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Impacts of US biodiesel mandates on world vegetable oil markets

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ABSTRACT

In this paper we seek to understand the impact of expanded use of soybean oil biodiesel to address biofuel mandates on global vegetable oil markets, and in particular on the demand for palm oil. An open-economy equilibrium model is derived to investigate the market effects of biodiesel expansion on related energy and vegetable oil markets. The model is calibrated to represent the recent benchmark data in calendar year 2014. The simulation estimates suggest that the expanded use of soy oil for biodiesel in the US will have considerable impacts on world vegetable oil markets. The majority of the vegetable oil replacement is likely to occur through substitution of palm oil under a wide range of plausible elasticity values on the demand for vegetable oil and the demand substitution between soy oils and palm oils.

1. Introduction

Under the recent Renewable Fuel Standards (RFS) program, the US Environmental Protection Agency (EPA) is finalizing the volume requirements for biomass-based diesel in calendar years from 2014 to 2017. The US biodiesel mandates grow steadily, increasing every year from 1 billion gallons (BG) by 2012 up to 2 BG by 2017. Driven by the rising mandates, biodiesel production in the US rises substantially from less than 0.5 BG in 2007 to 1.24 BG in the end of 2014. The majority of U.S. biodiesel has been produced from soybean oil, which is crushed from soybeans. On the one hand, increases in uses of soy oils for biodiesel could come primarily from reductions in the use of vegetable oils for food and feed purposes, leading to a so called food versus fuel trade-off that raises ethical concerns about the consequences of expanded soy biodiesel uses. On the other hand, the expansion of oilseed production is a major driver of global deforestation, calling for the life cycle re-assessment of GHG emissions saving for biodiesel from different feedstocks and pathway.[2]

The purpose of this paper is to provide an economic analysis of the incremental biodiesel mandate on related world vegetable oil markets, and its welfare implications on the US economy. Facets of this topic have been the subject of a few studies. Drabik et al. (2014) setup a partial equilibrium model, linking oilseed feedstocks with biodiesel market. They examine the impacts of exogenous crude oil shocks on world oilseed markets (i.e., soybeans and canola) through transmission of the biodiesel-feedstock linkage. Their analytic results show that the impacts depend on relative elasticity of world meal demand and canola supply. Kruse (2011) looks at two possible future scenarios regarding the opportunity of biodiesel production and the expansion of biodiesel mandate given current global economic growth and crude oil price projections. The US biodiesel module used in his work is a partial equilibrium model with behavioral supply and demand equations and an endogenous biodiesel price. To meet 3.3 BG of biodiesel mandate, about 80% of the increase of feedstock comes from soybean oils (31%), corn oils (22%), and palm fatty acid distillate (26%). Animal fats, yellow grease and other grease together supply another 16%, while the remaining is refined from canola and palm oil.

Earlier studies that are the basis for the administration of lifecycle based biofuel policies in the United States and California have predicted a limited impact of US soy oil consumption on vegetable oil production. The EPA study finds that expanding production of soy biodiesel by 540 million gallons would primarily lead to reduced use of vegetable oil and expanded soy oil production, and would have a modest impact on palm oil production (CARD, 2009). For every additional 1000 metric tons of soy oil used to produce biodiesel in the U.S. relative

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2 The two largest sources of vegetable oil, soybeans and palm oil, are both associated with substantial, and quite distinct patterns of deforestation. While soybean expansion has happened primarily in South America where it has competed with pastureland and forest, oil palm expansion has occurred in Southeast Asia, where its expansion has been associated with drainage and deforestation of peat forests.

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to the baseline, soy oil production expanded by 288 metric tons, palm oil increased by 79 metric tons, rapeseed oil increased by 51 metric tons, other sources of oil increased by 55 metric tons, and 526 tons were not replaced, as non-biodiesel vegetable oil consumption dropped in response to higher prices. Other projections (Birur et al., 2009; Hertel et al., 2010b; Taheripour et al., 2010; Beckman et al., 2012), in particular the GTAP study used by the California Air Resources Board (Tyner et al., 2010), do not differentiate separate sources of vegetable oil, although they do have a detailed treatment of oilseed meal markets required to accurately capture the changes on the meal demand side.

A number of studies about land use changes driven by US biofuel production have placed less emphasis on oilseeds (Elobeid et al., 2007; de Gorter and Just, 2009; Hayes et al., 2009; Keeney and Hertel, 2009; Hertel et al., 2010a, 2010b; Fabiosa et al., 2010; Timilsina et al., 2010; Chen et al., 2011; Villoria and Hertel, 2011; Khanna et al., 2016), because these have been expected to play a relatively minor role in U.S. biofuel expansion, which has been expected to come primarily from either corn, or ultimately from biomass.[3] However, events of the last few years have shown the potential for biodiesel and vegetable oil based renewable diesel to play a substantially larger role than previously expected. Recent efforts to evaluate the impact of U.S. biodiesel production on land use change and associated carbon emissions have led to considerable improvements in economic models, taking into careful consideration of the demand dynamics of animal feed markets (Beach and McCarl, 2010; Taheripour et al., 2011, 2013). However, an area which has been examined less carefully is the potential for other consumers of vegetable oil, outside the fuel and animal feed sector, to switch to other sources of vegetable oil. Biodiesel demand drives a wedge between demand for oil and demand for protein meal. Given that the changes in demand for oil can be quite large, there is a potential for a significant imbalance to arise. In 2013 the use of preliminary data suggests that biodiesel use grew by approximately 40%, of which more than half came from soybean oil. The additional 800,000 metric tons of soy oil being used for biodiesel represent a large and rapidly growing share of U.S. soybean oil production, and depending upon pending legislative, regulatory and judicial decisions, the potential remains for policy driven biodiesel demand to surge again in coming years (Irwin and Good, 2013). Rebalancing demand for oil and protein meal will lead to either a dramatic reduction in consumption of vegetable oil in other sectors or alternatively substitution of other sources of vegetable oil with lower meal to oil ratios. To the extent the latter occurs, increasing demand for soy biodiesel will play out in expanded palm production rather than expanded soybean production. This will in turn drive land use changes in different regions of the world, and is thus important to accurately model land use change associated with biodiesel production.

In this paper we consider to what extent additional vegetable oil demand will alter production of alternative sources of vegetable oil, particularly palm oil. Our analysis considers the two largest global sources of vegetable oil, which represent the extreme ends of the spectrum: soybeans, for which the primary economic value is the protein meal, and oil palm, for which the primary economic value is the vegetable oil. Palm oil is not the only alternative source of vegetable oil to soy oil, but it is particularly important both because it accounts for 1/3 of world vegetable oil production and is the fastest growing source of vegetable oil on the global marketplace (USDA, 2006), and because in contrast to soybeans and to a lesser oil extent rapeseed or canola, palm oil derives most of its value from the oil, rather than a protein meal byproduct, and as such is likely to be more responsive to changes in demand for vegetable oil.

This paper constructs a simple multi-market equilibrium model that applies and extends the analytic setup in Cui et al. (2011). The extended model incorporates the joint product feature of the oilseed crushing technology. We use this model to provide both qualitative and quantitative estimates of increasing biodiesel mandates on related energy and vegetable oil markets, in particular, palm oil. The model specifications allow endogenous determinations of equilibrium quantities and prices for crude oil, biodiesel, agricultural feedstock. Moreover, the model considers a scenario that allows the US biodiesel production to use imported palm oils as alternative feedstocks, while assuming perfect substitution between soy oil-based biodiesel and palm oil-based biodiesel. We calibrate the model to represent a recent baseline calendar year 2014. By varying the increment of biodiesel mandates proposed in recent RFS requirements, we explore how the increasing mandate affects equilibrium quantities and prices of world vegetable oils. We then investigate the robustness of our conclusions by varying with the values of two sets of parameters: one is the unconditional elasticity of demand for vegetable oils, and the other is the demand elasticity of substitution between soy and palm oils. A Monte Carlo simulation on selected key parameters is conducted as well.

Our results show how the impacts of increasing biodiesel production on soy meals and oils are related to the impacts on palm oil, depending upon the joint production technology of the oilseed crushing industry, the relative elasticity of world demand and supply of palm oils, and the demand elasticity of substitution across alternative vegetable oils. The simulation estimates suggest that the expanded use of soy oil for biodiesel in the US will have considerable impacts on world vegetable oil markets. The majority of the vegetable oil replacement is likely to occur through substitution of palm oil under a wide range of plausible elasticity values.

The remainder of this paper is organized as follows. The next section presents the analytic model setup that links the oilseed crushing industry with the biodiesel refining sector. The model calibration is summarized in Section 3. Simulated results about the market impacts of the increasing biodiesel mandates are shown in Section 4. The last section concludes the paper.

2. The model

The model is a stylized economy with three basic endowments: a numeraire good, agricultural feedstock, and crude oil. There are two main categories of agricultural feedstock: soybean, and palm oil. Soybean oil, which is crushed from soybean, could be used to produce biodiesel. The primary product crude oil is refined into diesel and others that are grouped as petroleum by-products. Transportation fuel is obtained by blending the intermediate products biodiesel and fossil fuels. Biodiesel from soybean oil together with its close substitute diesel are two complementary components of the diesel composite purchased by consumers if biodiesel mandates are binding.

2.1. Production

We construct a simplified multi-market equilibrium model with two regions: the US and the Rest of World (ROW). To capture the status quo that the US does not produce palm oil, we assume away its domestic production. Throughout this paper, we maintain the assumption that there is no international trade of biodiesel. In addition, we postulate that there is trade in crude oil, but no trade in the refined fossil fuels, which is a fair approximation of the status quo.[4] The assumption of constant returns to scale and no capacity constraints on the oilseeds crushing technology introduced shortly makes the interregional distribution of crushing soybeans undetermined in the equilibrium. Hence, we only consider the trade of soybean oils and meals instead of beans.[5] To sum

[3] Biofuel production in the European Union (EU) has been primarily through expansion of biodiesel, and analysis of land use changes driven by EU mandates has focused much more extensively on the fluidity of different vegetable oil sources (Timilsina et al., 2010; Al-Riffai et al., 2010; Laborde, 2011).

[4] The net trade of refined petroleum only accounts for less than 5% of total consumption over the period 2007–2013.

[5] Alternatively, one could allow beans to be tradable, but not for soy oils and meals. In this scenario, however, the excess supply of meals, as a result of the increasing crushed of beans, may cause a substantial drop in the domestic price of meals.

up, the ROW exports both crude oil and palm oil, and it imports soybean oils and meals from the US.

2.1.1. Agriculture sector

We postulate an upward sloping supply function of US soybean, denoted by $S_s(p_s)$, where p_s is the domestic price of soybeans. Soybeans can be crushed into meals and oils. The former is delivered into food/feed uses, while the latter with alternative food purposes can be converted into biodiesel. We assume a fixed coefficient technology defined as follows:

$$Q_{ml} = \min[\alpha_{ml} x_s, z_{ml}] \tag{1}$$

$$Q_{so} = \alpha_{so} Q_{ml}/\alpha_{ml} \tag{2}$$

where α_{ml} and α_{so} denote the units of meals and of soybean oils per unit of crushed beans, respectively. x_s is the amount of crushed soybeans, and z_{ml} is the amount of other inputs used in the crushing process. Perfect competition gives rise to the zero profit condition of the oilseed crushing industry:

$$\alpha_{so} p_{so} + \alpha_{ml} p_{ml} = p_s + \alpha_{ml} w_{ml} \tag{3}$$

where (p_{so}, p_{ml}) denote the prices of soybean oils and of meals, and w_{ml} is the price of other inputs used in the crushing industry.

