

Environmental Research Letters



LETTER

Carbon savings with transatlantic trade in pellets: accounting for market-driven effects

OPEN ACCESS

RECEIVED
3 July 2015REVISED
26 October 2015ACCEPTED FOR PUBLICATION
27 October 2015PUBLISHED
16 November 2015

Content from this work
may be used under the
terms of the [Creative
Commons Attribution 3.0
licence](#).

Any further distribution of
this work must maintain
attribution to the
author(s) and the title of
the work, journal citation
and DOI.

Weiwei Wang¹, Puneet Dwivedi², Robert Abt³ and Madhu Khanna¹¹ Department of Agricultural and Consumer Economics, University of Illinois, Urbana, IL-61801, USA² Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA-30602, USA³ Department of Forestry & Environmental Resources, North Carolina State University, Raleigh, NC-27695, USAE-mail: khanna1@illinois.edu**Keywords:** land use change, dynamic optimization, forest biomass, agricultural biomass, market inducedSupplementary material for this article is available [online](#)**Abstract**

Exports of pellets from the United States (US) are growing significantly to meet the demand for renewable energy in the European Union. This transatlantic trade in pellets has raised questions about the greenhouse gas (GHG) intensity of these pellets and their effects on conventional forest product markets in the US. This paper examines the GHG intensity of pellets exported from the US using either forest biomass only or forest and agricultural biomass combined. We develop an integrated dynamic, price-endogenous, partial equilibrium model of the forestry, agricultural, and transportation sectors in the US to investigate not only the direct life-cycle GHG intensity of pellets but also the accompanying indirect market and land use effects induced by changes in prices of forest and agricultural products over the 2007–2032 period. Across different scenarios of high and low pellet demand that can be met with either forest biomass only or with forest and agricultural biomass, we find that the GHG intensity of pellet based electricity is 74% to 85% lower than that of coal-based electricity. We also find that the GHG intensity of pellets produced using agricultural and forest biomass is 28% to 34% lower than that of pellets produced using forest biomass only. GHG effects due to induced direct and indirect changes in forest carbon stock caused by changes in harvest rotations, changes in land use and in conventional wood production account for 11% to 26% of the overall GHG intensity of pellets produced from forest biomass only; these effects are negative with the use of forest and agricultural biomass.

Introduction

Pellet exports from the United States (US) to the European Union (EU) have increased six-fold since 2008 and are anticipated to increase further to meet renewable energy and greenhouse gas (GHG) mitigation targets in the EU (Forisk Consulting 2014, Goetzl 2015). Pellets produced in the US are currently using forest biomass and 98% of the production of exported pellets from the US is concentrated in the Southern region only; over 80% of these pellets are being exported to the United Kingdom (UK) (EIA 2014, 2015). The extent to which these pellets result in GHG savings relative to electricity derived from various fossil fuels in the EU has been

controversial (New York Times 2015, Washington Post 2015). Some studies claim that electricity generation from pellets is more carbon intensive than coal (e.g. McKechnie *et al* 2014, Natural Resources Defense Council 2011, 2014, Walker *et al* 2010), while other studies claim that forest bioenergy could save 50%–73% of GHG emissions relative to grid electricity (Dwivedi *et al* 2011, 2014). These assessments were either based on commercially unlikely scenarios involving the use of whole trees for biomass and foregoing high value uses for timber (e.g. Walker *et al* 2010, McKechnie *et al* 2014, Natural Resources Defense Council 2011, 2014) or consider only the direct emissions during the production and transportation of pellets assuming no changes in forestlands, harvest

rotations, or forest inventories (Damen and Faaij 2006, Magelli *et al* 2009, Dwivedi *et al* 2011, 2014, Röder *et al* 2015).

The increased demand for pellets is likely to be met in part by additional harvests of existing forests by changing harvest rotations, conversion of land to forests from other uses, and by diversion of forest biomass from existing forest products to pellets; these indirect market-driven effects could have a positive or negative impact on the GHG intensity of pellets. The first objective of this study is to quantify the direct and indirect market impact of demand for pellets exports on harvest age, land use change, and conventional wood product markets in the US and its implications for the GHG intensity of pellets from forest biomass. The second objective of this study is to analyze the potential of agricultural biomass coupled with forestry biomass for meeting demand for pellet exports and its implications for land use changes and GHG emissions.

Wood is currently the preferred feedstock for pellets due to its low ash content. The high ash content of agricultural biomass negatively affects thermal efficiency of combustion equipment. The combustion of wood also results in lower emissions of various air pollutants (Fournel *et al* 2015). However, increasing competition for biomass in the future is expected to provide incentives to improve the technology to convert agricultural biomass to pellets and develop the supply chain needed to utilize agricultural biomass for pellet production which could make agricultural biomass less costly than wood since the latter has other higher-valued uses (Rabobank Report 2013). Dedicated energy crops, also have substantial potential to sequester carbon in the soil and thus, could have lower GHG intensity than forest biomass (Dwivedi *et al* 2015).

We undertake this analysis by developing an integrated dynamic, price-endogenous, partial equilibrium model of the agricultural and forestry sectors in the US with detailed life-cycle GHG accounting to investigate not only the direct emissions associated with the production, transportation, and conversion of the biomass to pellets but also the accompanying indirect market and land use effects induced by changes in prices of forest products and returns to agricultural and forestlands. This paper extends the Biofuel and Environmental Policy Analysis Model (BEPAM) developed previously as an integrated model of the agricultural and transportation sectors in the US (Huang *et al* 2013, Chen *et al* 2014) by integrating it with the forestry sector from the Forestry and Agricultural Sector Optimization Model (FASOM) (Adams *et al* 1996, 2005, Beach *et al* 2010) to examine the economic and GHG implications of the increased use of forest-based bioenergy development. The combined model, BEPAM-F, is a dynamic, nonlinear programming, multi-market equilibrium model that integrates the transportation, agricultural, and forestry sectors in the US (Hudiburg *et al* 2016). Unlike

BEPAM, in which forestland and forest pastureland acres were exogenously fixed, in BEPAM-F, the allocation of land across cropland, forestland, and pastureland is determined endogenously by equating the net present value of returns across uses. The model is dynamic as it simulates forest and agricultural activity over time taking into account the long-lived, age dependent growth of a forest stand and perennial energy crops, the changes in the timber inventory, and the changes in the stock of carbon sequestered in soil and forest biomass. Life-cycle GHG impacts of various production activities and land use changes are tracked and aggregated to determine the implications of various scenarios for aggregate GHG emissions.

A number of studies have assessed the land use and GHG implications of the domestic demand for bio-power in the US using either forest biomass only (Ince *et al* 2011, Abt *et al* 2012, Sedjo and Sohngen 2013, Galik *et al* 2015) or using forest and agricultural biomass (Latta *et al* 2013, White *et al* 2013). More recently, Galik and Abt (2015) examined the GHG savings by pellet exports from forest biomass in the US South and showed that compared to coal, use of wood pellets can achieve over 100% savings in cumulative emissions. A key determinant of the extent of land use change induced by pellet demand is the choice of modeling approach used. The Subregional Timber Supply Model (SRTS) for the US South used by Galik and Abt (2015) treats decision makers as myopic regarding future demand for pellets. SRTS a recursive dynamic model that maximizes net social surplus in each time period independently, typically updating key parameters such as forest stock and manufacturing capacity between solutions of adjacent periods (see review in Latta *et al* 2013). On the other hand, at the US scale, FASOM utilized by White *et al* (2013) and Latta *et al* (2013) is a fully forward looking dynamic model in which decision makers are assumed to have perfect foresight about the long term future (80–100 years) (Latta *et al* 2013). The length of the planning horizon and the assumption of perfect foresight affects the incentives for land use change—the anticipation of increased demand for forest-based bioenergy in the future with a longer planning horizon creates greater incentives for afforestation and increase in forest biomass stock in early years. A shorter planning horizon could result in lower carbon storage in the early years to meet later demand and thus provide a lower offset to increased emissions in later years as bioenergy production increases; this should raise the cumulative GHG intensity of forest bioenergy relative to that obtained under a longer planning horizon. Unlike the fully forward looking approach in FASOM and the myopic approach in SRTS, we use a rolling horizon approach in which landowners are assumed to make resource allocation plans for a shorter time horizon taking current prices, demand conditions, land availability in different categories and age distribution of the forest stock as given and then to update their

expectations about these every five years based on the realized market equilibrium. We examine the sensitivity of our results to different lengths of the rolling horizon.

