Prospects for Cellulosic Biofuel Production in the Northeastern United States

A Scenario Analysis

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:// Supporting information is available on the *JIE* Web site

Summary

Secure access to energy and food are two of the challenges facing the Northeast region of the United States. Traditional biofuel feedstocks, such as corn and oil seed, are able to satisfy energy requirements. However, they compete with food production for desirable land and water resources and, in any case, are not likely to exploit the region's current comparative advantages. This study investigates a potential solution to the energy security problem in the Northeast: biofuel from advanced feedstock in the form of net forest growth and woody wastes, of which the region has abundant endowments. The federal government has committed to requiring 79.5 billion liters (BL) of advanced biofuel production annually by 2022. We evaluate both the physical capacity for its production and its cost competitiveness using an input-output model of consumption, production, and trade in the 13-state region. The model minimizes resource use required to satisfy given consumer demand using alternative technological options and subject to resource constraints. We compile data from the technical literature quantifying state-level biofuel feedstock endowments and the technological requirements for cellulosic ethanol production. We find that exploiting the region's endowment of cellulosic feedstock requires either making the price of biofuels competitive with gasoline through subsidies or restricting imports of gasoline. Based on this initial investigation, we conclude that the region can produce significant amounts of advanced biofuel, up to 20.28 BL of cellulosic ethanol per year, which could displace nearly 12.5% of the gasoline that is now devoted to motorized transport in the region.

Introduction

This article investigates the potential for cellulosic biofuel production using lignocellulosic feedstock to decrease the dependency on outside regions for gasoline, the petrochemical product used in motorized transport. To address national energy security concerns, the U.S. federal government passed the Energy Independence and Security Act (EISA) to mandate use of 79.5 billion liters (BL) (21 billion gallons)[1] of advanced—also known as next-generation—biofuel production by 2022 (H.R. 6—110th Congress 2007). Advanced biofuels consist of fuels generated from sustainable and nonfood feedstock, such as cellulosic ethanol and algae fuel. The Act stipulates that 60 BL of the mandated amount needs to take the form of cellulosic ethanol. This mandate is likely to be accompanied by a combination of regulations and incentives.

The Northeast appears to be a good candidate for contributing to this production. Concerns have been raised about the use of biomass for energy owing to its potential competition with food systems for land and water. Researchers, including Runge and Senauer (2007), Mitchell (2008), and Cassman and Liska (2007), have established that conventional biofuel feedstocks, such as corn and soybeans, do affect food availability and prices adversely. However, this is not expected

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to be an issue for the cellulosic biofuel production that we will consider for the Northeast, a region rich in woody biomass because of its forest-dominated land cover. In fact, the woody biomass accumulated in forests in the region is expanding, even after accounting for extractions to satisfy industrial and consumption demand (USDA Forest Service 2012). The Northeast has a significant, sustainable supply of cellulosic feedstock suitable for biofuel production.

In the Northeast, as in the Midwest and South, a large majority of forested land is owned by private entities, whereas most forestland in the West is publicly owned. This is shown in table S1 in the supporting information available on the Journal's website, based on estimates from the Forest Inventory and Analysis Database (USDA Forest Service 2012). The majority of forested lands outside the West are not reserved (i.e., not protected). The table shows that the Northeast has the largest percentage of surface area covered by forest as well as the greatest volume of timber per square meter, compared with the other regions.

The economic and environmental implications of the production and use of biofuels on a large scale remain unclear. This article examines the implications of several policy options to discover the conditions under which cellulosic ethanol production can be physically sustainable and economically feasible in the Northeast. The analysis uses an inter-regional input-output (I-O) model of the 13-state region applied to a database describing each state's economy, including its feedstock availability and production technologies. We pose the following research questions:

- What portion of the region's liquid transportation fuel requirements can be met through local production of biofuel from net forest growth and woody wastes?
- What is the cost of producing cellulosic biofuels relative to gasoline? What regulations or incentives would be needed to assure their production?
- What are the broader economic implications of biofuel production, in particular, for jobs and factor use, within the Northeast?

Review of the Literature

In this section, we report on the literature on biofuels with particular concentration on cellulosic feedstocks. We review relevant I-O studies and studies conducted at the National Renewable Energy Laboratory (NREL) that provide detailed cost estimates for cellulosic biofuels using the two main technological pathways. The World Trade Model/Rectangular Choice-of-Technology (WTM/RCOT) framework to be described in the next section requires a description of the technology for producing cellulosic ethanol as a basis for evaluating costs. Cellulosic ethanol is produced from cellulosic biomass utilizing one of two main approaches: biochemical or thermochemical. The biochemical pathway involves chemical pretreatment to release hemicellulose sugars, after which the hydrolysis process breaks down the cellulose into sugars. Subsequently, the sugar mix is converted to ethanol by fermentation and distillation. The thermochemical pathway involves adding heat and chemicals to the feedstock to generate a synthesis gas of carbon monoxide and hydrogen. Subsequently, a catalyst is applied to this gas and it is converted to ethanol.

The growing body of literature evaluating the implications of substituting biofuels for petroleum-based transport fuels includes I-O studies of regions as diverse as the European Union (EU), Brazil, Thailand, Norway, and Canada. We first review I-O studies focusing on the economic implications of biofuels, followed by those concerned with environmental impacts. In the first category Neuwahl and colleagues (2008) use a single-region I-O model of the EU to investigate the impact of several biofuel scenarios on employment in 2020. The business-as-usual scenario assumes that a mix of first- and second-generation biofuels (25 million tons [Mt] of crude oil equivalent, of which 20% is advanced biofuel) will account for approximately 7% of transportation fuels, and an alternative scenario assumes a 15% share of transportation fuels for biofuels (51.2 Mt of crude oil equivalent, two thirds of which is advanced). The researchers conclude that these targets, if realized, would increase the unit price of transport fuel by 6.4% and 13.6% under the two scenarios. Subsidies would be needed in the amount of 8.4 and 18.7 billion Euros, respectively, to cover this increase. In both cases, they report near neutral effects on employment.

Scaramucci and Cunha (2006) analyze the impacts on the Brazilian economy if annual production of ethanol from sugarcane were to increase to 105 BL over the next 20 years (an increase of over 800%), enough to satisfy 5% of the predicted global demand for gasoline in 2025. They use an I-O database for 2002 and extrapolate the results to 2023. They conclude that an expansion of this magnitude of the Brazilian ethanol industry could have significant socioeconomic impacts, increasing gross domestic product (GDP) (factor earnings) by 11.4% and creating more than 5 million additional jobs, significant employment impacts by contrast with the findings of Neuwahl and colleagues (2008) for the EU.