2.1.2. Biofuel refining sector

The refinements of biodiesel from soybean oils assume a Leontief technology (fixed coefficient). The output of biodiesel produced from soybean oils is written as:

$$x_{bd,so} = \min[\alpha_{bd} x_{so}, z_{bd}] \tag{4}$$

where $x_{bd,so}$ is the output of biodiesel from soybean oils; x_{so} denotes the units of soybean oils used as a primary feedstock. z_{bd} represents the amounts of other inputs used per unit of biodiesel output. α_{bd} denotes the production coefficient of biodiesel refining industry. Following the similar definition in Lapan and Moschini (2012),[6] we express biodiesel output $x_{bd,so}$ in terms of the diesel-energy-equivalent gallons (DEEGs) to reflect its lower energy content relative to diesel. The energy content is accounted for in the production coefficients.

Given perfect competition in the biofuel sector, the zero-profit condition is given as follows:

$$p_{bd} = p_{so}/\alpha_{bd} + w_{bd} \tag{5}$$

where w_{bd} is the cost of all inputs other than feedstock per unit of biodiesel in energy-equivalent content and p_{bd} denotes the price of biodiesel per energy equivalent units.

2.1.3. Oil refining sector

There is an upward sloping domestic supply of crude oil, denoted by $S_o(p_o)$, where p_o is the domestic price of crude oil. The refinement of oil yields diesel x_d and petroleum by-product x_h with a fixed coefficient technology that is defined as follows:

$$x_d = \min[\beta_d x_o, z_d] \tag{6}$$

$$x_h = \beta_h x_d/\beta_d \tag{7}$$

where (x_d, x_h) represent gallons of diesel, and of petroleum by-products, respectively. x_o denotes barrels of oil input (where domestically produced oil and imported oil are perfect substitutes). z_d is the amount of a composite input, which aggregates all other inputs used in the oil refining process. (β_d, β_h) are production coefficients, measuring gallons of diesel, and of petroleum by-product per barrel of crude oil, respectively.

The fixed proportion technology and perfect competition together imply the following zero-profit condition:

$$\beta_d p_d + \beta_h p_h = p_o + \beta_d w_d \tag{8}$$

where (p_d, p_h, p_o) are prices of diesel, of petroleum byproducts, and of crude oil, respectively. w_d denotes the unit cost of the composite input z_d including the rental price of capacity.

2.2. Consumption

A representative consumer with quasi-linear preferences purchases the numeraire good, fuel, and food, and suffers from negative externality of carbon emissions from fuel combustion and from land conversion for palm oil plantation in the ROW. Thus the utility function of the representative consumer takes the following form:

$$U = y + \Phi(D_{fl}) + \Theta(D_{fd}) - \theta\left(x_d + \upsilon_{bd} x_{bd} + \upsilon_{po} \bar{S}_{po}\right) \tag{9}$$

where y denotes consumption of the numeraire and (D_{fl}, D_{fd}) represent consumption of fuel composite and of food composite, respectively. The last term, $\theta(\cdot)$, represents environmental damages from carbon emissions due to aggregate combustion of biodiesel and diesel. The parameters υ_{bd} reflects the relative carbon emissions of biodiesel compared with diesel. $\bar{S}_{po}$ denotes the world total supply of palm oil, and υ_{po} is the associated carbon emissions from land conversion for the palm oil purpose. The standard quasi-concavity of the utility function implies concave functions of $\Phi(\cdot)$ and of $\Theta(\cdot)$. Specific structure on these two functions is imposed as follows.

First, we postulate an additive separability in $\Phi(\cdot)$ between petroleum by-product and the diesel composite, that is,

$$\Phi(D_{dc}, D_h) = \Phi_{dc}(D_{dc}) + \Phi_h(D_h) \tag{10}$$

This convenient assumption captures the different purposes of consuming refined petroleum products. Diesel composite is used for fueling the tank, while the remaining refined petroleum products are burned for other purposes, e.g., residential heating. Standard utility maximization derives inverse demand functions of diesel composite and of petroleum byproducts, that is, $D_{dc}(p_{dc}) = \Phi_{dc}'^{-1}(p_{dc})$ and $D_h(p_h) = \Phi_h'^{-1}(p_h)$, respectively.

To capture different food/feed purposes between soybean meals and vegetable oils, the utility function of food consumption $\Theta(D_{fd})$ assumes an additive separability between meals D_{ml} and vegetable oils D_{vo}. The latter includes both soybean oils D_{so} and palm oils D_{po}, both of which are subject to a constant elasticity of substitution $\sigma = 1/(1-\rho)$. The function $\Theta(D_{fd})$ is given by $\Theta(D_{fd}) = \Theta_{ml}(D_{ml}) + \Theta_{vo}(D_{vo})$ with a CES structure on $\Theta_{vo}(D_{vo})$:

$$\Theta_{vo}(D_{vo}) = \frac{\phi}{a}\left[\gamma_{so}(D_{so})^{\rho} + \gamma_{po}(D_{po})^{\rho}\right]^{\frac{a}{\rho}} \tag{11}$$

where $0 \neq \rho < 1$, $0 \neq a < 1$ denotes the return to scale, $\phi > 0$ is the scaling parameter, and γ_i captures the consumption weight of product i, $i \in \{so, po\}$. Note that $\gamma_{so} + \gamma_{po} = 1$. Furthermore, standard utility maximization gives rise to the inverse demand function of soybean meals, that is, $D_{ml}(p_{ml}) = \Theta_{ml}'^{-1}(p_{ml})$.

Let D_{vo} be the aggregate quantity demanded for vegetable oils, and P_{vo} denote the corresponding aggregate price.

$$D_{vo} \equiv \left[\gamma_{so}(D_{so})^{\rho} + \gamma_{po}(D_{po})^{\rho}\right]^{1/\rho} \tag{12}$$

[6] Lapan and Moschini (2012) express all prices and quantities of biofuel related to the gasoline fuel market in gasoline energy-equivalent gallons.

$$P_{vo} \equiv \left[(\gamma_{so})^{\sigma} (p_{so})^{1-\sigma} + \left(\gamma_{po}\right)^{\sigma} \left(p_{po}\right)^{1-\sigma} \right]^{1/(1-\sigma)} \tag{13}$$

where $\sigma = 1/(1-\rho) > 0$ denotes the elasticity of substitution between palm oils and soybean oils. Thus, the aggregate quantity demand could be written as $D_{vo} = \phi^{-\mu} P_{vo}^{\mu}$, where $\mu \equiv -1/(1-a) < 0$. Hence, μ can be interpreted as the elasticity of the aggregate vegetable oil demand with respect to the aggregate oil price.

The demand function of product i within the vegetable oil composite has the following iso-elastic forms:

$$D_i(p_i, P_{vo}) = \phi^{-\mu} \left(\frac{p_i}{\gamma_i} \right)^{-\sigma} P_{vo}^{\sigma+\mu}, \qquad i = so, po \tag{14}$$

We define the standard Marshallian own-price elasticity of demand ($\varepsilon_i < 0$) and the cross-price elasticity demand $\varepsilon_{i,j}$ as:

$$\begin{aligned} \varepsilon_i \equiv \frac{\partial D_i}{\partial p_i} \frac{p_i}{D_i} &= \frac{\partial D_i(p_i, P_{vo})}{\partial p_i} \frac{p_i}{D_i(p_i, P_{vo})} + \frac{\partial D_i(p_i, P_{vo})}{\partial P_{vo}} \frac{P_{vo}}{D_i(p_i, P_{vo})} \frac{\partial P_{vo}}{\partial p_i} \frac{p_i}{P_{vo}} \\ &= -\sigma + (\sigma + \mu)\varphi_i \end{aligned} \tag{15}$$

$$\begin{aligned} \varepsilon_{i,j} \equiv \frac{\partial D_i}{\partial p_j} \frac{p_j}{D_i} &= \frac{\partial D_i(p_i, P_{vo})}{\partial p_j} \frac{p_j}{D_i(p_i, P_{vo})} + \frac{\partial D_i(p_i, P_{vo})}{\partial P_{vo}} \frac{P_{vo}}{D_i(p_i, P_{vo})} \frac{\partial P_{vo}}{\partial p_j} \frac{p_j}{P_{vo}} \\ &= (\sigma + \mu)\varphi_j \end{aligned} \tag{16}$$

where $\varphi_i \equiv \gamma_i^{\sigma} (p_i / P_{vo})^{1-\sigma}$ is the price weight of component i in the aggregate price of the vegetable oil composite, and $\sum_{i \in \{so, po\}} \varphi_i = 1$. Note that the term $\frac{\partial D_i(p_i, P_{vo})}{\partial p_i} \frac{p_i}{D_i(p_i, P_{vo})} = -\sigma$ could be interpreted as the price elasticity of demand conditional on the aggregate composite price of vegetable oils. In addition, $\varepsilon_{i,j} \neq \varepsilon_{j,i}$, $\forall i \neq j \in \{so, po\}$.

2.2.1. Row

Because in the welfare analysis we are only concerned with US domestic welfare, one does not need to be explicit about the cost structure and preferences of the ROW. Assuming that the ROW economic policy is given, this paper only models the relevant behavior functions. Here, we follow the convention by which the overbar denotes foreign variables. Let $\overline{S}_o(\overline{p}_o)$ be the ROW export supply of crude oil and $\overline{S}_{po}(\overline{p}_{po})$ be the ROW supply of palm oil. $(\overline{p}_{po}, \overline{p}_o)$ denote the world prices of palm oil and of crude oil, respectively.

To examine the effects of US biodiesel policy on the ROW vegetable oil market, we explicitly model the ROW demand and supply for soybean meals and oils. In the supply side, let $\overline{p}_s$ denote the world price of soybeans, and assume an upward sloping supply curve of soybeans $\overline{S}_s(\overline{p}_s)$. Beans are crushed into oils and meals with a Leontief technology,

$$\overline{Q}_{ml} = \min[\overline{\alpha}_{ml} \overline{x}_s, \overline{z}_{ml}] \tag{17}$$

$$\overline{Q}_{so} = \overline{\alpha}_{so} \overline{Q}_{ml} / \overline{\alpha}_{ml} \tag{18}$$

where $(\overline{\alpha}_{ml}, \overline{\alpha}_{so})$ represent units of meals and of soybean oils per unit of crushed beans, respectively. The zero profit condition of the ROW oilseed crushing industry is:

$$\overline{\alpha}_{so} \overline{p}_{so} + \overline{\alpha}_{ml} \overline{p}_{ml} = \overline{p}_s + \overline{\alpha}_{ml} \overline{w}_{ml} \tag{19}$$

where $(\overline{p}_{so}, \overline{p}_{ml})$ denote the ROW prices of soybean oils and of meals, and $\overline{w}_{ml}$ is the ROW price of other inputs used in the crushing industry.

In the demand side, meals and oils are directly delivered into food/feed uses without assuming alternative purposes (e.g., biodiesel production). The ROW food consumption, which is analogous to the US demand function in Eq. (11), is given by:

$$\overline{\Theta}(\overline{D}_{fd}) = \overline{\Theta}_{ml}(\overline{D}_{ml}) + \frac{\overline{\phi}}{\overline{a}} \left[\overline{\gamma}_{so} (\overline{D}_{so})^{\overline{\rho}} + \overline{\gamma}_{po} (\overline{D}_{po})^{\overline{\rho}} \right]^{\frac{\overline{a}}{\overline{\rho}}} \tag{20}$$

Thus, individual demand for meals is given by the inverse demand function $\overline{D}_{ml}(\overline{p}_{ml}) = \overline{\Theta}_{ml}'^{-1}(\overline{p}_{ml})$, which is derived from the standard utility maximization. The individual demands for soy oils and palm oils take the following iso-elastic forms:

$$\overline{D}_i(\overline{p}_i, \overline{P}_{vo}) = \overline{\phi}_{vo}^{-\overline{\mu}} \left(\frac{\overline{p}_i}{\overline{\gamma}_i} \right)^{-\overline{\sigma}} \overline{P}_{vo}^{\overline{\sigma}+\overline{\mu}}, \qquad i = so, po \tag{21}$$

where $\overline{\mu} \equiv -1/(1-\overline{a}) < 0$ and $\overline{\sigma} = 1/(1-\overline{\rho}) > 0$. We denote $\overline{\sigma}$ as the ROW demand elasticity of substitution between palm oils and soybean oils. $\overline{\mu}$ has an interpretation of the ROW elasticity of the aggregate vegetable oil demand for the aggregate oil price $\overline{P}_{vo}$, which is defined analogously to P_{vo} in Eq. (13).

