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<b>Authors</b>	Subhayu Bandyopadhyay, Sumon Bhaumik, and Howard J. Wall
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Federal Reserve Bank of St. Louis, Research Division, P.O. Box 442, St. Louis, MO 63166

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# Biofuel Subsidies and International Trade

Subhayu Bandyopadhyay\*

Federal Reserve Bank of St. Louis and IZA, Bonn

Sumon Bhaumik<sup>+</sup>

Aston University, UK, and IZA, Bonn

Howard J. Wall<sup>\$</sup>

Lindenwood University, MO

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## Abstract

This paper explores optimal biofuel subsidies in a general equilibrium trade model. The focus is on the production of biofuels such as corn-based ethanol, which diverts corn from use as food. In the small-country case, when the tax on crude is not available as a policy option, a second-best biofuel subsidy may or may not be positive. In the large-country case, the twin objectives of pollution reduction and terms-of-trade improvement justify a combination of crude tax and biofuel subsidy for the food exporter. Finally, we show that when both nations engage in biofuel policies, the terms-of-trade effects encourage the Nash equilibrium subsidy to be positive (negative) for the food exporting (importing) nation.

*JEL* Codes: F1, H2, O1

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\*Corresponding author: Research Division, Federal Reserve Bank of St. Louis, PO Box 442, St. Louis, MO 63166-0442, USA. E-mail: [bandyopadhyay@stls.frb.org](mailto:bandyopadhyay@stls.frb.org); Tel: 314-444-7425.

<sup>+</sup>Economics and Strategy Group, Aston Business School, Aston University, Aston Triangle, Birmingham B4 7ET, United Kingdom. E-mail: [s.bhaumik@aston.ac.uk](mailto:s.bhaumik@aston.ac.uk); Tel: 0121-204-3328.

<sup>\$</sup>Economics Department, Lindenwood University, 209 S. Kingshighway, St. Charles, MO 63301, USA. E-mail: [HWall@lindenwood.edu](mailto:HWall@lindenwood.edu); Tel: 636-949-4742.

## 1. Introduction<sup>1</sup>

The literature on trade and the environment has proceeded largely along two paths. One strand of the literature has examined the impact of trade itself on pollution (see Copeland and Taylor; 1994, 2003). It has highlighted the fact that by fostering economic growth, trade can have two opposing effects on environmental quality. On the one hand, the higher output resulting from trade would contribute to pollution (the “scale” effect).<sup>2</sup> On the other hand, higher income would result in greater demand for a cleaner environment and might, therefore, result in the adoption of pollution-reducing technologies (the “technique” effect).<sup>3,4</sup> A second strand of the literature has modeled strategic interactions between two trading partners. An important conclusion drawn by this line of inquiry is that, contrary to popular wisdom, it might not be optimal for a government to impose weak environmental standards on domestic industries to give them a competitive advantage. Strict standards might instead be optimal if firms compete in prices (Barrett, 1994).<sup>5</sup>

A policy issue that has been central to environmental policy in the United States, among other nations, relates to biofuels. The use of crops such as corn to make substances like bioethanol has several implications, including reduced reliance on oil imports from potentially unreliable trade partners and a moving to cleaner sources of energy. While our analysis can be

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<sup>1</sup> We thank an anonymous referee for helpful suggestions. The usual disclaimer applies.

<sup>2</sup> If, however, pollution quotas are enforced through the issuance of a fixed number of pollution permits, the environmental impact of trade liberalization might be negligible. Further, it can be shown that if pollution taxes are adjusted to equate the marginal cost of pollution with the marginal benefits of the associated production, the net impact on pollution is indeterminate (Lopez, 1994; Rauscher, 1997; Copeland and Taylor, 2003).

<sup>3</sup> Empirical evidence suggests that the effects of rising income might be the stronger driver of the trade-environment relationship, resulting in a positive impact of trade on environment in higher-income countries (Frankel and Rose, 2005).

<sup>4</sup> See Antweiler et al. (2001).

<sup>5</sup> A related issue is trade in hazardous substances, which can have a direct negative impact on the environment of the importing nation. A recent paper by Baggs (2009) provides an empirical analysis of this issue, where the focus is on country characteristics that determine trade in hazardous materials. Also, see Dean (1992), for a survey of issues that pertain to such trade.

adapted to address the first issue, in line with the trade and environment literature we choose to focus on the second.

This is an important issue given the longstanding government support for biofuels and the dramatically increased diversion of the US corn crop into ethanol production (Figure 1). In 1980, about one-half of a percent of US corn production was used to produce ethanol, but by 2009 this share was 33 percent, having risen more than five-fold between 2000 and 2009. More recently, on October 13, 2010, the US Environmental Protection Agency (EPA) raised the 30-year-old cap of 10 percent ethanol blend in fuel for ordinary cars to 15 percent (known as E15) for models 2007 onward (Power, 2010, and Wald, 2010). The implementation of this new rule has coincided with rising corn prices and severe drought, which highlights how the effects of biofuel policy do not occur in a vacuum. One of the central contributions of this paper is to provide a general equilibrium model that helps us to analyze such linkages, which, in turn, helps to enlighten policy.

The use of biofuels cannot be discussed in isolation from two related issues. First, it is generally accepted that the growth of the biofuel industry in all countries except Brazil, where it has attained scale economies, is contingent on significant subsidy.<sup>6</sup> Second, given the energy inefficiency of biofuels, an aggressive strategy to promote its use can lead to a significant increase in the world prices of food items.<sup>7</sup> Among other problems, this second issue can be

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<sup>6</sup> In the United States, where bioethanol production is corn based, the break-even price for petroleum is \$54 per barrel, and in Europe, where bioethanol production is wheat based, the break-even price is \$72 per barrel (Larson, 2008). The US government provides a subsidy of 51 cents per gallon to producers of bioethanol. In Germany, where the growth of the production and use of biofuels was among the fastest in EU member countries, biofuel producers not only enjoy a 35 percent tax advantage vis-a-vis the producers of traditional fuels, but the state also subsidizes construction of biofuel production units up to 50 percent.

<sup>7</sup> For example, corn-based ethanol has 57 percent energy efficiency while petroleum has 81 percent efficiency. OECD (2006) estimates suggest that, to account for 10 percent of vehicular fuel, 60-70 percent of the current crop area in the US, Canada, and the EU-15 countries would have to be devoted to crops that can be used to produce ethanol.

quite devastating for the developing nations.<sup>8</sup> Developed countries would be affected also if, as projected, there is a steep increase in the prices of staple items like corn and wheat. Such projections clearly warrant a discussion about the efficacy of opting for biofuel subsidies.<sup>9</sup>

The purpose of this paper is to provide a benchmark to think about biofuel subsidies within the context of international trade and pollution, where trade policies cannot be used due to conflicts with WTO rules. Pollution is treated here as a global public good because fossil fuels contribute (arguably) to atmospheric change. To simplify the analysis we treat a homogeneous food item like corn to have two potential uses. The first is direct consumption as food. The second is to use as an intermediate input in the production of energy. The other intermediate input used to produce energy is crude oil. Energy itself is treated as a non-traded commodity because of difficulties in shipping it across large distances. The focus of the analysis is on two nations, one of which (say US) exports corn, while the other (say China or Brazil) imports corn in exchange for manufacturing exports. The supply of crude comes from a third nation (say the Middle East), which is blackboxed here through the assumption that the price of crude is fixed.<sup>10</sup>

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<sup>8</sup> Runge and Senauer (2007) have argued that by pushing up the price of crops that are staples for the world's poor population, by 2025 biofuels could nearly double the number of people who are chronically hungry.