Silalertruksa and colleagues (2012) assess the economic impacts of producing a portfolio of biofuels—ethanol from cassava, molasses, and sugarcane as well as palm biodiesel—in Thailand. They make use of data from a process analysis to implement an I-O study of the Thai economy. They find that ethanol production requires approximately 17 to 20 times more labor input than gasoline per unit of energy content. The exogenous target is to produce 3.3 BL of biofuel per year to substitute for gasoline and diesel fuels, and they assume that yields of cassava and sugarcane increase by 128% and 82%, respectively, from 2000 to 2022. As with Scaramucci and Cunha (2006) for Brazil, they find large increases in employment, reflecting the labor-intensive nature of Thai agriculture.

A few studies use an I-O model framework to explore environmental impacts. Bright and colleagues (2010) construct a two-region I-O model of the economies of Norway and its primary trading partner, the EU, and combine it with a single-product life cycle assessment (LCA) of cellulosic ethanol. The analysis quantifies changes in greenhouse gas emissions that would accompany the substitution of cellulosic biofuels for fossil fuels (FFs) by 2050, assuming that biofuel targets specified in the EU Biofuel Directive were met. The researchers modify the technology for the production of transportation fuel and also phase out the domestic pulp and paper sector to free up additional woody feedstock for cellulosic ethanol. In their study, the biofuel sector purchases this input from the forestry sector: The endowment of this feedstock is limited by its availability according to a resource assessment for 2050. Their aggressive biofuels scenario displaces as much as 58% of domestically produced transportation FFs. This leads to an approximate 50% reduction in carbon dioxide (CO_2) emissions attributable to road transportation in Norway in 2050. No estimate of the money cost of their scenarios is provided.

In a study of the Canadian economy, Mukhopadhyay and Thomassin (2011) investigate both economic and environmental impacts of production of first-generation ethanol from corn and wheat using an I-O model for the year 2010. They fix the target ethanol production at 2 BL and reduce gasoline imports by the same amount. They find a small reduction in CO_2 emissions of 3.6 tons a year and modest increases in sectoral outputs, GDP (i.e., total factor costs), and labor requirements. Surprisingly, they conclude that the scenario represents "a strong positive impact of ethanol on the economy" (p. 2832), an optimistic interpretation of these results. These modest increases represent costs, not benefits, given that they are incurred in order to satisfy the same final demand as in the baseline case.

In summary, all the economic I-O studies that are reviewed above assume exogenous target amounts of biofuel production from a feedstock. Methodologically, that means that, in addition to specifying the technology for conversion to biofuel (one or more new columns in the I-O matrix), the row corresponding to each new biofuel sector is also exogenous at a given percent of the original row for petroleum-based fuel. All the studies show only modest increases in money costs, and job creation is significant only in contexts where agricultural production is especially labor intensive.

A number of LCA studies have been conducted to evaluate alternative feedstocks and develop process-level information about their conversion to biofuels (Bright and Strømman 2009; Williams et al. 2009; Chester and Martin 2009; Baral et al. 2012). For present purposes, we look closely at three process-level studies carried out by the NREL. These recent studies (Kazi et al. 2010; Humbird et al. 2011; Dutta et al. 2011) describe biofuel production technologies and associated costs to support the EISA. These studies estimate money costs for built capital, operations, and maintenance, taking account of capacity utilization, plant life, ethanol yield, and financing arrangements. Kazi and colleagues (2010) and Humbird and colleagues (2011) estimate costs for the conversion of corn stover using the biochemical method. Dutta and colleagues (2011), by contrast, assume the conversion of southern pine trees using the thermochemical method. Kazi and colleagues (2010) arrive at a minimum ethanol selling price per liter (L) of cellulosic ethanol of US $0.90, whereas Humbird and colleagues (2011) estimate it at US$0.57 and Dutta and colleagues (2011) at US$0.54/L, all in 2007 prices. The researchers report corresponding ethanol prices per L of gasoline equivalent to be US$1.36, US$0.86, and US$0.82, respectively. (These can be compared with New York harbor regular gasoline spot price [US EIA 2013a] in 2007, which is US$0.54, the figure we will use as a point of reference, below, in our analysis.) These studies describe the mixes of input requirements along with their costs for cellulosic ethanol production and gasoline equivalent prices.

For our I-O database, we choose to use the technological assumptions and numerical estimates provided in Dutta and colleagues (2011) to describe cellulosic ethanol production technologies. We select this study for two reasons. First, it is optimistic in terms of estimating lower biofuel costs than the other studies, thus providing a lower bound of the costs that can be anticipated. Second, the technological assumptions are for the southern pine as the feedstock, and this is closer to our main woody feedstock (timber from Northeastern forests) than corn stover utilized in the other two studies.

The literature includes few evaluations of biofuel production for a geopolitical unit that is subdivided into distinct subregions, the exception being Bright and colleagues (2010), who use a two-region model. Given that economic and biomass conditions within a region as large as a country can vary widely from one subregion to the next, and that biofuel production is likely to take place on a large scale in the near future, we undertake to evaluate that spatial variability within the 13 states comprising the Northeast of the United States. Some of the I-O studies reviewed above conduct a resource assessment and others make exogenous assumptions about the quantity of biofuel that will be produced in the economy. The present modeling framework determines the amount of biofuel production endogenously, based on its cost competitiveness with petroleum-based fuel under alternative scenario assumptions.

Methodology

The World Trade Model/Rectangular Choice of Technology Model

We implement an I-O model of the economy of the Northeast that combines two modeling frameworks, an infer-regional model based on comparative advantage and a model where the choice among well-defined technologies in each region is endogenous; both are described in the Supporting Information on the Web. The economy of each state is represented by a generalized form of Duchin and Levine's (2011) RCOT model, a linear programming formulation that allows individual sectors a choice among multiple technologies, including the possibility that any combination may operate simultaneously. The RCOT model is integrated into an I-O model of consumption, production, and inter-regional trade called the WTM (Duchin 2005). The WTM is here applied to the 13 states of the Northeast region of the United States, rather than to countries comprising the world economy. Also a linear programming formulation, the WTM satisfies demand in all states by assigning production to the relatively lowest-cost states and technologies, subject to state-specific resource constraints so as to minimize total

Table 1 Model parameters and variables

	Notation	*Dimension*	*Definition*
Exogenous parameters	A_i^*	nxt	Intermediate inputs per unit of output in region i
	F_i^*	$k \times t$	Factor inputs per unit of output in region i
Exogenous variables	y_i	$n \, x \, 1$	Final demand in region i, including net exports outside of Northeast region
	π_i	$k \, x \, 1$	Factor prices in region i
	f_i	$k \, x \, 1$	Factor endowments in region i
Endogenous variables	x_i^*	$t \, x \, 1$	Output in region i
	p_i	$k \, x \, 1$	Unit prices of outputs in region i
	r_i	$k \, x \, 1$	Factor scarcity rents in region i

Note: Each of m regions is represented by n sectors, t technologies, and k factors.

regional factor use. The combined WTM/RCOT model solves for region-wide prices of goods, state-level production and scarcity rents on resources, and interstate trade flows. This combined WTM/RCOT model was first implemented by Springer and Duchin (2014).