2.3. Equilibrium conditions with exogenous binding biodiesel mandates

To close the model, consider first that there are no border policies on imports of crude oil and palm oils and exports of soy meals and oils. Thus, prices of tradeable commodities do not differ across regions, that is, $p_o = \overline{p}_o$, $p_{po} = \overline{p}_{po}$, $p_{so} = \overline{p}_{so}$, and $p_{ml} = \overline{p}_{ml}$. Let x_{bd}^M denote the RFS mandate volume of biodiesel. Let (t_{dc}, b_{bd}) be the consumption tax on diesel composite per gallon and the volumetric subsidy on biodiesel, respectively. Thus, $\tilde{b}_{bd} \equiv [b_{bd} - t_{dc}(1-\lambda)]/\lambda$ denotes the effective net subsidy to biodiesel relative to diesel per DEEG and λ is the relative energy content of biodiesel to diesel.[7]

The zero profit condition of blending biodiesel with diesel, allowing for the existence of exogenous diesel taxes and biodiesel subsidies, can be expressed as:

$$(p_{dc} - t_{dc}) D_{dc}(p_{dc}) = p_d x_d + \left(p_{bd} - \tilde{b}_{bd} \right) x_{bd}^M \tag{22}$$

The left hand side of Eq. (22) is the value of diesel fuel composite demanded. The first term in the right hand side of Eq. (22) denotes the value of diesel excluding biodiesel, while the second term represents the value of biodiesel that has been domestically consumed.

The equilibrium with exogenous biodiesel mandates x_{bd}^M could be determined by a system of six equations, five market-clearing conditions plus one zero profit condition of blending biodiesel, with six unknowns $\{p_{ml}, p_{po}, p_{dc}, p_h, p_d, p_{bd}\}$. Note that $x_{bd}^M = x_{bd,so}$, implying that all biodiesel mandates are met by soy oil-based biodiesel only. The remaining endogenous quantities and prices could be expressed as functions of these six unknowns, using zero profit conditions and arbitrage relations.

$$\alpha_{ml} S_s(p_s) + \overline{\alpha}_{ml} \overline{S}_s(\overline{p}_s) = D_{ml}(p_{ml}) + \overline{D}_{ml}(\overline{p}_{ml}); \tag{23}$$
soy meal world market clear

$$\alpha_{so} S_s(p_s) + \overline{\alpha}_{so} \overline{S}_s(\overline{p}_s) = D_{so}(p_{so}, P_{vo}) + \overline{D}_{so}(\overline{p}_{so}, \overline{P}_{vo}) + x_{bd}^M / \alpha_{bd}; \tag{24}$$
soy oil world market clear

$$\overline{S}_{po}\left(\overline{p}_{po}\right) = D_{po}\left(p_{po}, P_{vo}\right) + \overline{D}_{po}\left(\overline{p}_{po}, \overline{P}_{vo}\right); \text{ palm oil world market clear} \tag{25}$$

[7] Following Cui et al. (2011), arbitrage relations for the equilibrium with diesel fuel taxes and biodiesel subsidies imply that $p_d = p_{dc} - t_{dc}$, $p_{bd} = p_{dc} + (b_{bd} - t_{dc})/\lambda = p_d + \tilde{b}_{bd}$, where $\tilde{b}_{bd} \equiv [b_{bd} - t_{dc}(1-\lambda)]/\lambda$ is the effective net subsidy to biodiesel, compared with diesel per DEEG.

$$D_{dc}(p_{dc}) = \beta_d\left[S_o(p_o) + \overline{S}_o(\overline{p}_o)\right] + x_{bd}^M; \tag{26}$$
diesel fuel composite domestic market clear

$$D_h(p_h) = \beta_h\left[S_o(p_o) + \overline{S}_o(\overline{p}_o)\right]; \tag{27}$$
petroleum byproduct domestic market clear

$$(p_{dc} - \tau_{dc})D_{dc}(p_{dc}) = p_d x_d + \left(p_{bd} - \tilde{b}_{bd}\right)x_{bd}^M;\ \text{zero-profit condition} \tag{28}$$

where $p_o = \overline{p}_o, p_{so} = \overline{p}_{so}, p_{ml} = \overline{p}_{ml}$, and $p_{po} = \overline{p}_{po}$, due to the assumption of no border policies on tradable commodities.

2.4. Extension with alternative feedstocks for biodiesel

In this subsection, we allow (imported) palm oils as an alternative feedstock for biodiesel production.[8] This feedstock could serve as a proxy for other biodiesel feedstocks (e.g., canola oil) assumed away in the model. The refinements of biodiesel from (imported) palm oils assume a Leontief technology (fixed coefficient). The output of biodiesel produced from palm oils is written as:

$$x_{bd,po} = \min\left[\alpha_{po}x_{po}, z_{po}\right] \tag{29}$$

where $x_{bd,po}$ is the output of biodiesel refined from palm oils, x_{po} denotes the units of palm oils used as alternative feedstocks. z_{po} represents the amounts of other inputs used per unit of biodiesel output. α_{po} denotes the production coefficient of biodiesel. We assume perfect substitution between soy oil biodiesel and palm oil biodiesel.[9] Given perfect competition in the biofuel sector, the zero-profit condition links the price of (imported) palm oil with the price of biodiesel in the following way:

$$p_{bd} = \overline{p}_{po}/\alpha_{po} + w_{po} \tag{30}$$

where w_{po} is the cost of all inputs other than feedstock per unit of biodiesel in energy-equivalent content and p_{bd} denotes the price of biodiesel per energy equivalent units.

We maintain the assumption about no border policies for traded commodities (i.e., soy meals, soy oils, palm oils, and crude oils). Thus, world prices of traded goods equal the corresponding domestic prices, that is, $p_{ml} = \overline{p}_{ml}$, $p_{so} = \overline{p}_{so}$, $p_{po} = \overline{p}_{po}$, and $p_o = \overline{p}_o$. With the zero profit condition of blending biodiesel and binding (exogenous) biodiesel mandates ($x_{bd}^M = x_{bd,so} + x_{bd,po}$), the equilibrium could be determined by a system of six equations, five market-clearing conditions plus one zero profit condition of blending biodiesel with six unknowns $\{p_{ml}, p_d, p_h, p_{bd}, p_{dc}, x_{bd,po}\}$.

$$\alpha_{ml}S_s(p_s) + \overline{\alpha}_{ml}\overline{S}_s(\overline{p}_s) = D_{ml}(p_{ml}) + \overline{D}_{ml}(\overline{p}_{ml}); \tag{31}$$
soy meal world market clear

$$\alpha_{so}S_s(p_s) + \overline{\alpha}_{so}\overline{S}_s(\overline{p}_s) = D_{so}(p_{so}, P_{vo}) + \overline{D}_{so}(\overline{p}_{so}, \overline{P}_{vo}) + x_{bd,so}/\alpha_{bd}; \tag{32}$$
soy oil world market clear

$$\overline{S}_{po}\left(\overline{p}_{po}\right) = D_{po}\left(p_{po}, P_{vo}\right) + \overline{D}_{po}\left(\overline{p}_{po}, \overline{P}_{vo}\right) + x_{bd,po}/\alpha_{po}; \tag{33}$$
palm oil world market clear

$$D_{dc}(p_{dc}) = \beta_d\left[S_o(p_o) + \overline{S}_o(\overline{p}_o)\right] + x_{bd}^M; \tag{34}$$
diesel fuel composite domestic market clear

$$D_h(p_h) = \beta_h\left[S_o(p_o) + \overline{S}_o(\overline{p}_o)\right]; \tag{35}$$
petroleum byproduct domestic market clear

$$(p_{dc} - t_{dc})D_{dc}(p_{dc}) = p_d x_d + \left(p_{bd} - \tilde{b}_{bd}\right)x_{bd}^M;\ \text{zero profit condition} \tag{36}$$

where $x_{bd,so}$ is the amount of biodiesel refined from soy oils. If palm oil is competitive enough to refine biodiesel, hence, $x_{bd,po} > 0$, the price of palm oil is linked with price of biodiesel, using the zero-profit condition, that is, $p_{bd} = \overline{p}_{po}/\alpha_{po} + w_{po} = p_{po}/\alpha_{po} + w_{po}$. In the case of no palm oil used as feedstocks for biodiesel ($x_{bd,po} = 0$), due to the less competitive price relative to soy oils, the system of equations returns to Eqs. (23)–(28).

3. Calibration

The model is calibrated to fit the baseline data in calendar year 2014. To calibrate it, we specify the values of exogenous parameters and values of policy instruments during the baseline period. In addition, we assume the following linear supply and demand curves: the domestic and world crude oil supply curves $S_o(p_o)$ and $\overline{S}_o(\overline{p}_o)$, the domestic and world supply for soybeans $S_s(p_s)$ and $\overline{S}_s(\overline{p}_s)$, the world palm oil supply curve $\overline{S}_{po}(\overline{p}_{po})$, the domestic demand for diesel composite fuel $D_{dc}(p_{dc})$ and for petroleum byproducts $D_h(p_h)$, the domestic and world demand for soybean meals $D_{ml}(p_{ml})$ and $\overline{D}_{ml}(\overline{p}_{ml})$. For these linear function forms, each supply and demand curve is calibrated using an estimate of elasticity for that function together with the price and the quantity of the relevant variables in the baseline year.

Prices and quantities of variables in the baseline period are summarized in Tables 1 and 2. Table 3 reports primitive parameters and the values of calculated parameters, while Table 4 provides elasticity values used in the calibration. In general, data for the utilization and prices of soybean, soybean oils and meals are gathered from the US Oil Crop Yearbook 2015 of the United States Department of Agriculture (USDA). The data for the ROW come from the Foreign Agricultural Service (FAS) of the USDA. Both the US and ROW data for crude oil, diesel, and other petroleum byproducts are obtained from the US Energy Information Agency (EIA). Biodiesel production output and input data are reported by the USDA Bioenergy Statistics. The US imports of palm oil are provided by the Global Agricultural Trade System in the FAS of the USDA, and the total world supply and demand of palm oil are also taken from the same source.

3.1. Prices in the baseline

Because biodiesel has a lower energy content than diesel, a gallon of biodiesel equals only 0.93 DEEG.[10] Thus, its quantity, price, fuel tax, and subsidy are all converted to DEEG units during the simulation, and then are converted back into gallon units when presenting the results. Diesel fuel composite is currently subject to a consumption tax of $t_{dc} = \$0.484$ per gallon, including the federal tax of \$0.244 per gallon and the averaged state tax of \$0.240 per gallon. In year 2014 biodiesel was still subject to tax credits of $b_{bd} = \$1.0$/gal, which is equivalent to a net subsidy to biodiesel of $\tilde{b}_{bd} = \$1.04$/DEEG.[11] The US biodiesel FOB price of \$3.46 per gallon corresponds to a price of \$3.72 per DEEG. The price of diesel subtracting taxes is $p_d = \$3.34$ per DEEG, obtained from the US on-highway diesel fuel prices by the EIA. In baseline year 2014, the United States consumed more biodiesel than domestically produced, due to the complex interaction between mandates and RINS (de Gorter and Drabik, 2015).[12] Hence, the model is calibrated with

[8] We thank an anonymous referee for pointing out this extension direction.

[9] Drabik et al. (2014) assume perfect substitution between soy oil-based biodiesel and canola oil-based biodiesel.

[10] According to the Alternative Fuels Data Center in the US Department of Energy, the energy content of diesel (No. 2) is 128,450 Btu/gal, while that of biodiesel (B100) is 119,550 Btu/gallon.

[11] $\tilde{b}_{bd} \equiv [b_{bd} - t_{dc}(1-\lambda)]/\lambda$.

[12] We thank an anonymous referee for pointing this out.

Table 1
Prices in the baseline.