Additionally, land allocation decisions in BEPAM-F are made on a finer spatial resolution than FASOM. BEPAM-F considers a Crop Reporting District (CRD) as the decision making unit in the agricultural sector and the model incorporates heterogeneity in agricultural crop yields, costs of production, and availability of cropland and cropland pasture across 295 CRDs in the US. By overlaying the CRDs on the forestland in the 11 forest marketing regions in FASOM together with recent county-level data on forest inventory (by age distribution, species, and land) from the Forest Service's 2010 timber land assessment, changes in forestland due to the pellet demand shock are allocated to the distribution of trees by age, species, and timber land acres at the CRD level. The economic incentives for conversion of land from one use to another is, therefore, based on a more spatially disaggregated assessment of the returns to land. This is particularly, relevant in scenarios where we consider the competitiveness of agricultural biomass and forest biomass for bioenergy given the spatial heterogeneity in bioenergy feedstock yields at a fine spatial resolution. This is in contrast to FASOM in which long term land allocations for forestry and agricultural production are made at the level of the 11 forest marketing regions in the US while in the SRTS model is limited to forest land in the Southern region only. Lastly, to the best of our knowledge, this is the first study which examines the economic and environmental implications of meeting the increased demand for pellet exports from the US using a mix of both agricultural and forest biomass.

Methods

The BEPAM-F endogenously determines the optimal land use, production of various agricultural and forestry products, alternative fuels and prices for an array of agriculture and forest products to maximize consumer and producer surplus in the agricultural, forestry, and transportation fuel sectors given a fixed demand for pellet exports, bio-electricity, transportation fuels, traditional forest and agricultural products, various material balance, and technological constraints. The model endogenously determines whether to continue growing a stand of trees or harvest it now, whether to replant a harvested stand or convert the land to other agricultural uses, the forest type and timber management plan to select if the land is planted in trees and the crop/livestock activity to undertake on land converted to agricultural use based on the relative returns to alternative actions. These decisions are made on a five-year time scale. Model outcomes include the harvest age of trees, the production of

various forest and agricultural products and their prices, allocation of land to different uses, and mix of feedstocks for meeting various demand for bioenergy and the associated GHG emissions. Unlike, the 100 year horizon with perfect foresight assumption in FASOM, we consider a rolling horizon of 30 years in the benchmark case and examine the sensitivity of our results to alternative horizons of 15 years and 50 years. The model is solved iteratively for a 30 (alternatively 15 or 50) year planning horizon. After solving each 30 (15 or 50) year market equilibrium problem, we take the first five year period's solution values for prices, land available in different categories, and age distribution of forest stock as 'realized', move the horizon one period forward and solve the updated model again (see Chen *et al* 2014). Model formulation is provided in the supplementary information.

The forestry sector in BEPAM-F like FASOM incorporates the family of timber assessment models that include Timber Assessment Market Model, North American Pulp and Paper Model, Aggregate Timber Assessment System (Adams *et al* 1996). The sector is represented by 11 marketing regions, forestry production occurs in nine of these regions. Forestland is characterized by two wood types, softwoods and hardwoods that are grown on land privately owned by the forest industry or land under non-industrial private ownership. Forestland is distinguished by various site productivity classes that determine yield of forest biomass per unit land. Current and future timber yields are based on the 2000 Forest and Rangeland Renewable Resources Planning Act Timber Assessment and differ depending on management intensity and age cohorts for stands (Beach and McCarl 2010). Timber growth and yield are included for existing stands, reforested stands, and afforested stands. Land conversion from one use to another within the sector and across sectors is constrained by pre-defined suitability classes that determine which land can be converted to forest, crop, cropland pasture, or forestland pasture. In the terminal period, returns on all standing perennial crops and timber stands are treated as an infinite annuity as in Beach *et al* (2010) and included in the terminal conditions. Harvest of an acre of forest land results in the simultaneous production of a mix of softwood and hardwood logs in the form of sawlogs, pulpwood, and fuelwood. The product mix varies with the stand age, regions, and site classes.

The model includes the conversion of these intermediate products into 40 major products including solid wood products (lumber, plywood, and OSB) and fiber products (newsprint, linerboard, and others). The production of these solid wood products results in milling residues as a byproduct. Demand for softwood and hardwood lumber, softwood and hardwood plywood, OSB, and a number of fiber products is represented at the national level by downward sloping demand functions. These demand curves shift to the right exogenously over time. Exports of wood

products to Canada and other regions of the world are specified exogenously while imports to the US from Canada and other regions are determined endogenously through an import supply function. We also incorporated the demand for bio-electricity using forest and agricultural biomass. Annual demand for bio-electricity is specified as 30% of the demand for electricity from renewable sources projected to be produced over this period by the Annual Energy Outlook (EIA 2013). The model is run in five-year time scales for the 2007–2032 time period.

The agriculture sector in the model includes fourteen major conventional crops, eight livestock animals, and two types of crop residues (corn stover and wheat straw), three energy crops (miscanthus, switchgrass, and energycane) and short rotation woody crops (poplar and willow). The costs of perennial energy crops and short rotation woody crops vary with the age of the crop and are specified annually and then annualized for each five year period in their life-span. The model also incorporates the differential costs during the early years of crop establishment from those in the later years of crop maintenance. More details of the data and model assumptions can be found in the supplementary information.

Linear downward sloping demand curves were specified for conventional crops and livestock and shift to the right exogenously over time. The model included demand for corn ethanol and soy diesel at mandated levels and the production of co-products that were used for animal feed. Production of energy crops and short rotation woody crops is driven by exogenously specified demand for biomass; the mix of these sources of bioenergy is determined endogenously depending on their competitiveness and can vary across CRDs.

Five types of agricultural land (irrigated and non-irrigated cropland, idle cropland, cropland pasture and pasture land) were specified for each CRD. Cropland is responsive to crop and livestock prices and can move freely between production of alternative crops with no extra cost but subject to a convex combination of both historical and synthetic crop mixes (Önal and McCarl 1991, Chen and Önal 2012). Cropland pasture can be converted to crop production but with one-third less productivity relative to the regular cropland following the assumption in Hertel *et al* (2010). The cost of converting cropland pasture to cropland was calibrated to replicate the observed use of land for crop production and crop-pasture in each CRD and to reflect the difference in land rental rates based on the assumed equilibrium of land markets (Beach and McCarl 2010). In the transportation sector in BEPAM-F, we imposed the targeted level of corn ethanol and soy diesel under the Renewable Fuel Standard in the benchmark case (as in Chen *et al* 2014). We added pellet demand for export as a new forest product to those included in FASOM.

We consider alternative scenarios in which the demand for bio-electricity and pellets can be met using forestry feedstocks only or using both forest and agricultural (crop residues and dedicated energy crops) feedstocks. The quantity of pellets demanded was specified exogenously for each five year period over the planning horizon and was increasing over time. The amount of pellets produced in different marketing regions was determined endogenously. A uniform cost of manufacturing wood pellets of $\$70.0 \text{ Mg}^{-1}$ (Dwivedi *et al* 2014) and of transporting it on rail roads from plant to the seaport for export of $\$6.98 \text{ Mg}^{-1}$ (fixed cost) and $\$0.01\text{--}0.039 \text{ Mg}^{-1} \text{ km}^{-1}$ (variable cost) was assumed to obtain the delivered cost of pellets (Lin *et al* 2015). We incorporated transportation distance for pellets from the center point of each region to the Savannah Seaport, Georgia (US), using railroads. We also incorporate the cost of shipping ($\$26 \text{ Mg}^{-1}$) the pellets from the Savannah Seaport to Immingham Seaport in the UK which is the destination for a dominant share of the exports from the US (Argusmedia 2014). We assumed that the harvest of logging residues was limited to 30% and that no more than 5% of pellet production was based on logging residues; the rest of the logging residues were used for domestic bio-electricity production.

