

Analysis of the global wood-chip trade's response to renewable energy policies using a spatial price equilibrium model

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Received September 30, 2016; revised January 24, 2017; accepted January 30, 2017 View online at March 9, 2017 Wiley Online Library (wileyonlinelibrary.com); DOI: 10.1002/bbb.1761; *Biofuels, Bioprod, Bioref,* 11:505–520 (2017)

Abstract: Wood chip, mainly used to produce paper and other products traditionally, has also been used to produce biofuel. The global demand for wood chip is increasing as policies promote the use of biomass for renewable energy. The USA has been a major exporter of wood chip worldwide, but US exports of wood chip could decline if this resource is increasingly used for domestic electricity generation and cellulosic biofuel production. Meanwhile, European Union (EU) demand for wood chip is expected to increase rapidly in response to its renewable energy policy. In this paper, we build the first global trade model for wood chip using available wood chip trade data and analyze the combined effects of local renewable energy policies in these jurisdictions on the global market of wood chip. We find that the tropical regions of Latin America and Southeast Asia as well as the Former Soviet Union would increase their export of wood chip significantly in response to the policy scenarios. If forest governance in some of these countries is weak, US and EU renewable energy policy could inadvertently exacerbate deforestation in these regions, with an associated negative impact on carbon storage and other environmental services. © 2017 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: wood chip; spatial price equilibrium; energy policy; positive mathematical programming; Renewable Fuel Standard

Introduction

he US Renewable Fuel Standard (RFS) mandates blending of biofuel in road gasoline and diesel.¹ The mandated volumes of biofuel are scheduled to increase every year to 2022, and cellulosic biofuel made from non-food feedstocks is the fastest growing component of this mandate. Although actual production of cellulosic biofuel has consistently fallen below mandated volumes in every year of the RFS program, commercial-scale cellulosic biofuel facilities continue to be built utilizing a wide range of feedstocks. EPA has approved a number of feedstocks that can be used to produce cellulosic biofuel that is eligible for RFS support, including perennial

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grasses like miscanthus and switchgrass, agricultural residues like corn stover, and forestry residues.¹ The agency is considering expanding this list to include pulpwood from whole trees,² which, if approved, could lead to increased demand for wood harvests. At the same time, US consumption of wood for electricity has been rising since $2009^{3}_{,3}$ and the EU's Renewable Energy Directive (RED) is driving very high imports and consumption of wood pellets,⁴ which are produced from wood chip and other pulpwood products, for heat and power generation in the EU.⁵ The EU has been increasingly dependent on biomass import for energy and its total imports of wood chip both for energy and pulp production have increased from 6 million cubic meters in 1997 to 16 million cubic meters in 2011 according to the FAOSTAT database.⁶ Wood pellets were identified as efficient to be used for co-firing to generate renewable electricity in Germany and Austria.⁷ However, co-firing coal with wood pellets is currently not economically feasible within the USA due to the recent US natural-gas boom.⁸

With these two policies working together to drive up demand for wood harvests, where will the additional supply come from? The answer is important to understanding the lifecycle environmental impacts of the potential pulpwood to biofuel pathway under the RFS. Some additional supply would very likely come from the Southeastern USA where most American pulpwood is produced. However, due to the EU's phytosanitary measures,⁹ US export of softwood chip to the EU has been very limited because of the existence of nematodes in US softwood chip. Therefore, the EU's increasing demand would need to be satisfied by other regions instead. If additional wood is produced from new forestry plantations on previously unforested land, cellulosic biofuel could deliver significant carbon savings. If, on the other hand, the increased wood supply comes from existing forests in countries with weak forest protection policies and enforcement, a pulpwood biofuel pathway in the USA would likely cause a net increase in emissions compared to fossil gasoline or diesel.¹⁰

Most previous studies about wood bioenergy markets were conducted at the country level, specifically for European countries such as Austria, Norway, Italy, and Poland. Those studies in general focus on three aspects: first, bioenergy potential of a certain region; second, demand, supply, and production of certain bioenergy; and third, bioenergy usage in a certain country. For example, Nilssona *et al.*¹¹ analyzed the status and potential of bioenergy in Poland in 2006 and found that firewood for heating was the main bioenergy usage, which consisted of 95% of renewable energy usage in 2003. Nilssona *et al.*¹¹ concluded that Poland's bioenergy market and policy were undeveloped even though it had a large potential for bioenergy. Paiano et al.¹² estimated the bioenergy potential in Italy and found 2.7% of the gross Italian energy consumption in 2013 could be generated from residual biomass, which could save about 52 Mt CO₂eq emission for Italy per year. Trømborg et al.¹³ analyzed the effect of various bioenergy policies on the usage of forest-based bioenergy in Norway using a spatial partial equilibrium model and found the share of bioenergy in the Norwegian energy market was much lower than other EU countries due to low electricity price and lack of heating facilities. They concluded that policy incentives including subsidies, deposit grants, and feed-in systems can significantly increase Norway's bioenergy production. Trømborg et al.14 also gave a detailed presentation of the forest biomass potential for heating in Norway in 2011 and concluded it is unlikely the government target of 14 Twh more bioenergy by 2020 can be met. In addition, those studies mainly focused on wood pellets but not on wood chip.

Few studies have been done about the international trade of wood bioenergy, especially for wood chip. One study presented an overview of the historical international trade flow, bioenergy policies, and market factors for solid biofuel such as wood pellet, wood chip, and roundwood in main markets including the EU, North America, the Russian Federation, and Japan.¹⁵ They identified that wood pellets have become the most traded solid biofuel as a globally traded commodity and its trade increased from 8.5 PJ to 120 PJ from 2000 to 2010. Another study reviewed the market factors and policies for the global wood pellet market and presented the opportunities and challenges for the wood pellets industry.¹⁶ They expected that the EU would remain the main wood pellets market and that the East Asia market would be further expanded. The only study on global wood chip trade for energy has been done by Lamers et al.9 They presented the historical global trade data for wood chip and estimated that the energy-related wood chip trade volume was less than 10% annually. In addition, they identified the key constraints of trading wood chip for energy as production and transportation costs. These studies provided an extensive overview of the wood chip trade data. Building on this data, our study takes a further step and analyzes the wood chip trade changes under different EU and US renewable energy policy scenarios.

