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Sustainability guidelines and forest market response: an assessment of European Union pellet demand in the southeastern United States

CHRISTOPHER S. GALIK[1] and ROBERT C. ABT[2]

[1]*Nicholas Institute for Environmental Policy Solutions, Duke University, Box 90335, Durham, NC 27708, USA,* [2]*Department of Forestry and Environmental Resources, North Carolina State University, Campus Box 8008, Raleigh, NC 27695, USA*

Abstract

Woody biomass from the southeast United States is expected to play an important role in meeting European Union renewable energy targets. In crafting policies to guide bioenergy development and in guiding investment decisions to meet established policy goals, a firm understanding of the interaction between policy targets and forest biomass markets is necessary, as is the effect that this interaction will have on environmental and economic objectives. This analysis increases our understanding of these interactions by modeling the response of southern US forest markets to new pellet demand in the presence of sustainability sourcing or harvest criteria. We first assess the influence of EU recommended sustainability guidelines on the forest inventory available to supply EU markets, and then model changes in forest composition and extent in response to expected increases in pellet demand. Next, we assess how sustainability guidelines can influence the evolution of forest markets in the region, paying particular attention to changes in land use and forest carbon. Regardless of whether sustainability guidelines are applied, we find increased removals, an increase in forest area, and little change in forest inventory. We also find annual gains in forest carbon in most years of the analysis. The incremental effect of sustainability guideline application on forest carbon and pellet greenhouse gas (GHG) balance is difficult to discern, but results suggest that guidelines could be steering production away from sensitive forest types inherently less responsive to changing market conditions. Pellet GHG balance shows significant annual change and is attributable to the complexity of the underlying forest landscape. The manner by which GHG balance is tracked is thus a critical policy decision, reinforcing the importance and relevance of current efforts to develop approaches to accurately account for the GHG implications of biomass use both in the United States and European Union.

Keywords: biomass, forest carbon, pellet, renewable energy directive, subregional timber supply model, sustainability guidelines

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Introduction

Woody biomass from the southeast United States is expected to play an important role in meeting European Union renewable energy targets over the course of the next decade (Joudrey *et al*., 2012; Goh *et al*., 2013a). In crafting policies to guide bioenergy development and in guiding investment decisions to meet established policy goals, a firm understanding of the interaction between policy targets and forest biomass markets is necessary, as is the effect that this interaction will have on environmental and economic outcomes of concern. Absent this understanding, it is possible that policies will either hinder the development of a sustainable bioenergy market or complicate the attainment of environmental (e.g., greenhouse gas mitigation) or economic (e.g., maintenance of traditional forest product markets) objectives.

Correspondence: Christopher S. Galik, tel. +1 919 681 7193, fax +1 919 613 8712, e-mail: christopher.galik@duke.edu

There are multiple factors influencing the volume of woody biomass material exported from the southeastern United States to the European Union, such as domestic production of wood products, the prevailing price of wood pellets, and policies in place both within the United States and the European Union (National Renewable Energy Laboratory, 2013; Abt *et al*., 2014). Here, we focus specifically on the role of EU policy. At present, there are multiple interrelated policy initiatives influencing biomass demand. One component of what are collectively referred to as the 20/20/20 by 2020 targets requires each EU Member State to contribute a set share of renewable energy so as to collectively meet a 20% EU-wide target (European Commission, 2009). A second component is an EU-wide 20% GHG reduction target, itself comprised of several directives and decisions (Directive 2009/28/EC, Decision 406/2009/EC, and

Decision 2013/162/EU). The third component of the 20/20/20 policy is outlined by Directive 2012/27/EU and requires an EU-wide 20% improvement in efficiency.

Although policy continues to evolve (European Commission, 2014), these policy initiatives and others operating within individual EU Member States [e.g., the Renewables Obligation in the United Kingdom, SDE+ (*Stimulering Duurzame Energieproductie*) program in the Netherlands] are likely to drive demand for renewable energy, generally, and southeastern US pellets, specifically. Previous analysis suggests that a doubling of biomass electricity production is possible by 2020 (Beurskens *et al*., 2011) and that increased biomass production within the EU itself is likely insufficient to meet projected demands (Hewitt, 2011). Against this potential shortfall, the United States is expected to supply a significant volume of pellets to the European Union (e.g., Goh *et al*., 2013a). As of 2013, trade data already suggested that wood pellets from the United States comprised nearly half (45%) of imports into the European Union, with approximately three-quarters of total US pellet production capacity falling within the southern region (Goetzl, 2015).

Other policy holds the potential to limit the supply of southeastern US biomass to European renewable energy markets, specifically criteria or requirements that govern the source and conditions under which woody biomass may be harvested and/or imported (Hewitt, 2011; Schueler *et al*., 2013; Lamers *et al*., 2014). These criteria or requirements are broadly referred to here as sustainability guidelines. Of particular relevance are proposed guidelines released by the European Commission in 2010 (European Commission, 2010). Although they themselves do not prescribe minimum performance requirements for woody biomass, these guidelines are intended to provide a basis for development of sustainability policies by individual Member States. In substance, the guidelines mirror previous requirements developed for biomass for liquid biofuel production and emphasize elements relating to GHG emissions, land use and land-use change, and chain of custody verification (European Commission, 2009, 2010). In practice, the guidelines add to an already complex policy landscape, one already characterized by the presence of multiple other requirements or draft standards (see, e.g., Vis *et al*., 2008; van Dam *et al*., 2010; Ladanai & Vinterbäck, 2010; Scarlat & Dallemand, 2011; Kittler *et al*., 2012; Fritsche *et al*., 2014; Lamers *et al*., 2014).

These evolving policies have prompted a wide array of supply assessments and other forest market analyses in recent years. Multiple woody biomass supply assessments have been generated for the southeastern United States and individual states within it (Galik *et al*., 2009; Gronowska *et al*., 2009; Abt *et al*., 2010b, 2014; La Capra Associates, 2011; Colnes *et al*., 2012). Research has also explored the role of global bioenergy policies in driving demand for biomass (Junginger *et al*., 2009; Sikkema *et al*., 2011; Joudrey *et al*., 2012; Lamers *et al*., 2012; Goh *et al*., 2013a). Of particular relevance to emerging bioenergy policy deliberations are those studies spanning the two literatures, those that provide an indication of potential supply under policy restrictions. Within this category of research, works by Frank *et al.* (2013), Schueler *et al.* (2013), Lamers *et al.* (2014), and Sikkema *et al.* (2014) are especially informative, speaking to the influence of policy in shaping the international market for bioenergy and bioenergy feedstock.