GHG emissions estimation

We estimated the direct GHG emissions in the process of fossil fuel production and all agricultural and forest activities included in the model. In the case of agricultural activities, aboveground GHG emissions from input and machinery use were included as described in Chen *et al* (2014) while estimates of carbon sequestration in soils due to agricultural biomass feedstock production, including energy crops and corn stover under different tillage and fertilizer management practices were obtained using the DAYCENT (Dwivedi *et al* 2015). Forest GHG emissions accounted for stocks and flows of carbon in forest ecosystem pools, timber production, and harvested wood products over the planning horizon of the BEPAM-F model as in FASOM (Beach *et al* 2010). The model incorporates carbon in standing live and dead tree biomass, forest understory vegetation, organic litter on the forest floor and in forest soils (Smith *et al* 2006). Emissions during harvesting and in harvested wood products were based on Skog and Nicholson (2000). GHG emissions involved in producing and transporting wood pellet to the port in the US and by ship to a port in the UK were also included (Dwivedi *et al* 2014).

There are considerable variations across studies in the GHG emissions intensity of the pellet production process from forest biomass depending on the type of woody biomass, duration of storage of woody biomass and fuel used for drying of woody biomass prior to

pelleting. This is mostly due to the fact that the duration of woody biomass storage at the pellet mill differs across mills, wood type (hardwoods or softwoods), and seasons⁴. Röder *et al* (2015) estimate the GHG intensity of pellet production ranges between 11.4 and 51.2 gCO₂e MJ⁻¹ with the upper end of this range occurring due to the use of diesel instead of biomass for drying the feedstock before pelleting. In addition, they find that methane emissions can be high and range from 51 to 203 gCO₂e MJ⁻¹ for forest residue and 99 to 245 gCO₂e MJ⁻¹ for sawmill residues depending on length of storage at the pellet mill prior to their conversion to pellets. We assume the GHG intensity of the wood pellet production process is 28.6 gCO₂e MJ⁻¹ (155.7 kgCO₂e Mg⁻¹) following Dwivedi *et al* (2014); this estimate is based on common industry practices which indicate that bark is used for drying forest biomass and biomass is stored for very short duration of days to few weeks at the mill prior to processing (Forest Resources Association (FRA) 2005, Hubbard *et al* 2007). Paucity of data, in the absence of large scale pellet production from agricultural biomass, has led to considerable uncertainty about the GHG intensity of the production process for pellets from agricultural biomass. We use the estimate obtained by Wilson *et al* (2012) for the GHG intensity of producing pellets from switchgrass. This is based on observed data from a pellet mill under construction and estimated to be 24 gCO₂e MJ⁻¹ (130 kg CO₂e Mg⁻¹).

The GHG intensity of agricultural biomass production (including soil carbon accumulation and above ground emissions) is determined endogenously in the model and varies across locations depending on changes in soil carbon accumulation. Our estimates of the above-ground GHG intensity of miscanthus and switchgrass production are about 10 gCO₂e MJ⁻¹ (56 kgCO₂e Mg⁻¹) and 14 gCO₂e MJ⁻¹ (78 kgCO₂e Mg⁻¹), respectively. The latter is close to the corresponding estimate of 16 gCO₂e MJ⁻¹ (87 kgCO₂e Mg⁻¹) obtained by Wilson *et al* (2012). Large levels of soil carbon sequestration by miscanthus and switchgrass make its net carbon intensity negative as shown in the supplementary information. The GHG emissions due to indirect land use change (ILUC) within the US are also estimated endogenously in the model.

We assume that converting cropland-pasture to cropland (either for producing traditional crops or dedicated energy crops) does not lead to soil carbon emissions. In the benchmark, we do not account for ILUC emissions in the rest of world (ROW) due to conversion of cropland to energy crop production. However, we include these emissions in the sensitivity analysis where we assume emissions from conversion of cropland pasture to cropland are 1.85 Mg CO₂ ha⁻¹ yr⁻¹ and from ROW ILUC for

miscanthus, switchgrass, and corn stover are 2.12, 7.92, and -1.06 gCO₂ MJ⁻¹ respectively (Taheripour and Tyner 2013).

Model scenarios

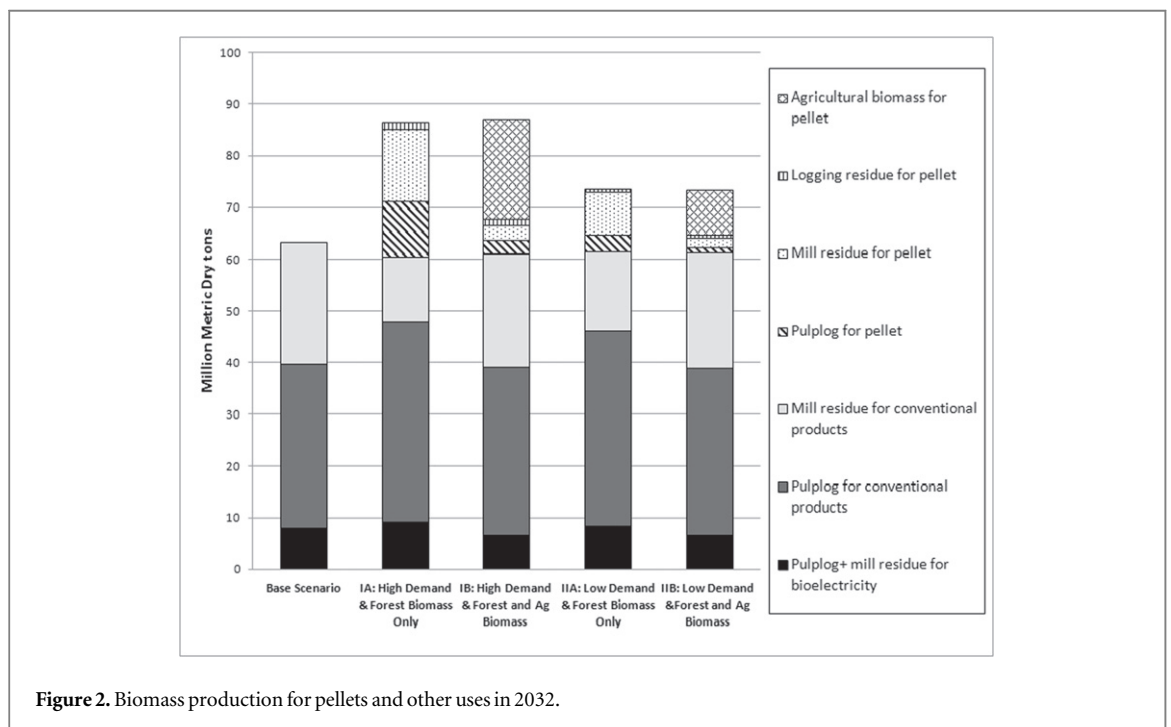
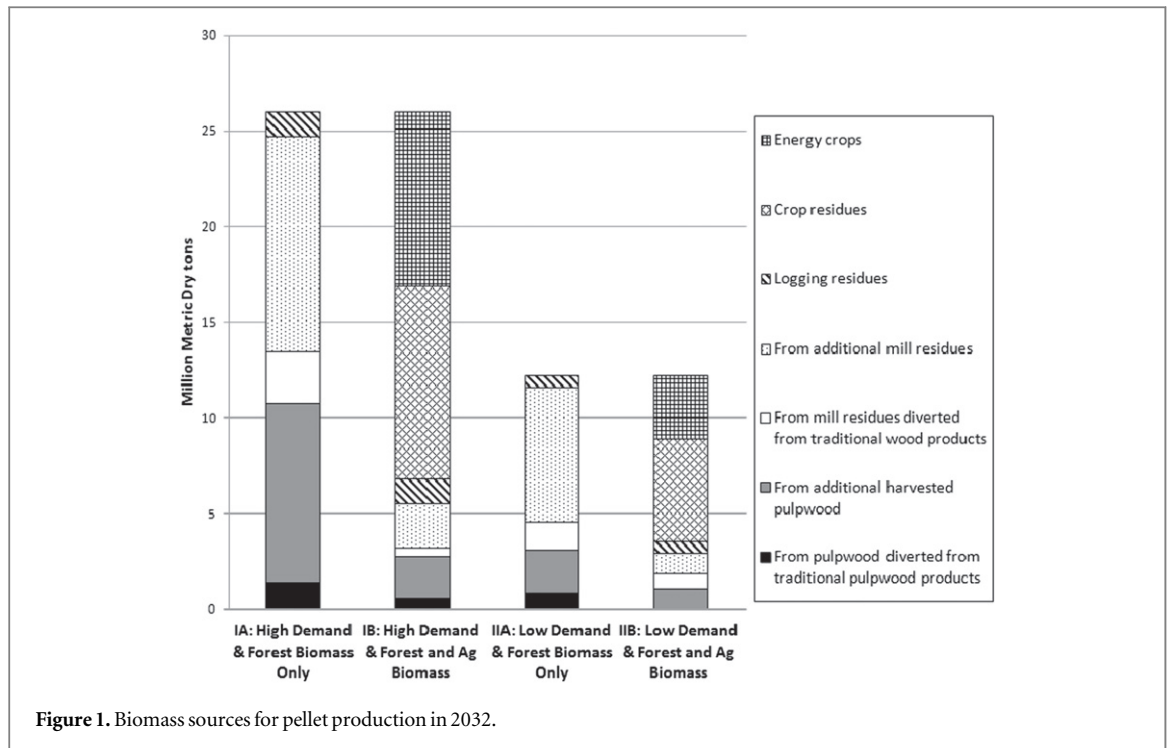
We consider two scenarios of demand for pellet exports over the 2007–2032 period based on the range of projections provided by RISI Inc (2013) and Abt *et al* (2014) for 2020 and assuming demand continues to grow at 1% yr⁻¹ in the future after that. Scenario IA considers the case of a High Demand target for pellets of 26 million metric tons in 2032 to be met by forest biomass only while Scenario IB considers the High demand target met by both forest and agricultural biomass (from crop residues and dedicated energy crops). Scenario IIA and IIB consider Low Demand target of 12.2 million metric tons in 2032, met by forest biomass and by forest and agricultural biomass respectively (table S1). In all cases, exports of pellet levels increase from the observed level in 50 000 metric tons in 2007 (Spelter and Toth 2009). In Scenarios IB and IIB, the mix of forest and agricultural biomass was determined endogenously based on the relative competitiveness of various biomass sources. In each scenario, we compare the effects relative to the Base Case in which demand for pellets was maintained at the 2007 level.