Variable	Symbol	Value	Explanation/Source
Diesel fuel tax ($/gallon)	t_{dc}	0.48	Sum of federal tax $0.24/gal and avg. state tax $0.24/gal (EIA)[a]
Biodiesel tax credit ($/gallon)	b_{bd}	1.00	Yacobucci (2012)
Effective biodiesel subsidy ($/DEEG)	$\tilde{b}_{bd}$	1.04	$\tilde{b}_{bd} = [b_{bd} - t_{dc}(1-\lambda)]/\lambda$
Price of soybean ($/MT)	p_s	371.1	Average received by farmers, (Oil Crop Yearbook, USDA)[b]
Price of soybean meals ($/MT)	p_{ml}	406.2	48% protein, Decatur (solvent), (Oil Crop Yearbook, USDA)[b]
Price of soybean oils ($/MT)	p_{so}	696.6	Crude, Decatur (Oil Crop Yearbook, USDA)[b]
Price of palm oils ($/MT)	p_{po}	803	Malaysia FOB price, (FAS, USDA)[c]
Price of crude oil ($/barrel)	p_o	92.0	Composite acquisition cost of crude oil (EIA)[d]
Price of biodiesel ($/DEEG)	p_{bd}	3.72	FOB price at IL, IN and OH (USDA)[e]
Price of unblended diesel ($/DEEG)	p_d	3.34	On high-way diesel price (EIA) subtracted taxes[f]
Price of petroleum byproducts ($/DEEG)	p_h	3.76	Average residential heating oil (EIA)[g]
Price of diesel fuel ($/DEEG)	p_{dc}	3.82	$p_{dc} = \left(p_{bd} - \tilde{b}_{bd} + t_{dc}\right)\frac{x_{bd}^M}{x_d + x_{bd}^M} + (p_d + t_{dc})\frac{x_{bd}^M}{x_d + x_{bd}^M}$
Price of other inputs in soybean crushing industry ($/MT)	w_{ml}	108.7	$w_{ml} = (\alpha_{so}p_{so} + \alpha_{ml}p_{ml} - p_s)/\alpha_{ml}$
Price of other inputs in soy oil biodiesel refining industry ($/DEEG)	w_{bd}	2.3	$w_{bd} = p_{bd} - p_{so}/\alpha_{bd}$
Price of other inputs in palm oil biodiesel refining industry ($/DEEG)	w_{po}	2.1	$w_{po} = p_{bd} - p_{po}/\alpha_{po}$
Price of other inputs in crude oil refining industry ($/DEEG)	w_d	4.7	$w_d = (\beta_d p_d + \beta_h p_h - p_o)/\beta_d$
Aggregate price of veg oil composite ($/MT)	P_{vo}	1075.5	$P_{vo} \equiv \left(\gamma_{so}^{\sigma} p_{so}^{1-\sigma} + \gamma_{po}^{\sigma} p_{po}^{1-\sigma}\right)^{1/(1-\sigma)}$
ROW aggregate price of veg oil ($/MT)	$\overline{P}_{vo}$	1482.0	$\overline{P}_{vo} \equiv \left(\overline{\gamma}_{so}^{\overline{\sigma}} \overline{p}_{so}^{1-\overline{\sigma}} + \overline{\gamma}_{po}^{\overline{\sigma}} \overline{p}_{po}^{1-\overline{\sigma}}\right)^{1/(1-\overline{\sigma})}$

[a] Historical federal and state taxes, EIA: http://www.eia.gov/tools/faqs/faq.cfm?id=10&t=10.
[b] Tables 3–5, US Oil Crop Yearbook 2015, USDA: http://www.ers.usda.gov/data-products/oil-crops-yearbook.aspx.
[c] Oilseeds: World Market and Trade, FAS, USDA: http://apps.fas.usda.gov/psdonline/circulars/oilseeds.pdf.
[d] Table of Refiner Acquisition cost of crude oil, EIA: http://www.eia.gov/dnav/pet/pet_pri_rac2_dcu_nus_m.htm.
[e] Table 17 of Biodiesel and Diesel Prices, U.S. Bioenergy Statistics, USDA: http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx#30041.
[f] US On-Highway Diesel Fuel Prices, EIA: http://www.eia.gov/petroleum/gasdiesel/.
[g] US Average Residential Heating Oil Price, EIA: http://www.eia.gov/petroleum/heatingoilpropane/#itn-tabs-2.

the quantity of biodiesel mandate set at the observed consumption level of $x_{bd}^M = 1.548$ BG rather than the production level of 1.24 BG. Thus the price of diesel composite is computed as the weighted average of biodiesel and diesel prices, adjusted for the tax credit, tax, energy content, and the observed consumption of biodiesel mandate. That is, $p_{dc} = (p_{bd} - \tilde{b}_{bd} + t_{dc})x_{bd}^M/(x_d + x_{bd}^M) + (p_d + t_{dc})x_d/(x_d + x_{bd}^M) = \$3.82/\text{DEEG}$.

Table 2
Quantities in the baseline.

Variable	Symbol	Value	Explanation/Source
Soybean supply (MMT)	S_s	101.16	Production with stock changes (Oil Crop Yearbook, USDA)[a]
Observed soybean net export (MMT)	NX_s	50.17	Net exports (USDA)[a]
Crushed soybeans (MMT)	x_s	50.99	$x_s = S_s - NX_s$
Soybean meal production (MMT)	Q_{ml}	40.88	Production (USDA)[a]
Observed soybean meal net export (MMT)	NX_{ml}	11.63	Net export (USDA)[a]
Soybean meal demand (MMT)	D_{ml}	29.24	Domestic consumption (USDA)[a]
Soybean oil production (MMT)	Q_{so}	9.70	Production (USDA)[a]
Observed soybean oil net export (MMT)	NX_{so}	0.79	Net export (USDA)[a]
Soy oil used in biodiesel production (MMT)	x_{so}	2.28	Biodiesel feedstock uses (USDA)[a]
Residual soybean oil demand (MMT)	D_{so}	6.63	$D_{so} = Q_{so} - NX_{so} - x_{so}$
ROW soybean production (MMT)	$\overline{S}_s$	211.68	Total production (FAS, USDA)[b]
ROW soybean oil production (MMT)	$\overline{Q}_{so}$	39.24	Total production (FAS, USDA)[b]
ROW Soybean meal production (MMT)	$\overline{Q}_{ml}$	166.07	Total production (FAS, USDA)[b]
Simulated ROW soy meals demand (MMT)	$\overline{D}_{ml}$	224.94	$\overline{D}_{ml} = \overline{\alpha}_{ml}NX_s + NX_{ml} + \overline{\alpha}_{ml}\overline{S}_s$
Simulated ROW soy oil demand (MMT)	$\overline{D}_{so}$	49.34	$\overline{D}_{so} = \overline{\alpha}_{so}NX_s + NX_{so} + \overline{\alpha}_{so}\overline{S}_s$
ROW palm oil supply (MMT)	$\overline{S}_{po}$	61.34	Total production (FAS, USDA)[b]
US palm oil demand (MMT)	D_{po}	1.19	Net import (FAS, USDA)[b]
ROW palm oil demand (MMT)	$\overline{D}_{po}$	60.16	$\overline{D}_{po} = \overline{S}_{po} - D_{po}$
Crude oil domestic supply (BB)	S_o	3.17	Production plus adjustments and stock changes (EIA)[c]
Crude oil foreign supply (BB)	$\overline{S}_o$	2.55	Net import (EIA)[c]
Total crude oil supply (BB)	x_o	5.73	$x_o = S_o + \overline{S}_o$
Diesel production (BG)	x_d	75.36	Distillate fuel oil production (EIA)[c]
Biodiesel production (BG)	x_{bd}	1.24	Bioenergy Statistics (USDA)[d]
Biodiesel consumption (BG)	x_{bd}^M	1.55	Short-term Energy Outlook (EIA)[e]
Diesel fuel consumption (BG)	D_{dc}	76.61	$D_{dc} = x_d + x_{bd}$
Petroleum byproduct production (BG)	x_h	180.98	$x_h = \beta_h x_o$
Aggregate demand of veg oil composite (MMT)	D_{vo}	5.01	$D_{vo} = [\gamma_{so}D_{so}^{\rho} + \gamma_{po}D_{po}^{\rho}]^{1/\rho}$
ROW aggregate demand of veg oil composite (MMT)	$\overline{D}_{vo}$	55.65	$\overline{D}_{vo} = [\overline{\gamma}_{so}\overline{D}_{so}^{\rho} + \overline{\gamma}_{po}\overline{D}_{po}^{\rho}]^{1/\rho}$

[a] Tables 3–5, US Oil Crop Yearbook 2015: http://www.ers.usda.gov/data-products/oil-crops-yearbook.aspx#.UkD2uobTxSA.
[b] Tables 7 and 11 from USDA, FAS PSDO: http://apps.fas.usda.gov/psdonline/.
[c] Table of supply and disposition, EIA: http://www.eia.gov/dnav/pet/pet_sum_snd_d_nus_mbbl_a_cur-1.htm.
[d] Tables 2–3, USDA bioenergy stats: http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx#.UkD2aIbTxSA.
[e] Biodiesel consumption, Short-term energy outlook, EIA: http://205.254.135.24/forecasts/steo/query/.

Table 3
Parameters in production and consumption.

Variable	Symbol	Value	Explanation/Source
Diesel energy-equivalent gallons (DEEG)	λ	0.931	Alternative Fuels Data Center
Production of soybean meals per crushed beans	α_{ml}	0.802	$\alpha_{ml}=Q_{ml}/x_s$
Production of soybean oils per crushed beans	α_{so}	0.190	$\alpha_{so}=Q_{so}/x_s$
ROW production of soybean oils per crushed beans	$\overline{\alpha}_{so}$	0.185	$\overline{\alpha}_{so}=\overline{Q}_{so}/\overline{S}_s$
ROW production of soybean meals per crushed beans	$\overline{\alpha}_{ml}$	0.815	$\overline{\alpha}_{ml}=1-\overline{\alpha}_{so}$
Biodiesel per soybean oils (DEEG/MT)	α_{bd}	505.15	$\alpha_{bd}=x_{bd}/x_{so}$
Biodiesel per palm oils (DEEG/MT)	α_{po}	505.15	Assumed
Diesel per crude oil (gallon/barrel)	β_d	13.15	$\beta_d=x_d/x_o$
Petroleum byproduct per crude oil (gallon/barrel)	β_h	31.57	$\beta_h=42\times 1.065-\beta_d$
Soy oil factor weight in veg oil composite	γ_{so}	0.882	$\gamma_{so}\equiv p_{so}D_{so}^{1/\sigma}\Big/\left(p_{so}D_{so}^{1/\sigma}+p_{po}D_{po}^{1/\sigma}\right)$
Palm oil factor weight in veg oil composite	γ_{po}	0.118	$\gamma_{po}=1-\gamma_{so}$
ROW soy oil factor weight in veg oil composite	$\overline{\gamma}_{so}$	0.346	$\overline{\gamma}_{so}\equiv\overline{p}_{so}\overline{D}_{so}^{1/\overline{\sigma}}\Big/\left(\overline{p}_{so}\overline{D}_{so}^{1/\overline{\sigma}}+\overline{p}_{po}\overline{D}_{po}^{1/\overline{\sigma}}\right)$
ROW palm oil factor weight in veg oil composite	$\overline{\gamma}_{po}$	0.654	$\overline{\gamma}_{po}=1-\overline{\gamma}_{so}$
Soy oil price weight in veg oil composite	φ_{so}	0.829	$\varphi_{so}\equiv\gamma_{so}^{\sigma}(p_{so}/P_{vo})^{1-\sigma}$
Palm oil price weight in veg oil composite	φ_{po}	0.171	$\varphi_{po}=1-\varphi_{so}$
ROW soy oil price weight in veg oil composite	$\overline{\varphi}_{so}$	0.416	$\overline{\varphi}_{so}\equiv\overline{\gamma}_{so}^{\overline{\sigma}}(\overline{p}_{so}/\overline{P}_{vo})^{1-\overline{\sigma}}$
ROW palm oil price weight in veg oil composite	$\overline{\varphi}_{po}$	0.584	$\overline{\varphi}_{po}=1-\overline{\varphi}_{so}$
CO_2 emission rate of diesel fuel		10.21 kg/DEEG	EPA (2015)[a]
The relative emission efficiency factor of biodiesel	υ_{bd}	0.50	Yacobucci (2012)
CO_2 emissions from land conversion for palm oil supply (MMT per MMT)	υ_{po}	1.91	Carlson et al. (2013); FAS of the USDA.[b]
Marginal carbon social damage	$\theta'(\cdot)$	\$37/tCO_2	Assumed

[a] Emission factors for greenhouse gas inventories, EPA: https://www.epa.gov/sites/production/files/2015-12/documents/emission-factors_nov_2015.pdf.
[b] https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery.