This study builds upon these recent contributions and assesses the interaction between EU bioenergy policy and southeastern US woody biomass supply. By assessing possible compliance of discrete forested areas in the southeast United States against EU sustainability criteria, the analysis represents a more tailored approach to the work conducted in Schueler *et al.* (2013) and Lamers *et al.* (2014), in which they model the implications of various sustainability criteria on the global trade of biomass. It also mirrors the approach of Frank *et al.* (2013), in which EU Renewable Energy Directive 2009/28/EC (RED) sustainability criteria are applied to global liquid biofuel production. In another respect, the analysis broadens the forest carbon assessment conducted by Jonker *et al.* (2014) to include an evaluation of the market feedbacks triggered by an increase in biomass demand. The end result is an integrated economic assessment of southeastern US wood pellet supply in the presence of sustainability and GHG reduction criteria, indirect market effects, and spatially explicit land-use change.

Materials and methods

In the section that follows, we first describe the subregional timber supply (SRTS) model. Next, we outline the approach by which expected pellet demand is estimated. We follow with a description of two interrelated components of the recommended sustainability guidelines and how these are incorporated into the analysis. The first component is a minimum GHG reduction for feedstocks used to meet renewable energy targets. The second component is a suite of broader sustainability requirements that speak more to where and how that material is sourced. We follow with a description of how these guidelines may be applied in the southeastern United States. We then examine the influence of sustainability guideline sourcing restrictions on forests and forest markets in the presence of expected increases in pellet demand. Finally, we outline a comparative analysis to examine the influence of sourcing restrictions on resulting GHG balance.

Overview and application of the subregional timber supply (SRTS) model

The subregional timber supply (SRTS) model is a timber market projection system. It solves for a recursive product market equilibrium using market parameters derived from econometric studies, forest dynamics based on USDA Forest Service data, and exogenous demand forecasts. It utilizes field inventory and timber product output data from the US Forest Inventory and Analysis (FIA) program to characterize resource conditions and harvest activity. For each year, SRTS models equilibrium harvest and stumpage price by product category (softwood/hardwood, pulpwood/sawtimber) and owner type (corporate/noncorporate) in response to demand shifts, adjusting forest inventories to account for equilibrium-derived removals and empirically estimated growth. It has, in recent years, been used to evaluate the contributions of forest biomass to regional renewable energy policy targets (Abt *et al.*, 2010a,b), the possible influence of biomass harvest restrictions on domestic energy policy compliance (La Capra Associates, 2011), the influence of different accounting methods on bioenergy GHG balance (Galik & Abt, 2012), the influence of improved productivity on forest carbon storage (Abt *et al.*, 2012), and the possible effects of EU pellet demand in the southeastern United States (Abt *et al.*, 2014). A more detailed overview of the model itself can be found in Abt *et al.* (2009) and Prestemon & Abt (2002).

This analysis compares multiple SRTS runs to gain insight into two separate but related phenomena: (i) the influence of the projected level of pellet demand on US southeastern forest markets, with an emphasis on the resulting changes in forest extent and composition, and (ii) the incremental influence of EU sustainability guidelines on forest markets, again with an emphasis on forest extent and composition. In practice, this yields four separate model runs that can be compared to generate insight into the question of interest: a baseline run (no pellet demand), a restricted sourcing baseline run (no pellet demand, areas screened for sustainability guideline compliance), a pellet scenario run (new pellet demand in the absence of sustainability guidelines), and a restricted sourcing pellet run (new pellet demand and areas screened for sustainability guideline compliance). Comparison of pellet and baseline scenarios provides insight into the influence of the projected level of pellet demand on forest markets in the southeastern US. Comparison of the restricted and unrestricted pellet sourcing scenarios meanwhile helps to discern the potential influence of EU sustainability guidelines on forest market response.

Estimation of expected pellet demand

Estimation of expected pellet demand, including imports from the United States, can be achieved through multiple avenues. One approach is to look to individual EU Member State National Renewable Energy Action Plans (NREAP), which outline the expected use of renewable energy over the coming years, including specific estimates of total biomass demand. Also generally included in NREAPs are projections of domestic biomass supply and expected biomass imports. Although conceivably a valuable resource for determining total EU and Member State demand for imported biomass (e.g., Frank *et al.*, 2013), it is difficult to use the plans for the express purpose of determining the magnitude of non-EU imports (Atanasiu, 2010; Beurskens *et al.*, 2011). Analysis by Joudrey *et al.* (2012) makes this readily apparent, exposing large gulfs between individual Member State domestic supplies, Member State expected imports, and total projected renewable generation.

In light of these challenges, we instead generate our estimate of pellet demand in the southeastern US based on announced pellet production capacity data from Forisk Consulting LLC. Forisk tracks current, in process, and announced pellet production volumes and provides an indication of changes in pellet production expected to occur in the near future. To assess the likelihood that announced production will actually result in built capacity, Forisk applies screens to the announced data based on permitting, site acquisition, and technology filters. Even with these feasibility screens, it is difficult to know which of these facilities will actually be built. To account for this uncertainty, we simply take the average of the total from facilities that meet Forisk's screen and the total from all announced facilities as of December 2014, yielding an annual demand of 12.2 million green tonnes (13.4 million green short tons) of consumption for pellets, or approximately 5.9 million tonnes of new pellet demand. We assume that demand increases logarithmically from zero to 12.2 million tonnes over a period of 15 years and then remains constant for the balance of our 30-year projection period. This time period extends well beyond the aforementioned 2020 policy target, but provides an indication of how forest markets respond to the imposition of new demand in both short- and mid-term time horizons. Both projection timing and magnitude of additional demand are well within the range of previous analyses making use of the SRTS modeling platform (Abt *et al.*, 2012; Galik & Abt, 2012).