Results

We first validate the model for 2007 assuming existing demand for food, fuel, forest products, and policy constraints. We compared the model results with the corresponding observed values in 2007. The differences between model results and the observed data for a wide range of variables are typically less than 10% (table S2). We note, however, that the model's ability to predict economic effects in the future will depend on the extent of divergence between assumed parameters values and observed changes in various economic, institutional, and climate variables over time. We now present our findings on the sources of the biomass used to meet the additional demand for pellets in the different scenarios and its implications for forest product prices, land use change, and forest removals. We also discuss the implications of these for the GHG intensity of pellets under different scenarios and its sensitivity to various modeling assumptions.

We found that in Scenario IA, about 36% of forest biomass used for production of pellets in 2032 came from mill residues diverted from other forest products, while about 36% was sourced through additional pulpwood harvesting (figure 1). Corresponding values were 67% and 19% in Scenario IIA. In Scenarios IB and IIB, 77%–87% of the demand for pellets was met by agricultural biomass with relatively low share

⁴ Personal conversation with greenhouse gas specialist in Enviva LP, Bethesda, MD.



(7%–8%) of forest biomass. The diversion of pulpwood and milling residues from forest products to pellet production raised the price of OSB and paper relative to the Base Case while the demand for additional pulpwood harvests increased the forestland rents and increased incentives for afforestation. Despite the significant diversion of mill residues for pellet production in Scenario 1A, forest biomass for conventional (non-energy production) and domestic bio-electricity declined by only 4.5%; corresponding reduction under Scenario IIA is 2.6%. As shown in

figure 2, this was due to the substitution of additionally harvested pulplogs for mill residues diverted for pellet production. The corresponding reduction in forest biomass for conventional products when pellets could be produced using agricultural and forest biomass in Scenarios IB and IIB was even smaller.

As a result, the effect of pellet production on forest product production (table S1) and prices (figure 3) was very modest. Across all four scenarios, the change in prices of forest products relative to the base case ranged between –2% and 3% (figure 3). The increase in

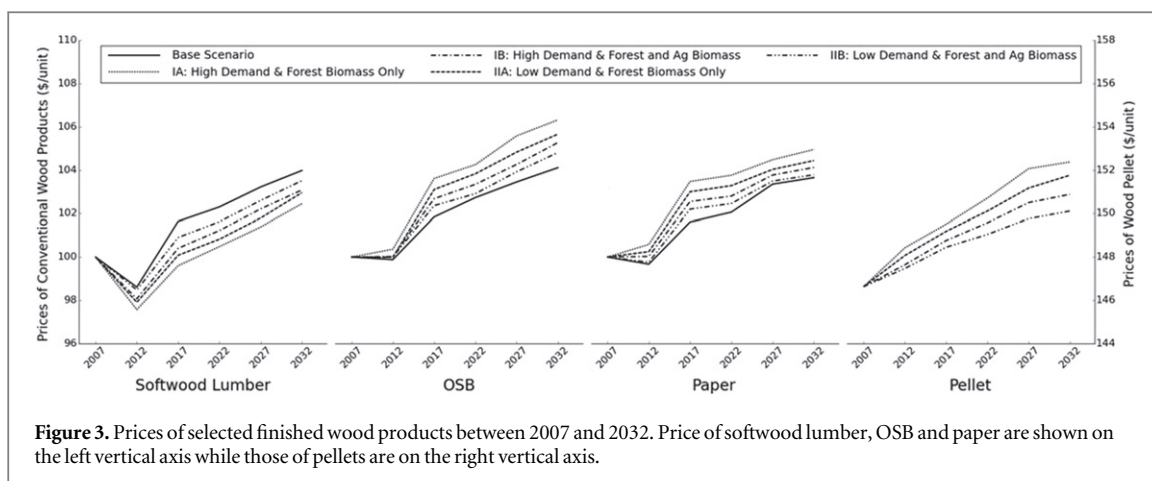


Figure 3. Prices of selected finished wood products between 2007 and 2032. Price of softwood lumber, OSB and paper are shown on the left vertical axis while those of pellets are on the right vertical axis.

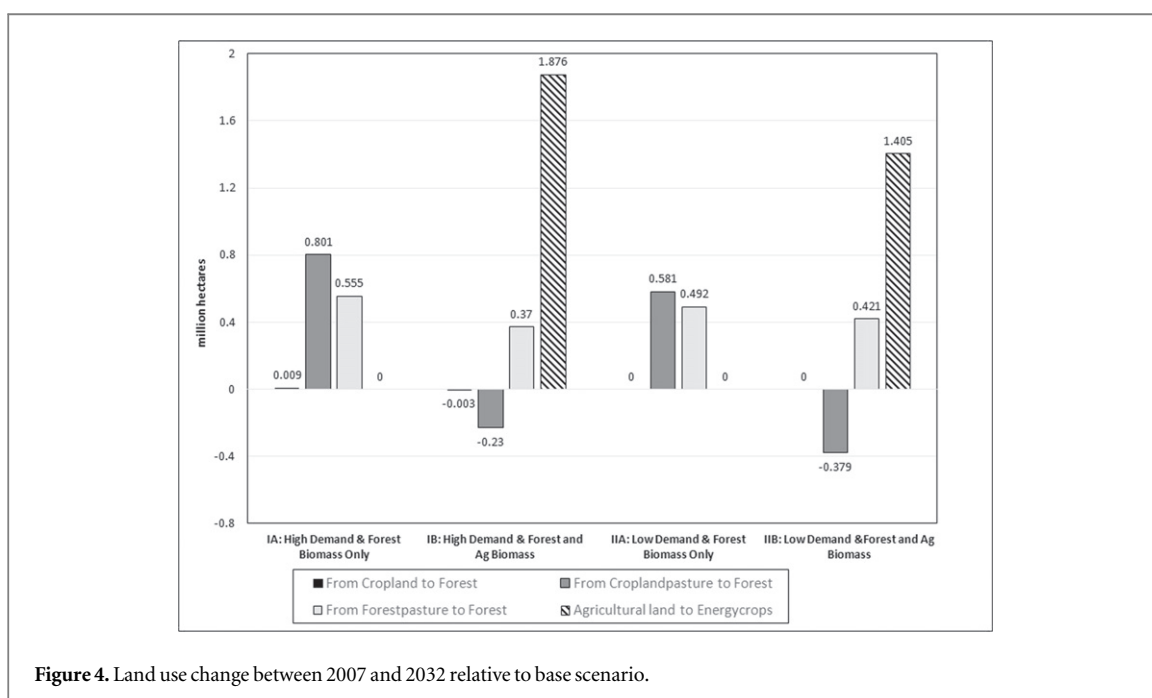


Figure 4. Land use change between 2007 and 2032 relative to base scenario.

price of OSB and paper was highest in Scenario IA followed by Scenario IIA in which demand for pellets was met by using forest biomass only. The increased production of pellets also raised demand for milling residues. Since milling residues are a by-product of lumber production and because pulpwood and saw timber production are joint products, the increased production of pellets was accompanied by increased production of lumber. With the demand for lumber remaining the same as in the Base Case, the increase in its production results in lower lumber prices in all four scenarios.

