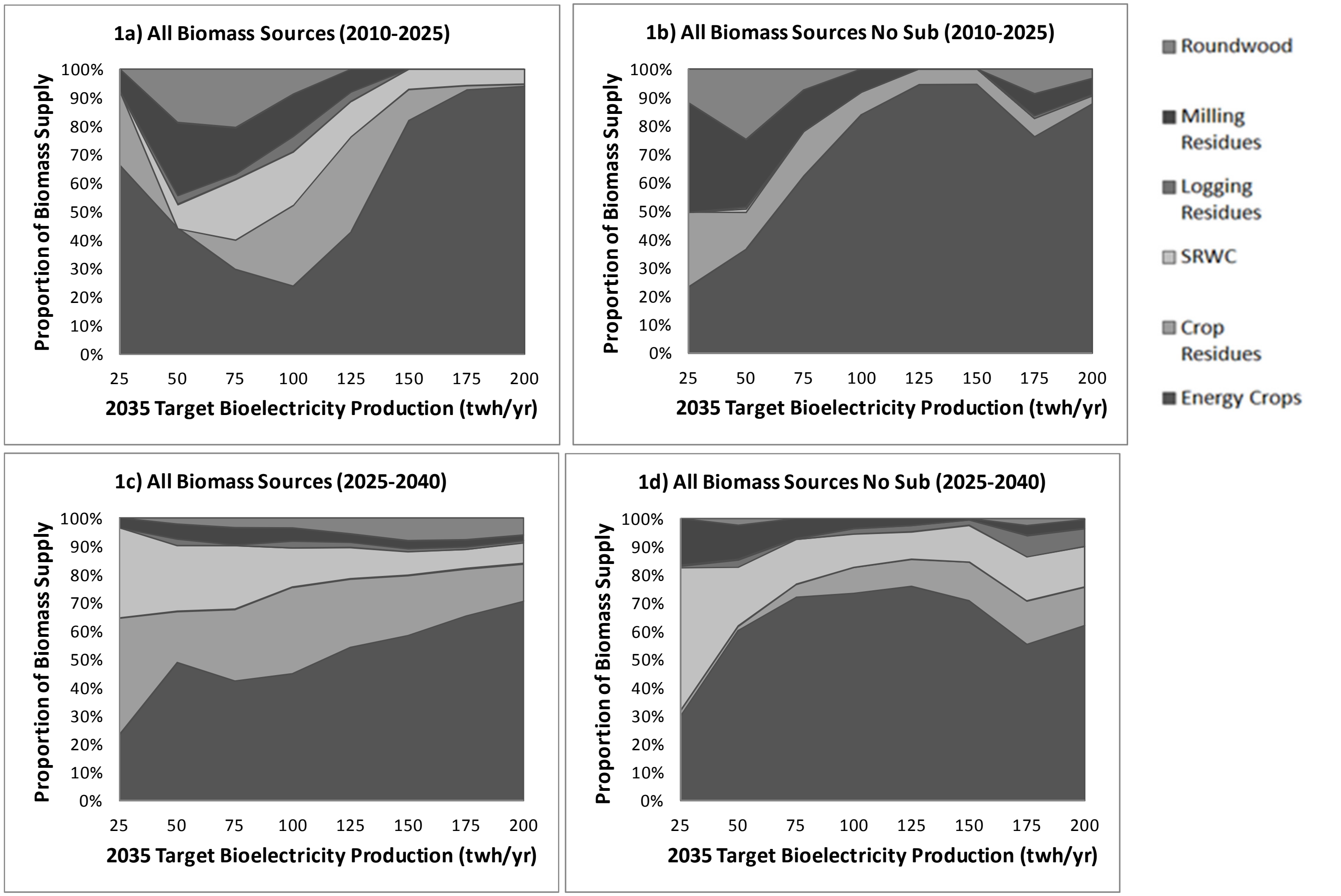
[1] *All Biomass Sources* includes all biomass feedstock sources, *Only Agricultural Sources* allows only agricultural feedstock sources, *Only Forestry Sources* allows only forest biomass feedstock sources, *Only Roundwood* allows only roundwood feedstock sources, *Only Residues* allows only logging and milling residue feedstock sources, *Only Roundwood and Logging Residues* allows only roundwood and logging residue feedstock sources, *All Biomass Sources No Sub* allows all feedstocks but allows no land use or commodity exchanges between agriculture and forestry. Scenario labels hold for all following tables.