Junginger *et al.*¹⁷ also identified logistics including transportation as the major barrier for solid biomass commodities due to their low energy density and a relatively low value. A recent financial analysis of the transport

of wood chip from the USA to Germany estimated that transporting wood chip per weight is more than twice as expensive as transporting wood pellets, because wood pellets have a much higher density.¹⁸

In addition, phytosanitary requirements are another barrier for the trade of wood chip that is infected by insect pests. For example, export of softwood chip from the USA to the EU was restricted due to the EU's phytosanitary requirement regarding wood chip as previously mentioned.

The main contribution of this study is that we build the first global trade model for wood chip and analyze how local energy policy from the USA and the EU will affect the global market of wood chip. Specifically, we find that wood chip exports from tropical regions would increase significantly. Implementation of sustainability criteria for biomass should focus on these regions. To ensure the imported biomass feedstock is sustainable, the EU has initiated the BioTrade2020plus project. Iriarte et al.¹⁹ suggested the sustainability criteria and assessed the sustainability risks for biomass including wood chip focusing on current and potential major sourcing regions including Latin America, Asia, and Russia. We estimate supply elasticity and transportation cost of wood chip using positive mathematical programming, an automatic calibration technique that has been extensively used to overcome limited availability of trade data and supply data.

In addition, our analysis can be a springboard toward deeper analysis by including other policy, environmental, and technical factors such as the implementation of sustainability criteria, technology changes, and forest growth.

Methods

Data preprocessing

Wood chip trade data were downloaded from the FAOSTAT database.⁶ The commodity extracted from this database was 'wood chip and particles'. The data included the quantity and value of wood chip traded between countries. Quantity was measured in cubic meters and value was measured in thousands of US dollars. Export values are generally reported as free on board value while import values consist of cost, insurance, and freight, according to the Food and Agricultural Organization of the United Nations (UN FAO).²⁰

It is important to note that the wood chip trade data we used is the entire trade of wood chip, not solely the bioenergy-related wood chip trade. We did not separate the wood chip trade data based on its end-use, i.e., used for bioenergy or for paper production, for three reasons. First, our goal was to analyze the changes of wood chip trade due to renewable energy policies. Our goal was not to track the bioenergy-related trade of wood chip. Otherwise, we would have needed to separate wood chip trade based on its end-use. For example, in 2006, Hillring analyzed the trade patterns for forest product and wood fuel.²¹ For wood fuel, Hillring's analysis focused on charcoal trade. Wood chip trade data were presented in the analysis but not categorized based on end-use. Later in 2012, Lamers et al.¹⁵ estimated that annually reported energy-related wood chip trade volumes were less than 10% based on anecdotal evidence, literature review, and personal assumption, for example, assuming the global trade of wood chip for energy was exclusively toward the EU. We believe wood chip traded for paper production (pulpwood) can also be used for bioenergy. For example, as Olsson and Hillring mentioned, in 2009, the global financial crisis reduced demand for pulpwood from Swedish pulp and paper producers, which led to excessive export of pulpwood for energy to Denmark.²² Therefore, we modeled the entire demand and supply of wood chip, but our scenarios only modeled changes in policies from energy. Changes in energy policy resulted in absolute changes in wood chip consumption globally. Second, there are no trade data currently available for wood chips used for bioenergy in international statistics because the current six-digit international trade code for wood chip does not differentiate by end-use. Third, indirect trade of woody biomass makes it further complicated to separate energy-related wood chip trade from wood chip traded for pulp and paper production. For instance, for the Kraft pulp production, part of the pulpwood is used to produce heat in the pulp mills.^{23,24} This part of pulpwood was not explicitly traded for energy but still ends up in energy production. Therefore, we used the overall wood chip trade data for our analysis given the goal of our study.

The dataset contains both volume and prices for wood chip between countries. This country-level dataset gives us the flexibility to do analysis both at a country level and at an aggregated regional level. However, there were several discrepancies in the raw data from year to year. For example, the main discrepancy in quantities was that imports and exports between countries did not match. There are various reasons that can lead to trade data discrepancies. For example, country A's exports could arrive at country B the following year, leading to total exports not matching total imports for the year. Moreover, some exporters may underreport to reduce tariff costs. It could also be caused by data entry errors. To deal with this data discrepancy, we first aggregated the data from all countries into 14 regions. Aggregating the data into 14 regions reduced the discrepancy because many discrepancies, for example within a region, cancelled out each other after aggregation. At the same time, we only considered trade between regions and ignored trade within a region. We chose to use year 2011 data for our analysis, which are the most recent data available with relatively small data discrepancy compared to other years. In the end, we only used export data because the data discrepancy may have resulted from importers reporting less to reduce import duties. Table 1 displays the list of the countries aggregated into each region, and the total exports and total imports of wood chip for each region in 2011.