<sup>9</sup> By contrast, the discussion in the trade and environment literature largely involves policies that either cap pollution through fiat and permits or raise the cost of producing the polluting good (see Copeland and Taylor, 2004, for a discussion).

<sup>10</sup> This assumption simplifies the analysis considerably. For example, even in a simple model like Bhagwati et al. (1983) where there are two goods (and hence a single relative price) and free trade, the introduction of a third, non-participant, nation can generate price amplification and transfer paradoxes that do not arise in two-country models. Our model, although not terribly complicated, has an additional traded intermediate input (hence, two relative prices to be potentially determined by the world market), a non-traded good, and several policy variables. Endogenizing the price of crude in even our simple structure would add several layers of complexity. Given that the point of our paper is to consider how biofuel policies affect food prices, and not to analyze fossil fuel prices, our assumption is a tractable compromise. Of course, one can always look at the effects of fossil fuel price changes in our model by conducting comparative static exercises. The outline of such an analysis is presented in section C of the appendix at the end of this paper, for the case of Laissez Faire. Finally, we refer the reader to an important paper by Lapan and Moschini (2009) which does analyze multiple relative prices. They use some functional separability assumptions and quasi-linearity to achieve tractability, although their general equilibrium sectoral structure is quite different from ours.

Consequently, the terms-of-trade that we consider is between food and manufacturing, where the latter is treated as the numeraire good.

To keep the analysis simple, we assume that the use of crude in energy production is polluting, while the use of corn in making energy is not.<sup>11</sup> The analysis proceeds in three parts. In the first, we consider a small open economy facing given prices of all the traded goods. The only market failure here stems from the pollution externality created by crude use in energy production, which can be corrected by an appropriate tax on crude. If the tax on crude is not available because of political economy considerations, the second-best policy may be a tax rather than a subsidy on biofuel. This result complements and extends the findings of Vedenov and Wetzstein (2008) and Khanna et al. (2008), who have also noted this possibility in other contexts. We discuss the differences between our analysis and their respective papers in the next section.<sup>12</sup> At this point, it is also worthwhile to note that the wisdom of biofuel subsidization has also been questioned by Grafton et al. (2010). Using a dynamic model, they show that biofuel subsidies may increase the rate of fossil-fuel extraction, and thereby make potential climate-change damages more imminent.

The second part of this paper deals with the case where the terms-of-trade for food is endogenous to the system. In this context, we consider welfare-maximizing crude tax and biofuel subsidy combination for the food-exporting nation (the other nation is assumed to be passive). The tax on crude departs from the Pigouvian level, because in addition to targeting pollution it also affects the terms-of-trade of food by raising the demand for corn to be used as a substitute for crude in energy production. In addition, a biofuel subsidy is also used to

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<sup>11</sup> This assumption keeps the analysis clean without sacrificing the basic thrust of our results as long as crude use is assumed to be more polluting than biofuel use. The point of this paper is not to justify bioethanol policies, but to suggest that even if they are clean, they can still be misused compared to first or second-best benchmarks. Of course, if they are more polluting than crude, then our arguments about possible misallocations caused by such policies are strengthened.

<sup>12</sup> Also see de Gorter and Just (2010) in this context.

complement the terms-of-trade improving impact of the crude tax.<sup>13</sup> Effectively, in a world where beggar-thy-neighbor trade policies cannot be used because of WTO rules, a tax on crude and a biofuel subsidy may serve a similar purpose.

When the food exporting nation uses biofuel subsidy to improve its terms of trade, the food importing nation suffers. However, the food importing nation can also use its biofuel subsidy to counter this adverse terms-of-trade movement. This strategic interdependence of biofuel policy has not yet been analyzed in this literature. Our paper is the first to cast this problem in the context of a Johnson (1953) type Nash policy equilibrium, which is augmented to consider pollution as a global public good. Instead of using imports tariffs or export taxes, the nations use biofuel subsidies to target both pollution and terms-of-trade. When a subsidy is warranted by the pollution motive, the terms-of-trade motive complements it for the food exporter. In contrast, for the food importer, the terms-of-trade motive pulls the biofuel subsidy below the level suggested by the pollution motive.

## 2. The Benchmark Case: A Small Open Economy

Let us consider a small open economy with representative consumers. Each consumer maximizes utility given by  $U = U(\tilde{F}, \tilde{E}, \tilde{M}, G)$ , where  $\tilde{F}$ ,  $\tilde{E}$ ,  $\tilde{M}$ , and  $G$  are consumption levels

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<sup>13</sup> Lasco and Khanna (2009) analyze terms-of-trade effects of biofuel subsidies. However, their context is one of an ethanol importing nation, where a biofuel subsidy leads to a terms-of-trade loss. Of course, in such a setting there is no incentive to subsidize biofuels purely for terms-of-trade reasons. In contrast, we want to highlight the gain of US corn farmers from a higher price of corn in the world market. Hence terms-of-trade gain is an integral motive of biofuel subsidization in this paper. Lapan and Moschini (2009) also analyze biofuel subsidies in a trade model. While this paper complements their analysis, we have some important differences. First, the functional separability assumptions in their paper seal off many of the intersectoral linkages that we consider. Second, the fuel tax that they consider is a tax that discourages use of both fossil fuel and ethanol (i.e., it is imposed on the blend). Thus, a rise in their fuel tax will reduce the demand for ethanol. In contrast, the burden of our fossil fuel tax falls exclusively on the use of fossil fuel as an input in energy production. This causes substitution toward biofuel (as an input in energy), and raises the demand for biofuel/corn. In turn, this confers terms-of-trade benefits to the food exporting nation. Finally, a major difference between our models is that we consider a three nation context, where two nations import crude from a third nation, and both of these nations engage in biofuel policy. The strategic interdependence in biofuel policy that arises in this context is novel to the literature and complements the aforementioned papers.

of food, energy, a manufactured good, and clean environment, respectively.  $M$  is the numeraire good. If  $p$  is the price of food and  $q$  is the price of energy, the expenditure function is

$$e(p, q, 1, u, G) \equiv \text{Min } p\tilde{F} + q\tilde{E} + \tilde{M}, \text{ subject to } u = U(\tilde{F}, \tilde{E}, \tilde{M}, G), \quad (1)$$

which yields the usual Hicksian demand functions. In addition,  $e_u > 0$ <sup>14</sup> and  $e_G = -e_u U_G < 0$ .<sup>15</sup>

In this economy, all commodities are produced using constant returns to scale (CRS).

Food ( $F$ ) is produced using labor ( $L^F$ ) and land ( $T$ ). Assuming that land is specific to food and that its endowment is given, we have

$$F = F(L^F, T) = f(L^F), \text{ where } f'(\cdot) > 0 \text{ and } f''(\cdot) < 0. \quad (2)$$

Competitive profit maximization ensures that  $w = pf'(\cdot)$ , implying that  $L^F = L^F(p, w)$ .