The crude oil price p_o of \$92.02/barrel is the refiner's composite acquisition cost of crude oil as provided in the EIA. The soybean price of \$10.10/bushel, which is converted to $p_s = \$371.1$/metric ton, is the average price received by farmers provided by the US Oil Crop Yearbook of USDA. The soybean meal price of \$368.5/short ton, which is equivalent to $p_{ml} = \$406.2$/metric ton, is the price for meals with 48% protein, Decatur (solvent), while the soybean oil price of \$0.32/lb., which amounts to $p_{so} = \$696.6$/metric ton, is the price for the crude soybean oils, Decatur. The palm oil world price $\overline{p}_{po}$ of \$803.0/metric ton is the Malaysia FOB price. The petroleum byproduct price is simply taken from the retail price of heating oil, that is, $p_h = \$3.76$/DEEG. The prices of other inputs used in the oil refining industry w_d, soybean crushing industry w_{ml}, and biodiesel refinery (w_{bd}, w_{po}) are all calculated from zero profit conditions, that is, $w_d = (\beta_d p_d + \beta_h p_h - p_o)/\beta_d = \$4.7$/DEEG, $w_{ml} = (\alpha_{so}p_{so} + \alpha_{ml}p_{ml} - p_s)/\alpha_{ml} = \$108.7$/metric ton, $w_{bd} = p_{bd} - p_{so}/\alpha_{bd} = \$2.3$/DEEG, and $w_{po} = p_{bd} - p_{po}/\alpha_{po} = \$2.1$/DEEG. The production parameters of α_{so}, α_{ml}, α_{bd}, α_{po}, β_d, and β_h would be discussed shortly.

3.2. Quantities in the baseline

For the baseline scenario, domestic supply is measured by domestic production plus stock changes and other adjustments. In addition, we use net imports or exports to measure international trade. Hence, in the status quo, there are 101.16 MMT of soybean supplied (S_s) in the US. Among them, 50.17 MMT are demanded by the ROW, leaving the rest of the 50.99 MMT beans to be crushed into meals and oils. The domestic production of soybeans meals is $Q_{ml} = 40.88$ MMT, while that of soybean oils Q_{so} is 9.70 MMT. There are 29.24 MMT meals consumed

Table 4
Elasticity parameters in the baseline.

Parameter	Symbol	Value	Explanation/Source
Price elasticity of domestic oil supply	η_o	0.25	EIA (2014)
Price elasticity of foreign oil supply	$\overline{\eta}_o$	0.500	Brown et al. (2014)
Price elasticity of diesel fuel demand	ε_{dc}	−0.500	assumed
Price elasticity of petroleum byproduct demand	ε_h	−0.500	assumed
Price elasticity of ROW palm oil supply	$\overline{\eta}_{po}$	0.640	Talib and Darawi (2002)
Price elasticity of soybean supply	η_s	0.120	Piggot et al. (2000)
Price elasticity of ROW soybean supply	$\overline{\eta}_s$	0.300	FAPRI Elasticity Database[a]
Price elasticity of soybean meals demand	ε_{ml}	−0.15	Piggot et al. (2000)
Price elasticity of ROW soybean meals demand	$\overline{\varepsilon}_{ml}$	-0.35	FAPRI Elasticity Database[a]
Unconditional demand elasticity of veg oil aggregate	μ	−0.047	Commodity and Food Elasticity (USDA)[b]
ROW unconditional demand elasticity of veg oil	$\overline{\mu}$	−0.347	Commodity and Food Elasticity (USDA)[b]
Demand elasticity of substitution between soybean oils and palm oils	σ	0.800	Assumed
ROW demand elasticity of substitution between soybean oils and palm oils	$\overline{\sigma}$	0.400	Assumed
Own-price elasticity demand of soy oil	ε_{so}	−0.173	$\varepsilon_{so}=-\sigma+(\sigma+\mu)\varphi_{so}$
Own-price elasticity demand of palm oil	ε_{po}	-0.674	$\varepsilon_{po}=-\sigma+(\sigma+\mu)\varphi_{po}$
ROW own-price elasticity demand of soy oil	$\overline{\varepsilon}_{so}$	-0.377	$\overline{\varepsilon}_{so}=-\overline{\sigma}+(\overline{\sigma}+\overline{\mu})\overline{\varphi}_{so}$
ROW own-price elasticity demand of palm oil	$\overline{\varepsilon}_{po}$	−0.370	$\overline{\varepsilon}_{po}=-\overline{\sigma}+(\overline{\sigma}+\overline{\mu})\overline{\varphi}_{po}$
Cross-price elasticity demand of soy oil w.r.t. palm oil	$\varepsilon_{so,po}$	0.126	$\varepsilon_{so,po}=(\sigma+\mu)\varphi_{po}$
Cross-price elasticity demand of palm oil w.r.t. soy oil	$\varepsilon_{po,so}$	0.627	$\varepsilon_{po,so}=(\sigma+\mu)\varphi_{so}$
ROW cross-price elasticity demand of soy oil w.r.t. palm oil	$\overline{\varepsilon}_{so,po}$	0.030	$\overline{\varepsilon}_{so,po}=(\overline{\sigma}+\overline{\mu})\overline{\varphi}_{po}$
ROW cross-price elasticity demand of palm oil w.r.t. soy oil	$\overline{\varepsilon}_{po,so}$	0.023	$\overline{\varepsilon}_{po,so}=(\overline{\sigma}+\overline{\mu})\overline{\varphi}_{so}$

[a] FAPRI, Elasticity Database: http://www.fapri.iastate.edu/tools/elasticity.aspx.
[b] Commodity and Food Elasticity Database, USDA: http://www.ers.usda.gov/data-products/commodity-and-food-elasticities.aspx.

domestically, that is $D_{ml} = 29.24$ MMT, and the remaining 11.63 MMT meals exported to the ROW. The amount of soybean oils used as inputs in the biodiesel production is roughly $x_{so} = 2.28$ MMT, that of oils exported to meet foreign demand is 0.79 MMT, and the rest of oils left for domestic food purposes are $D_{so} = 6.63$ MMT.

The ROW supply of soybeans $\overline{S}_s$ reaches 211.68 MMT, while its meal and oil productions are $\overline{Q}_{ml} = 166.07$ MMT and $\overline{Q}_{so} = 39.24$ MMT, respectively. To account for trade of beans, the ROW demand of meals are simulated as the sum of three parts: observed net imports of meals, indirect net imports of meals converted from the imported beans given the ROW crush ratio, and observed ROW domestic supply of meals. Hence, the simulated ROW demand of meals is $\overline{D}_{ml} = 224.94$ MMT. Similarly, the simulated ROW demand of oils $\overline{D}_{so}$ is 49.34 MMT, including the indirect net imports of soy oils converted from the imported beans. When it comes to palm oil, the ROW supplies $\overline{S}_{po} = 61.34$ MMT in the baseline year of 2014. Whereas only a very small portion of palm oils in the ROW are exported and consumed in the US, that is, $D_{po} = 1.19$ MMT, the remaining palm oils are left to meet its demand for food and other purposes, i.e., $\overline{D}_{po} = 60.16$ MMT.

The EIA reports a total supply of around 5.73 billion barrels (BB) of crude oil x_o, including a domestic supply S_o of 3.17 BB plus foreign supply $\overline{S}_o$ of 2.55 BB. The amount of diesel production associated with refined crude oil is $x_d = 75.36$ BG provided by the EIA. The US biodiesel production exceeds 1 BG in year 2014, that is, $x_{bd} = 1.24$ BG. Final fuel consumption of diesel composite is the sum of diesel and biodiesel consumption in the DEEG units, $D_{dc} = x_d + x_{bd} = 76.61$ billion DEEGs. The production of petroleum by-product is given as $x_h = \beta_h x_o = 180.98$ BG.

3.3. Productivity parameters

The technology coefficient of soybean meals in the US crushing industry is recovered from the ratio of observed production of soybean meals to units of crushed beans. One metric ton of crushed beans could yield around 0.802 metric ton of meals and 0.190 metric ton of oils, i.e., $\alpha_{ml} = 0.802$, and $\alpha_{so} = 0.190$. Similarly, the technology coefficients of the ROW crushing industry for meals and for soy oils are $\overline{\alpha}_{ml} = 0.815$ and $\overline{\alpha}_{so} = 0.185$, respectively. The technology coefficient of the biodiesel refining industry is calculated from DEEGs of biodiesel per metric ton of soybean oils, that is, $\alpha_{bd} = x_{so}/x_{bd} = 505.15$ DEEGs/metric ton. When it comes to palm oils as potential feedstocks for refining biodiesel, we could not obtain any data reporting the amounts of palm oil used in biodiesel production from the Bioenergy Statistics from the USDA. We assume the same technology coefficient as the biodiesel production refined from soy oils, that is, $\alpha_{po} = \alpha_{bd} = 505.15$ DEEGs/metric ton. The sensitivity analysis regarding this technology coefficient will be discussed, with the relative production efficiency α_{po}/α_{bd} ranging from [0.75, 1.25]. Lastly, the assumed fixed-proportions technology in the oil refining industry gives rise to the calculated yield of gallons of diesel per barrel of crude oil, that is, $\beta_d = x_d/x_o = 13.15$ DEEGs/barrel. Given β_d, the yield of petroleum by-products is $\beta_h = 31.57$ DEEGs/barrel.

3.4. CES demand parameters

With observed prices and quantities demanded, we could calibrate parameters in the CES demand function in Eq. (14). As for the unconditional demand elasticity of vegetable oil composite, we adopt the value of $\mu = -0.047$ for oil and fat category provided by the USDA. For the unconditional demand elasticity of the ROW vegetable oils, we take this value for Argentina, that is, $\overline{\mu} = -0.347$.[13] The demand elasticity of substitution between soybean oils and palm oils assumes an inelastic value of $\overline{\sigma} = 0.4$ for the ROW. This value is chosen such that the simulated price elasticity demand for soy and palm oils are close to $\overline{\varepsilon}_i = -0.37$, which are the corresponding elasticity values for each good in regions other than the US as provided in the Food and Agricultural Policy Research Institute (FAPRI) Elasticity Database. Similarly, $\sigma = 0.8$ is chosen for the elasticity of substitution between soy oils and palm oils in the US. To highlight the importance of these two key parameters (i.e., σ and μ) and isolate the impact of each parameter, we conduct sensitivity analysis allowing these two to vary. For the unconditional demand elasticity of vegetable oils, we consider lower and higher values to range from -0.40 to -0.02 for the US and ROW. For the elasticity of substitution between soy and palm oils in the demand side, a range of [0.40, 2.00] is taken for σ in the US, while a range of [0.35, 2.00] is adopted by $\overline{\sigma}$ in the ROW.