A caveat of our data input is that we did not explicitly consider the bioenergy potential for each region; for example, forest growth in the USA. Instead, our data input is the export and import of wood chip for each region as we are not trying to predict whether a region has the capacity to satisfy the EU's demand for wood chip as bioenergy. Instead, we are trying to predict how the global trade of wood chip would change under various scenarios. Knowing the bioenergy potential alone would not inform those changes of trade. For example, we believe that our results will not be affected even considering the forest growth in the USA due to EU phytosanitary measures. The EU's requirements for phytosanitary measures have significantly limited the trade of softwood chip from the USA to the EU. In fact, our model took this into account through model calibration using year 2011's global wood chip trade data. In year 2011, the USA exported 64 000 cubic meters of wood chip to the EU, which is only 1% of the USA's total export of wood chip in that year. Thus, wood chip from the USA's forest growth is unlikely to satisfy EU demand for bioenergy given the EU's phytosanitary measure unless the USA can eradicate nematodes in its wood chips in the

| Table 1. Total exports and imports of wood chip for each region in 2011. Trade quantity was measured in |
|---|
| cubic meters. The column 'Countries' contains the countries that were aggregated into its corresponding |
| region. The total exports and imports for a region is the sum of the exports and imports from all the |
| countries in that region. |

| Region | Countries | Total Exports (m ³) | Total Imports (m ³) |
|------------------------|--|------------------------------------|------------------------------------|
| Central America | Bahamas, Barbados, Belize, Costa Rica, Dominican Republic, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama | 150 | 4,126 |
| Canada | Canada | 1,033,724 | 2,004,236 |
| East Asia | China, Democratic People's Republic of Korea, Japan, Republic of Korea | 1,173 | 35,240,325 |
| European Union | Austria, Belgium, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom | 1,006,527 | 6,625,972 |
| Former Soviet Union | Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Uzbekistan | 2,899,220 | 5,079 |
| Latin America | Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Venezuela | 10,058,072 | 106,356 |
| Middle East | Bahrain, Iran (Islamic Republic of), Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates | 143 | 3,190,897 |
| North Africa | Egypt, Libya, Mauritania, Morocco, Niger, Tunisia | 21,974 | 20,871 |
| Oceania | Australia, Fiji, French Polynesia, New Caledonia, New Zealand, Papua New Guinea Solomon Islands, Tonga, Vanuatu | , 9,755,830 | 26,050 |
| Other Europe | Albania, Bosnia and Herzegovina, Iceland, Norway, Switzerland, Ukraine | 502,738 | 1,180,499 |
| South Asia | India, Nepal, Sri Lanka | 15,904 | 946 |
| Southeast Asia | Cambodia, Indonesia, Philippines, Singapore, Thailand, Viet Nam | 15,103,185 | 18,294 |
| Sub-Saharan Africa | Burkina Faso, Cameroon, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Ethiopia, Gambia, Ghana, Guinea, Liberia, Madagascar, Malawi, Mauritius, Mozambique, Nigeria, Rwanda, South Africa, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe | 2,501,317 | 6,106 |
| USA | USA | 5,659,235 | 129,435 |

future. Nonetheless, as we will discuss in the Discussion section, estimating the sustainable bioenergy potential will help inform us whether deforestation will happen or not.

The difference between export values and import values should include the transportation cost, but due to several issues with valuing freight transportation costs, such as time lag and custom tax avoidance,¹⁸ we needed to calibrate the cost within the model to achieve results that matched reality. Calibration was a natural solution to this problem as transportation cost plays a significant part in the trade of wood chip.¹⁸

Mathematical model

General model framework

As mentioned previously, the EPA is considering whether to approve pulpwood from whole trees to be used as bioenergy that is eligible for RFS support. Meanwhile, the EU RED is increasing the demand of wood bioenergy for heat and power generation in the EU. We want to study how these energy policies would affect the global trade of wood chip. Given this application problem and based on the literature review we conducted, we chose to use the spatial price equilibrium model (SPE) and the FAOSTAT data previously described.

We adapted the static SPE model to model the global wood chip trade flow for one year.^{25,26} Since Samuelson presented the equivalence between SPE and linear programming theory, SPE has been used for modeling regional and international trade in food and forest sectors.²⁷ Lauri *et al.*²⁸ applied a partial equilibrium model which is based on an SPE model to estimate the biomass energy potential in 2050. The general optimization form of the SPE model is as following:

 $M_{ax_{ij}} \left\{ \sum_{i} \int_{0}^{D_i} \theta_i(D_i) dD - \sum_{j} \int_{0}^{S_j} P_j(S_j) dS - \sum_{ij} c_{ij} x_{ij} \right\}$

s.t.

$$\sum_{i} x_{ij} \ge D_{j}$$

$$\sum_{j} x_{ij} \le S_{i}$$

$$S_{ij}, D_{ij}, x_{ij} \ge 0, \quad \forall i, j$$
(1)

Samuelson defined the objective function as 'net social payoff'. The first term, second term, and third term in the objective function, respectively, represent the consumers' utility, production cost, and transportation cost. The constraints represent the trade flow conservation. Subscript i represents demander i and j represents supplier j. Table 2

Table 2. Model variables and parameters. This table contains the list of variables and parameters used in our model and their descriptions.

| Symbol | Description |
|----------------------------------|---|
| X _{ij} | trade flow from region <i>i</i> to region <i>j</i> |
| D_j | demand at region j |
| Si | supply at region <i>i</i> |
| θ _i (D _i) | demand function at region <i>i</i> |
| $P_j(S_j)$ | supply function at region <i>j</i> |
| C _{ij} | unit transportation cost from region i to region j |
| E _{s,j,k} | price elasticity of supply for region k in year j |
| S _{j,k} | supply quantity of wood chip for region k in year j |
| P _{j,k} | supply price of wood chip for region k in year j |
| S _{2011,k} | supply quantity of wood chip for region k in year 2011 |
| P _{2011,k} | supply price of wood chip for region k in year 2011 |
| $\alpha_{i,j}, \Gamma_{i,j}$ | model calibration parameters between region <i>i</i> and <i>j</i> , derived from first stage linear programming model |

gives a description of the model variables. When this optimization problem is solved, the outputs are the trade flow x_{ij} , demand prices as the dual variables for the demand constraints, and supply prices as the dual variables for the supply constraints.

Model details

In this section, we describe the details of our underlying model as well as the implications for our adaptation of the general SPE model. While our assumptions are necessary for a global trade analysis given the availability of data, we justify our approach using available evidence and provide information on how the results can change if we had more detailed data.