Similarly, the manufactured good is produced using labor ( $L^M$ ) and energy ( $E^M$ ):

$$M = M(L^M, E^M). \quad (3)$$

The profit maximization conditions are  $w = M_L(L^M, E^M)$  and  $q = M_E(L^M, E^M)$ . Labor supply

is given at  $\bar{L}$ , such that

$$L^F + L^M = \bar{L}.^{16} \quad (4)$$

Finally, energy is produced using food for biofuel ( $B$ ) and crude oil ( $R$ )—our proxy for fossil fuel.<sup>17</sup> All of  $R$  is assumed to be imported at a given price  $r$ :

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<sup>14</sup> Throughout the paper we use the convention that unless specified otherwise,  $\phi_i$  and  $\phi_{ij}$  are, respectively, the first- and second-order partial derivatives of any function  $\phi(x_i, x_j)$ .

<sup>15</sup> Consider quasi-linear preferences and separability of  $G$ :  $U = \theta(\tilde{F}, \tilde{E}) + \tilde{M} + \gamma(G)$ . The expenditure function associated with this utility function is:  $e(p, q, u, G) = p\tilde{F}(p, q) + q\tilde{E}(p, q) + u - \theta[\tilde{F}(p, q), \tilde{E}(p, q)] - \gamma(G)$ , which implies  $e_p = \tilde{F}(p, q)$ ,  $e_q = \tilde{E}(p, q)$ ,  $e_u = 1$ ,  $e_G = -\gamma'(G) < 0$ , and  $e_{pu} = e_{qu} = 0$ .

<sup>16</sup> The production structure in this model is somewhat similar to Marjit et al. (2007), in that a policy induced wage rise in the manufacturing sector must have a negative effect on the landowners in the agricultural sector, who own an immobile fixed factor.

<sup>17</sup> Biofuel  $B$  in our model is just corn used as an intermediate input for production of energy  $E$ . The sum of  $B$  and the consumption demand for corn (food) is the total demand for corn in this economy. Thus, corn can either be an exportable or an importable in the small open economy case, depending on the underlying production and consumption parameters that define this economy. In the large country case analyzed later, we assume that the third



$$E = E(B, R). \quad (5)$$

The function  $E(B, R)$  is a standard production function in the inputs  $B$  and  $R$ , with diminishing marginal rate of substitution, such that one can imperfectly substitute  $B$  for  $R$  along a given energy isoquant. We should note that  $R$  is not directly consumed—it is a pure intermediate input in producing energy. Thus, there is no direct relationship between  $R$  and  $B$  in consumption. However, energy and food are both consumed, and our expenditure function allows for substitutability or complementarity. Thus, although there is no direct relationship between  $B$  and  $R$  on the consumption side, their effects on food or energy prices will lead to cross-effects between food and energy consumption. Finally, we note that the profit-maximization conditions in the energy sector equate the net input prices of  $B$  and  $R$  to the values of their marginal products.

The environment here is treated as a global public good, where carbon emissions lead to global pollution. Carbon emissions occur at the energy production stage, and, consistent with a view of biofuel as being cleaner, we assume that crude is polluting but that biofuel is not.<sup>18</sup> Let  $R^*$  be the amount of crude used in the foreign nation. Clean environment is a decreasing function of the amount of global crude use, such that

$$G = G(R + R^*), \quad G'(\cdot) < 0. \quad (6a)$$

Further, noting that in the small country case the amount of crude used by the rest of the world ( $R^*$ ) is taken as given by the domestic nation, (6a) reduces to

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country neither produces nor consumes corn. Thus, the first two nations (Home and Foreign) have to balance the world market for corn. Without loss of generality, we have assumed there that corn is an exportable for the home country and, thus, an importable for the foreign country.

<sup>18</sup> An alternative would be to propose that global pollution is a function of biofuel and crude, with biofuel being relatively less polluting. Our polar assumption considerably simplifies the analysis without compromising the basic messages that can be drawn from it.

$$G = G(R), \quad G'(R) < 0. \quad (6b)$$

The expenditure-revenue identity for this economy (equivalently, its trade balance equation) is

$$e(p, q, 1, u, G) = pf(L^F) + M(L^M, E^M) + qE(B, R) - pB - rR - qE^M. \quad (7)$$

Given the difficulties in trading energy in its final form over long distances, we assume that  $E$  is a nontraded good with its price determined by the zero profit condition:

$$q = C(p, r, 1), \quad (8)$$

where  $C(\cdot)$  is the unit cost of producing energy. The assumption of CRS implies that

$$qE - pB - rR = 0. \text{ Substituting this expression in (7) and using (8), total differentiation of (7)}$$

yields

$$\frac{du}{dR} = -\frac{e_G G'}{e_u} < 0. \quad (9)$$

It is clear from Eq. (9) that the competitive Laissez Faire equilibrium is not socially optimal in the sense that a small reduction in  $R$  will raise the utility of the representative agent of this small open economy. This is the standard market failure outcome where energy producers do not have to pay for the costs of pollution that they create. The next sections explore the different policy options available to correct this distortion.

## 2.1 Optimal Subsidy on Biofuel and an Optimal Tax on Crude

Suppose that the government subsidizes the use of biofuel ( $B$ ) such that its input price in energy production, net of subsidy  $s$ , is  $p^s = p - s$ . Also, assume that the government uses a tax  $t$  on crude, so the domestic price of crude is  $r^d = r + t$ .<sup>19</sup> Using (8),

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<sup>19</sup> Given the production function described in Eq.(5), where we assume a diminishing marginal rate of substitution between the two inputs, a rise in either  $t$  or  $s$  will raise  $B$  and reduce  $R$  through the substitution effect, although the effect on output effects will differ. From (10) it is evident that the subsidy will reduce the price of energy, while the

$$q = C(p^s, r^d, 1) \Rightarrow q = q(s, t), q_s = -\frac{B}{E}, \text{ and } q_t = \frac{R}{E}. \quad (10)$$

Under CRS,  $qE - pB - rR = -sB + tR$ . Using (7) and (10) we get

$$e_u du = -s dB + (t - e_G G') dR, \quad (11)$$

where the first term on the right-hand side is the loss due to the distortion in input use, and the second term is the net benefit due to the reduction of crude use. From (11), the optimal subsidy condition is

$$e_u \frac{\partial u}{\partial s} = 0 \Rightarrow s^{opt} = (t - e_G G') \frac{R_s}{B_s}.^{20} \quad (12)$$

Using (12),

$$e_u \frac{\partial u}{\partial t} = (t - e_G G') \left( R_t - \frac{R_s B_t}{B_s} \right) = 0 \Rightarrow t^{opt} = e_G G' > 0, \text{ assuming } R_t - \frac{R_s B_t}{B_s} \neq 0. \quad (13)$$

Notice that  $e_G G'$  measures the amount of the numeraire good that the consumer will need to be compensated for a unit rise in  $R$  (and hence pollution). Therefore, using (12) and (13), it is clear that the optimal crude tax is the Pigouvian tax, which equals the marginal damage from pollution. Also, when this tax is in place, the optimal biofuel subsidy is zero. In this small open economy, the only source of market failure is the environmental externality of crude production. An appropriate tax is enough to rectify this failure, and no other instrument is necessary. This is a useful benchmark for the analysis and results below, where we extend the model to consider

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crude tax will raise the energy price. As the crude tax raises the price of energy, the quantity of energy demanded will fall, reducing the scale of production. This output effect may or may not offset the rise in biofuel demand because of the substitution effect. However, demand for crude will surely fall. By analogous reasoning, the biofuel subsidy will surely raise the use of biofuel, but may or may not raise crude use. This issue is analyzed in detail in section 2.2, where equations (19) through (22) provide the relevant mathematical proofs.