The variables and parameters of the WTM/RCOT model are defined in table 1. The primal model takes the following form (equation 1):

$$Minimize\ Z = \sum_i \pi_i' F_i^* x_i^* \quad \forall i \tag{1}$$

subject to (equations 2, 3, and 4):

$$\sum_i (I^* - A_i^*) x_i^* = \sum_i y_i, \quad \forall i \tag{2}$$

$$F_i^* x_i^* \le f_i, \quad \forall i \tag{3}$$

$$x_i^* \ge 0, \quad \forall i \tag{4}$$

Equation (1) is the objective function that minimizes factor use, equation (2) assures that production is adequate to satisfy consumption demand, and equation (3) imposes region-specific factor constraints. The algebra for the dual price follows directly from the primal and is not shown explicitly. Note that the asterisk (*) indicates the presence of alternative technologies for one or more sectors. Thus, the matrix A* is rectangular, given that it may have several technologies, in separate columns, for producing a particular good, but it will have only one row for that good on the assumption that purchasers are indifferent as to how it was produced.

Database

We compile an I-O database for 13 states, 18 economic sectors, one of which is represented by three alternative technologies, and four factors of production. The classification schemes are given in tables S2, S3, and S4 in the supporting information on the Web. State-level I-O tables for 2009 (obtained from Economic Geographics 2012) are aggregated to the sectoral classification, and A, F, and y are derived for all states. Labor force and wage rates reported by the Bureau of Labor Statistics (2010) are the basis for labor coefficients in person-years and wage rates as well as the labor endowment. We next quantify endowments (f) and unit prices (π) for two sources of cellulosic biomass feedstock and the technologies for processing them (columns in A* and F*) into a liquid fuel for transport.

The database includes three alternative technologies for production of liquid fuel for motorized transportation. One of these fuel alternatives is gasoline. We disaggregate it from the more inclusive sector for the production of petroleum products and estimate the corresponding final demand based on refinery output (US EIA 2013b) for the production of gasoline from crude oil. We constrain its output in different states according to current refinery capacities from the same data set. We use the New York harbor gasoline spot price (US EIA 2013a) and the gasoline equivalent price of cellulosic ethanol specified by Dutta and colleagues (2011) to represent the cost differential between these products. (According to a petroleum expert at the US EIA, the spot price is the best approximation to the refinery gate price, given that it reflects the point in the supply chain where petroleum products are traded with the expectation of immediate, physical delivery of the product [Klein 2013]; naturally, this price is lower than the retail price of gasoline at the pump [US EIA 2013b].) Using the spot price of gasoline as the effective cost of its production, we increase the coefficients for producing cellulosic ethanol by the ratio of the ethanol price to the gasoline spot price. The resulting total (converted to money values) of the corresponding columns of coefficients in A* plus F*, in the case of the biofuels in question, is, by design, greater than 1. (As discussed in more detail below, this is a departure from the standard assumption among I-O practitioners that the sum of intermediate and factor inputs for any sector must equal exactly 1.0 if all quantities are measured in money values.) This representation reflects the reality that the ethanol fuel is more costly to produce at current prices than the equivalent amount of gasoline from refined petroleum.

As with Bright and colleagues (2010), we distinguish two woody biomass resources: timber from new forest growth and woody wastes from industry. Other cellulosic feedstock candidates, such as switchgrass, are not considered in this study. We treat these resources as factors of production, rather than intermediate products, and add two corresponding rows to F*. We use state-specific wage rates (Bureau of Labor Statistics 2010) and feedstock prices (Dutta et al. 2011) to construct the factor price vector, π. Based on unpublished work at the Idaho National Laboratory, Dutta and colleagues (2011) estimated a unit price for obtaining the feedstock. Their estimate includes not only the value of the feedstock, but also the costs of harvest and collection, in-field preprocessing, transportation and handling, and costs at the plant for receiving, storage and queuing, and in-feed preprocessing. We use only the payment to the grower as the unit price of the feedstock in our analysis and distribute the other cost components as purchases from sectors, such as forestry and transportation, in the A* matrix. The same unit price for the feedstock is assumed for all states because no information is available to make a finer distinction. For feedstock endowments (f), we use net forest growth by state reported in the Forest Inventory and Analysis Database (USDA Forest Service 2012). The supply of wood waste by state is taken from geographical information systems (GIS) maps produced by the NREL (2009).

The inputs required for ethanol production from cellulosic biomass are taken from the NREL report by Dutta and colleagues (2011). We generate two columns in A* and F* on the basis of this information, one employing timber from forests and the other using woody wastes. The major intermediate inputs to cellulosic ethanol production include chemical products and a variety of services. Each of the new sectors uses one or the other of the two new factors of production.

Production of liquid fuel for motorized transport using the three technologies in each state will be determined in model calculations not only by their costs of production, relative to one another and to costs in other states, but also by the availability of the factors of production (components of f) on which each relies. Capacities of refineries of gasoline and their utilization rates within the region are provided in US EIA publications (US EIA 2012, 2013b). The availability of timber from forest growth and from cellulosic waste is shown in table 2. The former is measured as the annual net change in the mass of live trees. We assume that no deforestation and no use of reserved forests take place and that all net forest growth that is not exploited for other purposes can be utilized for biofuel production. Removing only net growth (growth minus removals) assures a sustainable supply of feedstock from the region's forests. Available woody biomass (a component of f) is calculated using the Forest Inventory and Analysis Database (USDA Forest Service 2012) as follows:

$$\frac{a}{b} \times (c - d) \times e$$

where the variables measure the quantities on forested land of

(a) Above-ground dry weight of live trees (at least 1 inch d.b.h.^{2}/d.r.c^3), in metric tons
(b) Net volume of live trees (at least 5 inches d.b.h./d.r.c.), in cubic meters (m^3)
(c) Average annual net growth of live trees (at least 5 inches d.b.h./d.r.c.), in m^3
(d) Average annual removals of live trees (at least 5 inches d.b.h./d.r.c.), in m^3
(e) Share of nonreserved net growth in total net growth, which is 94% in the Northeast.