First, we assumed perfectly inelastic demand of wood chip for our policy analysis. Our study focuses on how supply would be affected by increased demand. So, for our policy scenario analysis, it makes sense to fix demand but not supply and to adjust demand for different policy scenarios. While there is no previous study about the demand elasticity of wood chip, Kristöfel *et al.*²⁹ found the demand for wood pellets in Austria to be inelastic in the short run using a two-stage least squares regression. Our assumptions are consistent with this result.

Second, we assumed a linear supply curve. For a perfectly competitive market, the supply curve is equivalent to the upward-sloping part of marginal cost curve where the marginal cost is larger than the supplier's average variable cost.³⁰ Therefore, for a linear supply curve, the change in marginal cost is constant as production increases. However, if we use a quadratic supply curve, the change in marginal cost would increase as production increases. The total production cost could be much higher if we used a quadratic supply curve at higher levels of production. Normally this is because of limitations of technology and the increasing cost of extracting a resource close to its capacity.³¹ As it is unlikely for the production of wood chip to reach its production capacity in any one region during the year, a linear approximation to the supply curve is justified. More data would have allowed us to better determine the functional form, but a linear supply curve captures the dynamics of supply for one year. We constructed our supply curve using arc supply elasticities, reference supply, and reference supply price based on our data as described in detail in the Model Construction section. There are no comprehensive studies about supply elasticity of wood chip.

Finally, we represented transportation cost as a quadratic function of the traded amount of wood chip. A quadratic transportation cost function means the marginal transportation cost is increasing linearly. Intuitively, this makes sense, as when the total amount of wood chip transported increases, the unit price of transporting unit amount of wood chip will increase due to reasons such as the shipping vessels reaching capacity. A quadratic transportation cost also implies there is an optimal amount of wood chip to transport, which occurs when the corresponding marginal transportation cost is zero. A marginal transportation cost of zero means it is most cost effective to transport that amount of wood chip. In conclusion, a quadratic transportation cost function allows for a good representation of increasing marginal costs while still allowing for analysis and calibration.

Given these assumptions, the first term in the objective function of the general SPE model became constant and can be ignored since we used perfectly inelastic demand, i.e., the demand is constant. Therefore, we are minimizing total production cost plus transportation cost given fixed demand. Then we only need supply functions $P_i(S_i)$ and transportation costs c_{ii} to construct the model as described in the next sections. Furthermore, we assumed the supply curve is linear and transportation cost is a quadratic function of trade quantity of wood chip. So, supply function $P_i(S_i)$ is a linear function and a quadratic term for the transportation cost would be added to the objective function in model (1) in the model construction section. Table 2 contains the list of variables used in our model and their corresponding descriptions.

Model calibration

The goal of calibration is to choose model parameters so that the outputs exactly match or are as close as possible to the observed data. In our case, the transportation cost parameters were perfectly calibrated using 2011 wood chip trade data, to ensure that the factors determining transportation costs are embedded in the calibrated parameters. This includes any contracts, taxes, and other cost components of transporting wood chip. Model calibration is a type of parameter estimation and is also called inverse optimization. Several previous studies solved inverse linear programming problems for purposes of calibration.^{32,33,34}

We used the positive mathematical programming (PMP) approach for our model calibration.³⁵ PMP calibrates parameters perfectly and the calibrated model will produce exactly the same solution as observed data. It has been mainly applied to policy analysis and studied in the field of agricultural economics.³⁶ PMP is a two-stage process. In the first stage, we solved the original optimization problem (linear programming in our case). At the second stage, we constructed parameters using duals from the first stage problem and observed data. We added another nonlinear term to the objective function in stage 1 using the constructed parameters to form the objective function for the stage 2 problem. The constraints are the same for two stages. The model at stage 2 will give a solution that is the same as the observed data.³⁶

Model construction

Overview

s.t.

We built our final calibrated SPE model in two steps. First, we calibrated the transportation cost of a basic linear programming transportation model. Then, we added production cost to the calibrated model and relaxed the fixed supply constraints. The detailed model construction proceeds as follows.

Linear programming transportation model

When demand and supply are constant, then the SPE model is equivalent to a linear programming transportation model. So first, we solved a linear programming transportation model as follows:

 $Max - c^{T}x$ $Ax \le b \quad (duals)$

(2)

$$hx \le b \quad (duals \hat{\lambda})$$

 $x \ge 0$

where $x \in \mathfrak{R}^{n}$, $A \in \mathfrak{R}^{m \times n}$, $b \in \mathfrak{R}^{m}$, $c \in \mathfrak{R}^{n}$, $\hat{\lambda} \in \mathfrak{R}^{n}$

Here, n = 196, m = 28 for the entire model. The symbols $c(\$/m^3)$ are the unit transportation costs of wood chip between regions. Since we do not have perfect transportation cost data, we start with using export prices as c for the linear part of the transportation cost function that we will calibrate. The parameter b represents the wood chip supply and demand for all the regions. $\hat{\lambda}$ denotes the dual variables for the constraints at the optimal point.

Define parameter $\hat{\gamma} \in \Re^n$ as:

$$\hat{\gamma} = -c - A^T \,\hat{\lambda} \tag{3}$$

The goal is to find a constant vector $\alpha \in \mathbf{R}^n$ such that:

$$\hat{\gamma} - \alpha > 0 \tag{4}$$

Define parameter $\Gamma \in \Re^{n \times n}$ as a positive definite diagonal matrix:

$$\Gamma = diag \left[\frac{\left(\hat{\gamma}_{1} - \alpha_{1}\right)}{\hat{x}_{1}}, \dots, \frac{\left(\hat{\gamma}_{i} - \alpha_{i}\right)}{\hat{x}_{i}}, \dots, \frac{\left(\hat{\gamma}_{196} - \alpha_{196}\right)}{\hat{x}_{196}}\right]$$
(5)

where \hat{x} is the observed wood chip trade flow. Build a new quadratic programming model using parameters Γ , α .