Figure 4 shows the land use change likely to result from the additional demand for pellets relative to the Base Case. In Scenarios IA and IIA the additional demand for pulpwood leads to conversion of land from cropland pasture and forestland pasture to forests. Forestland increased by 1.36 million hectares and 1.1 million hectares, respectively, over the 2007–2032

period. In Scenarios IB and IIB, with pellet demand met by both forest and agricultural biomass, the conversion from forest pastureland to forests is much smaller (0.4 million hectares) but there is significant conversion of cropland pasture to energy crops (1.9 and 1.4 million hectares).

The impact of the increased demand for pellets on land use differs across regions in the US. Figure 5 shows that the majority of pellets (77.9%) were produced from feedstock sourced from Southern forestlands in 2032 under Scenario IA (High Demand and Forest Biomass Only) while this percentage was 100% in Scenario IIA (Low Demand and Forest Biomass Only). The majority of pellets in Scenarios IB (53%) and IIB (71%) were produced in the Midwestern region; Southern forestlands contributed 26% and 29%, respectively. Table S3 shows the distribution of land use change relative to the Base Case across five major regions in the US. There was a conversion of

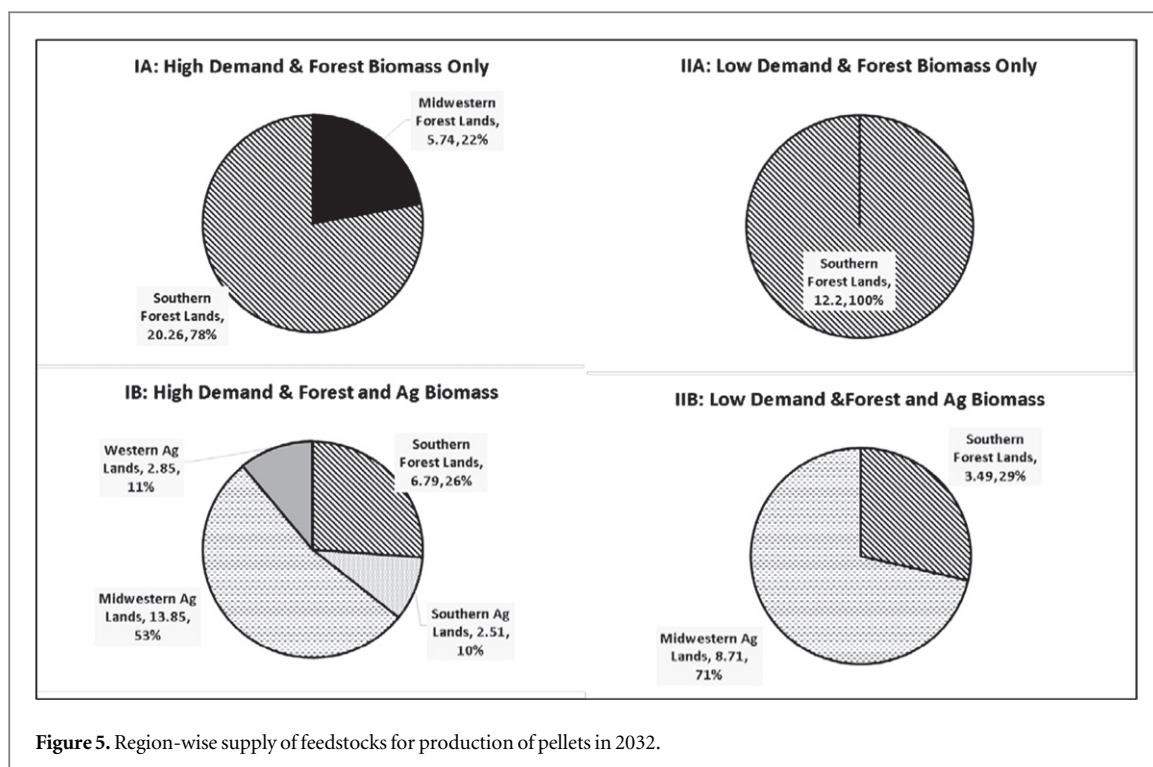


Figure 5. Region-wise supply of feedstocks for production of pellets in 2032.

cropland pasture and forestland pasture to forests in all other regions with the exception of the Pacific Northwest; the largest of this is in the South. Scenarios IB and IIB also lead to conversion of cropland, cropland pasture and idle land to energy crop production, particularly in the Midwest.

Another indirect impact of the increased demand for pellets and the resulting increase in price of pulpwood was the incentive to harvest trees at a younger age than otherwise because the availability of pulpwood relative to saw timber decreases with age of the tree. Figure 6 shows the impact of pellet demand on the age distribution of the standing softwood and hardwood stands in the High Demand Scenarios (IA and IB). More acres of younger softwood trees (less than 34 years) were harvested relative to the Base Case to meet the additional demand of pulpwood for the production of pellets under Scenario IA (High Demand and Forest Biomass). We also find that more acres of hardwood trees were harvested in this scenario from stands with ages between 35 and 64 years. This indicates that an increase in demand for pellets derived from forest biomass will decrease the average harvest age of the softwood and hardwood stands relative to base demand scenario. A similar trend was observed in Scenario IB, but the magnitude of change in harvest ages is relatively lower than in Scenario IA.

GHG intensity of pellets

The trajectory of carbon dynamics over time across different carbon pools is shown in figure S1. Across all scenarios, the net carbon sequestered on forestland

and in standing trees increased initially due to afforestation in anticipation of the increased demand for pellets in later years. However, these carbon pools become net emitter of carbon emissions over time relative to the Base Case as carbon sequestered on afforested lands and in live trees reached a stabilization state. We find that these two carbon pools become significant determinants of net carbon emissions over time relative to other carbon pools (carbon sequestered in wood products and emissions during agricultural crop production) across scenarios.

Overall, we find that the GHG intensity of pellet-based electricity ranges from $78 \text{ g CO}_2 \text{ MJ}^{-1}$ in Scenario IA to $44 \text{ g CO}_2 \text{ MJ}^{-1}$ in Scenario IIB. GHG intensity is 28% to 34% lower in scenarios that consider the potential to use agricultural biomass for pellets relative to corresponding scenarios that use forest biomass only (table 1). Although direct comparison of these values with those reported in Dwivedi *et al* (2014) or Röder *et al* (2015) which do not account for indirect GHG emissions is not possible, we can separate those components of the life-cycle assessment that represent GHG emissions related to pellet production and trade from those related to emissions due to changes in forest rotation, land use (including soil carbon effects), and diversion of forest products to bioenergy production. The magnitude of these latter impacts ranges from $19.9 \text{ g CO}_2 \text{ MJ}^{-1}$ in Scenario IA (High Demand and Forest Biomass Only) to $7 \text{ g CO}_2 \text{ MJ}^{-1}$ in Scenario IIA (Low Demand with Forest Biomass Only). These effects represent 26% and 11% of the total GHG intensity of pellets in the two scenarios, respectively. These effects are negative at $-1.25 \text{ g CO}_2 \text{ MJ}^{-1}$ and $-14.9 \text{ g CO}_2 \text{ MJ}^{-1}$ in Scenarios IB and IIB