Table 5. Annual average forest harvest, initial standing tree carbon stocks, and change in those stocks on privately owned U.S. timberland with increases in biopower

Policy[1]	Harvest			Tree Carbon Stocks		
Base	*Million m^3/yr*			*Mt CO_2*		
Short-term(2010-2025)	379			26,529		
Longer-term(2025-2040)	421			26,096		
Biolelectricity Target Levels	**25**	**100**	**200**	**25**	**100**	**200**
Short-term (2010-2025)	*difference from base (Million m^3/yr)*			*difference from base tree carbon stock growth (Mt CO_2/yr)*		
All Biomass Sources	2.4	7.6	3.5	(1)	1	8
Only Agricultural Sources	0.8	1.1	(4.3)	(3)	3	(16)
Only Forestry Sources	4.6	17.9	21.3	(9)	(39)	(19)
Only Residues	1.9	7.5	76.0	(3)	18	(474)
Only Roundwood and Logging Residues	1.2	15.4	22.1	(1)	(31)	(28)
Only Roundwood	2.0	11.1	12.6	(3)	(9)	(25)
All Biomass Sources No Sub	2.7	2.2	5.9	(6)	(5)	(7)
Only Agricultural Sources No Sub	(0.1)	1.0	2.2	(2)	(4)	(7)
Only Forestry Sources No Sub	1.2	17.5	31.4	(1)	(58)	(163)
Longer-term (2025-2040)						
All Biomass Sources	(0.7)	0.7	(0.7)	(2)	(15)	(34)
Only Agricultural Sources	(0.6)	(2.3)	(0.1)	(6)	(2)	(2)
Only Forestry Sources	1.9	16.0	95.7	(7)	(50)	(108)
Only Residues	4.1	116.9	370.6	2	(75)	246
Only Roundwood and Logging Residues	3.8	8.5	90.2	(16)	(50)	(150)
Only Roundwood	7.0	11.7	132.9	(4)	(4)	(126)
All Biomass Sources No Sub	1.7	1.1	3.5	2	6	12
Only Agricultural Sources No Sub	0.8	3.3	0.2	(0)	(9)	(1)
Only Forestry Sources No Sub	7.9	62.2	165.9	(14)	(93)	(212)

Table 6. Annual average GHG emissions associated with producing biomass to meet simulated RES targets for each of the feedstock groups

Policy[1]	Agriculture			Afforestation			Forestry			Total		
	25	100	200	25	100	200	25	100	200	25	100	200
	additional emissions in million metric tonnes per year											
Short-term (2010-2025)												
annual avoided fossil fuel emissions										*10*	*38*	*76*
All Biomass Sources	7	12	10	(2)	7	7	(3)	5	(7)	1	24	10
Only Agricultural Sources	(0)	7	14	0	(2)	31	7	7	11	7	12	55
Only Forestry Sources	-	16	55	(3)	(8)	(96)	12	48	71	12	55	30
Only Residuesy	4	98	160	(7)	(166)	(391)	13	68	725	11	(0)	494
Only Roundwood and Logging Residues	(1)	(11)	43	2	33	(56)	(3)	25	53	(1)	47	40
Only Roundwood	2	15	113	(1)	(8)	(133)	(2)	21	77	(1)	28	57
All Biomass Sources No Sub	9	11	17	-	-	0	8	6	13	16	17	31
Only Agricultural Sources No Sub	2	13	8	-	(0)	(0)	2	5	10	4	18	18
Only Forestry Sources No Sub	1	2	1	(0)	0	(1)	3	76	224	4	78	224
Longer-term (2025-2040)												
annual avoided fossil fuel emissions										*22*	*89*	*178*
All Biomass Sources	0	12	3	(5)	3	14	11	11	29	6	25	45
Only Agricultural Sources	(1)	1	16	(2)	(4)	(5)	8	6	7	4	3	18
Only Forestry Sources	2	20	94	(3)	(19)	(190)	14	78	257	12	78	158
Only Residues	0	(4)	(14)	(1)	(90)	(346)	(2)	158	(135)	(3)	64	(498)
Only Roundwood and Logging Residues	15	24	49	(4)	(25)	(127)	21	62	297	32	60	215
Only Roundwood	9	35	2	(25)	(42)	(199)	17	17	335	2	10	136
All Biomass Sources No Sub	(2)	26	11	-	-	(0)	(2)	(7)	(17)	(4)	19	3
Only Agricultural Sources No Sub	(47)	(48)	(25)	0	5	3	1	8	(1)	(45)	(34)	(20)
Only Forestry Sources No Sub	6	8	8	(0)	(14)	39	18	142	271	24	137	318