Availabilities of the main sources of the second feedstock, cellulosic waste, are shown in table 2: They include crop residues, forest residues, primary mill residues, secondary mill residues, and urban wood waste. In estimating the endowment, we assume that half of available cellulosic waste can be used as feedstock. Note that the feedstock from forests is 4 times that from cellulosic wastes, and this ratio is reflected in the results.

Scenarios and Results

Scenarios

An initiative similar to the mandate of the U.S. Congress for 2022 was taken by the EU in 2003 with the goal of substituting 2% of conventional fuels by biomass by 2005 and 5.75% by 2010 (European Parliament and The Council Of The European Union 2003). This initiative has not achieved its goals (Commission Of The European Communities 2007) owing, according to Edwards and colleagues (2008), to the lack of a support system to compensate producers for the higher cost of producing biofuels. Such support can be provided by subsidies or other monetary incentives or by regulations that prohibit or require certain practices. As described above, cellulosic ethanol is more expensive to produce (per unit of energy provided) than gasoline, and this cost differential is captured by the reference prices cited earlier. Based on those numbers—even assuming that the required quantities of feedstocks are available at those prices and that there will be adequate demand for the amounts of ethanol produced—the cost of producing the ethanol equivalent of 1 L of gasoline at current prices for inputs exceeds the price of gasoline by approximately US$0.28/L (US$0.82 vs. US$0.54), or approximately 50%.

Our objective for the scenario analysis is to discover the amount of subsidy or type and extent of regulation that could enable the Northeast to exploit its full endowment of renewable woody biomass for biofuel and determine the implications for costs and prices. The first experiment stimulates cellulosic ethanol production by providing a monetary subsidy to producers. The subsidy is represented in a row of each state's F* matrix, with the amount of subsidy appearing (as a negative value) in the column corresponding to the sector receiving it. This scenario is run repeatedly with the subsidy, starting at a low level and increasing incrementally until the entire endowment of feedstock is utilized. For the second experiment, we assume that gasoline imports into the region, which start at their actual level, are gradually reduced, forcing the production of additional transportation fuel within the region, until further reduction of gasoline imports yields no feasible solution because even the most costly means of producing liquid fuel within the region has run into factor constraints. In both experiments, the scenario solutions provide the changes in the price of the fuel (and in other prices) as well as the distribution of production among the states, reflecting their differential costs of production.

Our scenarios place no exogenous restriction on the ratio of ethanol that can be blended with gasoline. The EISA mandating the use of cellulosic ethanol (H.R. 6—110th Congress 2007) also contains objectives on producing flex-fuel engines capable of handling mixtures with up to 85% ethanol content

Table 2 Cellulosic feedstock availability by weight (10^3 metric tons)

		Cellulosic waste					
	Forest net change	*Crop residues*[a]	*Forest residues*[b]	*Primary mills*[c]	*Secondary mills*[d]	*Urban wood*[e]	*Total*
Connecticut	1,888	0	12	38	24	376	450
District of Colombia	0	0	0	0	0	56	56
Delaware	361	308	48	18	8	85	466
Maine	315	0	3,317	419	15	133	3,885
Maryland	2,426	806	264	184	33	624	1,911
Massachusetts	2,980	0	106	106	52	687	950
New Hampshire	1,757	0	445	278	18	126	867
New Jersey	1,447	130	12	7	58	894	1,102
New York	9,232	660	1,208	1,025	119	2,041	5,053
Pennsylvania	11,889	1,357	1,661	1,357	127	1,238	5,740
Rhode Island	423	0	3	13	6	109	130
Vermont	2,596	0	287	87	9	65	447
Virginia	10,659	747	3,358	2,172	62	812	7,151
Total	45,975	4,009	10,721	5,703	530	7,246	28,208

Note: See text for discussion of factor endowments.
Source: USDA Forest Service (2012) and NREL (2009).

[a] Includes corn, wheat, soybeans, cotton, sorghum, barley, oats, rice, rye, canola, dry edible beans, dry edible peas, peanuts, potatoes, safflower, sunflower, sugarcane, and flaxseed.

[b] Includes logging residues and other removable material left after carrying out silviculture operations and site conversions.

[c] Includes wood materials and bark generated at manufacturing plants.

[d] Includes wood scraps and sawdust from woodworking shops: furniture factories, wood container and pallet mills, and wholesale lumberyards.

[e] Includes wood residues from municipal solid waste, utility tree trimming and/or private tree companies, and construction and demolition sites.

and corresponding infrastructure changes, as needed, for distributing the mixed fuel. Infrastructural changes have not been taken into account in our analysis.

Results

The outcomes show that a substantial amount of cellulosic ethanol can be produced in the Northeast region under both sets of scenarios. As a context for evaluating the results, we provide, in table S5 in the supporting information on the Web, relevant quantities of liquid fuels and unit prices.

Figures 1, 2, and 3 display results from the scenarios regarding subsidies, and figures 4 and 5 show the outcomes in the case of import restrictions. We now revisit the research questions and offer answers to them.

Regarding the first question: Using the total net annual forest growth and half of woody wastes, the Northeast can produce a significant amount of advanced biofuel, namely, up to 13.37 BL (gasoline equivalent) of cellulosic biofuel, as illustrated in figures 1 through 4. (This requires producing 20.28 BL of cellulosic ethanol, using the energy content figures in Dutta and colleagues [2011].) This outcome, corresponding to the full utilization of the available feedstock, can be achieved by either subsidies or the imposition of import restrictions: It would substitute for nearly 17% of total motor gasoline consumption in the Northeast (table 3), meaning a blend with gasoline of 17% ethanol. This quantity of ethanol is the energy equivalent of more than half the amount of gasoline that Northeastern refineries produced in 2012. This quantity, 20.28 BL of cellulosic ethanol, also corresponds to over 25% of the advanced biofuel production and over 33% of the cellulosic biofuel production mandated by the U.S. Congress as the target for the entire nation by 2022. Ethanol production by state, assuming full utilization of feedstock, is shown in table S6 in the supporting information on the Web.