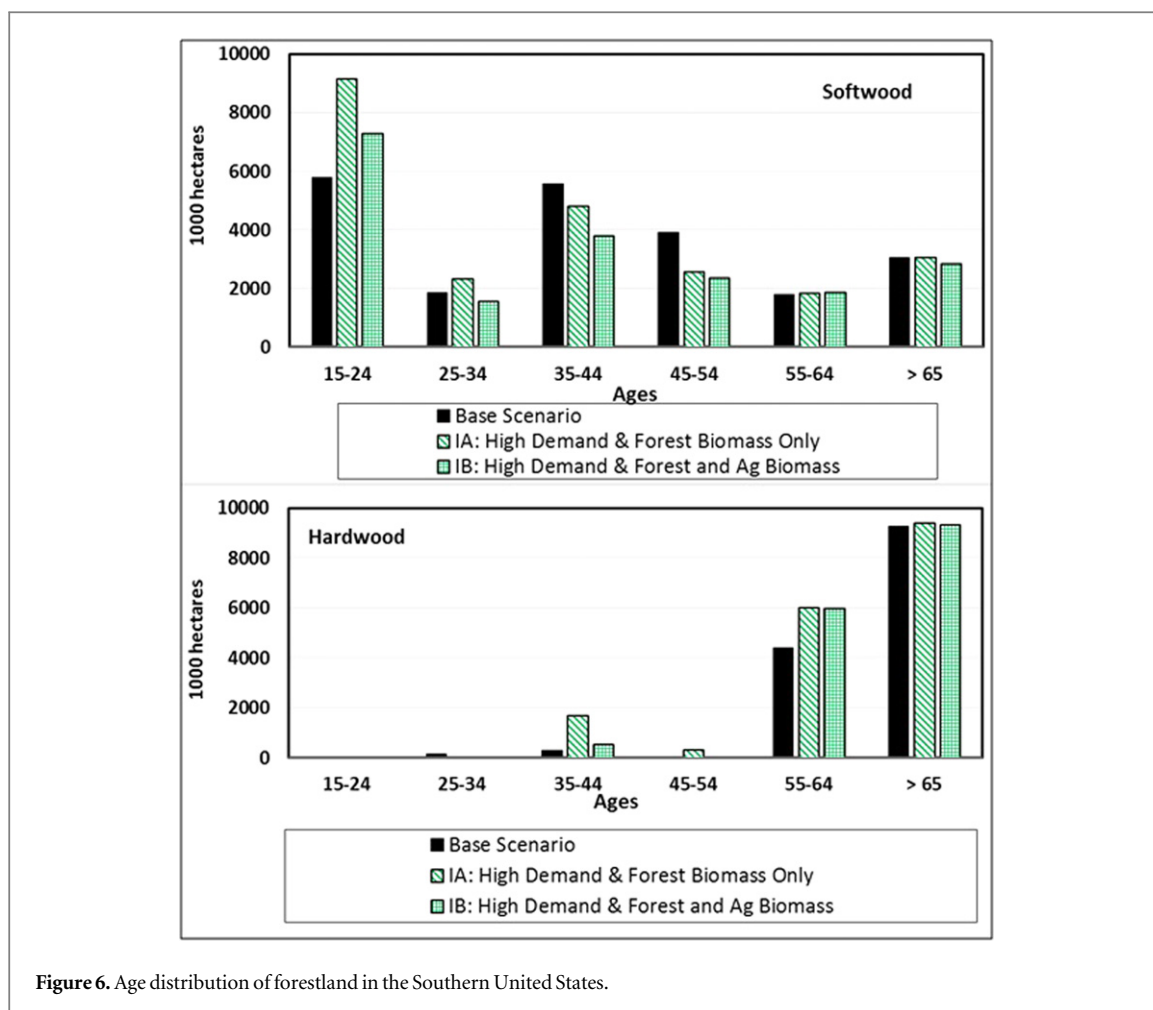


Figure 6. Age distribution of forestland in the Southern United States.

with forest and agricultural biomass due to the large soil carbon accumulation with energy crops. These results indicate that even after accounting for land use and market-mediated changes in forest management and forest product production, the GHG savings with pellet-based electricity relative to coal-based electricity $299.44 \text{ gCO}_2 \text{ MJ}^{-1}$ (Stephenson and Mackay 2014) ranged 74% in Scenario IA (High Demand and Forest Biomass Only) to 85% for Scenario IIB (Low Demand & Forest and Ag Biomass) with the benchmark case assumptions; the potential for GHG savings was larger in cases when a large share of pellets were manufactured from agricultural biomass and their land use and market effects on GHG intensity were negative. The GHG savings estimated here are within the same range as those reported in Dwivedi *et al* (2014) even after including market effects; they are similar to Röder *et al* (2015) when the duration of storage of feedstock is short and biomass is used for drying the feedstock. Storing feedstock for a duration of three months or more can, however, significantly erode these GHG savings relative to grid-based electricity as shown by Röder *et al* (2015). This indicates the importance of designing supply chains for pellet production that limit use of fossil fuels and diminish biomass losses and decay during the pelleting process to reduce the GHG emissions intensity of this process.

Sensitivity analysis

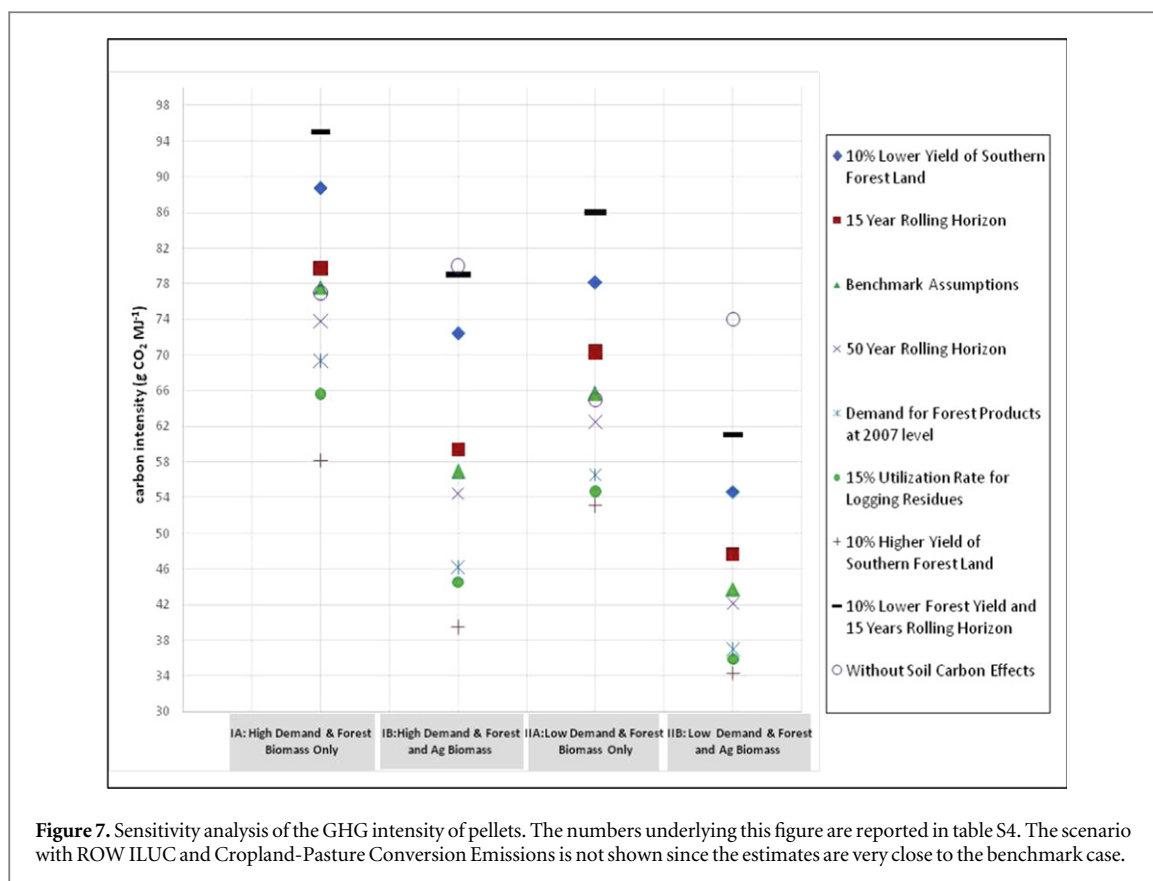
We examined the sensitivity of the GHG intensity of pellet-based electricity to alternative assumptions about some key parameters relative to the benchmark case about forest biomass yield of Southern forestland ($\pm 10\%$), length of rolling horizon (15 and 50 years), extent of use of logging residues for pellets (15%), and trend in demand for conventional forest products over time (table S4). We also examine the effects of including the ILUC in the ROW, emissions due to conversion of pastureland to crop production, and exclusion of the soil carbon benefits of energy crop production.