With the observed quantities demanded and prices of soy oils and palm oils, the parameters of factor weights in the vegetable oil composite are calibrated by using the pseudo-shares $\gamma_{so} \equiv p_{so} D_{so}^{1/\sigma} / (p_{so} D_{so}^{1/\sigma} + p_{po} D_{po}^{1/\sigma}) = 0.882$, hence $\gamma_{po} = 1 - \gamma_{so} = 0.118$. With the calibrated factor weights, the aggregate price of vegetable oil is calculated following $P_{vo} \equiv (\gamma_{so}^{\sigma} p_{so}^{1-\sigma} + \gamma_{po}^{\sigma} p_{po}^{1-\sigma})^{1/(1-\sigma)} = \$1075.5$/metric ton. The price weight of soybean oils in the vegetable oil composite is then given as $\varphi_{so} \equiv \gamma_{so}^{\sigma} (p_{so}/P_{vo})^{1-\sigma} = 0.829$, and that of palm oils takes a value of $\varphi_{po} = 1 - \varphi_{so} = 0.171$. Likewise, we could recover parameters in the ROW demand function for the vegetable oil composite.[14] Factor weights are $\overline{\gamma}_{so} = 0.346$ and $\overline{\gamma}_{po} = 0.654$. The aggregate price of vegetable oil is $\overline{P}_{vo} = \$1482.0$/metric ton. Price weights of soybean oils and palm oils are $\overline{\varphi}_{so} = 0.416$ and $\overline{\varphi}_{po} = 0.584$, respectively.

3.5. Elasticities

The elasticity values are taken from the literature to reflect the consensus on the available econometric evidence. For the US soybean supply elasticity we take an estimate of $\eta_s = 0.12$, and for the US soybean meals demand elasticity we set $\varepsilon_{ml} = -0.15$, both of which are drawn from Piggot et al. (2000) and Knittel and Pindyck (2013). The ROW supply elasticity of soybeans and demand elasticity of meals are obtained from the FAPRI Elasticity Database.[15] Hence, we set $\overline{\eta}_s = 0.30$ and $\overline{\varepsilon}_{ml} = -0.35$ as the benchmark values. In the sensitivity analysis, we consider a lower and upper bound value of 0.10 and of 0.50 for the elasticity η_s and $\overline{\eta}_s$, and adopt a range of [-0.50, -0.10] for the elasticity ε_{ml} and $\overline{\varepsilon}_{ml}$.

For the elasticity of domestic oil supply, we set the benchmark value of $\eta_o = 0.25$, based upon the value used by the US EIA National Energy Modeling System (EIA, 2014). A sensitivity analysis of this parameter ranging from [0.1, 0.8] is conducted in the sensitivity analysis. For the price elasticity of foreign export oil supply, an inelastic value of $\overline{\eta}_o = 0.5$ in the benchmark is taken from Brown et al. (2014), and a lower and upper value from 0.10 to 3.00 are accounted for in the sensitivity analysis. The elasticity value of the fuel composite is assigned a value of $\varepsilon_{dc} = -0.5$. Little explicit evidence exists on the elasticity of petroleum by-product demand represented by ε_h, hence we adopt the same baseline value as the elasticity of fuel diesel demand. A range of [0.10, 0.50] is considered in the sensitivity analysis regarding both ε_{dc} and ε_h. As suggested by Talib and Darawi (2002), the ROW supply elasticity for palm oil takes an estimate of $\overline{\eta}_{po} = 0.64$ in the benchmark, and assumes a range of [0.10, 0.90] in the sensitivity analysis. As for the own-price demand elasticities of soybean oils and palm oils, although the CES structure of demand for vegetable oils does not need these as

[13] The values of unconditional demand elasticity for vegetable oils in other regions (e.g., Brazil) are close to -0.3, as provided in the FAPRI Elasticity Database.

[14] Noting that total expenditure is $\sum_{j=1}^{n} p_j D_j = \phi^{-\mu} P_{vo}^{1+\mu}$, the scaling parameter is then calibrated as $\phi = (p_{so} D_{so} + p_{so} D_{po})^{-1/\mu} P_{vo}^{(1+\mu)/\mu}$.

[15] The FAPRI Elasticity Database reports the supply price elasticity and own-price demand elasticity of soybeans and meals. The ROW supply elasticity of soybeans is close to the elasticity value for beans from South America, e.g., 0.32 for beans from Argentina, and 0.34 for beans from Brazil. The demand elasticity of soy meals from Argentina and that from Brazil are -0.35.

Table 5
Simulated prices of increasing biodiesel mandate and the Monte Carlo simulation results in 95% confidence interval.

Biodiesel mandate (BG)	Baseline	Soy oil as biodiesel feedstock		Soy and palm oil as biodiesel feedstocks	
	(1)	(2)	(3)	(4)	(5)
	1.55	2.0	3.4	2.0	3.4
Soybean price ($/MT)	373.53	376.64 [374.62, 377.79]	387.21 [379.91, 391.03]	373.82 [373.30, 374.70]	376.79 [375.39, 379.27]
ROW soybean price ($/MT)	373.51	376.46 [374.52, 377.59]	386.47 [379.50, 390.22]	373.78 [373.26, 374.65]	376.59 [375.23, 378.99]
Soybean meals price ($/MT)	407.34	404.94 [404.03, 406.69]	396.76 [393.13, 402.73]	407.12 [406.43, 407.85]	404.83 [402.75, 406.21]
Soybean oils price ($/MT)	704.73	731.20 [715.23, 737.10]	821.13 [762.24, 843.84]	707.19 [704.36, 712.55]	732.42 [722.78, 750.81]
Palm oils price ($/MT)	803.31	804.30 [803.42, 811.28]	807.54 [804.48, 831.61]	813.53 [811.53, 818.10]	838.76 [831.90, 854.40]
Crude oil price ($/barrel)	91.84	91.58 [91.23, 91.81]	90.73 [89.52, 91.42]	91.59 [91.24, 91.81]	90.77 [89.57, 91.43]
Biodiesel price ($/gallon)	3.47	3.52 [3.49, 3.53]	3.69 [3.58, 3.73]	3.48 [3.47, 3.49]	3.53 [3.51, 3.56]
Diesel price ($/gallon)	3.32	3.28 [3.26, 3.29]	3.16 [3.07, 3.20]	3.28 [3.26, 3.29]	3.16 [3.08, 3.20]
Heating oil price ($/gallon)	3.76	3.77 [3.76, 3.78]	3.79 [3.77, 3.82]	3.77 [3.76, 3.78]	3.79 [3.77, 3.82]

Notes: the results in brackets are reported in a form of 95% confidence interval for the Monte Carlo simulation on a set of selected 15 key parameters including elasticities, technology coefficient and marginal carbon social costs.

primitive parameters, the implied elasticities are easily derived for the purpose of comparison with other models.[16]

3.6. Carbon emissions and damage costs

The CO_2 emission rate of diesel fuel that we used is 10.21 kg/DEEG (EPA, 2015).[17] The relative emission efficiency factor in the benchmark case takes a value of $\upsilon_{bd} = 0.5$, representing that biomass-based biodiesel (either from soy oils or palm oils) reduces the emissions over 50% relative to conventional fuels (Yacobucci, 2012). There is considerable concern about carbon emissions from land conversion by oil palm plantations.Carlson et al. (2013) find that plantation expansion of oil palm in Kalimantan alone would contribute around 20% of Indonesia's 2020 CO_2-equivalent emissions, that is, around 20 MMT of carbon emissions per year associated with 31,640 km^2 area of palm oil plantation. Given 321.245 MT palm oil per km^2 of harvest area (USDA, FAS),[18] the parameter for carbon emissions from land conversion of palm oil plantation υ_{po} takes a value of 1.91 MMT CO_2 emissions per MMT of palm oil supply. Given such uncertainty about carbon emissions of palm oil plantation, the sensitivity analysis carried out later assumes the upper and lower bound of the parameter υ_{po} by floating 50% up and down based upon the benchmark value.

The carbon damage function, $\theta(\cdot)$, assumes a linear form. Hence, the marginal effect $\theta'(\cdot)$ represents the normalized constant marginal emissions damage from diesel fuels. There are many estimates regarding the social costs of CO_2 emissions (Stern, 2007; Tol, 2008). We take a value of $37/t$CO_2$ for the cost of pollution externality in the baseline, and conduct sensitivity analysis on this parameter, ranging from $5/t$CO_2$ to $80/t$CO_2$.

4. Simulation results

4.1. Benchmark results

The key question our model attempts to address is how much of the impact of expanded biodiesel uses in the US will show up in soy markets, and how much will be transmitted to other vegetable oil markets, particularly palm. The RFS requirements for biodiesel standards grow steadily over the next several years, increasing every year from 1.63 BG to 2 BG by 2017.[19] We consider two different biodiesel mandates (i.e., 2 BG, and 3.4 BG) to examine their non-linear impacts on world vegetable oil markets. In addition, two modeling scenarios are simulated. One is the scenario that soy oils are used as only feedstocks for biodiesel production, and the other is to incorporate imported palm oil as alternative feedstocks for refining biodiesel. Tables 5 and 6 present the simulated impacts on prices and quantities of related energy commodities and agricultural markets. The results for the baseline year 2014 are shown in column (1). Columns (2)–(3) present the results of increasing biodiesel mandates with soy oils used as only feedstocks for biodiesel production, while columns (4)–(5) show the corresponding results by extending the model to consider both soy and palm oils used as feedstocks for biodiesel production. All columns assume the binding biodiesel mandate with diesel fuel taxes of $0.48/gal accounted for. Unlike the baseline column (1), the remaining columns (2)–(5) assume away tax credits of $1.0/gal for biodiesel, given the pending legislation of renewing the tax credits for biodiesel production. Because border policies on soybean meals, soy oils, palm oils, and crude oil are assumed away, the ROW prices of these traded commodities equal their corresponding US domestic prices, hence are not reported in Tables 5 and 6.

4.1.1. Impacts on energy

The increasing biodiesel mandate leads to a replacement of traditional fossil fuels by biodiesel. In the scenario of only soy oil-based biodiesel, as the biodiesel mandate reaches 2 BG, only less than 0.1 BG of diesel fuels are replaced by the increasing biodiesel consumption. Due to a drastic increase of biodiesel mandate up to 3.4 BG presented in column (3) of Table 6, the diesel consumption falls slightly about 0.44%,

[16] The US own-price elasticities of demand for soybean oils and palm oils are $\varepsilon_{so} = -\sigma + (\sigma+\mu)\varphi_{so} = -0.173$, and $\varepsilon_{po} = -\sigma + (\sigma+\mu)\varphi_{po} = -0.674$, respectively. The implied cross-price elasticities are given as $\varepsilon_{so,po} = (\sigma+\mu)\varphi_{po} = 0.126$, and $\varepsilon_{po,so} = (\sigma+\mu)\varphi_{so} = 0.627$. Likewise, the own-price elasticities in the ROW are $\bar{\varepsilon}_{so} = -0.377$ and $\bar{\varepsilon}_{po} = -0.370$; and the cross-price elasticities in the ROW are $\bar{\varepsilon}_{so,po} = 0.030$, and $\bar{\varepsilon}_{po,so} = 0.023$.

[17] Please see the Emission Factors for Greenhouse Gas Inventories, EPA: https://www.epa.gov/sites/production/files/2015-12/documents/emission-factors_nov_2015.pdf.

[18] This value is obtained by using world total palm oil production divided by harvested area in 2014/2015. Please see the Production, Supply and Distribution Database in the FAS of the USDA, https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery.

[19] Please see the Final Renewable Fuel Standards for 2014, 2015, and 2016, and the Biomass-Based Diesel Volume for 2017, Docket Number: EPA-HQ-OAR-2015-0111.

Table 6
Simulated quantities of increasing biodiesel mandate and the Monte Carlo Simulation results in 95% confidence interval.