Table 1 Relevant proposed sustainability guidelines for the use of solid and gaseous biomass sources in electricity, heating, and cooling. Source: European Commission (2009, 2010)

Objective	Proposed target or requirement
Greenhouse gas reductions	Requires minimum initial GHG reductions of 35%, increasing to 50% by 2017 and 60% by 2018
Land-use protection	Prohibits harvested material from high biodiversity value areas, high carbon stock areas, and undrained peat land
Sourcing verification	Requires chain of custody verification using a mass balance approach

Applying sustainability guidelines to southeastern US forests

Elements of the proposed guidelines most relevant for biomass production in the southeastern United States for use in the European Union are described in Table 1. As with estimation of pellet demand itself, there are several means by which sustainability guidelines may be operationalized so as to provide an indication of the expected direction and magnitude of guideline influence on the development of domestic pellet markets. In practice, this has the potential to yield a variety of outcomes depending on how the guidelines are applied (Thiffault

Table 2 Data used to evaluate the influence of sourcing restrictions on woody biomass supply dynamics. Source and description are indicated for each

State	Data layer/source	Description	Relevant sustainability criteria
AL	Alabama Gap Analysis Project (AL-GAP), 'private land – no known restrictions' removed*	Conservation lands, both public and voluntarily-provided private.	Exclusion of lands with high biodiversity value; Exclusion of lands designated for nature purposes
AR	AR-GAP Land cover and Stewardship GIS data, Gap Status 1–3 only†	Areas managed for conservation purposes by federal, state, or private entities.	
FL	Florida Conservation Lands 2013‡	Local, State, Federal, and Private lands managed for conservation.	
GA	Stewardship Lands, Gap Status 1–3 only§	Areas currently managed by state, local, and private entities for conservation purposes.	
LA	National Conservation Easement Database, All recorded easements¶	All recorded easements, regardless of GAP status, holder, or landowner type	
	National Wildlife Refuges and other Federal Lands‖	National Wildlife Refuges	
MS	Stewardship Lands, Gap Status 1–3 only§	Areas managed for conservation purposes by federal, state, or private entities.	
NC	Stewardship Lands, Gap Status 1–3 only§	Areas managed for conservation purposes by federal, state, or private entities.	
SC	Stewardship Lands, Gap Status 0 removed (no protection information provided)§	Areas managed for conservation purposes by federal, state, or private entities.	
TN	Stewardship Lands, Gap Status 5 removed (no legal protections)§	Areas managed for conservation purposes by federal, state, or private entities.	
VA	Conservation Lands**	Lands in public and private protective management (excluding private conservation easements)	
ALL	Conterminous United States Land Cover, 200-Meter Resolution††	1992 Raster providing land cover characteristics for conterminous United States.	N/A
	Water bodies and Wetlands of the United States‡‡	1 : 1 000 000-Scale water bodies and wetlands of the United States, clipped to region	Exclusion of wetlands and peat lands
	National Parks§§	Boundaries of National Parks, clipped to region	Exclusion of lands designated for nature purposes

*http://www.auburn.edu/academic/forestry_wildlife/alabama_gap_analysis_project/index.php?id=stewardship_data (last accessed 29 January 2015).
†http://cast.uark.edu/gap/arcdata.html (last accessed 29 January 2015).
‡http://www.fnai.org/gisdata.cfm (last accessed 10 December 2013).
§ftp://ftp.gap.uidaho.edu/products/ (last accessed 29 January 2015).
¶http://nced.conservationregistry.org/reports/easements?report_state=Louisiana&report_type=All (last accessed10 December 2013).
‖refuges: http://www.atlas.lsu.edu/search/ (last accessed 29 January 2015).
**http://www.dcr.virginia.gov/natural_heritage/cldownload.shtml (last accessed 10 December 2013).
††http://nationalmap.gov/small_scale/mld/lancovi.html (last accessed 29 January 2015).
‡‡http://nationalmap.gov/small_scale/mld/1lakesp.html (last accessed 10 December 2013).
§§http://www.nps.gov/gis/data_info/ (last accessed 10 December 2013).

et al., 2015). One conceptual approach for applying the guidelines to a given landscape is to assume a narrow window of compliance and assume that only those lands certified to an existing forest certification program are eligible to supply EU pellet markets. An alternative approach is to assume a broader window and assume that only those areas that specifically fail to meet the conditions outlined in the recommended guidelines are ineligible to supply EU markets.

Forest certification standards – such as Sustainable Forestry Initiative (SFI), Forest Stewardship Council (FSC), and American Tree Farm System (ATFS) – and metastandards – Program for the Endorsement of Forest Certification (PEFC) – generally do not contain provisions directly pertaining to EU GHG reduction requirements. They do, however, contain several provisions with the potential to address a variety of other sustainability requirements, particularly those pertaining to management and land-use change (e.g., Kittler *et al.*, 2012; UK Department of Energy and Climate Change, 2014). Attempts to use certified acres in the southeastern US to estimate the minimum land base from which biomass may be supplied proved unsuccessful, however. Searches of individual program websites for up-to-date and comprehensive data on total area certified and certified tract location yielded only FSC state-level totals (Forest Stewardship Council, 2013). Data requests sent directly to FSC, SFI, and ATFS programs (all messages sent December 3, 2013) were likewise unsuccessful in yielding more comprehensive data, as was a review of alternative third-party summaries (e.g., Forest2Market, 2011).

In the absence of spatially explicit data on certified forest areas, we instead establish a maximum area from which biomass may be supplied by screening for areas specifically prohibited by EU sustainability criteria: protected areas; areas of high biodiversity and conservation value; and undrained peat lands or wetlands. This exercise is similar to the approach conducted in La Capra Associates (2011) and Galik & Abt (2011). Here, the analysis begins with an assembly of natural resource and land management data (Table 2). We utilize National Atlas water body and wetland data to simulate the effect of barring material harvested from wetlands. We likewise utilize state-level stewardship data, generally obtained from the USGS Gap Analysis Program (GAP), to simulate the effect of barring harvests from lands with either high biodiversity lands or those that are specifically set aside for conservation purposes. When an appropriate GAP dataset could not be located for a given state, we made use of state-level data on easements and protected areas to yield a similar outcome. Areas identified through this exercise can be seen in Fig. 1.