 $M_{ax} - c^T x - \frac{1}{2} x^T \Gamma x - \alpha^T x$

s.t.

$$Ax \le b \ (\ duals \ \hat{\lambda})$$
$$x \ge 0$$

where $x \in \mathfrak{R}^n$, $A \in \mathfrak{R}^{m \times n}$, $b \in \mathfrak{R}^m$, $c \in \mathfrak{R}^n$

When problem (6) is solved, $x = \hat{x}$ and $\lambda = \hat{\lambda}$. This can be proven by looking at the problem's optimality conditions.

Add supply function and relax fixed supply

We add supply functions to the objective function and relaxed the fixed supply in the constraint. We first estimated arc elasticities of supply for each region by using the median value of historical arc elasticities. We took supply quantity and supply price of year 2011 as reference. For each region, we compute the arc elasticities for each year since 1996 as follows:

$$E_{s,j,k} = \frac{\left(\frac{S_{j,k} - S_{2011,k}}{S_{j,k} + S_{2011,k}}\right)}{\left(\frac{P_{j,k} - P_{2011,k}}{P_{j,k} + P_{2011,k}}\right)}$$
(7)

where $S_{j,k}$ and $P_{j,k}$ are the wood chip supply quantity and supply price in year *j* for region *k*. We used historical US consumer price index data to correct the export prices for inflation. All the prices were adjusted to base on US dollars in year 2011.

Before calculating the elasticities, we filtered out supply prices which are either below \$10/tonne or above \$200/tonne. We considered supply prices out of this range (\$10/tonne to \$200/tonne) to be outliers. Regions that have supply price outliers comprise less than 20% of total volume of wood chip exports worldwide from year 1997 to 2011 in our dataset. These price outliers were very likely to be incorrect, so to obtain a robust supply elasticity estimate, we excluded these price outliers.

We used the average value of $E_{s,j,k}$ as the supply elasticity for that region k which we denoted as $E_{s,k}$. For regions that have negative elasticities, we set their elasticities to be the smallest positive supply elasticities among other regions. The estimated supply elasticities are shown in Table 3.

We constructed a linear supply function for region *k* using estimated elasticity and reference (year 2011) supply quantity and price:

$$S_{k} = S_{2011,k} \left[1 + E_{s,k} \left(\frac{P_{k}}{P_{2011,k}} - 1 \right) \right]$$
(8)

The inverse supply function is:

(6)

$$P_{k} = P_{2011,k} \left[1 + \frac{1}{E_{s,k}} \left(\frac{S_{k}}{S_{2011,k}} - 1 \right) \right]$$
(9)

Table 3. Estimated wood chip supply elasticitiesfor each region

| Region | Supply Elasticities |
|---------------------|---------------------|
| Central America | 0.27 |
| Canada | 1.85 |
| East Asia | 0.27 |
| European Union | 2.76 |
| Former Soviet Union | 5.56 |
| Latin America | 4.58 |
| Middle East | 0.27 |
| North Africa | 0.27 |
| Oceania | 0.39 |
| Other Europe | 1.10 |
| South Asia | 0.27 |
| Southeast Asia | 5.30 |
| Sub-Saharan Africa | 0.57 |
| USA | 0.27 |

Note $P_{2011,k}$ is the supply price for region k from the above quadratic programming model i.e., the dual corresponding to the supply constraint in the quadratic programming model. By constructing such supply functions, we could relax the fixed supply constraint and add a production cost to the objective function without changing the solutions from the calibrated quadratic programming model.

Another simple approach to construct a linear supply curve is to fit a linear regression curve to the supply quantity and price data of wood chip. However, due to insufficient amount of data (we only had annual data) and high variability of supply price data, such an approach was not possible. The availability of more wood chip trade data, for example, monthly data, would help produce a more robust linear supply curve using this approach.

Final SPE model

Finally, our calibrated adapted SPE model is the following:

$$\underset{x_{ij},S_{j}}{Max} - \sum_{j} \int_{0}^{S_{j}} P_{j}(S_{j}) dS - \sum_{ij} c_{ij} x_{ij} - \sum_{ij} \frac{1}{2} \Gamma_{ij} x_{ij}^{2} - \sum_{ij} \alpha_{ij} x_{ij}$$

s.t.

$$\sum_{i} x_{ij} = D_j$$

$$\sum_{j} x_{ij} \le S_i$$

$$S_{j} x_{ij} \ge 0, i, j \in \{1, 2, \dots, 14\}$$
(10)

Scenarios

Overview

The objective function is to minimize the production cost plus transportation cost. Subscript *i* represents region *i* and *j* represents region *j*. The equality constraint means the total imports into region *j* equals to region *j*'s demand. The inequality constraint means the total exports from region *j* cannot exceed its supply. A detailed description of each model variable is available in Table 2.

We considered two types of scenarios: first, the USA decreases its supply to other countries to satisfy its increasing domestic demand for cellulosic biofuel and biomass electricity, and second, the EU increases its demand for renewable energy. To model the first type of scenario, we set an upper bound for the USA's supply. We obtained the upper bound by reducing the USA's supply for the base case by the projected amount, which is the USA's increased demand for that scenario. For the second type of scenario, we simply increased the EU's demand to the projected level. For each type of scenario, there are different levels of demand and supply given by our projections for the year 2022.