Biodiesel Mandate (BG)	Baseline	Soy oil as biodiesel feedstock		Soy and palm oil as biodiesel feedstocks	
	(1)	(2)	(3)	(4)	(5)
	1.55	2.0	3.4	2.0	3.4
Soybean supply (MMT)	101.25	101.35 [101.27, 101.62]	101.69 [101.42, 102.42]	101.26 [101.23, 101.42]	101.35 [101.29, 101.69]
ROW soybean supply (MMT)	212.10	212.60 [212.20, 212.81]	214.32 [212.99, 214.98]	212.15 [211.99, 212.31]	212.63 [212.29, 213.07]
Soybean meals supply (MMT)	81.17	81.25 [81.18, 81.46]	81.53 [81.30, 82.11]	81.17 [81.15, 81.30]	81.25 [81.20, 81.52]
Soybean meals demand(MMT)	29.23	29.26 [29.24, 29.27]	29.34 [29.27, 29.45]	29.23 [29.22, 29.24]	29.26 [29.24, 29.29]
ROW soybean meals supply (MMT)	172.78	173.19 [172.86, 173.36]	174.59 [173.51, 175.12]	172.82 [172.69, 172.95]	173.21 [172.93, 173.57]
ROW soybean meals demand (MMT)	224.72	225.18 [224.85, 225.34]	226.77 [225.60, 227.31]	224.76 [224.64, 224.89]	225.20 [224.94, 225.59]
Soybean oils supply (MMT)	19.27	19.29 [19.28, 19.34]	19.36 [19.30, 19.50]	19.27 [19.27, 19.31]	19.29 [19.28, 19.36]
Soybean oils demand (MMT)	6.62	6.57 [6.53, 6.61]	6.45 [6.30, 6.57]	6.62 [6.60, 6.63]	6.61 [6.53, 6.62]
Soybean oils in biodiesel production (MMT)	2.85	3.68 [3.68, 3.68]	6.26 [6.26, 6.26]	2.90 [2.81, 3.06]	3.62 [3.31, 4.14]
ROW soybean oils supply (MMT)	39.32	39.41 [39.34, 39.45]	39.73 [39.49, 39.85]	39.33 [39.30, 39.36]	39.42 [39.36, 39.50]
ROW soybean oils demand (MMT)	49.13	48.45 [48.34, 48.50]	46.38 [46.00, 46.55]	49.08 [48.94, 49.17]	48.48 [48.02, 48.78]
ROW palm oils supply (MMT)	61.36	61.41 [61.36, 61.73]	61.56 [61.41, 62.67]	61.86 [61.69, 62.04]	63.09 [62.53, 63.71]
Palm oils demand (MMT)	1.20	1.22 [1.20, 1.24]	1.31 [1.22, 1.39]	1.19 [1.18, 1.19]	1.19 [1.18, 1.20]
ROW palm oils demand (MMT)	60.16	60.18 [60.14, 60.52]	60.25 [60.11, 61.41]	59.89 [59.81, 60.02]	59.26 [59.01, 59.69]
Palm oils in biodiesel production (MMT)	0.00	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.78 [0.67, 0.86]	2.64 [2.27, 2.91]
Crude oil domestic supply (BB)	3.18	3.17 [3.17, 3.18]	3.17 [3.15, 3.17]	3.17 [3.16, 3.18]	3.17 [3.15, 3.18]
Crude oil import demand (BB)	2.55	2.55 [2.54, 2.55]	2.53 [2.51, 2.55]	2.55 [2.54, 2.55]	2.54 [2.52, 2.55]
Biodiesel from soy oils (BG)	1.55	2.00 [2.00, 2.00]	3.40 [3.40, 3.40]	1.58 [1.52, 1.66]	1.97 [1.79, 2.25]
Biodiesel from palm oils (BG)	0.00	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.42 [0.34, 0.48]	1.43 [1.15, 1.61]
Diesel quantity (BG)	75.31	75.24 [75.17, 75.30]	74.98 [74.76, 75.18]	75.24 [75.17, 75.30]	75.00 [74.77, 75.19]
Heating oil quantity (BG)	180.85	180.67 [180.51, 180.82]	180.06 [179.53, 180.52]	180.67 [180.51, 180.82]	180.09 [179.56, 180.55]

Notes: the results in brackets are reported in a form of 95% confidence interval for the Monte Carlo simulation on a set of selected 15 key parameters including elasticities, technology coefficient and marginal carbon social costs.

resulting in a lower price of diesel fuels from $3.32/gal down to $3.16/gal. As the demand for traditional diesel fuels decreases, both domestic and imported crude oil are required less in the oil refining industry. Given the recent inelastic domestic supply of crude oil ($\eta_0 = 0.25$) and the foreign oil supply ($\overline{\eta}_o = 0.5$), the domestic supply of crude oil falls only by 0.30%, and the US import demand of oil is down by about 0.61%. This declining supply of crude oil cuts down the production of petroleum by-product, leading to a slightly higher by-product price (i.e., heating oil price). Due to the significant increase of biodiesel production up to 3.4 BG, the biodiesel price rises by 6.17% from $3.47/gal up to $3.69/gal, but diesel price lowers down by 4.93% from $3.32/gal to $3.16/gal. As the traditional fossil fuels (i.e., diesel) are partially replaced by biodiesel, crude oil price drops slightly by 1.21% from $91.84/barrel to $90.73/barrel.

The expansion of biodiesel mandates would raise the feedstock price of soy oils and the price of palm oils. The former is through the production input–output linkage, while the latter is through the channel of imperfect substitution between two alternative vegetable oils in the demand side. When allowing palm oils used as alternative feedstocks for refining biodiesel, the increasing price of feedstock would trigger the production of biodiesel from palm oils. As the biodiesel mandates grow from 2 BG to 3.4 BG, palm oil-based biodiesel quantity rises from 0.42 BG to 1.43 BG shown in the last two columns of Table 6. With the palm oil-based biodiesel to meet the increasing mandate, the price of biodiesel experiences less upward pressure, falling from $3.69/gal (column [3]) to $3.53/gal (column [5]).

4.1.2. Impacts on agricultural feedstock

To meet the increasing biodiesel mandate, soybean oil, which is assumed as the only biofuel feedstock in columns (1)–(3) of Table 6, is demanded more in the biodiesel refinery sector. The drastic increase of biodiesel mandate up to 3.4 BG leaves the significant impacts on world soy oil markets through international trade. Before the increase, as shown in column (1) of Tables 6, 2.85 MMT soy oils are used in biodiesel production, 6.62 MMT soy oils are consumed domestically, and the rest 9.80 MMT are exported to the ROW. After the increase, as presented in column (3) of Tables 6, 6.26 MMT soy oils are diverted into biodiesel production, while the US domestic supply only reaches 19.36 MMT. This significant increase leaves only 6.65 MMT soy oils to export and feed the ROW. The (world) price of soy oils rises substantially from $704.73/MT up to $821.13/MT. By switching from expensive soy oils to palm oils, the ROW consumption of soy oils falls by 5.59%, while that of palm oils rises slightly by 0.15%. The overall ROW consumption of vegetable oils, which is the sum of soy and palm oils, is down by roughly

2.43% as a result of the 3.4 BG biodiesel mandate. The magnitude of this vegetable oil replacement depends upon the demand elasticity of substitution $\overline{\sigma}$ assumed in the model. With the postulated ROW value of $\overline{\sigma} = 0.6$ in the benchmark, one could expect a slight increase in palm oils to replace soy oils. As this elasticity substitution value rises, the replacement of palm oils to soy oils becomes appealing.

The rising demand of soy oils for the biodiesel purposes raises the US domestic price of soybeans over 3.66% from $373.53/MT to $387.21/MT. As a consequence, the US domestic supply of soybeans increases approximately 0.44% given the inelastic domestic supply elasticity of 0.12 assumed in the benchmark. To meet the rising ROW demand of soy oils, the ROW supply of soybeans reaches 214.32 MMT, which is a 1.05% increase from the initial level of 212.10 MMT. Both increasing domestic and ROW supply of beans provide excess supply of meals, lowering the (world) meal price by 2.60% from $407.34/MT to $396.76/MT.

When allowing the US biodiesel production to refine from imported palm oils, the rising price of soy oils could trigger the zero-profit threshold of the palm oils-based biodiesel refinery industry, thereby diverting palm oils into the biodiesel production. As biodiesel mandates grow steadily to 2 BG, as shown in column (4) of Table 6, palm oil-based biodiesel starts to replace soy oil-based biodiesel. Among 2 BG biodiesel mandates, 1.58 BG biodiesel is refined from soy oils and the rest of the 0.42 BG is diverted from palm oils. Comparing the scenario without and with palm oils as biodiesel feedstocks, this replacement leads to a 3.40% drop in the price of soy oils from $731.20/MT to $707.19/MT, and a 1.13% increase in the price of palm oils from $804.30/MT to $813.53/MT. Although the ROW supply of palm oils rises to 61.86 MMT, the ROW consumption of palm oils falls to 59.89 MMT, which is the opposite case when palm oils could not be used as biodiesel feedstocks. As the biodiesel mandate keeps reaching 3.4 BG, 2.64 MMT of imported palm oils are diverted into refining biodiesel and producing 1.43 BG palm oil-based biodiesel. By incorporating palm oil-based biodiesel, the price of soy oil experiences less upward pressures, from $821.13/MT (in column [3]) down to $732.42/MT (in column [5]), while the price of palm oils rises from $807.54/MT (in column [3]) up to $838.76/MT (in column [5]). Although palm oil is diverted from consumption purposes to biodiesel production, more soy oils are released from refinery sector to food/feed uses. Comparing with the baseline, the total ROW consumption of vegetable oils, sum of soy oils and palm oils in column (5), declines by only 1.42%, which is less than a 2.43% drop in the scenario that soy oils are used as only biodiesel feedstocks.

As a result of the rising mandate, the replacement of soy oil-based biodiesel by palm oil-based biodiesel puts upward pressures on the world palm oil price, but less pressures on the world vegetable oil market. This result is sensitive to the relative technology efficiency of palm oil-based biodiesel to soy oil-based biodiesel production in the supply side. In the baseline we assume the same technology coefficient of biodiesel refinery from either soy oils or palm oils. As refining from palm oil becomes relatively more efficient in terms of requiring less feedstocks to produce a unit of biodiesel, out of conventional consumption purposes, more palm oils would be diverted into the refinery sector. On the one hand, this replacement raises the price of palm oils, and on the other hand, more soy oils are released from biodiesel production to meet world food consumption.

4.1.3. Impacts on US social welfare

The US social welfare is the sum of net tax revenue (tax on fuels minus subsidy on biodiesel), producer surplus of domestic oil supply, of domestic soybean supply, consumer surplus of heating oil, of diesel composite demand, of soy meals, of soy oils, and of palm oils, subtracting carbon social damage. Table 7 presents the simulated US welfare implications of the expanded biodiesel mandates. Columns (1)–(2) are results when soy oils are used as only feedstocks for biodiesel refinery, while columns (3)–(4) are results when alternative feedstocks of palm oils are allowed to produce biodiesel. All simulated results are percentage changes relative to the baseline.

Under the scenario of soy oil as only biodiesel feedstocks, the increasing biodiesel mandate up to 2.0 BG, on the one hand, lifts up the producer's price of soybean, but lowers down the consumer's prices of soy meals, thereby increasing the producer surplus of soybeans by 0.89% and consumer surplus of soy meals by 0.18% relative to the baseline. On the other hand, this expansion of biodiesel mandate cuts down consumer surplus of soy oils and of palm oils by 1.33% and 0.26%, respectively. As a consequence of the rising mandate, the replacement of diesel fuels by biodiesel results in 0.87% welfare gains in consumer surplus of diesel fuel composite demand, but 0.21% losses in consumer surplus of petroleum byproducts and 0.33% losses in producer surplus of domestic crude oil supply. In addition, a small reduction in diesel fuel consumption is replaced by a substantial increase in biodiesel quantity.

Table 7
Welfare effects of alternative biodiesel mandates and the Mont Carlo simulation results in 95% confidence interval (percentage changes relative to baseline).