Table 3 Crude oil refinery capacity in Northeast states in 2007–2012 (10^6 liters)

State	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*
DE	10,573	10,573	10,573	0	10,573	10,573
NJ	38,014	38,014	38,014	29,603	31,797	31,797
PA	44,850	44,850	44,850	44,850	44,850	23,800
VA	3,450	3,689	3,736	3,847	3,847	0
Total NE	96,887	97,141	97,189	78,301	91,084	66,170

Note: Capacity in Delaware is zero in 2010 because the state's only refinery, Delaware City refinery, closed in 2009 because of operating losses and was reopened by a new owner in 2011. Similarly, Virginia's only oil refinery stopped operation in 2012, sold to a new owner to be used as a storage depot and a transportation hub.
Source: US EIA (2012).
DE = Delaware; NJ = New Jersey; PA = Pennsylvania; VA = Virginia.

Figure 1 shows the progression in the increase in ethanol production in the Northeast region, and the corresponding decrease in the production of gasoline, as the subsidy increases from US$0.17 to US$0.29/L. The states most affected by this shift are identified for gasoline in figure 2 and for ethanol in figure 3. Fully 80% of the biofuel originates from the forest feedstock (table S6 in the supporting information on the Web),

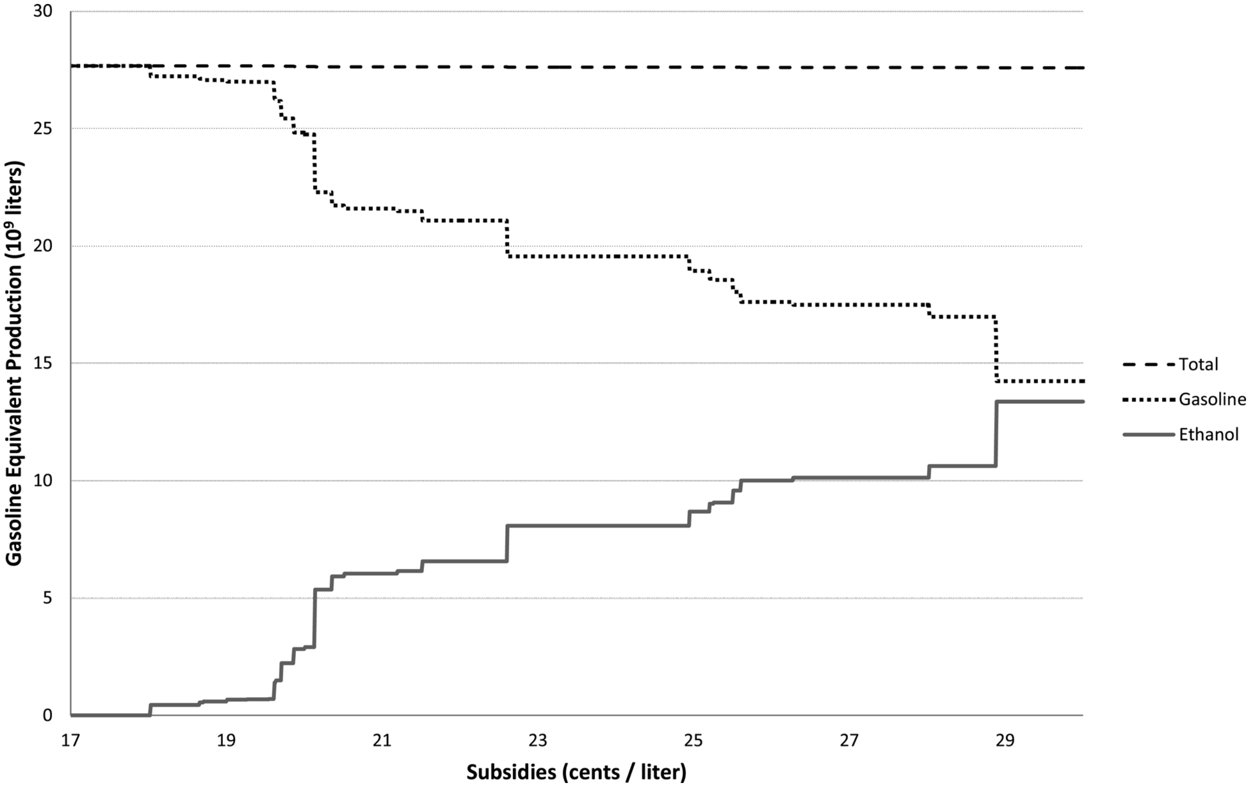

Figure 1 Fuel production in the Northeast for different amounts of ethanol subsidy (10^9 L of gasoline equivalent).
Source: Model results.

and the major producers of cellulosic biofuels from timber are New York, Pennsylvania, and Virginia (see figure 3; note that ten states are grouped into the residual category, All other). This is as expected, given that these states have the largest net growth of forests. Maine, as the lowest-cost producer, is the first state to start producing ethanol, followed by Rhode Island and Vermont, all contributing only small quantities of cellulosic ethanol because of limited feedstock endowments.

The imposition of restrictions on gasoline imports from outside the Northeast necessarily stimulates production of liquid fuel within the region. This is seen in figure 4, which shows that a small reduction in imports can be compensated by increased gasoline production within the region. However, when the reduction exceeds 3.6% (or 2.8 BL), all the deficiency is substituted by production of ethanol. Beyond a 21% reduction in gasoline imports (or 16.3 BL), production of both additional gasoline and additional ethanol in the region becomes physically infeasible as the region's production limits have been reached, both the capacities of petroleum refineries producing gasoline and the renewable endowment of cellulosic feedstock.

Regarding the second question: The cost of producing cellulosic ethanol needs to be evaluated, relative to the price of gasoline, which is known to be volatile. Based on our results (see figure 1), a subsidy of at least US$0.18/L is needed to stimulate any production of cellulosic biofuel in the region. This is roughly the difference between the reference (gasoline equivalent) price per L of cellulosic ethanol and the reference price of gasoline (a difference of US$0.28). The reason that some production can be achieved at a subsidy of only US$0.18 is that some states have lower costs than others, even assuming the same technological processes, based on their factor prices (such as the average wage rate). Our analysis shows that to ensure full utilization of the region's cellulosic feedstock requires, however, nearly US$0.29 of subsidy per L to the sector producing cellulosic ethanol, assuming that the subsidy is the same for all states.