Our results indicate that the GHG intensity of pellets was sensitive to assumptions about parameters used in the model (figure 7); however, the effect of this on the percentage GHG savings relative to coal-based electricity is relatively small. We found that GHG intensity was most sensitive to the assumption of forest biomass yield on Southern forestland. A 10% lower yield leads to a significantly higher GHG intensity with pellets while a 10% higher yield of Southern forestlands resulted in much lower GHG intensities across the four scenarios (table S4). We also find that a shorter rolling horizon of 15 years increases the GHG intensity of pellets by about 4% in all scenarios relative

Table 1. Average direct and indirect components of the GHG intensity of pellets (2007 to 2032) ($\text{gCO}_2\text{e MJ}^{-1}$).

	IA: High Demand and Forest Bio-mass Only	IB: High Demand and Forest and Ag Biomass	IIA: Low Demand and Forest Bio-mass Only	IIB: Low Demand and Forest and Ag Biomass
GHG Emissions Due to				
Pellet Production, Transportation, Electricity Generation	58.17	55.69	58.17	57.04
Change in Carbon Stored in Forest	129.13	40.97	192.75	50.15
Change in Conventional Wood Product Production	-85.26	-16.56	-141.04	-32.91
Change in Land Use	-24.42	-0.83	-45.45	-1.57
Aboveground Emissions from Agricultural Production	-0.41	1.24	0.78	1.57
Change in Soil Carbon Accumulation	0.41	-24.83	0.78	-30.56
GHG Intensity of Pellets	77.6	55.7	66.0	43.7
GHG Intensity of Average Coal-based Electricity in UK	299.4	299.4	299.4	299.4
Savings in GHG Emissions Relative to Coal-based Electricity (%)	74%	81%	78%	85%

Note: All changes are measured relative to a Base Case in which demand for pellets was maintained at the 2007 level.



to the corresponding value in the benchmark case with a 30 year rolling horizon. The interaction of a 10% lower yield and a shorter rolling horizon of 15 years leads to the highest level of GHG intensity of pellets in all scenarios. It results in a 22%–41% higher GHG intensity of pellets relative to the benchmark case. The effect of inclusion of carbon emissions due to ROW ILUC and conversion of cropland pasture to cropland on the overall GHG intensity of pellets is small to none.

Conclusions

Growing concerns about the sustainability of using pellets produced and transported from the US to the EU have led to increased attention to accounting for both the direct and the market induced GHG emissions associated with pellet production in the US and exported to the EU. This paper examines the GHG emissions intensity of pellets exported from the US using either forestry feedstocks only or a mix of forest and agricultural feedstocks. The framework applied here incorporates not only the direct life-cycle GHG intensity of pellets but also the accompanying indirect market and land use effects induced by changes in prices of forest and agricultural products over the 2007–2032 period. Although we do not conduct a comprehensive uncertainty analysis of GHG intensity of pellets, we assess the extent to which assumptions

about key parameters could affect our estimate of the GHG intensity of pellets.

We find that in scenarios that restrict pellet production from forest biomass only the demand for pellets would divert a substantial amount of mill residues from existing uses. But it would also lead to additional harvesting of pulpwood from standing forest stock and afforested land which is used both for producing pellets as well for non-energy products previously produced using mill residues. As a result, the impact of expansion in demand on forest product prices is modest. In scenarios that consider the potential to use agricultural and forest biomass for pellets, we find that the lower cost of agricultural biomass results in it meeting a dominant share of the demand for pellets.

Across different scenarios, we find that the use of pellets produced in the US and transported to UK has significant potential to reduce the GHG intensity of electricity generated relative to coal-based electricity. The extent to which this is the case varies widely with assumptions about forest yields, length of rolling horizon of landowners, and whether forest and agricultural biomass is used or only forest biomass is used. The range of GHG savings with the use of pellets is between 74% and 85% across the various scenarios with the benchmark case assumptions. Across a wider range of parameter assumptions and assumptions about the use of forest biomass only or a mix of forest and agricultural biomass, we find that the range of GHG emissions intensity for pellets is between 69%

and 89%. These estimates are most sensitive to assumptions about the type of biomass used for pellets and about forest biomass yield and the length of rolling horizon used by landowners. GHG intensity of pellets produced using agricultural and forest biomass is 28% to 34% lower than that of pellets produced using forest biomass only. GHG effects due to induced changes in forest harvest rotations, changes in land use and soil carbon, and conventional wood production are substantial and account for 11% to 26% of the overall GHG intensity of pellets produced from forest biomass only; these effects are negative with the use of forest and agricultural biomass.

The modeling approach used here considers the US as an open economy that trades with the rest of the world. However, we model land use change explicitly only in the US. As a result, the ILUCs in the ROW are not endogenously determined within the model. Incorporating estimates of this from other studies, however, shows that it has a small to zero impact on the GHG savings that can be achieved by pellets.

In this study, we have not accounted for the climatic effects of emissions of low-volatility secondary organic aerosols (Ehn et al 2014). We have also not considered climatic effects of short-lived climate forcers like black carbon and primary organic carbon (Cai and Wang 2014). There are also several approaches to account for the potential climate impacts of carbon storage in soils, vegetation and long-lived products, release of biogenic carbon and avoided carbon emissions (Cherubini et al 2011, Brandão et al 2013, Helin et al 2013). We have also not considered GHG emissions due to dry matter losses during storage of pellets and consequent methane generation and the use of diesel for drying biomass as in Röder et al (2015). However, our study demonstrates that low GHG-intensive supply-chain management practices for pellet production are possible, by avoiding extended storage of biomass. It provides a framework for determining the effects of market-driven direct and ILUCs on GHG intensity of pellets in the US. We leave the analysis of the climate impact of these changes in GHG emissions for future research.

References

- Abt K L, Abt R C and Galik C 2012 Effect of bioenergy demands and supply response on markets, carbon, and land use *Forest Sci.* **58** 523–39
- Abt K L, Abt R C, Galik C S and Skog K 2014 Effects of policies on pellet production and forests in the US South *A Technical Document Supporting the Forest Service Update of the 2010 RPA Assessment. SRS-202* USDA, Southern Research Station, Asheville, NC p 33
- Adams D M, Alig R J, Callaway J M, McCarl B A and Winnett S M 1996 *The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications* USDA, Pacific Northwest Research Station, Portland, OR p 68
- Adams D M, Alig R J, McCarl B A and Murray B C 2005 FASOMGHG Conceptual Structure and Specification: Documentation (http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf)
- Argusmedia 2014 Argus biomass markets, London, UK, available at (<http://media.argusmedia.com/~media/Files/PDFs/Samples/Argus-Biomass.pdf>)
- Beach R H, Adams D A, Alig R, Baker J, Latta G S, McCarl B A, Murray B C, Rose S K and White E 2010 *Model Documentation for the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG)* p 188 (http://cof.orst.edu/cof/fr/research/tamm/FASOMGHG_Model_Documentation_Aug2010.pdf)
- Beach R H and McCarl B A 2010 *US Agricultural and Forestry Impacts of the Energy Independence and Security Act: Fasom Results and Model Description* Final report prepared for US Environmental Protection Agency, Washington DC
- Brandão M, Levasseur A, Kirschbaum M U F, Weidema B P, Cowie A L, Jergensen S V, Hauschild M Z, Pennington D W and Chomkhamri K 2013 Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting *Int. J. Life Cycle Assess.* **18** 230–40
- Cai H and Wang M Q 2014 Consideration of black carbon and primary organic carbon emissions in life-cycle analysis of greenhouse gas emissions of vehicle systems and fuels *Environ. Sci. Technol.* **48** 12445–53
- Chen X, Huang H, Khanna M and Önal H 2014 Alternative transportation fuel standard: welfare effects and climate benefits *J. Environ. Econ. Manage.* **67** 241–57
- Chen X and Önal H 2012 Modeling agricultural supply response using mathematical programming and crop mixes *Am. J. Agric. Econ.* **94** 674–86
- Cherubini F, Peters G P, Berntsen T, Strømman A H and Hertwich E 2011 CO₂ emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming *Glob. Change Biol. Bioenergy* **3** 413–26
- Damen K and Faaij A 2006 A greenhouse gas balance of two existing international biomass import chains *Mitigation Adaptation Strateg. Glob. Change* **11** 1023–50
- Dwivedi P, Bailis R, Bush T G and Marinescu M 2011 Quantifying GWI of wood pellet production in the southern united states and its subsequent utilization for electricity production in the Netherlands/Florida *Bioenergy Res.* **4** 180–92
- Dwivedi P, Khanna M, Bailis R and Ghilardi A 2014 Potential greenhouse gas benefits of transatlantic wood pellet trade *Environ. Res. Lett.* **9** 023007
- Dwivedi P, Wang W, Hudiburg T, Jaiswal D, Parton W, Long S, DeLucia E and Khanna M 2015 Cost of abating greenhouse gas emissions with cellulosic ethanol *Environ. Sci. Technol.* **49** 2512–22
- Ehn M et al 2014 A large source of low-volatility secondary organic aerosol *Nature* **506** 476–9
- Energy Information Administration (EIA) 2013 *Annual Energy Outlook* US Energy Information Administration, Office of Integrated Analysis and Forecasting, US Department of Energy, Washington, DC
- Energy Information Administration (EIA) 2014 (<http://eia.gov/todayinenergy/detail.cfm?id=16391>)
- Energy Information Administration (EIA) 2015 (<http://eia.gov/todayinenergy/detail.cfm?id=20912>)
- Forisk Consulting 2014 Wood Bioenergy US (Spreadsheet data) *Wood Bioenergy US* vol 6 Jan/Feb 2014, available at (<http://forisk.com/products/category/bioenergy-2/>) (accessed 7 November 2014)
- Fournel S, Palacios J H, Morissette R, Villeneuve J, Godbout S, Heitz M and Savoie P 2015 Influence of biomass properties on technical and environmental performance of a multi-fuel boiler during on-farm combustion of energy crops *Appl. Energy* **141** 247–59
- Forest Resources Association (FRA) 2005 *Annual Pulpwood Statistics Summary Report 2001–2005* Rockville, Maryland
- Galik C S and Abt R C 2015 Sustainability guidelines and forest market response: an assessment of european union pellet