The resulting geospatial dataset is then overlaid with land cover data in ArcGIS 10.2.2. (Esri, Redlands, CA, USA), using the Tabulate Area tool to estimate the percent area of different forest types potentially restricted from harvest. The forest types reflect primary land-use cover types as defined by the US Geologic Survey and represented in the 1992 land-use cover dataset (US Geologic Survey, 2015). These four classification types – (41) deciduous, (42) evergreen, (43) mixed, and (91) woody wetland – correspond to four of the five primary management types used in the SRTS model (upland hardwood, natural pine, mixed pine, and lowland hardwood, respectively). A fifth SRTS management type – planted pine – was assumed to be unaffected by the sustainability guidelines.

Values of potential harvest restriction were found to vary by both forest type and county, ranging between zero and well over 40% of presently harvestable forest area, but with a majority of county–forest type combinations falling in the 0–5% range (Figs S1–S4). These county-level harvest restrictions were

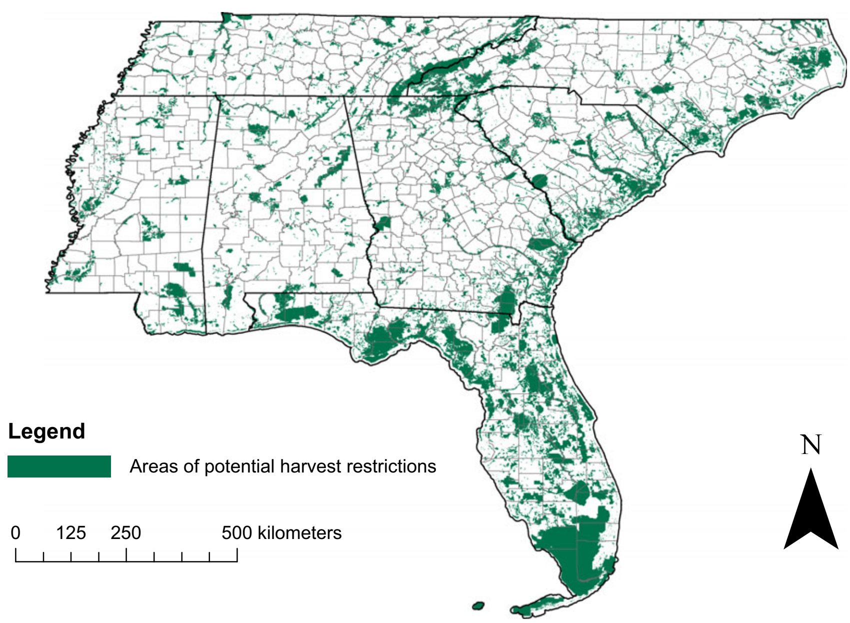

Fig. 1 Map of potential areas of harvest restrictions based upon an interpretation of proposed European Union sustainability guidelines. Shown are protected areas, areas identified as having special conservation significance, private lands covered by conservation easements, or areas classified as wetlands or other water bodies.

then used to adjust the inventory input files upon which SRTS model runs were made. In this way, the inventory adjustments are derived directly from adjustments in forest area. It is possible that the areas identified in this screening process are fundamentally different that areas not identified, possessing either a higher or lower per area volume. The exercise is likewise limited to an identification of so-called no go areas and does not directly consider the influence of harvest or management restrictions on remaining lands (see, e.g., Fritsche *et al.*, 2014). For this analysis, however, this screening process provides a sufficient approximation of the effects of applying sustainability guidelines at the regional, landscape level.

Calculation of GHG balance

Once model output was generated under baseline and pellet demand scenarios, price, inventory, removals, land-use change, and carbon data were compared to assess potential drivers of observed outcomes. Output was also assessed for compliance against GHG reduction targets. To estimate approximate annual GHG emission (*AE*) per tonne of pellets in year *t*, the following equation was used:

$$AE_t = \frac{((D_t * (2.032 * 0.25) + F_t) * 3.667) + (D_t * P)}{D_t} \quad (1)$$

where D_t is the pellet demand in tonnes in year *t*, and F_t is the observed change in forest carbon in year *t*. Conversion factors of 2.032 and 0.25 are used to convert pellet demand into units of green tonnes of biomass input and fraction carbon, respectively. A conversion factor of 3.667 is used to convert units of carbon into units of carbon dioxide equivalent (CO_2e). *P* is equal to a per pellet process and transportation emissions factor, estimated by Dwivedi *et al.* (2014) to be 34.4 g CO_2e per kg pellet burned. To convert from an annual GHG balance to cumulative GHG balance, we modify Eqn (1), in which the cumulative emissions (*CE*) per tonne of pellets in year *t* is now equal to as follows:

$$CE_t = \frac{\left(\left(\sum_t^1 D * (2.032 * 0.25) + \sum_t^1 F\right) * 3.667\right) + \left(\sum_t^1 D * P\right)}{\sum_t^1 D} \quad (2)$$

AE_t and CE_t are then compared to emissions associated with coal generation to estimate percent reduction in year *t* per the following equations:

$$\text{Annual Percent Reduction} = \frac{C - AE_t}{C} \quad (3)$$

$$\text{Cumulative Percent Reduction} = \frac{C - CE_t}{C} \quad (4)$$

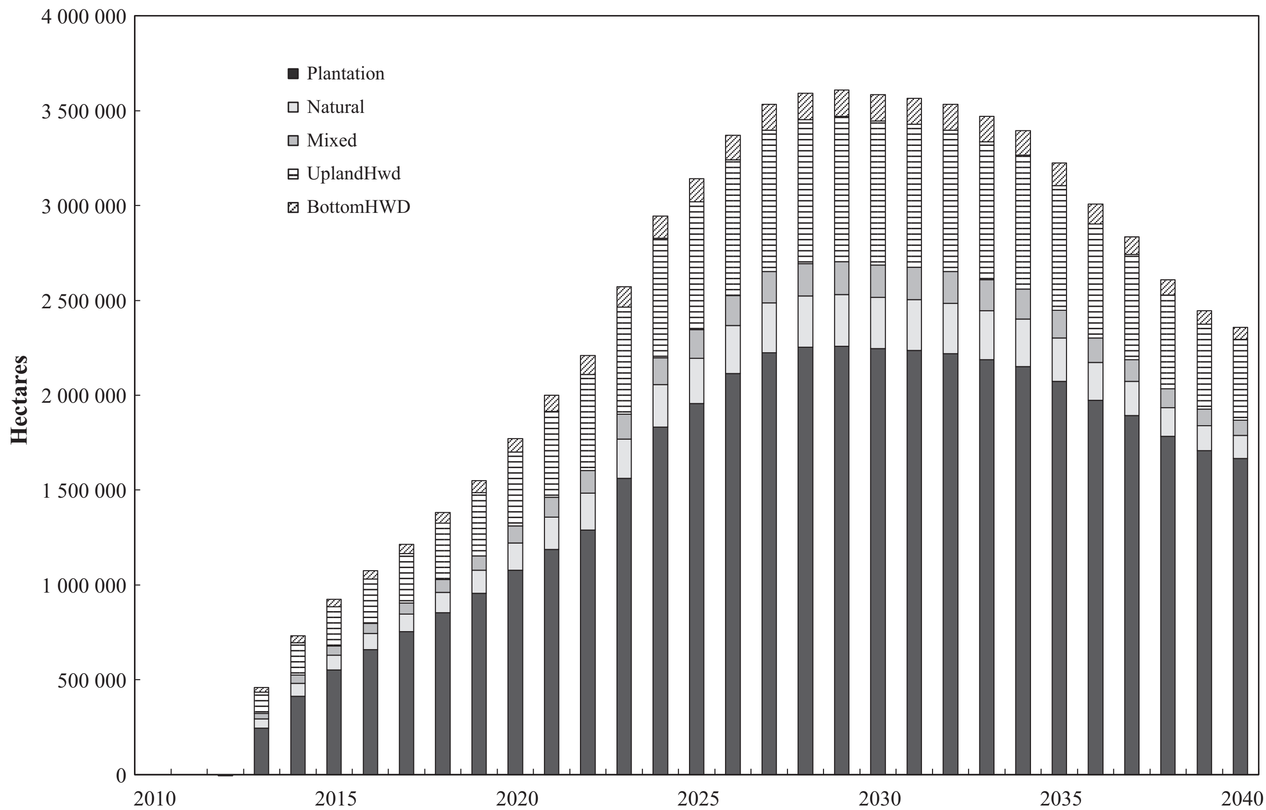

Fig. 2 Land-use change associated with imposing an expected pellet consumption of 12.2 million tonnes in the presence of sustainability guideline sourcing restrictions.

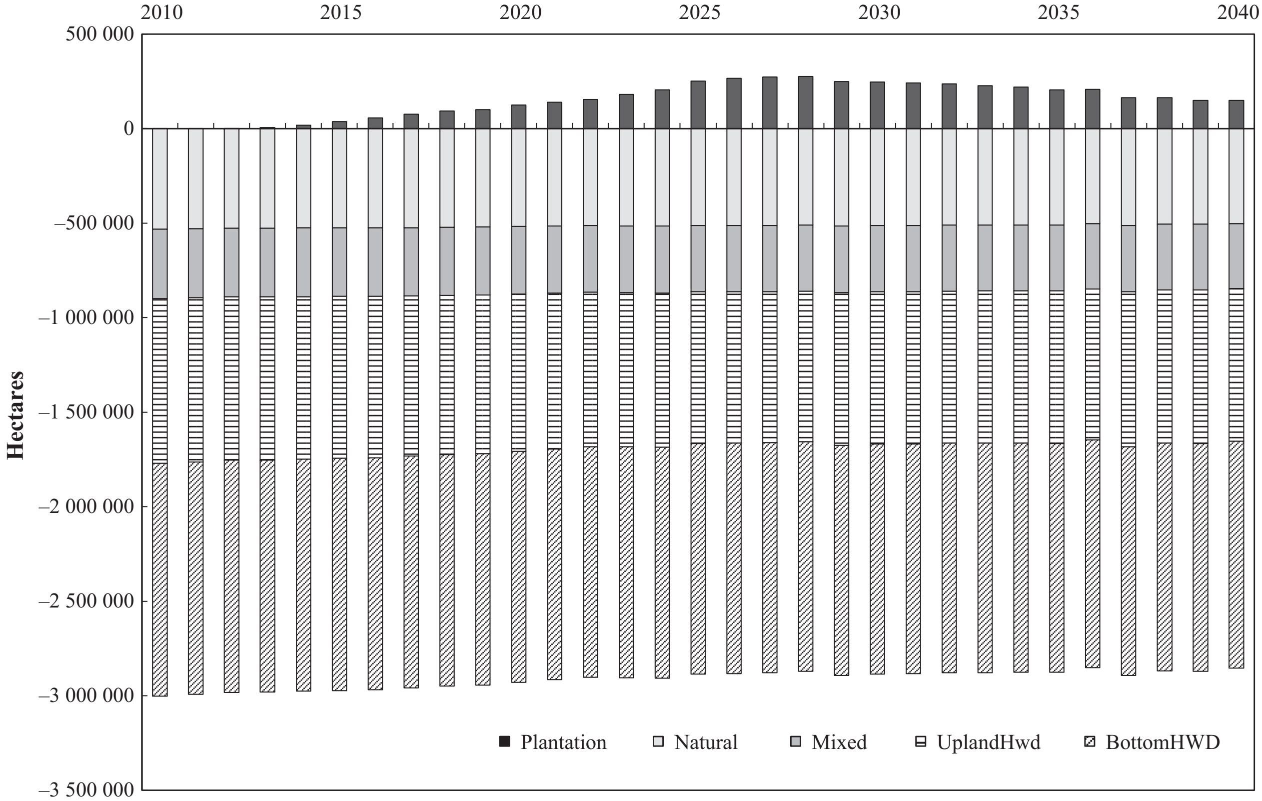

Fig. 3 Relative land-use change in the restricted sourcing scenario as compared to the unrestricted scenario. Both scenarios assume an expected pellet consumption of 12.2 million tonnes.

where *C* is the emission rate of coal per the energy equivalent of 1 tonne of wood pellet, assumed here to be constant for all years in the projection period. We assume wood pellets to have an energy content of 18 MJ per tonne (Goh *et al.*, 2013b) and coal to have an emissions rate of 252.8 g CO_2e per MJ. Coal emissions' intensities are derived from 2012 Fuel Mix Disclosure (FMD) regulations as reported in UK Department of Energy and Climate Change (2011) and converted to units of g CO_2e/MJ using a conversion factor of 1 kWh equals 0.0036 GJ as reported for 2013 by UK Department for Environment Food & Rural Affairs (2015).