Restricting imports of gasoline from outside the Northeast results in comparable outcomes. Our results show that a small quantity (less than 5% of imported gasoline) of cellulosic biofuels could be produced within the region at a lower cost per L of gasoline equivalent than the region's highest-cost gasoline producer, Pennsylvania. However, figure 5 shows that there is a large increase in unit price as higher-cost producers begin ethanol production. Beyond a 5% substitution for gasoline imports, the unit price increases only incrementally until the entire feedstock is utilized, as seen in the trade-off curve (figure 5) of fuel price as a function of import restrictions.

Regarding the third question: Here, we find that the introduction of cellulosic ethanol production creates some additional employment in the region, but only negligible amounts, a finding consistent with that of Neuwahl and colleagues (2008) for the European context.

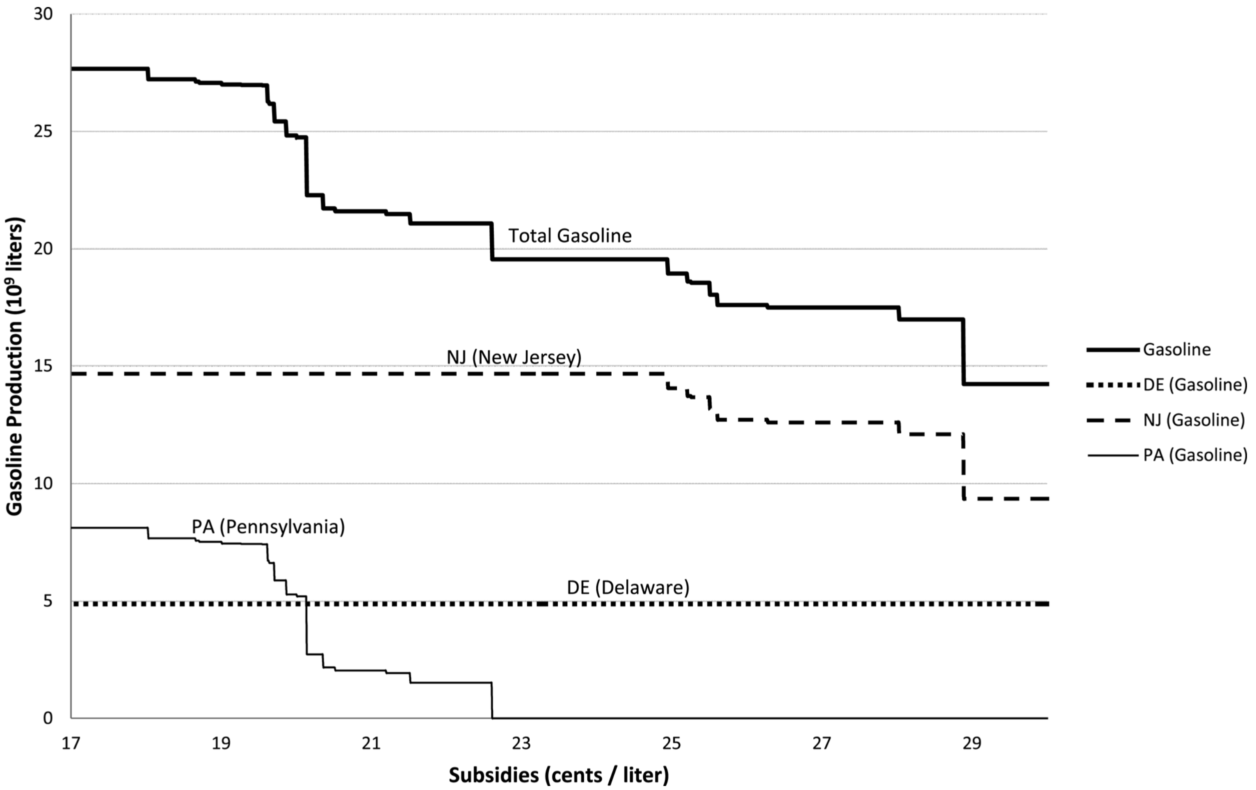

Figure 2 Gasoline production by major producers for different amounts of ethanol subsidy (10^9 L of gasoline equivalent).
Source: Model results.

Discussion and Conclusions

We conclude that one of the two economic components, a production subsidy or regulation restricting gasoline imports, is necessary to make the production of cellulosic ethanol production competitive with gasoline in even the lowest-cost state in the region. To utilize progressively larger portions of the available feedstock requires increasing the size of the subsidy or the stringency of the import restriction given that higher-cost states are called upon to produce. The targeted levels of ethanol production cannot be achieved in a market economy only by setting targets and fining refineries for not mixing nonexistent biofuels (Wald 2012).

Under the technological and factor price assumptions of our scenarios, complete independence for liquid fuels for motor transport looks implausible for the region if only sustainable sources of cellulosic feedstocks are to be utilized. However, potential sustainable production in the Northeast alone can account for a large share of the goal for nation-wide cellulosic ethanol production mandated by the U.S. Congress. If feedstock constraints are relaxed by introduction of additional sustainable sources, such as switchgrass, a significant increase beyond the production estimated in this study is possible. It appears likely that technologies for production of cellulosic ethanol can be improved to reduce costs, a conclusion shared by Baral and colleagues (2012). Among the NREL articles on production technologies for cellulosic ethanol and their unit costs (Kazi et al. 2010; Humbird et al. 2011; Dutta et al. 2011), the more recent the study, the lower the production cost, suggesting that competiveness of ethanol is, in fact, improving.

The other I-O studies reviewed analyze the cost or impact on employment of a given amount of biofuel production that is specified exogenously, typically for a single region. In our framework, the amount of production is determined endogenously with a number of production options, namely, the choice among 13 states with different costs of production and three alternative technologies in each state. This analytic framework makes it possible to pose a broader set of questions, in particular, to examine the impacts on production quantities and unit prices of progressively steeper subsidies or legislative constraints. It also can identify when mandated goals are likely to be unachievable, whether owing to physical constraints or lack of economic competitiveness.