- demand in the southeastern United States *Glob. Change Biol. Bioenergy* (doi:10.1111/gcbb.12273)
- Galik C S, Abt R C, Latta G and Vegh T 2015 The environmental and economic effects of regional bioenergy policy in the southeastern US *Energy Policy* **85** 335–46
- Goetzl A 2015 *Developments in the Global Ttrade of Wood Pellets Office of Industries Working paper* US International Trade Commission, Washington, DC
- Helin T, Sokka L, Soimakallio S, Pingoud K and Pajula T 2013 Approaches for inclusion of forest carbon cycle in life cycle assessment—a review *Glob. Change Biol. Bioenergy* **5** 475–86
- Hertel T W, Golub A A, Jones A D, O’Hare M, Plevin R J and Kammen D M 2010 Effects of US maize ethanol on global land use and greenhouse gas emissions: estimating market-mediated responses *Bioscience* **60** 223–31
- Huang H, Khanna M, Önal H and Chen X 2013 Stacking low carbon policies on the renewable fuel standard economic and greenhouse gas implications *Energy Policy* **56** 5–15
- Hubbard W, Biles L, Mayfield C and Ashton S (ed) 2007 *Sustainable Forestry for Bioenergy and Bio-based Products: Trainers Curriculum Notebook* (Athens, GA: Southern Forest Research Partnership, Inc.)
- Hudiburg T W, Wang W, Khanna M, Long S P, Dwivedi P, Parton W J, Hartmann M and DeLucia E H 2016 Impacts of a 32 Billion Gallon Bioenergy Landscape on Land and Fossil Fuel use in the US *Nat. Energy* accepted
- Ince P J, Kramp A D, Skog K E, Yoo D I and Sample V A 2011 Modeling future US forest sector and trade impacts of expansion in wood energy consumption *J. Forest Econ.* **17** 142–56
- Latta G S, Baker J S, Beach R H, Rose S K and McCarl B A 2013 A multiple-sector intertemporal optimization approach to assess the GHG Implications of US forest and agricultural biomass electricity expansion *J. Forest Econ.* **19** 361–83
- Lin T, Rodriguez L F, Davis S, Khanna M, Shastri Y, Griff T, Long S and Ting K C 2015 Biomass feedstock preprocessing and long-distance transportation logistics *Glob. Change Biol. Bioenergy* (doi:10.1111/gcbb.12241)
- Magelli F, Boucher K, Bi H T, Melin S and Bonoli A 2009 An environmental impact assessment of exported wood pellets from Canada to Europe *Biomass Bioenergy* **33** 434–41
- McKechnie J, Colombo S and MacLean H L 2014 Forest carbon accounting methods and the consequences of forest bioenergy for national greenhouse gas emissions inventories *Environ. Sci. Policy* **44** 164–73
- Natural Resources Defense Council 2011 Forests not Fuel: Burning Trees for Energy Increases Carbon Pollution and Destroys our Forests, Forest Facts (<http://nrdc.org/energy/forestsnotfuel/files/forests-not-fuel.pdf>)
- Natural Resources Defense Council 2014 *Burning Trees for Electricity Will Accelerate Climate Change and Destroy Southern Forests* Fact sheet: 13-04-A (<http://nrdc.org/energy/forestsnotfuel/files/burning-trees-southern-forests-FS.pdf>)
- New York Times 2015 http://nytimes.com/2015/02/11/business/economy/a-biofuel-debate-will-cutting-trees-cut-carbon.html?_r=0
- Önal H and McCarl B A 1991 Exact aggregation in mathematical programming sector models *Can. J. Agric. Econ.* **39** 319–34
- Rabobank Report 2013 <http://rabobank-food-agribusiness-research.pr.co/67056-rabobank-report-agricultural-residue-provides-the-answer-to-eu-s-bioenergy-needs>
- RISI Inc 2013 North American Bioenergy Forecast, June 2013 (<http://risiinfo.com/risi-store/do/product/detail/north-american-bioenergy-forecast-5-year.html>)
- Röder M, Whittaker C and Thornley P 2015 How certain are greenhouse gas reductions from bioenergy? life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues *Biomass Bioenergy* **79** 50–63
- Sedjo R A and Sohngen B 2013 Wood as a major feedstock for biofuel production in the United States: impacts on forests and international trade *J. Sustainable Forestry* **32** 195–211
- Skog K and Nicholson G 2000 Carbon Sequestration in wood and paper products *The Impact of Climate Change on American Forests General Technical Report RMRS-GTR-59* ed L Joyce and R Birdsey USDA Forest Service ch 5, pp 79–88
- Smith J E, Heath L S, Skog K E and Birdsey R A 2006 Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States *General Technical Report NE-343* USDA Forest Service, Northeastern Research Station, Newtown Square, PA p 216
- Spelter H and Toth D 2009 North America’s wood pellet sector *Research Paper FPL-RP-656* US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI p 21
- Stephenson A L and Mackay D J C 2014 *Life Cycle Impacts of Biomass Electricity in 2020* Department of Energy and Climate Change. The National Archives, Kew, London
- Taheripour F and Tyner W E 2013 Induced land use emissions due to first and second generation biofuels and uncertainty in land use emission factors *Econ. Res. Int.* **2013** 315787
- Walker T, Cardellichio P, Colies A, Gunn J, Kittler B, Recchia C and Saah D 2010 *Biomass Sustainability and Carbon Policy Study*, Manomet Center for Conservation Science, Massachusetts
- Washington Post 2015 http://washingtonpost.com/national/health-science/how-europes-climate-policies-have-led-to-more-trees-cut-down-in-the-us/2015/06/01/ab1a2d9e-060e-11e5-bc72-f3e16bf50bb6_story.html
- Wilson T O, McNeal F M, Spatari S, Abler D G and Adler P R 2012 Densified biomass can cost-effectively mitigate greenhouse gas emissions and address energy security in thermal applications *Environ. Sci. Technol.* **46** 1270–7
- White E M, Latta G, Alig R J, Skog K E and Adams D M 2013 Biomass production from the US forest and agriculture sectors in support of a renewable electricity standard *Energy Policy* **58** 64–74