Results

Estimated pellet demand is found to have a small relative impact on regional forest product prices, removals, and inventories. Removals and price show upward pressure in all forest product categories across both restricted and unrestricted sourcing scenarios (Figs S5–14). Price of pine pulpwood increases approximately 50% over the baseline in both sourcing scenarios. Pulpwood provides the majority of feedstock to meet the 12.2 million tonnes of estimated pellet consumption and thus bears the brunt of expected harvest change. Even so, projected levels of price change for this feedstock fall within levels of historic variation. Indices of change are substantially lower in all other metrics and forest product categories.

The small relative changes in price, inventory, and removals do, however, translate into substantial land-use and carbon effects at the regional level. Comparing restricted baseline and pellet scenarios indicates the relative change attributable to additional pellet demand under sustainability sourcing restrictions (Fig. 2). We show a substantial increase in the area of all forest types in the presence of increased pellet demand, with the change dominated by an increase in planted pine. In comparing the land-use change projected in the sourcing restriction scenario with that in the unrestricted scenario (Fig. 3), two findings quickly become apparent. The first is the reduced area of natural pine, mixed pine, bottomland hardwood, and upland hardwood in the restricted scenario. This is understandable, as land area in these forest types was removed from the scenario to model compliance with the sustainability guidelines. A second finding is the relative increase in planted pine in the sourcing restriction scenario. As land area in this forest type was unaffected by application of the sustainability guidelines, the change reflects a net gain in

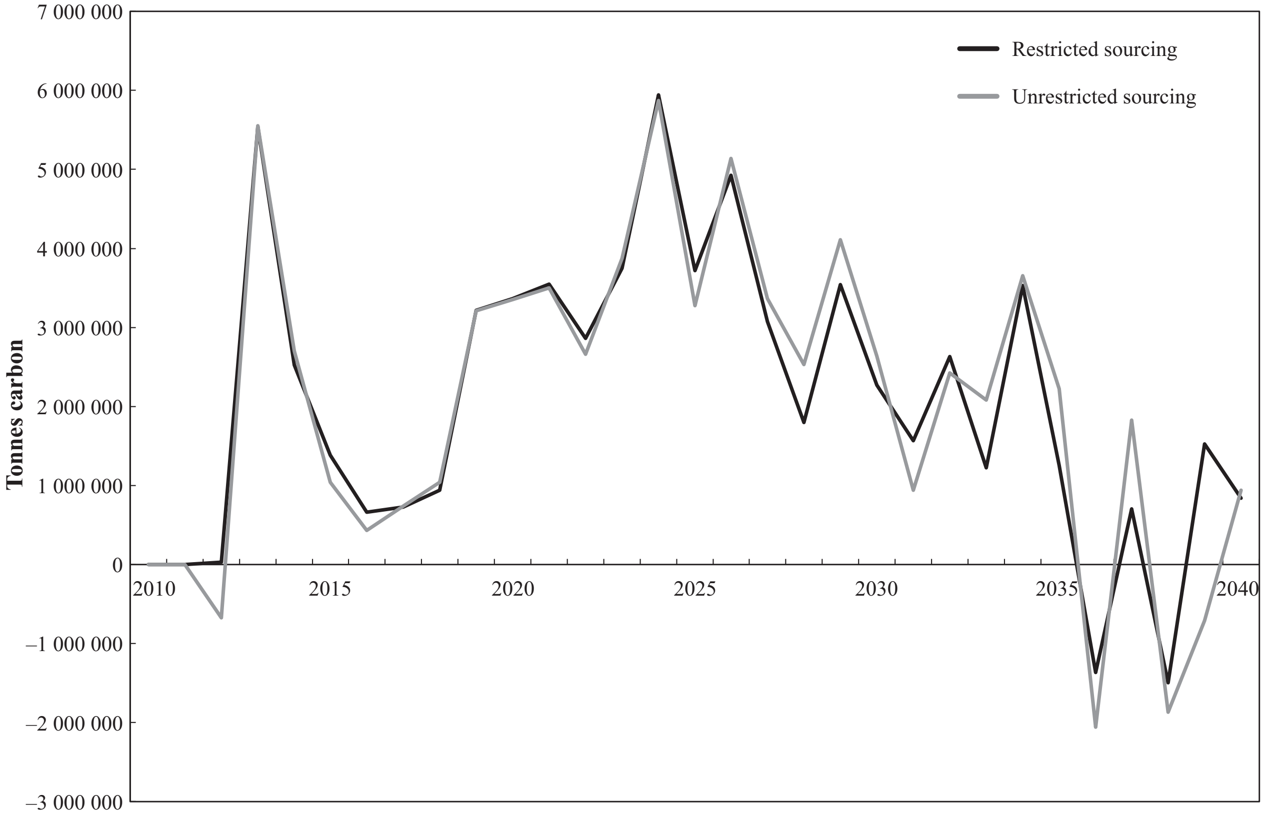

Fig. 4 Estimate of annual changes in forest carbon (tonnes C) associated with the estimated level of pellet production in both restricted and unrestricted sourcing scenarios. Positive values reflect a net greenhouse gas benefit.

planted pine acreage in the presence of increased pellet demand in the restricted sourcing scenario as compared to the unrestricted one.

The inventory, removal, and land-use change effects collectively influence regional carbon storage (Fig. 4). Across both restricted and unrestricted sourcing scenarios, the imposition of 12.2 million tonnes of woody biomass demand generates annual gains in forest carbon in most assessment years, with very little change seen between the two scenarios. Compiling these annual fluxes shows a slow increase in forest carbon stock over time, accumulating to well over 60 million tonnes of carbon over the baseline scenarios by the end of the assessment scenario in 2040. This finding in itself suggests compliance with sustainability guideline criteria that pellets achieve specific levels of net GHG reductions, but conversion of estimated carbon gains to a per tonne pellet unit of measure can help to better evaluate performance.