<sup>20</sup> Part B of the appendix derives  $R_s$ ,  $R_t$ ,  $B_s$ , and  $B_t$  for both the small- and the large-country cases using a quasi-linear utility function that is also separable in  $G$ . This provides a tractable example, and there is no loss in generality. Indeed, the analysis in the text is for general utility functions. Details of derivations for the general case, which allows for income effects, are available from the authors on request.

situations where either a tax is not available as an instrument or other externalities exist (such as a terms-of-trade externality) that the tax instrument cannot address fully.

## 2.2 *Second-Best Biofuel Subsidy (when a crude tax is not feasible)*

A tax on crude might not be available as a policy instrument, perhaps because of the country's political economy.<sup>21</sup> On the other hand, the presence of a strong agricultural lobby can make biofuels attract policy attention. Consider ethanol produced from corn, which is mixed with crude to make the final fuel. Although the efficiency of making corn-based ethanol is questionable, it is quite popular in the United States because it is good for the corn belt states like Iowa and Minnesota and draws support from both the agricultural and ethanol producing lobbies.<sup>22</sup> The analysis below describes the biofuel subsidy as a second-best instrument.

Using  $t = 0$  in (11),

$$e_u \frac{\partial u}{\partial s} = 0 \Rightarrow s^{SB} = -e_G G' \frac{R_s}{B_s}, \quad (14)$$

where  $s^{SB}$  is the second-best biofuel subsidy. Note that

$$R = C_r(.)E \Rightarrow dR = C_r(.)dE - EC_{rp^s}(.).ds. \quad (15)$$

Also, total energy use must equal the amount used as an input in the manufacturing sector plus the amount used directly in consumption:

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<sup>21</sup> While section 2.2 considers the polar case where a tax on crude is not allowed, it is not difficult to adapt it to cases where such taxes are allowed but political compulsions limit their level. In such a case, the tax may be restricted to not exceed a level  $t_{\max}$ , such that  $t = t_{\max} < e_G G'$ . Using Eq. (11) it is clear that in such a case a biofuel subsidy is potentially welfare improving. The case analyzed here is one where  $t_{\max} = 0$ , and it facilitates exposition, without sacrificing anything critical. Furthermore, the paper does conduct a careful analysis of the crude tax in sections 2.1 and 3.1. Although we do not pursue an explicit political economy analysis in this paper, it is possible to do so along the lines of Fredriksson (1997) and others.

<sup>22</sup> See, for example, Power (2010), which states “The cause of boosting ethanol use in cars has been strongly championed by Growth Energy, an ethanol trade group led by Wesley Clark, the retired army general and 2004 Democratic presidential candidate.”

$$E = e_q [p, q(s), 1, u, G(R)] + E^M(p, q) \stackrel{23}{\Rightarrow} dE = (e_{qq} + E_q^M) dq + e_{qu} du + e_{qG} G' dR. \quad (16)$$

Using (15) and (16),

$$dE = \delta \left[ \left( (e_{qq} + E_q^M) q_s - EC_{rp^s} e_{qG} G' \right) ds + e_{qu} du \right], \text{ where, } \delta = 1 / (1 - C_r G' e_{qG}). \quad (17)$$

Using (10), note that when  $t = 0$ ,  $q = q(s)$  and  $q_s = -B/E < 0$ . Using this fact, along with (15)

and (17), we have

$$dR = (A q_s + Z) ds + Y du, \quad (18)$$

where  $A = \delta(e_{qq} + E_q^M) C_r < 0$ ,  $Z = -\delta E C_{rp^s} < 0$ , and  $Y = \delta e_{qu} C_r$ .<sup>24,25</sup> At the utility-maximizing

$s$ ,  $du = 0$  and

$$R_s = A q_s + Z. \quad (19)$$

Following a similar set of steps as above, we can compute the impact on food demand of a biofuel subsidy:

$$dB = (A^F q_s + Z^F) ds + Y^F du, \quad (20)$$

where  $A^F = \delta C_{p^s} (e_{qq} + E_q^M) < 0$ ,  $Z^F = -E(\delta C_{rp^s} e_{qG} G' C_{p^s} + C_{p^s p^s}) > 0$ ,<sup>26</sup> and  $Y^F = \delta e_{qu} C_{p^s}$ . Once

again, at the utility-maximizing subsidy rate,  $du = 0$  and

$$B_s = A^F q_s + Z^F > 0. \quad (21)$$

Using (19) and (21) in (14) (i.e., after taking into account the impact of the subsidy on the use of crude and the demand for biofuel for energy production), the second-best subsidy is

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<sup>23</sup> The zero profit condition in manufacturing is  $C^M(w, q, 1) = p^M = 1$ . This implies that  $w = w(q)$  and that  $E^M = -w'(q)L^M$ . Using (2) and (4),  $L^M = L^M(p, w(q)) = L^M(p, q)$ . Thus,  $E^M = E^M(p, q)$ .

<sup>24</sup> It can be shown that  $A < 0$  if  $\delta < 0$ , which is the case when  $e_{qG} = -(U_G e_{qu} + e_u U_{Gq})$  is small.

<sup>25</sup> Note that in the two-input case, concavity of the cost function requires that the cross effect is strictly positive.

<sup>26</sup> We assume here that the environment-generated income effect on energy demand (i.e.,  $e_{qG}$ ) is sufficiently small, such that the own-price effect  $C_{p^s p^s}$  dominates.

$$s^{SB} = -e_G G' \frac{Aq_s + Z}{A^F q_s + Z^F} > 0 \text{ iff } Aq_s + Z = R_s < 0. \quad (22)$$

**Proposition 1:** In the absence of a tax on crude, the second-best policy is to subsidize the use of biofuel if and only if the cross input substitution effect in energy production overcomes the subsidy's *scale effect* via a reduction in the price of energy.

The term  $Aq_s$  captures the *scale effect* of the subsidy on crude demand, while  $Z$  is the *cross-substitution effect* between the two inputs in energy production. The latter effect is easy to understand. The biofuel subsidy reduces the relative price of biofuel, thereby providing an incentive to substitute biofuel for crude in the production of energy. Its magnitude depends on the elasticity of substitution between the two inputs. Consider now the scale effect. The subsidy reduces the net input price of biofuel. This is passed on as a reduction in energy price, which stimulates the aggregate demand for energy, which in turn raises production (the scale effect). The net impact of these two effects is *ex ante* ambiguous and is determined by demand-side parameters and the aforementioned elasticity of substitution. If technology is Leontief type, for example, the cross-substitution effect will disappear altogether. In such a case, the demand for crude would unambiguously increase with a subsidy, and a government that aims to improve environmental quality should tax biofuel rather than subsidize it.