Note: *All Biomass Sources* includes all biomass feedstock sources, *All Biomass Sources No Sub* allows all feedstocks but allows no land use or commodity exchanges between agriculture and forestry

Figure 1. Sources of Biomass in the short and longer term with and without land and commodity substitution

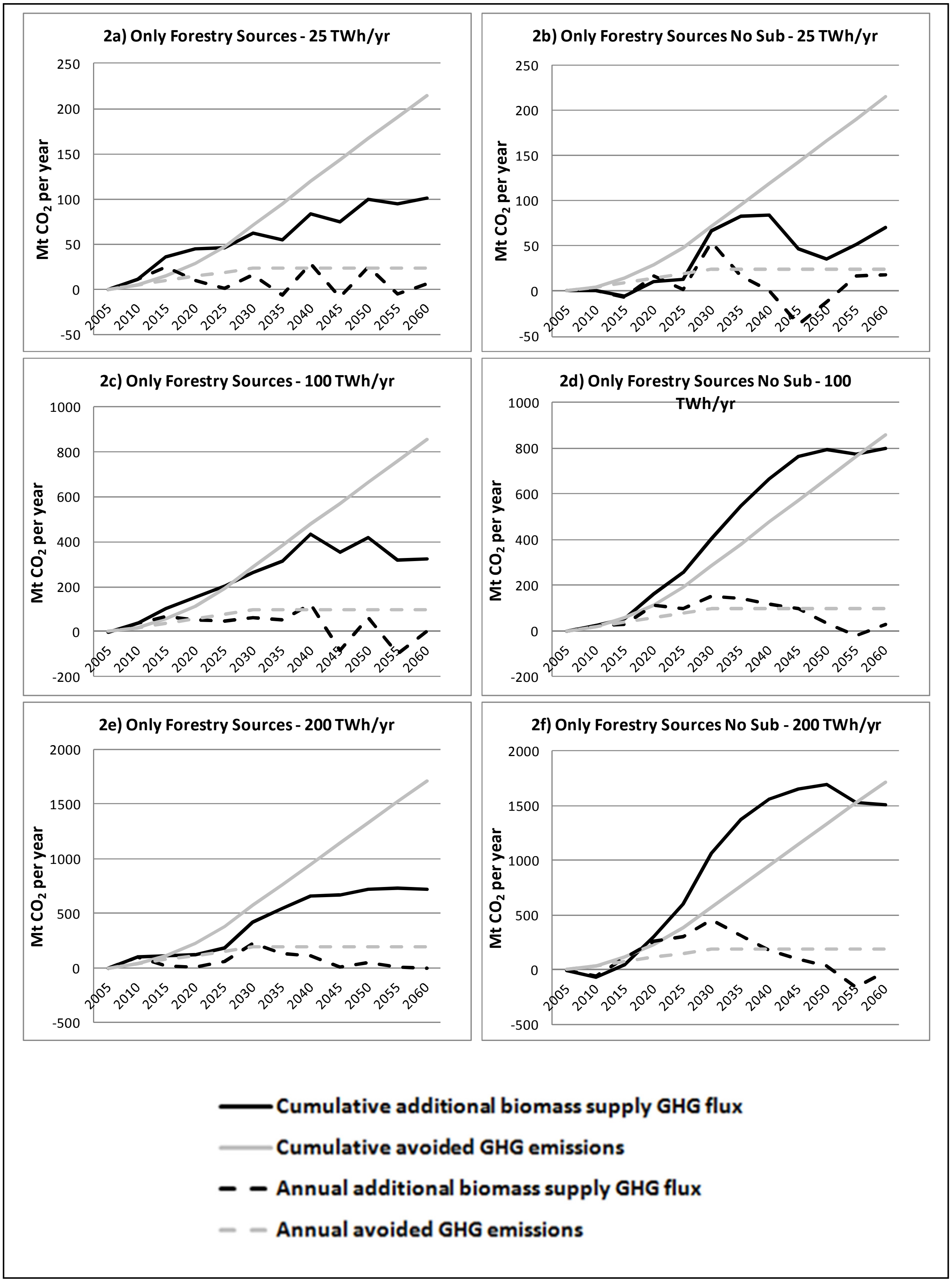


Figure 2. Additional GHG and avoided fossil fuel emissions over time for the All Forest Sources case with and without land and commodity substitutability.