Intuitively, the annual and cumulative forest carbon benefit per tonne of pellets produced under both a restricted and unrestricted policy scenario follows the annual change in forest carbon displayed in Fig. 4, with the exception that early year changes are somewhat exacerbated (Fig. S15). This is attributable to the early 'ramping up' trajectory assumed for the onset of pellet demand, meaning that there are fewer pellets to which changes in forest carbon may be allocated. Comparing cumulative carbon change to cumulative pellet production reduces year-over-year volatility, yielding a positive long-term GHG benefit per tonne pellet produced (i.e., a net GHG reduction relative to no pellet increase baseline). Note that these measures of cumulative benefit are simply measures of annual carbon change and pellet production volume; they do not take into account the timing of emissions of sequestration, suggested elsewhere in the literature to be an important component of GHG accounting (Cherubini *et al*., 2011).

Comparing these annual changes in forest carbon to the emissions associated with pellet combustion, emissions associated with pellet production and transport, and the emissions associated with coal generation, a more complete sense of the aggregate GHG impact of pellet production becomes apparent (Fig. 5). When compared against the GHG reduction standards proposed for years 2017 and 2018, pellets in both restricted and unrestricted sourcing scenarios generally meet minimum reduction requirements when used as a substitute

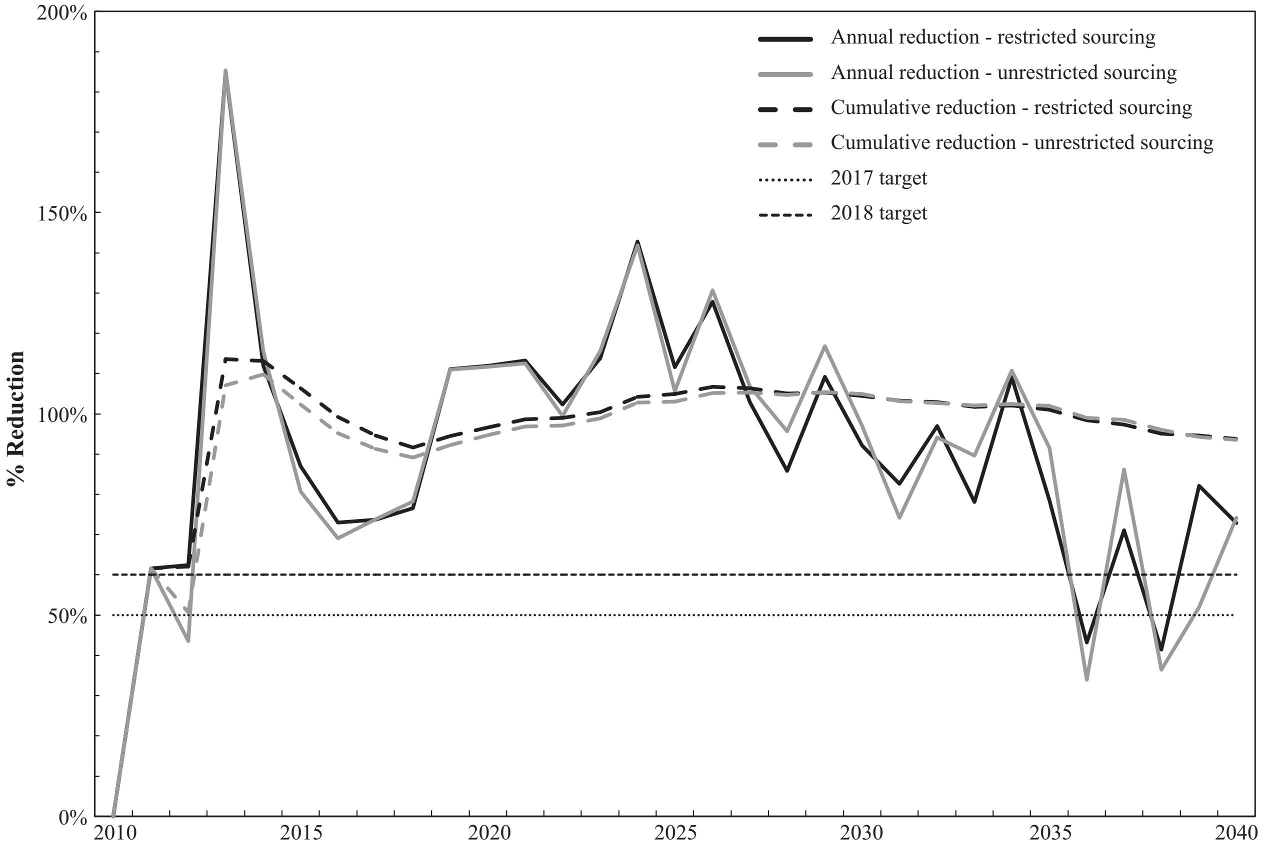

Fig. 5 Percent emission reduction achieved by pellet use compared to a coal alternative under both restricted and unrestricted sourcing scenarios. Horizontal lines indicate draft sustainability guideline greenhouse gas reduction targets for years 2017 and 2018.

for coal. Also apparent is the inherent differences between annual and cumulative measures. The annual estimate is associated with a great deal of volatility and fails to meet established standards in two years near the end of the projection. The cumulative estimate is less volatile, reflecting the same dynamics described above for the forest carbon response.

Discussion

We find that application of sourcing restrictions to simulate compliance with European Union recommended sustainability guidelines may reduce the area capable of supplying EU markets. This is the very point of the guidelines – to limit sourcing from sensitive areas. We likewise find a complex forest sector response to the imposition of additional pellet demand in the presence of these sourcing restrictions. Across both the restricted and unrestricted pellet sourcing scenarios, we find increased removals, an increase in forest area, and little change in forest inventory. At the same time, we see annual gains in forest carbon for most years of the analysis (Fig. 4). These findings collectively suggest that the market is responding positively to the imposition of pellet demand, but not so much that inventory is substantially reduced (thus driving net carbon storage down). The increased demand for biomass to produce pellets leads to an increase in forest rent, reducing the pressure on conversion of existing forests to some other, lower carbon use (e.g., agriculture). As the forests that are most likely to be lost to these other uses tend to be mature (and therefore high carbon) stands, any reduction in the rate of loss will yield a sizable increase in carbon storage.