It is important to note that both Vedenov and Wetzstein (2008) and Khanna et al. (2008) find similar results. The model analyzed by Vedenov and Wetzstein (2008) is analogous to our special case where technology is of the Leontief type. This is because their equation (3') fixes the ratio in which ethanol must be used with fossil fuel to cater to aggregate fuel consumption, which rules out substitution between ethanol and fossil fuel. In contrast, the primary role of the

biofuel subsidy in our model is to reduce the relative price of using corn as an input in energy production, which makes the role of input substitutability central to our analysis. Khanna et al. (2008) is closer to our modeling. First, they acknowledge the role of input substitutability through a CES production function for energy, where the inputs are gasoline and ethanol. Then they show that an ethanol subsidy may raise or reduce emissions, because the substitution toward ethanol may be offset by the increase in miles driven because of the price reducing effect of input subsidization. There are important differences between our analyses. First, we consider use of energy not only for consumption but also as an input in the manufacturing sector. This amplifies the scale effect, because cheaper energy not only spurs consumer demand but also makes industries more energy intensive (this shows up as the term  $E_q^M$  in Eq. (16) and in the analysis following it). Another difference is an explicit recognition of the feedback income/pollution effects of subsidization. For example, the second term on the right-hand-side of Eq. (16) accounts for changes in the demand for energy from direct income changes (given pollution), while the third term relates to pollution induced change in demand (for a given  $u$ ). Finally, at the heart of our analysis is the dual use of corn as input into energy production and as final consumption good (i.e., food). This allocation is affected when the biofuel subsidy affects the price of food. While proposition 1 is derived under the assumption of a constant food price (small open economy assumption), this assumption is relaxed starting from the next section. In such a context, a rise in corn prices due to a greater demand for corn will move the relative price of food against domestic consumers. The resulting substitution in consumer demand toward energy will further amplify the harmful scale effect of the subsidy. These are all distinct insights that complement the existing literature.

### 3. The Large-Country Case

The small-country assumption retained up to this point requires that the price for food (i.e.,  $p$ ) is given exogenously by the world market. An important issue regarding biofuel subsidies is that they encourage alternate uses of food products, thus reducing the net availability of food and raising its price in the global market. This issue can be modeled in the context of a large open economy where the food price is endogenous. If the subsidy raises the net global demand for food, its international price will rise, conferring terms-of-trade gains to the food-exporting nation. In addition, following the logic of the previous sections, such a subsidy will also affect pollution.

Suppose that there are three nations: home, foreign, and the rest of the world (ROW). The home country exports food to the foreign country and imports a manufactured good from it. It also imports crude from the ROW at a given terms-of-trade  $r$  and pays in terms of the manufactured good (the numeraire). Thus, the home trade balance requires that the value of its food exports must equal the value of its net imports of the manufactured good. The latter equals the sum of home consumption of the manufactured good and its payment to the ROW for crude, net of home production of the manufactured good. Analogously, the foreign country's net export of the manufactured good equals its production minus the sum of its consumption demand and payment to the ROW (for crude). Finally, the ROW is assumed to not have any domestic consumption of crude, and its only role in the model is to provide crude to the home and foreign countries in exchange for the manufactured good.<sup>27</sup> Home and foreign trade balance conditions are, respectively,

$$pX = \tilde{M} + rR - M \quad \text{and} \quad pX^* = \tilde{M}^* + rR^* - M^*, \quad (23)$$

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<sup>27</sup> This structure lends tractability to the model. Admittedly, allowing for price of crude to be endogenous and for the ROW to consume crude are realistic assumptions, but they come at the cost of complicating an already-complex analysis. The central points that we make are intuitive and can be made without adding to the model's complexity.



where  $X = f - e_p - B$  and  $X^* = f^* - e_p^* - B^*$  are their net exports of food.<sup>28</sup>

### 3.1 Optimal Policy: The One-Sided Case

This subsection considers optimal policy choice for the home nation, where the foreign nation is passive (i.e., when  $s^* = t^* = 0$ ). In the presence of a home tax  $t$  on crude and a subsidy  $s$  on biofuel, the home expenditure-revenue relationship is

$$e(p, q, 1, u, G) = pf(L^F) + M(L^M, E^M) + qE(B, R) - pB - rR - qE^M. \quad (24)$$

Noting that in the large-country case  $R^*$  is endogenous, (6) has to be replaced by  $G = G(R + R^*)$ .

We differentiate (24) to get

$$e_u du = Xdp - sdB + (t - e_G G')dR - e_G G' dR^*. \quad (25)$$

Equation (25) is similar to (11) in the small open-economy case, with two important differences.

The first is the terms-of-trade effect, which is captured by the first term on the right-hand-side of (25). Home's utility will rise to the tune of a rise in the price of food (i.e.,  $dp$ ) weighted by its level of food export (i.e.,  $X$ ). The second critical difference (compared with the small-country case) is that when the home country affects  $p$ , it affects the foreign country's net input price of biofuel as well. In turn, this changes  $R^*$ , and hence  $G$ . Given that the foreign government is assumed to be passive,

$$e_u^* du^* = X^* dp - e_G^* G' dR^W \text{ and } R^W = R + R^*, \quad (26)$$

where  $R^W$  is global crude use.<sup>29</sup> The market-clearing equation for food is

$$f + f^* = e_p + B + e_p^* + B^* \Rightarrow X + X^* = 0, \quad (27)$$

<sup>28</sup> Note that production and consumption structure in both nations are the same as in section 2. The notation is similar, except that an asterisk refers to the foreign country.

<sup>29</sup> We relax this passivity assumption in the next subsection, where both nations may use biofuel subsidies.

which implies that

$$p = p(s, t) .^{30} \quad (28)$$

Using (25) and (28), the optimal subsidy and tax levels are

$$s^{opt} = \frac{(Xp_s - e_G G' R_s^*) R_t + (e_G G' R_t^* - Xp_t) R_s}{B_s R_t - R_s B_t}, \quad B_s R_t - R_s B_t \neq 0; \quad (29a)$$

$$t^{opt} = e_G G' + \frac{B_t s^{opt} + e_G G' R_t^* - Xp_t}{R_t}. \quad (29b)$$

**Proposition 2:** A large open-economy's optimal tax on crude will depart from the standard Pigouvian tax of the small open-economy case.<sup>31</sup> Also, even if an optimal tax on crude is in place, the optimal biofuel subsidy may be nonzero.

It is clear from an inspection of (29a) and (29b) that even if an optimal crude tax is in place, a biofuel subsidy is still required. Consider for expositional purposes the case where  $R_s$  is zero and  $p_s$  is positive. In this case, assuming that  $B_s$  is positive,<sup>32</sup> the optimal subsidy is positive if and only if the term  $Xp_s$  is larger than  $e_G G' R_s^*$ . The term  $Xp_s$  is the standard terms-of-trade effect, while  $e_G G' R_s^*$  is home's utility loss from increased crude use (and pollution) by the foreign country, induced by a rise in the price of food (and hence the price of biofuel) due to home's subsidization. These two effects are novel to the large-country case and explain why the

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<sup>30</sup> The terms-of-trade effects are analyzed by using a quasi-linear utility function that is also separable in  $G$ . This serves as a tractable example and does not compromise the generality of our results.