Our modeling framework introduces several methodological innovations for I-O modeling that can be valuable as the analysis of substitutes for petroleum products intensifies. One is the I-O model of inter-regional trade based on comparative advantage, the WTM, applied here to a subnational spatial setting consisting of 13 states. Another is the choice among alternative technologies available to each state by generalizing from a square I-O matrix to a rectangular one. Whereas this feature can be easily exploited even in a one-region model, it runs counter to the widespread, but erroneous, conviction that an I-O matrix

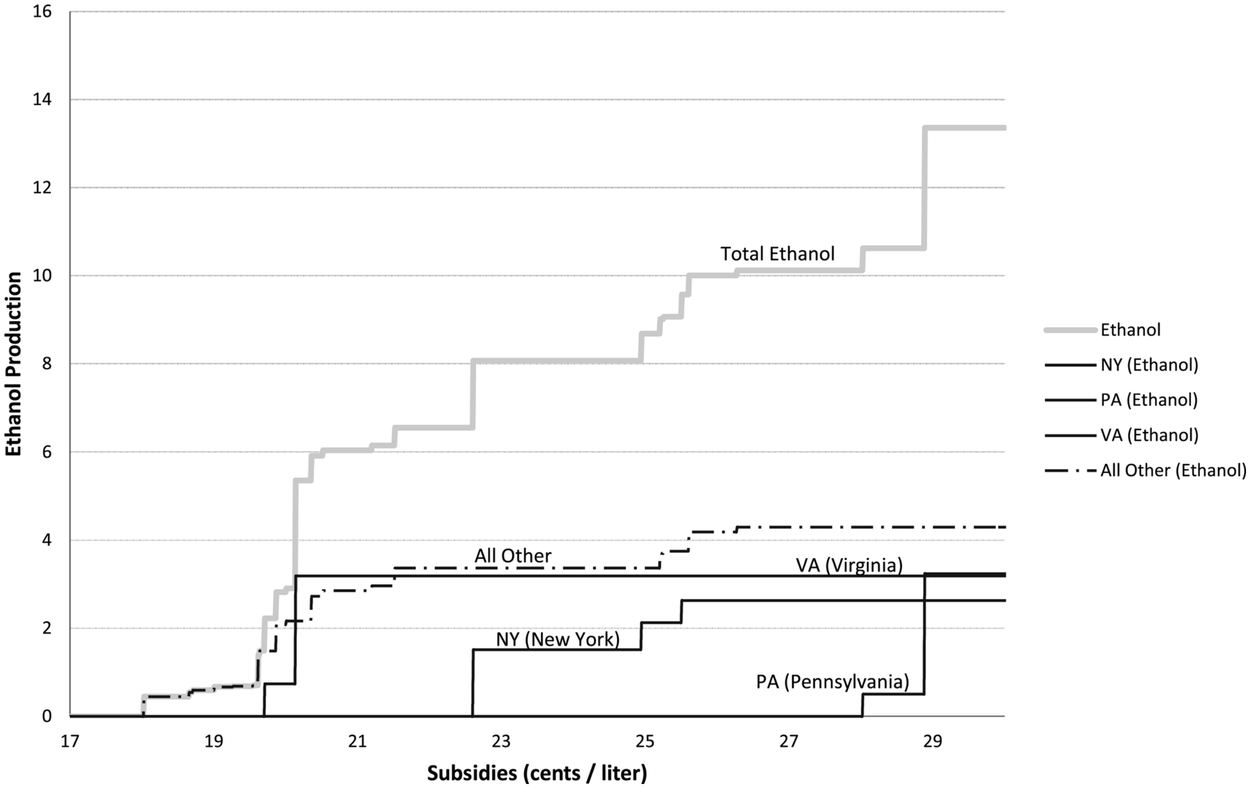

Figure 3 Ethanol production by major producers for different amounts of ethanol subsidy (10^9 L of gasoline equivalent).
Source: Model results.

must, by definition, be square. The choice among alternative technologies (i.e., use of a rectangular matrix) requires a criterion for choosing among them, and cost-minimization is an obvious criterion for an economic analysis. These two model features allow for a substantial increase in the scope and flexibility of I-O studies.

We have introduced an additional methodological innovation that runs counter to another widespread, but erroneous, conviction: that I-O coefficients for a given sector must add to 1.0 (when all inputs are measured in money values). This conviction is related to the fact that most I-O studies are conducted for past time periods, such that every sector does take in exactly as much revenue as it pays out for inputs (including profits). When examining scenarios about the future and allowing the explicit choice among alternative technologies, it is evident that, in general, some will be more or less costly than others. That reality is readily achieved by allowing technical coefficients for alternative technologies—when measured in money values—to total to a number greater or less than 1.0. Less-costly options reflect technological advances and earn extra profits (in the form of rents), and more-expensive alternatives will be utilized if less-costly ones have run out of factors of production before total demand can be satisfied. This procedure is also valuable for introducing new technologies that are potentially lower cost than other options, but may rely on factors that are in limited supply. We believe that the wider adoption of this procedure (i.e., column sums that, if evaluated in money values, are different from 1.0) will turn out to be useful in many kinds of inquiries.

The present study depends upon a number of assumptions that can be relaxed in further investigations. Crude oil prices change, and if they are systematically higher in the future while the cost of producing ethanol falls, the size of subsidies required or restrictions on imports could fall substantially. One could also foresee changes in the amounts of timber removed from forested lands for other purposes, making more available for ethanol production. This is the assumption made in the study by Bright and colleagues (2010), where paper production in Norway is eliminated to increase the feedstock availability for biofuels. Of course, there is also the possibility of increasing output by deforestation, or allowing feedstock production to compete for land and water with crop production. Both of these eventualities are legitimate concerns posed by the use of biomass for energy, and their prospect merits close attention. On the technical side, there is room for substantial improvement in representing production characteristics. We assume that the two sources of woody feedstock have comparable cellulose content per unit of mass and biofuel yields; a more refined study would distinguish their attributes and even differentiate among the mixes of tree species in different states, not to mention considering additional ethanol feedstocks. That level of feedstock detail can be reflected in I-O studies once process-level studies provide input structures in physical units that distinguish the technologies for transforming them to biofuels.