Our projections are based on expected outcomes from two major policies: the EU RED, which incentivizes biomass heat and power as a compliance option for its renewable energy mandate, and the US RFS, which could incentivize pulpwood biofuel as an eligible compliance option if this pathway is approved. We also consider the growing demand for biomass in electricity production in the USA. For the EU RED, the total expected heat and power demand is taken from National Renewable Energy Action Plans for all EU member states. Our scenarios assume that 40% of the target for renewable heat and power in the EU is met with wood chip, and subtract estimated consumption of biomass in 2014 to project the demand increase from the present. The EU RED is binding through the year 2020, and we assume constant levels from 2020 to 2022 to be able to compare with the US RFS outcomes. For the US RFS, we assume total cellulosic biofuel production of 1 billion gallons in 2022, which is roughly consistent with current growth of the industry from 2013-2016 according to historical production and EPA projections,² and that 25% of total cellulosic biofuel is produced from wood chip. We assume a cellulosic ethanol yield of 105.7 gallons per tonne biomass, based on a futuristic yield from Bloomberg New Energy Finance.³⁷

Note that our current scenario analysis is based on possible implementation pathways of existing policies (e.g. US RFS), not bioenergy in general. The possible pathway is using wood chip as a bioenergy feedstock. Our scenario analyses can be cited as strategies to help meet broader energy and climate policies such as Paris Agreement goals, which do not specifically address how bioenergy should be used to meet the target.

After running our model under different scenarios, we looked at the resulting supply from each region and compared it to the base case. We were specifically interested in which regions increase their supply significantly in each scenario.

Specific scenarios

In Figs 1 and 2, we show the results for the following five specific scenarios:

- 1. The USA increases its demand of wood chip by 2.37 million tonnes for biofuel, corresponding to 250 million gallons of pulpwood ethanol in 2022.
- 2. The EU increases its demand of wood chip by 34.78 million tonnes, corresponding to 40% of the EU's renewable energy mandate in 2020–2022.



Figure 1. Comparison of export of wood chip from different regions between the base case and the first three scenarios. Exports from the Middle East, North Africa, Central America and South Asia were omitted here because they are negligible. Base case: actual exports in year 2011. Scenario 1: Increase in US demand for cellulosic biofuel. Scenario 2: Increase in EU demand for renewable energy mandate. Scenario 3: Combined demand increase in US and EU.

- 3. The USA increases its demand by 2.37 million tonnes for biofuel and EU increases its demand by 34.78 million tonnes, corresponding to 250 million gallons of pulpwood ethanol and 40% of the EU's renewable energy mandate in 2020–2022.
- 4. The USA increases its demand by 2.37 million tonnes for biofuel plus 25 million tonnes for power, corresponding to 250 million gallons of pulpwood ethanol and expected growth in US biomass power in 2022.
- 5. The USA increases its demand by 2.67 million tonnes for biofuel plus 25 million tonnes for power and the EU increases its demand by 34.78 million tonnes, corresponding to 250 million gallons of pulpwood ethanol, expected growth in US biomass power and 40% of the EU's renewable energy mandate in 2020–2022.

Results and discussion

Base case results

The base case represents the actual trade of wood chip between regions in the year 2011. Table 4 displays the

trade between major exporters and major importers and a summary of the major export and import data for that year. The largest flow of wood chip between regions is from Southeast Asia to East Asia. Southeast Asia, mainly Vietnam and Thailand, had boosted its exports since 2010 to satisfy East Asia, especially China's fast growing demand of wood chip for paper and pulp production. Oceania is the second largest wood chip supplier for East Asia and has been a major exporter worldwide since 1997 because of the demand from Australia. The EU mainly imports wood chip from Latin America and the former Soviet Union. The Middle East also has been a major importer, largely due to a recent increase in Turkey's wood chip demand. Besides year 2011, our analysis using year 1997 to 2011 data shows that historically, Latin America, North America, Southeast Asia, and Oceania has been major exporters of wood chip and the major importers are Southeast Asia and the EU. Hillring also identified those regions strong in international trade of wood fuel using year 2000 to 2002 data.²¹

One obvious characteristic of these trade flows is that exporters tend to supply wood chip to geographically closer



Figure 2. Comparison of export of wood chip from different regions between the base case and the fourth and fifth scenarios. Exports from the Middle East, North Africa, Central America and South Asia were omitted here because they are negligible. Base case: actual exports in 2011. Scenario 4: Increase in US demand for cellulosic biofuel and biomass power. Scenario 5: Combined increase in US demand for cellulosic biofuel and biomass power and EU demand for renewable energy mandate.

Table 4. Major trade of wood chip in the year 2011. Trade quantity was measured in thousand cubicmeters. Row names represent major exporters and column names represent major importers. Thecolumn and row 'Percentage' represent each region's percentage of global imports or exports.

| Major Regions | East Asia (<i>Km</i> ³) | EU (Km ³) | Middle East (Km ³) | Canada (Km ³) | Other Europe (<i>Km</i> ³) | Total Exports (<i>Km</i> ³) | Percentage (%) |
|------------------------|---|--------------------------|-----------------------------------|------------------------------|--|---|----------------|
| Southeast Asia | 15,103 | 0.277 | 0.075 | 0.001 | 0.001 | 15,103 | 31.1 |
| Latin America | 5,820 | 3,479 | 424 | 0.001 | 314 | 10,058 | 20.7 |
| Oceania | 9,736 | 0.693 | 0.001 | 0.001 | 1000 | 9,757 | 20.1 |
| USA | 1,517 | 64 | 1,989 | 2,004 | 0.194 | 5,659 | 11.7 |
| Former Soviet Union | 207 | 2,691 | 1 | 0.001 | 0.246 | 2,899 | 6.0 |
| Sub-Saharan Africa | 2,258 | 189 | 0.001 | 0.001 | 0.001 | 2,501 | 5.2 |
| Total Imports | 35,240 | 6,626 | 3,191 | 2,004 | 1,180 | | |
| Percentage (%) | 72.6 | 13.6 | 6.6 | 4.1 | 2.4 | | |

regions. Even though Southeast Asia is a major exporter and the EU is a major importer, there is almost no trade from Southeast Asia to the EU. The reason is very likely that the shipping cost from Southeast Asia is too high. Intuitively, these trade flows make sense because trade between closer regions has smaller transportation cost.