<sup>31</sup> Lapan and Moschini (2009, discussed earlier) also show that a tax on fuel will depart from its Pigouvian level. However, the role that their fuel tax plays is quite different. Their tax improves the nation's terms-of-trade in crude imports, and discourages both ethanol and fossil fuel use. In contrast, we assume a fixed fossil fuel terms-of-trade, while our tax encourages substitution towards biofuel (as an input into energy), and raises the demand for biofuel/corn, conferring terms-of-trade benefits in terms of food exports.

<sup>32</sup> In the appendix we show that while  $B_s$  is necessarily positive in the small-country case, there is some ambiguity in the current context.

optimal biofuel subsidy here departs from the zero level of the small-country case discussed earlier. In the small-country case, the only role of the biofuel subsidy is to target the domestic crude level ( $R$ ). When an optimal crude tax is in place, there is no reason to use the subsidy. This is not true in the large-country case. Even if the effect of a biofuel subsidy on domestic crude use is zero (i.e., if  $R_s = 0$ ), there are still gains from using a biofuel subsidy.

Turning to the optimal tax on crude, it is clear from (29b) that the expression for the optimal tax here is different from  $e_G G'$  (which was the optimal tax level in the small-country case). The expression differs because the tax here has three additional effects. First, it affects the use of biofuel and therefore the burden of the subsidy to the extent  $B_t s^{opt}$ . Second, by changing  $p$ , the price of crude relative to the net input price of  $B^*$  is affected in the foreign nation. If this leads to an increase in foreign crude use (i.e., if  $R_t^* > 0$ ), then home utility is reduced. Finally, if the tax raises the price of food (i.e., if  $p_t > 0$ ), then the home nation gains to the tune of  $X p_t$ .<sup>33</sup>

### 3.2 Nash Biofuel Subsidies

Here we consider a scenario in which a crude tax is unavailable as a policy instrument, although home and foreign can both use biofuel subsidies.<sup>34</sup> Each nation's subsidy affects the net global demand for food and, hence the common international price of food. Therefore, each

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<sup>33</sup> The expression for  $p_t$  is in the appendix. Suffice it to note here that a tax affects the net global demand for food through various channels, including the substitution of biofuel for crude in energy production when crude becomes more expensive. This effect by itself will tend to raise demand and the price of food, but there are countervailing effects. For example, the tax raises the input price for energy production, in turn raising the energy price. This will tend to reduce energy demand, which will reduce the derived demand for biofuel. For details, we refer the reader to the appendix.

<sup>34</sup> This assumption lends tractability and allows us to focus better on the role of interdependence between nations in their choice of biofuel subsidies. This is a relatively small sacrifice to make, because the fundamental insights of using a crude tax and biofuel subsidy combination have already been discussed.

country's biofuel subsidy affects the other's utility, raising strategic considerations for both nations. We assume that the nations play Nash in the sense that each takes the other's subsidy rate as given when choosing its own utility-maximizing subsidy. The market-clearing equation (27) yields

$$p = p(s, s^*). \quad (30)$$

Using (24) and (30),

$$e_u u_s = Xp_s - sB_s - e_G G' R_s^W. \quad (31)$$

Assuming  $B_s > 0$  (see the appendix for details), the Nash utility maximizing subsidy is

$$s^{Nash} = \frac{Xp_s - e_G G' R_s^W}{B_s} \geq 0, \text{ iff } Xp_s \geq e_G G' R_s^W. \quad (32a)$$

Analogously, we can derive the foreign subsidy rule. In addition, using  $X^* = -X$ , we get

$$s^{*Nash} = \frac{X^* p_{s^*} - e_G^* G' R_{s^*}^W}{B_{s^*}^*} \geq 0, \text{ iff } Xp_{s^*} \leq -e_G^* G' R_{s^*}^W \quad (32b)$$

The details of the terms-of-trade effects ( $p_s$  and  $p_{s^*}$ ) are analyzed in the appendix.

Suffice it to say here that one of the primary effects of a biofuel subsidy is to encourage the use of biofuel instead of crude. This increases the demand for food (as biofuel) and raises its price regardless of which country is providing the subsidy. Thus, both  $p_s$  and  $p_{s^*}$  are likely to be positive. On the other hand, there is an asymmetry in the terms-of-trade effect on the utility of the two nations, because while home is an exporter of food (i.e.,  $X > 0$ ), foreign is an importer (i.e.,  $X^* = -X < 0$ ). First, consider the case where  $R_s^W$  is negative. Home subsidization reduces global pollution, and this benefit, coupled with the terms-of-trade gain, suggests that the Nash subsidy in (32a) is positive. On the other hand, if the scale effect makes  $R_s^W$  positive, the terms-of-trade motive and the pollution-reduction motive conflict and a subsidy might or might not be

justified. Using (32b) we can see that analogous considerations suggest that the foreign country, which suffers from a terms-of-trade loss when it uses a biofuel subsidy, will subsidize only if its subsidy reduces pollution (i.e., only if  $R_{s^*}^W < 0$ ). The foreign country will choose a subsidy if the aforementioned necessary condition is met, and if the pollution-reduction effect dominates the adverse terms-of-trade effect that the foreign nation imposes on itself.

It is easy to see from the discussion above that terms-of-trade considerations might lead the home country to choose a biofuel subsidy even when it increases pollution, and conversely, the foreign country may choose a tax even when its subsidy reduces pollution. It is obvious that such an equilibrium is jointly suboptimal: the terms-of-trade effects wash out between the two nations while the pollution increase reduces joint welfare. This is explained below by adapting equation (25) to the current context:

$$e_u du + e_u^* du^* = (X + X^*)dp - s dB - s^* dB^* - (e_G + e_G^*)G'dR^W. \quad (33a)$$

Note that market clearing for food requires that  $X + X^* = 0$ . Thus, (33a) simplifies to

$$e_u du + e_u^* du^* = -s dB - s^* dB^* - (e_G + e_G^*)G'dR^W. \quad (33b)$$

Evaluating (33b) at the nonintervention outcome ( $s = s^* = 0$ ), and normalizing marginal utility of income for both nations to unity at this outcome:

$$d(u + u^*)|_{s=s^*=0} = -(e_G + e_G^*)G'dR^W. \quad (34)$$

It is clear that joint utility can rise only starting from nonintervention if global crude use falls, leading to less pollution. Therefore, any policy intervention by either nation that leads to a net rise in crude use is jointly suboptimal.

**Proposition 3:** If biofuel subsidy reduces global pollution, terms-of-trade considerations imply that: (i) the Nash policy for the food exporter is to use a biofuel subsidy; and, (ii) the Nash policy of the food importer is a biofuel tax iff the terms-of-trade motive dominates the pollution-reduction motive. Such a Nash equilibrium is jointly suboptimal, and may or may not dominate the free trade outcome.

The discussion preceding the proposition provides the proof. It is clear from (34) that the Nash subsidy equilibrium may be associated with less pollution relative to free trade, which in turn implies that Nash intervention may dominate free trade. On the other hand, a bad Nash equilibrium emerges when, for example,  $R_s^W > 0$ ,  $R_{s^*}^W < 0$ , and terms-of-trade motives dominate for both nations, so that home imposes a biofuel subsidy while foreign imposes a biofuel tax. Because  $R_s^W > 0$  and  $R_{s^*}^W < 0$  in this case, the home subsidy and the foreign tax both raise pollution. Clearly, in this case, the Nash equilibrium is worse than free trade. The welfare ranking of other possible cases is not obvious, and one has to proceed on a case-by-case basis.