The incremental effect of sustainability guideline application on net forest carbon and by extension pellet carbon balance is difficult to discern. This is an important finding, given the aforementioned reduction in forest area on which biomass may be sourced. In effect, we are seeing a situation in which harvestable area goes down but with minimal effect on forest carbon response. Figure 3 offers one possible explanation for this, specifically in the increased plantation area seen in the restricted sourcing scenario as compared to an unrestricted scenario. The increased area of planted pine suggests that the sustainability guidelines could be

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steering production toward those management types most responsive to changing market conditions. Conversely, application of the guidelines could also be seen as steering production away from sensitive management types that are inherently less responsive to changing market conditions. Application of the guidelines could therefore be further focusing harvests on more productive forests, limiting the role of less efficient sources. Stated another way, removal of sensitive lands from potential harvest could be enhancing the response of remaining areas, areas which are likewise capable of significant production response. This is in line with previous research showing the intensification of management in other systems in response to the imposition of new demand (e.g., Hertel *et al.*, 2010).

Broadly speaking, these findings are also in line with previous research that found GHG-based sustainability criteria to have only limited effect on bioenergy market development (Hoefnagels *et al.*, 2014). They are, however, somewhat in contrast to the substantial reduction in trade volume found in work assuming a feedstock-based exclusion or 'blacklist' type approach (Lamers *et al.*, 2014). This highlights the crucial role that sustainability guideline implementation and GHG accounting decisions are expected to play (Galik & Abt, 2012; Thiffault *et al.*, 2015). With specific regard to the latter, the development of accounting systems to adequately capture the GHG implications of biomass use remains underway in both the United States and European Union (Stephenson & MacKay, 2014; US Environmental Protection Agency, 2014). The findings here reinforce the importance and relevance of these efforts. As Fig. 5 shows, cumulative GHG benefit in the restricted sourcing scenario is positive across the entire model run. This is in contrast to a rising and then falling annual estimate. If one uses cumulative GHG balance (or if one is allowed to 'bank' years of realized overcompliance with a reduction standard), the results here suggest that use of US southeastern pellets sourced in compliance with EU recommended sustainability guidelines could represent a viable GHG reduction strategy, at least at the magnitude of pellet demand and over the time periods assessed here. Use of an annual GHG balance metric suggests that there will be multiple years of clear overcompliance and some years in which compliance must be more closely scrutinized.

Furthermore, regional phenomena such as changes at the extensive (i.e., land-use change) and intensive (i.e., management) margins imply that an individual stand- or harvest-level accounting approach is likely to be incomplete. The inherent dynamics of the US southeastern forest landscape make it difficult for a single-pellet purchaser to know for certain what the full GHG implications of his or her purchase will be absent the use of outside data or tools to assess the broader impacts. Complicating matters further, any significant addition of new bioenergy demand introduces the possibility of inter-regional shifts in patterns of biomass supply, also known as leakage. Although these shifts are expected to be small in this analysis given the magnitude of additional demand assessed, previous analyses have highlighted the potential significance of the phenomenon on a global scale (Frank *et al.*, 2013).

Ultimately, the ability of biomass produced in the southeastern United States to meet projected EU demand will likely depend on satisfaction of multiple policy criteria. Despite the important role southeastern US forests are expected to play in meeting EU renewable energy targets, an integrated assessment of biomass supply from the region against these sustainability criteria has heretofore been performed. Here, we provide such an analysis. We establish the primary drivers of EU biomass demand, identify the relevant sustainability criteria that they contain, review the relevant data from which biomass supply may be screened, and conduct a comparative economic modeling exercise to isolate the incremental changes associated with increasing pellet demand and application of sustainability criteria. In doing so, the analysis fills a critical gap in the literature and helps to inform ongoing policy deliberations both within the United States and in the European Union.

Future work can build upon the approach outlined here. Although justified, critical assumptions are made for both wood pellet demand and the basis for sustainability guideline implementation in the southeastern United States. Future analyses should assess the extent to which the findings of this analysis hold across a variety of other potential demands and policy drivers. For example, this analysis assumes constant biomass demand within the United States, but current regulatory proceedings under the auspices of the President's Clean Power Plan could provide incentives for greater domestic biomass use in the future. Examining the implications of directing harvests to certified acres is another exercise that was precluded by available data here, but would nonetheless be of great use and importance to ongoing policy deliberations. Future research could likewise add Natural Heritage data as a separate sensitivity analysis to better gauge the effects of biodiversity-related sustainability criteria. In an era where increasing attention is being paid to alternative generation technologies and the full suite of services provided by forest ecosystems, such integrated analyses are not only timely but of critical importance to informed decision making.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Proportion of timberland classified as 'Deciduous' and potentially restricted from harvest under proposed EU sustainability guidelines.
Figure S2. Proportion of timberland classified as 'Evergreen' and potentially restricted from harvest under proposed EU sustainability guidelines.
Figure S3. Proportion of timberland classified as 'Mixed' and potentially restricted from harvest under proposed EU sustainability guidelines.
Figure S4. Proportion of timberland classified as 'Woody Wetland' and potentially restricted from harvest under proposed EU sustainability guidelines.
Figure S5. Relative change indices for pine pulpwood, comparing baseline and pellet demand scenarios absent sourcing restrictions.
Figure S6. Relative change indices for hardwood pulpwood, comparing baseline and pellet demand scenarios absent sourcing restrictions.
Figure S7. Relative change indices for pine small sawtimber, comparing baseline and pellet demand scenarios absent sourcing restrictions.
Figure S8. Relative change indices for pine sawtimber, comparing baseline and pellet demand scenarios absent sourcing restrictions.
Figure S9. Relative change indices for hardwood sawtimber, comparing baseline and pellet demand scenarios absent sourcing restrictions.
Figure S10. Relative change indices for pine pulpwood, comparing baseline and pellet demand scenarios in the presence of sourcing restrictions.
Figure S11. Relative change indices for hardwood pulpwood, comparing baseline and pellet demand scenarios in the presence of sourcing restrictions.
Figure S12. Relative change indices for pine small sawtimber, comparing baseline and pellet demand scenarios in the presence of sourcing restrictions.
Figure S13. Relative change indices for pine sawtimber, comparing baseline and pellet demand scenarios in the presence of sourcing restrictions.
Figure S14. Relative change indices for hardwood sawtimber, comparing baseline and pellet demand scenarios in the presence of sourcing restrictions.
Figure S15. Estimate of the annual and cumulative GHG benefit of pellet production in both restricted and unrestricted sourcing scenarios.