Another characteristic is that the USA's and Latin America's exports are more dispersed to different regions. Both regions export significant quantities to East Asia and the EU, and to the Middle East, and Latin America exports large quantities of wood chip to other European countries.

Scenario results

Figures 1 and 2 show the export of wood chip for scenarios 1 to 5 compared with the base case for each region. Figures 3 and 4 show the major changes of trade flow of wood chip for scenarios 1 and 3. The quantitative scenario results for major changes of trade flow of wood chip are shown in Tables 5 and 6.

From Fig. 1, we can see that for the first three scenarios, the main regions that provide the extra supply of wood chip are Latin America, the former Soviet Union, and Southeast Asia. Table 5 displays the trade flow changes when only the USA increases its demand of wood chip by 2.4 million tonnes for biofuel. Increasing demand will limit the USA's export to other countries, as it will only consume its domestic supply. As a result, other major wood chip importers will have to increase their imports from regions other than the USA. In this scenario, the Middle East will increase its import from Latin America instead of the USA to satisfy its demand. Southeast Asia will increase its export to East Asia in place of the USA. The former Soviet Union will increase its export to EU in place of the USA. Table 6 shows that if the EU and the USA both increase their domestic demand, exports from Latin America and the former Soviet Union to the EU will soar. At the same time, Southeast Asia's exports to East Asia will also increase significantly because all the other major exporters except Oceania will shift their export from East Asia to the EU.

Figure 2 shows that if the USA further increases its demand by 25 million tonnes for power, in addition to the 2.4 million tonnes of domestic demand increase for biofuel, the USA will not be able to satisfy its own demand and will become a net importer of wood chip. In this scenario, Canada's export to the USA will increase significantly. Figure 2 also shows greatly increased exports from Latin America and Southeast Asia, and to a lesser extent, from the former Soviet Union, to satisfy the combined mandates in the USA and the EU (scenario 5).

Increased exports from Latin America and Southeast Asia may have a negative environmental impact on these regions, especially those countries with differing forest protection policies and enforcement. For instance, Chile has already been experiencing clearing of natural forest and plantation expansion for the past few decades,³⁸ partly caused by increasing demand for timber and fuel wood product. Our data analysis also shows that Chile has constantly been a major exporter of wood chip from 2001 to 2010; its export of wood chip is about 9% of global



Figure 3. Global wood chip trade flow changes for scenario 1. Red arrows show increase and green arrows show decrease in trade as results for scenario 1 when compared to the base case. The width of the arrow represents the relative magnitude of the trade flow changes. Please see Table 5 for the actual values. Here 11 regions were filled with different colors. The other 3 regions have negligible trade changes and were not color-filled.



Global wood chip trade flow changes for Scenario 3

Figure 4. Global wood chip trade flow changes for scenario 3. Red arrows show increase and green arrows show decrease in trade as results for scenario 3 when compared to the base case. The width of the arrow represents the relative magnitude of the trade flow changes. Please see Table 6 for the actual values. Here 11 regions were filled with different colors. The other 3 regions have negligible trade changes and were not color-filled.

Table 5. Major changes in trade between major regions for the first scenario compared to the base case in the year 2011. Trade quantity was measured in thousand cubic meters. Row names represents exporters and column names represents importers. Positive numbers mean trade increased compared to the base case and vice versa.

| Major Regions | East Asia (<i>Km</i> ³) | European Union (<i>Km</i> ³) | Middle East (<i>Km</i> ³) | Canada (Km ³) | Other Europe (Km ³) | USA (Km ³) |
|---------------------|-----------------------------|----------------------------------|---|------------------------------|------------------------------------|---------------------------|
| Southeast Asia | 2,096 | 0.019 | 0.031 | 0.006 | 0 | 0.008 |
| European Union | -1 | 0 | -4 | 655 | -406 | -26 |
| Latin America | -132 | -80 | 1,141 | 0.03 | 404 | 0 |
| Oceania | 96 | 0 | 0 | 0.006 | 3 | 7 |
| USA | -1,517 | -64 | -1,989 | -1,077 | -0.194 | 0 |
| Former Soviet Union | 37 | 324 | 1 | 0.006 | 0.2 | 0 |
| Sub-Saharan Africa | -9 | -0.743 | 0 | 0.006 | 0 | 0 |
| Canada | -570 | -0.001 | 644 | 0.006 | 0 | 11 |

export of wood chip annually. So, increasing exports of wood chip from Latin America may cause further clearing of natural forest and plantation expansion in Chile, which would likely have negative impacts on the environment and biodiversity.³⁹ Another example is Sumatra, Indonesia, where increased value of agricultural commodities eroded enforcement efforts and led to increased deforestation in the late 1990s,⁴⁰ illustrating that increasing demand for forest products can put pressure on forest protection efforts. In addition, there is already evidence showing that UK demand for wood pellets has threatened the wetland forests in the southern USA.⁴¹ A Freedom of Information request by environmental organization Biofuelwatch showed that British utility company Drax Power requires wood from slow-growing trees, not forest residues or energy crops as its source of wood pellets.^{42,43}

Discussion

Our results show that if a significant fraction of the cellulosic biofuel mandate under the RFS is met by pulpwood Table 6. Major changes in trade between major regions for the third scenario compared to the base case in the year 2011. Trade quantity was measured in thousand cubic meters. Row names represent exporters and column names represent importers. Positive numbers mean trade increased compared to the base case and vice versa.