Biodiesel mandate (BG)	Soy oil as biodiesel feedstock		Soy and palm oil as biodiesel feedstocks	
	(1)	(2)	(3)	(4)
	2.0	3.4	2.0	3.4
Carbon social damage	0.17% [0.11%, 0.23%]	0.66% [0.44%, 0.96%]	0.24% [0.17%, 0.29%]	0.92% [0.65%, 1.15%]
Net tax revenue	−0.06% [−0.13%, −0.01%]	−0.27% [−0.55%, −0.03%]	−0.06% [−0.13%, −0.01%]	−0.25% [−0.53%, −0.03%]
PS of domestic oil supply	−0.33% [−0.64%, −0.15%]	−1.39% [−2.68%, −0.65%]	−0.32% [−0.63%, −0.15%]	−1.33% [−2.63%, −0.62%]
PS of domestic soybean supply	0.89% [0.45%, 1.09%]	3.90% [1.96%, 4.86%]	0.08% [0.01%, 0.29%]	0.93% [0.61%, 1.60%]
CS of petrol. byproduct demand	−0.21% [−0.34%, −0.10%]	−0.87% [−1.43%, −0.41%]	−0.20% [−0.34%, −0.09%]	−0.84% [−1.40%, −0.39%]
CS of diesel composite demand	0.87% [0.74%, 0.98%]	3.53% [2.98%, 4.00%]	0.88% [0.74%, 0.98%]	3.56% [3.01%, 4.01%]
CS of soy meals demand	0.18% [0.07%, 0.37%]	0.78% [0.28%, 1.61%]	0.02% [0.00%, 0.08%]	0.19% [0.08%, 0.49%]
CS of soy oils demand	−1.33% [−2.42%, −0.51%]	−5.80% [−10.41%, −2.19%]	−0.12% [−0.56%, −0.01%]	−1.40% [−3.33%, −0.65%]
CS of palm oils demand	−0.26% [−1.38%, −0.07%]	−1.87% [−7.28%, −0.55%]	−1.71% [−3.12%, −0.84%]	−5.94% [−11.34%, −3.01%]
Welfare	0.03% [0.00%, 0.08%]	0.10% [−0.01%, 0.29%]	0.02% [−0.01%, 0.07%]	0.07% [−0.03%, 0.26%]

Notes: the results in brackets are reported in a form of 95% confidence interval for the Monte Carlo simulation on a set of selected 15 key parameters including elasticities, technology coefficient and marginal carbon social costs.

This replacement leads to a slight loss in net tax revenue, which is the sum of tax collected from fuel consumption minus subsidy. Moreover, CO_2 emissions saving from the small reduction in diesel fuel consumption is offset by CO_2 releases from the substantial increase in biodiesel quantity, leading to an increase in total CO_2 pollution from the fuel combustion, and henceforth a rise in carbon social damage by 0.17%. Compared with the baseline, the overall US social welfare rises slightly by 0.03% due to the 2 BG biodiesel mandate. As the biodiesel mandate continues to expand up to 3.4 BG, the magnitude of the distributional welfare implications expands. The US experiences slightly 0.10% welfare gains relative to the baseline 2014.

When palm oils are allowed to refine biodiesel, the expansion of biodiesel mandates up to 3.4 BG results in less upward pressures for soy oil price but more for palm oil price. Consumers of soy oils suffer a modest welfare loss from the rising soy oil price by 1.40%, while consumers of palm oil experiences 5.94% welfare losses. Comparing with the scenario of soy oils as only biodiesel feedstocks, the inclusion of palm oil-based biodiesel has a modest welfare distributional impact on the fuel markets, but a substantial influence on the vegetable oil markets. The welfare of both consumers of palm oils and producers of soy oils is redistributed to consumers of soy oils. The overall US social welfare gains by only 0.07% relative to the baseline.

4.2. Sensitivity analysis

To further test the robustness of our conclusions, we first carry out a Monte Carlo simulation to represent our uncertainty about the model's true parameters. A set of 16 key parameters including elasticities, technology coefficient, and marginal carbon social costs, is considered in this exercise. Alternative values of these key parameters are summarized in Table A1 in the online appendix. In the Monte Caro simulation, a set of parameters was randomly drawn 100,000 times from a beta distribution consistent with the ranges reported in Table A1 in the online appendix.[20] For each vector of these random parameters we recalibrate the model to the baseline 2014, and then explore the impacts of alternative biodiesel mandates and their welfare implications. The results of the Monte Carlo simulation in a form of 95% confidence interval are summarized in the brackets along with the benchmark results in Tables 5–7. One way to interpret the results of this Monte Carlo experiment is as a robustness check on the magnitude of the policy tool parameters that we computed in the baseline. Within this perspective, some of our main conclusions are re-emphasized by the Monte Carlo simulation.

With soy oils as only feedstocks for biodiesel production, the rising biodiesel mandate up to 2 BG is associated with a modest increase in the (world) price of vegetable oils (soy and palm oils). Relative to the baseline 2014, the price of soy oils has been raised by a range of 1.57% to 6.74%, while the price of palm oils experiences a slight increase up to 0.88%.[21] As biodiesel mandates reach 3.4 BG, more soy oils are diverted into the biodiesel refinery sector, leading to a substantial increment of soy oil price from 8.44% to 27.78%, but a slight increase of palm oil price up to 3.12%. With palm oils as alternative feedstocks for refining biodiesel, the price responses of palm oil to the rising mandates become more appealing. To meet the 3.4 BG mandate, relative to the baseline 2014, the price of palm oils rises from 3.56% to 6.36%, while the price of soy oils increases with a range of 2.56% to 6.58%.

When it comes to the welfare implications, with a 3.4 BG biodiesel mandate, the social welfare gains by only 0.10% and 0.07%, respectively, depending upon whether palm oils could be used as biodiesel feedstocks or not. These welfare gains have 95% confidence intervals of [−0.01%, 0.29%] and of [−0.03%, 0.26%], respectively, both of which are fairly compact, suggesting that the welfare impacts of alternative US biodiesel mandates would not be statistically significant from zero. Although the relative changes in the overall social welfare are not substantial in response to the expanding biodiesel mandates, the distribution of the social welfare varies drastically with the proposed mandate levels. For example, in responding to a level of 3.4 BG biodiesel mandate, if soy oils are used as only biodiesel feedstocks, the consumer surplus of soy oil demand ranges from [−10.41%, −2.19%], while that of palm oil demand is shown to range from −7.28% to −0.55%. By relaxing the restriction of no palm oil used as biodiesel feedstocks, the consumer surplus of palm oil demand becomes more negative, ranging from −11.34% to −3.01%.

Moreover, we undertake a series of sensitivity analysis for each of selected key parameters. Specifically, we vary with one parameter at a time and recalibrate the model at the baseline 2014, and then explore the impacts of the rising biodiesel mandates on the replacement of vegetable oils between soy and palm oils. The simulation results are reported in Tables A2–A7 in the online appendix. We first examine how the unconditional price elasticity of demand for vegetable oils in the US (μ) and in the ROW ($\overline{\mu}$) would alter the impact of expanded biodiesel production. As the US demand for vegetable oils becomes more inelastic, Table A2 shows that the expansion of biodiesel production slightly lifts up the (world) prices of soy oils and of palm oils. When the ROW demand for vegetable is more inelastic, as shown in Table A3, for a 2 BG biodiesel mandate, the (world) price of soy oils rises up to $754.77/MT, which is around 3.22% higher than the effects in the benchmark elasticity value, while for a 3.4 BG biodiesel mandate, the (world) price of soy oils reaches $913.10/MT, which is approximately 11% higher than the effects in the benchmark elasticity level. Next, the role of the demand elasticity of substitution between soy and palm oils in the US (σ) and in the ROW ($\overline{\sigma}$) is explored in Tables A4 and A5. The more elastic the demand of substitution, the lower the (world) price of soy oils would be, but the higher the (world) price of palm oils becomes. This is because the replacement of soy oils by palm oils becomes more appealing. The world demand for palm oils rises, while that for soy oils falls. Furthermore, we are interested in investigating how the relative technology efficiency of refining biodiesel from palm oils compared with that from soy oils (α_{po}/α_{bd}) would affect the replacement of palm and soy oils in food purposes in response to the expansion of biodiesel mandates. When palm oil becomes more efficient in refining biodiesel in terms of requiring less feedstocks to produce one unit of biodiesel as shown in Table A6, the effects of expanded biodiesel mandates on both (world) prices of soy oils and of palm oils become less appealing, because less palm oils are demanded in the biodiesel refinery sector, leaving much more oils for food consumption purposes. Last, but not least, as the domestic supply of crude oil becomes more elastic as presented in Table A7, the same amount of biodiesel production expansion has a less substantial impact on world crude oil price cuts, which in turn leads a smaller US social welfare gain.

5. Conclusion

This paper applies and extends the analytical setup of Cui et al. (2011) to analyze the economic impacts of the expansion of US biodiesel mandates on world vegetable oil markets. The model is calibrated to fit the baseline year of 2014. We simulate the market effects of recent volume requirements for biodiesel proposed by the RFS program of the EPA, and then discuss how the potential production of palm oil-based biodiesel would affect the world vegetable oil markets in response to the rising mandates.

Some interesting findings arise. First, the expanded use of soy oil for biodiesel in the US will have considerable impacts on world vegetable oil markets. The majority of the vegetable oil replacement is likely to occur through substitution of palm oil. As for 3.4 BG mandates, the ROW consumption of soy oils falls by 5.59%, while that of palm oils

[20] Each beta distribution has a finite support on [a, b], where the extremes of this interval are the minimal and maximal parameter values reported in Table A1 in the online appendix. Given [a, b], the shape parameters of the beta distribution are picked so that the standard deviation satisfies (b − a)/6 and the mean is equal to the baseline value.

[21] Percentage changes are calculated from prices between the baseline and the simulated prices in 97.5% or 2.5% percentile points.

rises slightly by 0.15%. The overall ROW consumption of vegetable oils, which is the sum of soy and palm oils, is down by roughly 2.43%. As this elasticity substitution value between palm oil and soy oils in the demand side rises, the replacement of palms oils to soy oils becomes appealing.

Second, as imported palm oils used in biodiesel production, the rising price of soy oils could trigger the zero-profit threshold of producing biodiesel from palm oils, thereby diverting some palm oils into the biodiesel production. Out of 3.4 BG biodiesel mandates, there is 1.43 BG of palm oil-based biodiesel refined from 2.64 MMT of imported palm oils. Although palm oil is diverted from consumption purposes to biodiesel production, more soy oils are released from the biodiesel refinery sector to food/feed uses. Comparing with the baseline, the total ROW consumption of vegetable oils declines by only 1.42%, which is less than a 2.83% drop when soy oils are used as only biodiesel feedstocks.

Third, there is a replacement of a small reduction in diesel fuel consumption by a substantial increase in biodiesel quantity. CO_2 emissions saving from the small reduction in diesel fuel consumption is offset by CO_2 releases from the substantial increase in biodiesel production, leading to an increase in total CO_2 pollution from fuel combustion. Consequently, carbon social damage rises. Although the expansion of biodiesel mandate does not achieve carbon reduction, this policy raises the overall US social welfare through the terms of trade effect benefited from cheap oil imports because of the magnitude of US oil imports. With 3.4 BG biodiesel mandates, the US experiences slightly 0.10% welfare gains relative to baseline 2014. The Monte Carlo simulation results suggest that the impacts of alternative US biodiesel mandates are more substantial on the distribution of the social welfare rather than on the overall welfare.

Finally, a few caveats. Our stylized model involves only two separate oils (soy and palm) and two markets (US and ROW). More detailed modeling could consider a greater variety of oils, including oils like canola or rapeseed that are intermediate in the share of their value arising from oil versus meal, and other sources of biodiesel feedstock (e.g., secondary fats and oils and fatty acids) that could arise in response to price changes in the soy oil market. In addition, it is widely believed that CO_2 is a global pollutant. We only account for carbon emissions of land conversion for the palm oil purposes in the ROW, but not consider carbon emissions from other sources in the ROW. Another limitation of our model is the absence of the impacts foreign emissions (other than palm plantation) have on the US domestic welfare and potential emission leakage effects associated with the US biodiesel policies. With these two effects considered, the incentives for the US domestic policies to control emissions are further weakened.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2017.04.010.

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