#### 4. Conclusion

The main contribution of this paper is to provide a tractable general equilibrium analysis of biofuel subsidies (in the tradition of a neoclassical competitive trade model) to provide guidance on optimal policies under certain constraints. Accordingly, most of the policies analyzed are of the second-best variety. In the first part of the paper we outline the role of opposing scale and substitution effects of biofuel subsidization, keeping in mind different general equilibrium linkages on both the consumption and production side. Next, we extend the model to consider terms-of-trade considerations, and explore the link between the use of corn as

an input in producing energy and its demand as a final consumption good. In this context, a combination of a tax on fossil fuel and a biofuel subsidy is shown to be optimal to target pollution and terms-of-trade. Finally, we consider international interdependence in biofuel policy, and show that terms-of-trade considerations will amplify the biofuel subsidy of the food exporting nation, while it will moderate the level of this subsidy for the food importing nation. The effect of such Nash policies on global pollution (starting from a non-intervention outcome) is ambiguous.

## Appendix

### A. Terms-of-Trade Effects

For tractability, we assume quasi-linearity of preferences and separability of  $G$  for this appendix. These assumptions allow us to abstract from income effects, considerably simplifying the discussion, without changing the thrust of our analysis. The general case is available on request. Using equations (27) and (28) from the text, it can be shown that

$$p_s = \frac{\partial p}{\partial s} = \frac{N_s}{D^F}, \quad (A1)$$

where  $D^F > 0$ , because of the Marshall-Lerner condition, and

$$N_s = \left( e_{pq} + C_{p^s}(\cdot) E_q - f' L_q^F \right) q_s - EC_{p^s p^s}. \quad (A2)$$

Noting that the concavity of the unit cost function in sector  $M$  ensures that  $w(q)$  [defined in footnote 24] is convex, we get

$$E_q = \frac{\partial E}{\partial q} = e_{qq} + E_q^M < 0 \text{ because } e_{qq} < 0 \text{ and } E_q^M = -L^M w''(q) + \frac{(w'(q))^2}{pf''(L^F)} < 0. \quad (A3)$$

Also,

$$L_q^F = \frac{w'(q)}{pf''(L^F)} > 0 \text{ because } w'(q) = -\left( \frac{E^M}{L^M} \right) < 0 \text{ and } f''(\cdot) < 0. \quad (A4)$$

Finally,

$$q = C(p - s, r + t, 1) \Rightarrow q_s = -C_{p^s} < 0. \quad (A5)$$

Using (A3) through (A5) in (A2), and noting that  $C(\cdot)$  is concave in input prices,

$$N_s = \left( e_{pq} + C_{p^s}(\cdot) E_q - f' L_q^F \right) q_s - EC_{p^s p^s} > 0 \text{ if } e_{pq} \leq 0. \quad (A6)$$



(A6) provides a sufficient but not necessary condition for the biofuel subsidy to raise the international price of food. Indeed, even if  $e_{pq}$  is positive (i.e., food and energy are Hicksian substitutes in consumption), the price of food will rise unless this cross-substitution effect in consumption overwhelms all the other effects.

The primary effect of the subsidy is to raise the use of biofuel as an input into energy at given prices. This is captured by the term  $-EC_{p^s p^s} > 0$ . The subsidy also reduces the price of energy because of a reduction in the unit cost (i.e.,  $q_s < 0$ ). The lower energy price directly raises food demand if they are Hicksian complements (i.e., if  $e_{pq} < 0$ ). It also boosts the demand for energy for consumption and as an input in manufacturing, thereby raising the demand for food as an input in energy production:  $C_{p^s} (e_{qq} + E_q^M) q_s > 0$ . Finally, the lower energy input price expands the manufacturing sector at the expense of the food sector, driving down food supply:  $-f' L_q^F < 0$  because  $L_q^F > 0$ . All these effects contribute to a rise in the net demand for food (unless  $e_{pq}$  is positive and larger than the sum of the other effects), raising the price of food. This confers a terms-of-trade benefit to the home country as the exporter of food, and a loss to the foreign country.

Similarly,

$$p_t = \frac{\partial p}{\partial t} = \frac{N_t}{D^F}, \quad (A7)$$

where

$$N_t = \left( e_{pq} + C_{p^s}(\cdot) E_q - f' L_q^F \right) q_t + EC_{p^s r^d}, \quad (A8)$$

and

$$q_t = C_{p^d}(\cdot) > 0, \quad C_{p^s p^d} = -\left(\frac{p-s}{r+t}\right) C_{p^s p^s} > 0. \quad (\text{A9})$$

Using equations (A3) to (A6),

$$e_{pq} + C_{p^s}(\cdot) E_q - f' L_q^F < 0 \text{ if } e_{pq} \leq 0. \quad (\text{A10})$$

Using (A9) and (A10) in (A8), we see that while the first term on the right-hand side of (A8) is negative, the second term is positive. Thus the sign of  $N_t$  is ambiguous. This happens for the following reasons. First, the tax raises the relative price of crude as an input and increases the input demand for biofuel (and, therefore, for the food product) via the cross-substitution effect. On the other hand, the remaining effects all reduce demand for food as follows: (i) The crude tax raises the price of energy, which results in reduced consumption demand for food, if food and energy are Hicksian complements in consumption, (ii) The rise in the price of energy reduces the demand for energy, resulting in a decline in the derived demand for biofuel in energy production, (iii) Since  $L_q^F > 0$ , the rise in the energy price raises home's supply of food, reducing the excess demand for food.

If, in the final analysis, the effects of the induced change in energy price are dominated by the primary cross-substitution effect, then  $N_t > 0 \Rightarrow p_t > 0$ . The analysis for  $p_s$  is similar to that for  $p_s$  above.

## B. Effects of Policy Variables on Biofuel and Crude Use

Noting that  $C(p-s, r+t, 1)$  is the unit cost function in the energy sector, CRS ensures that

$$B = EC_{p^s}(p-s, r+t, 1). \quad (\text{A11})$$

Under quasi-linearity and separability in  $G$ ,

$$E = e_q(p, q) + E^M. \quad (\text{A12})$$

Noting that  $w = w(q)$ , using  $E^M = -L^M w'(q)$  from (A4), and using (2) and (4) [which yields

$L^M = L^M(p, w)$ ], we get

$$E^M = E^M(p, q) \equiv -L^M[p, w(q)]w'(q), \quad (\text{A13})$$

where  $E_p^M = -w'(q)L_p^M < 0$ , and  $E_q^M < 0$  as shown in (A3).