| Major Regions | East Asia (<i>Km</i> ³) | European Union (<i>Km</i> ³) | Middle East (<i>Km</i> ³) | Canada (Km ³) | Other Europe (Km ³) | USA (Km ³) |
|---------------------|---|----------------------------------|-------------------------------|------------------------------|------------------------------------|---------------------------|
| Southeast Asia | 10,037 | 8 | 0.475 | 0.015 | 0 | 0.108 |
| European Union | -2 | 0 | -25 | -0.102 | -865 | -105 |
| Latin America | -5,820 | 48,758 | 183 | 0.077 | 818 | 0 |
| Oceania | 365 | 2 | 0 | 0.015 | 47 | 105 |
| USA | -1,517 | -64 | -1,989 | -1,102 | -0.194 | 0 |
| Former Soviet Union | -207 | 15,412 | -1 | 0.014 | -0.034 | 0 |
| Sub-Saharan Africa | -2,258 | 3,469 | 0 | 0.015 | 0 | 0 |
| Canada | -598 | 3 | 2,161 | 0.015 | 0 | 8 |

biofuel, this pathway would likely have indirect effects on the global wood market, leading to increased wood harvesting in vulnerable tropical nations. Our model isolates these demand shocks and does not account for potential demand reduction for wood chip, and so we may overestimate the market effects of the RFS and RED; however, our analysis is illustrative of the type of effects that are likely to occur.

Our results indicate that, to ensure sustainable development of wood chip bioenergy, environmental, social, and economic sustainability criteria should be implemented, especially in these potential major sourcing regions for bioenergy. On the supply side, in 2011, Janssen and Rutz identified that no specific biofuel sustainability certification system has been implemented, but several sustainability initiatives have been established by stakeholders and governmental bodies from Latin America.44 On the demand side, EU-wide sustainability schemes and criteria exist for biofuel but not for biomass.^{4,45} If sustainability criteria and a certification system regarding wood chip is implemented in these sourcing regions and if we can estimate the sustainable wood chip bioenergy potential, we may be able to tell whether deforestation will occur given the predicted scenario results from our model. More specifically, if the sustainable wood chip bioenergy potential from these regions cannot satisfy the increased demand for those scenarios and the sustainability scheme is not implemented in these regions, then theoretically it could lead to deforestation. If the sustainable wood chip bioenergy potential cannot satisfy the increased demand and if sustainability criteria are implemented in these regions, deforestation may still happen due to potential leakage. For example, let us say sustainable wood can be used for both furniture manufacturing and bioenergy. Due to a

higher price for sustainably certified wood for bioenergy and the lack of explicit sustainability criteria for furniture, the sustainable plantation owner will sell wood for bioenergy while cutting down non-sustainably certified wood for furniture. Therefore, the implementation of sustainability criteria for bioenergy can reduce, but not eliminate unsustainable deforestation. Therefore, to predict whether increased demand for wood chip from the EU and the USA will cause deforestation in these major sourcing regions, we need to consider the sustainability constraints regarding wood chip, the amount of sustainable wood chip bioenergy from the sourcing regions, and the potential leakage effect. Lamers et al.46 studied the impact of sustainability criteria on potential imports and supply costs of global solid biomass trade to Northwest Europe. Their approach incorporated sustainability criteria using feedstock exclusion. However, this approach is not applicable for our analysis since we are studying a single type of feedstock. Incorporating sustainability constraints into our model would also lead to more realistic results in the future when the sustainability criteria are actually implemented in these major sourcing regions. However, estimating sustainable wood chip bioenergy potential is beyond the scope of this study. Nonetheless, our model can use the results from other studies to estimate sustainable wood chip bioenergy potential as input and answer the question regarding deforestation.

Our results are dependent on value of supply elasticities, but our methodology provides an approach to make inferences from limited and noisy wood chip trade data. Better data and better estimates of supply elasticities will allow for deeper insights. For example, Kristöfel *et al.*²⁹ applied a two-stage least regression method to estimate the demand supply elasticities of wood pellet in Austria by constructing demand and supply models. Their demand and supply models include factors that affect both the quantity and price of wood pellet demand and supply, such as the number of total installed pellet boilers, heating degree days, and production capacity. These methods can be used to estimate elasticities with relevant data for wood chips as well.

Meanwhile, technological, economic and policy factors regarding wood chip bioenergy has been changing such as combustion technology, quality standards, shipping costs, oil prices, and phytosanitary rules. In future studies, we can include these factors as constraints and parameters into our model. For example, if we know quantitatively how much combustion technology has improved the efficiency of using wood chip as bioenergy, we can adjust the demand of wood chip accordingly in our model.

For future work, we propose a more nuanced representation of supply and demand. Detailed representation of the availability of wood chip through analysis of forest area, governance quality and production profiles will grant further validation to our results. If data of wood chip directly traded as bioenergy is available in the future, we can use that data and better estimate the effect of bioenergy policy on global trade of wood chip. Finally, a multi-period analysis will give better indications of trends over time. Our model is also amenable to be coupled with other policy models for the renewable fuel standard,^{47,48,49} and can thus allow for a more robust policy analysis pertaining to climate change mitigation.^{50,51,52}

Conclusions

Countries in Latin America, Southeast Asia, and the former Soviet Union have great amounts of forest resource compared to other countries. Our study quantitatively shows that increased demand of wood chip from the USA and the EU driven by a combination renewable energy policies would increase harvests in these countries. Our methodology helps us answer the counterfactual questions for different bioenergy policy scenarios given limited data. This will assist policymakers to make sustainable bioenergy policies. If these countries have poor management and regulation of their forest resources, this may lead to unsustainable development of wood chip bioenergy with negative impacts on carbon stocks, biodiversity, and the rights of indigenous people. Thus, increased demand for wood chip from new renewable energy policies, including a pulpwood biofuel pathway under the RFS, may not deliver the full environmental benefits intended by those policies. To actually study whether these renewable energy

polices will lead to unsustainable development of wood chip bioenergy, further analysis by interviews with industry experts and field studies can be carried out and combined with our model results.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors thank the reviewers for their thoughtful comments. We also thank Chris Malins from the International Council on Clean Transportation (ICCT), Jimi Oke from Massachusetts Institute of Technology, and Christian von Hirschhausen from DIW Berlin for their valuable comments and suggestions.

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