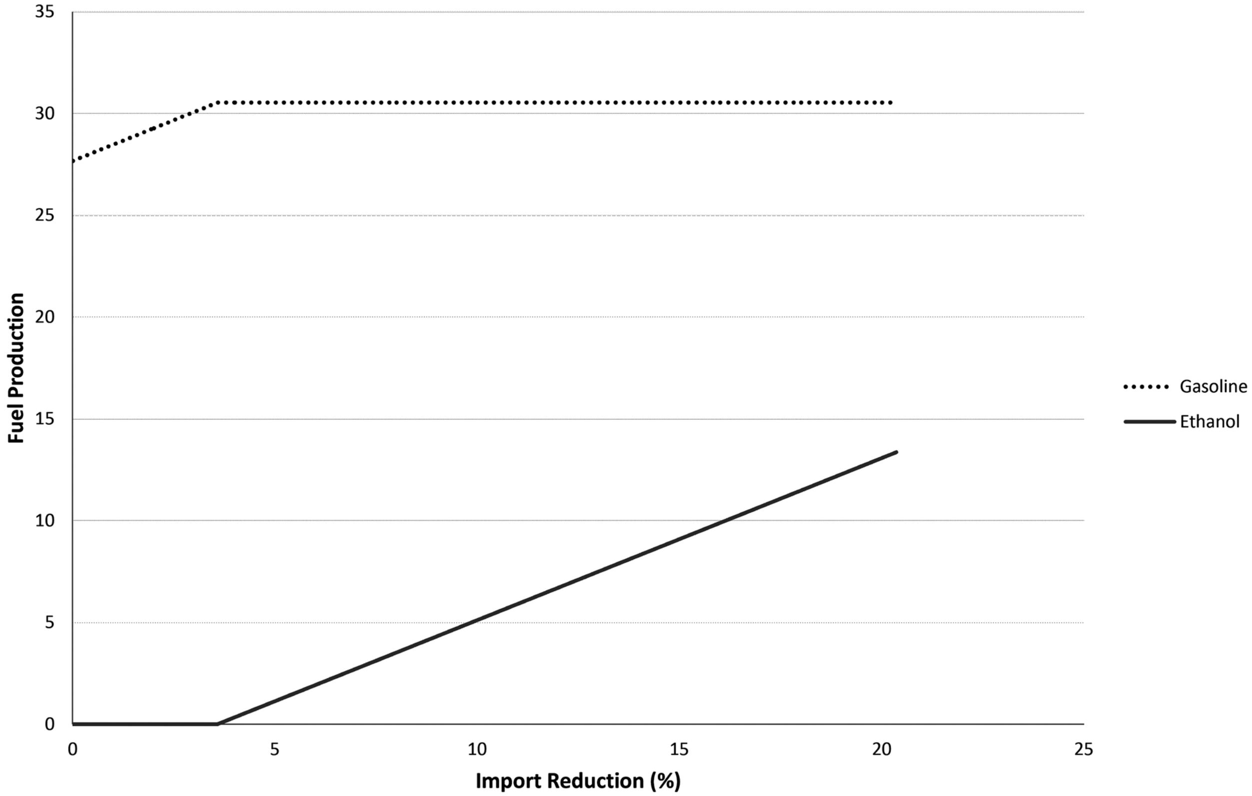

Figure 4 Fuel production for different amounts of import restriction (10^9 L of gasoline equivalent).
Source: Model results.

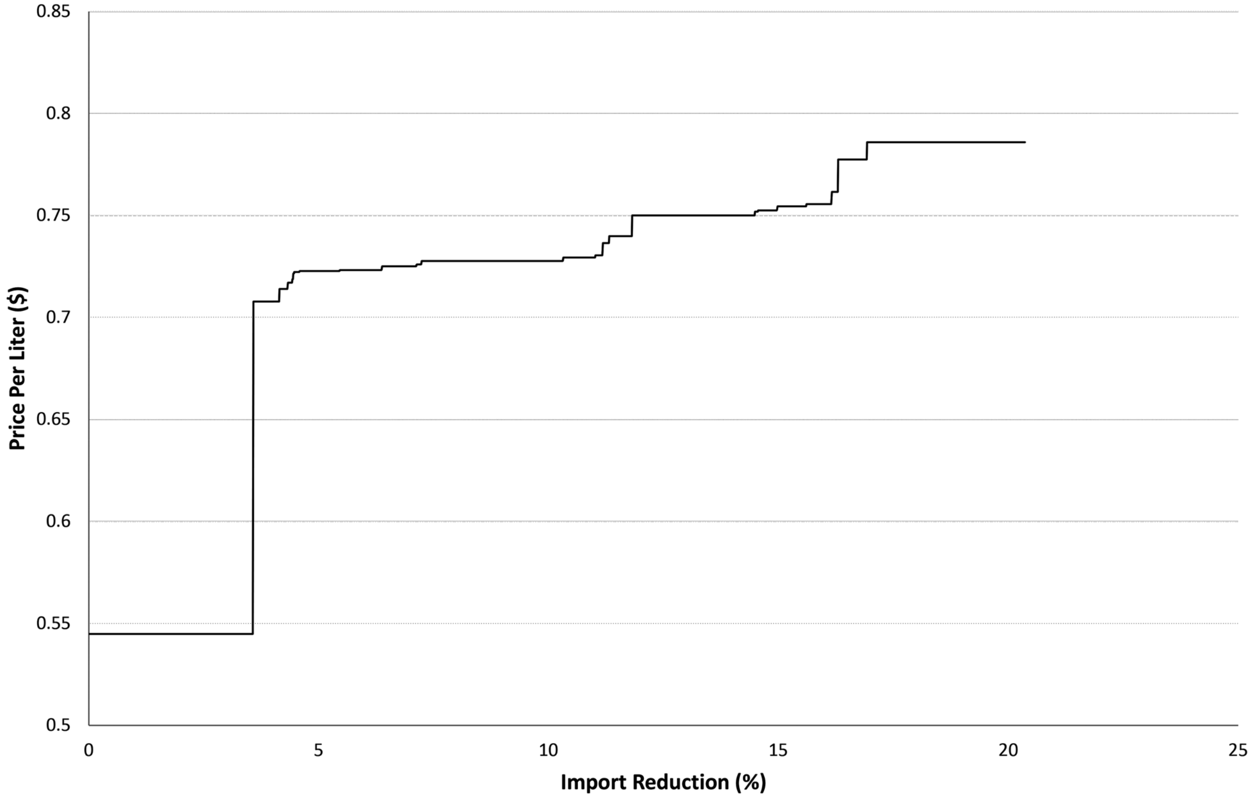

Figure 5 Fuel price for different amounts of import restriction (US$/L of gasoline equivalent).
Source: Model results.

Acknowledgment

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Notes

1. We use metric units throughout the article, converting from other units as necessary.
2. Diameter at breast height.
3. Diameter at root collar.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information provides information about the world trade model with rectangular choice of technologies. It contains six tables. Table 1 is about forest area and volume of timber by U.S. region. Table 2 is about regional classification. Table 3 is about sectors and technologies. Table 4 is about factors of production. Table 5 is about liquid fuel prices and volumes. Table 6 is about cellulosic ethanol production by state under full utilization of feedstock.