Allowing for all the policy variables considered in this paper to be present, the market clearing equation for food dictates that

$$p = p(s, t, s^*). \quad (\text{A14})$$

Using (A5),

$$q = C(p - s, r + t, 1) \Rightarrow q = q(p, s, t), \quad (\text{A15})$$

where  $q_p = C_{p^s} > 0$ ,  $q_s = -C_{p^s} = -q_p < 0$ , and  $q_t = C_{r^d} > 0$ . Using (A12) through (A15),

$$E = E(s, t, s^*) \equiv e_q[p(\cdot), q(p(\cdot), s, t)] + E^M[p(\cdot), q(p(\cdot), s, t)], \quad (\text{A16})$$

where  $p(\cdot) = p(s, t, s^*)$ . Using (A11) and (A16),

$$B(s, t, s^*) = E(s, t, s^*)C_{p^s}(p(\cdot) - s, r + t, 1). \quad (\text{A17})$$

Using (A17) and simplifying, we get

$$B_s = C_{p^s}(e_{qp} + E_p^M)p_s + [C_{p^s}q_s(e_{qq} + E_q^M) - EC_{p^s p^s}](1 - p_s). \quad (\text{A18})$$

In the small-country case  $p_s = 0$  and (A18) reduces to

$$B_s = C_{p^s}q_s(e_{qq} + E_q^M) - EC_{p^s p^s} > 0, \quad (\text{A19})$$

because  $q_s < 0$  and  $E_q^M < 0$  from (A3) and because of concavity of the cost and expenditure functions.

Using (A18), it is clear that in the large-country case, if  $1 > p_s > 0$ , then  $B_s > 0$  if the last term on the right-hand side of (A18) dominates or if  $e_{qp} > 0$  and dominates the negative term  $E_p^M$ . Similarly, using (A17),

$$B_t = E \left( C_{p^s p^s} p_t + C_{p^s r^d} \right) + C_{p^s} E_t, \quad (\text{A20})$$

where  $E_t = (e_{qp} + E_p^M) p_t + (e_{qq} + E_q^M)(q_p p_t + q_t) < 0$ , if  $p_t > 0$  and  $e_{qp} \leq 0$ . In the small-country case,  $p_t = 0$  and (A20) boils down to

$$B_t = EC_{p^s r^d} + C_{p^s} E_t, \quad E_t = (e_{qq} + E_q^M) q_t < 0. \quad (\text{A21})$$

The two terms on the right hand side of the first equality in (A21) have opposite signs.

Therefore, the sign of  $B_t$  is ambiguous even in the small-country case. Using (A20) we can infer that the same is true in the large-country case.

Analogous to (A11),

$$R = EC_{r^d} (p - s, r + t, 1). \quad (\text{A22})$$

Using (A16), we can differentiate (A22) to obtain:

$$R_t = C_{r^d} E_t + E \left( C_{r^d p^s} p_t + C_{r^d r^d} \right), \quad (\text{A23})$$

where  $E_t$  is defined in (A20) above. In the small-country case,

$$R_t = C_{r^d} E_t + EC_{r^d r^d} = C_{r^d} (e_{qq} + E_q^M) q_t + EC_{r^d r^d} < 0. \quad (\text{A24})$$

Using (A23) and (A20) we can see that there is ambiguity in the large-country case, but  $R_t < 0$  if

the term  $\left( C_{r^d p^s} p_t > 0 \right)$  is sufficiently small and if  $e_{qp} \leq 0$ . Using (A22) and (A16),

$$R_s = C_{r^d} E_s - EC_{r^d p^s} (1 - p_s), \quad (\text{A25})$$

where  $E_s = \left[ e_{qp} + E_p^M + (e_{qq} + E_q^M) q_p \right] p_s + (e_{qq} + E_q^M) q_s$ .

In the small-country case, (A25) reduces to

$$R_s = C_{r^d} (e_{qq} + E_q^M) q_s - EC_{r^d p^s}. \quad (\text{A26})$$

Since  $C_{r^d} (e_{qq} + E_q^M) q_s > 0$  and  $EC_{r^d p^s} > 0$ , the sign of  $R_s$  is ambiguous even in the small-country case. Finally, consider foreign crude use  $R^*$ . Analogous to (A22), and noting that  $t^* = 0$ ,

$$R^* = E^* C_r^* (p - s^*, r, 1). \quad (\text{A27})$$

Like (A16),

$$E^* = E^*(s, t, s^*) \equiv e_q^* \left[ p(\cdot), q^*(p(\cdot), s^*) \right] + E^{M^*} \left[ p(\cdot), q^*(p(\cdot), s^*) \right], \quad (\text{A28})$$

where  $p(\cdot) = p(s, t, s^*)$ . Thus,

$$R_s^* = E_s^* C_r^* (p - s^*, r, 1) + E^* C_{rp^s}^* p_s = \left( Z^* C_r^* + E^* C_{rp^s}^* \right) p_s, \quad (\text{A29})$$

where  $E_s^* = Z^* p_s$ ,  $Z^* = e_{q^* p}^* + E_p^{M^*} + (e_{q^* q^*}^* + E_q^{M^*}) q_p^*$ .

It is clear from (A29) that in the small-country case  $R_s^* = 0$ . In the large-country case, the sign is ambiguous because  $Z^* < 0$  if  $e_{q^* p}^* \leq 0$ . Similar derivations yield

$$R_t^* = \left( Z^* C_r^* + E^* C_{rp^s}^* \right) p_t. \quad (\text{A30})$$

$R_t^* = 0$  in the small-country case, whereas its sign is ambiguous in the large-country case.

### C. Effect of Crude Price on Food and Manufacturing Output (under Laissez Faire)

Using the labor demand function in food defined following Eq. (2), and using Eq. (8) and footnote 24, we get

$$L^F = L^F \left[ p, w \{ C(p, r, 1) \} \right]. \quad (\text{A31})$$

Differentiating (A31),

$$\frac{\partial L^F}{\partial r} = \left( L_p^F + L_w^F w' C_p \right) p_r + L_w^F w' C_r; \quad (\text{A32})$$

where,  $p_r = \frac{\partial p}{\partial r}$ ,  $L_p^F > 0$ ,  $L_w^F < 0$ ,  $w' < 0$ ,  $C_p > 0$ , and  $C_r > 0$ .

In the small country case  $p_r = 0$  and, hence, (A32) implies that  $\frac{\partial L^F}{\partial r} > 0$ . In this case, it is clear from Eq. (2) that food output must increase when the price of crude rises in the world market. In the large country case, analysis along the lines of Section A above suggests that  $p_r$  can take either sign. If it is positive, (A32) suggests that food output must rise. If it is negative, the impact on food output is ambiguous.

Using Eq. (4) and the (A32):

$$\frac{\partial L^M}{\partial r} = -\frac{\partial L^M}{\partial r} < 0 \text{ if } p_r \geq 0. \quad (\text{A33})$$

Using footnote 24, Eq. (8) and (A33), and noting that  $w''(q) \geq 0$  [explained in Section A above]:

$$E^M = -w'(q) L^M \Rightarrow \frac{\partial E^M}{\partial r} = -\left( w' \frac{\partial L^M}{\partial r} + L^M w'' C_r \right) < 0 \text{ if } p_r \geq 0. \quad (\text{A34})$$

Thus, in the small country case,  $L^M$  and  $E^M$  must both fall as the price of crude rises and, therefore, manufacturing output falls. In the large country case, as long as the rise in the crude

price raises the food price also, manufacturing output must fall. If the food price falls, then the effect on manufacturing is ambiguous.

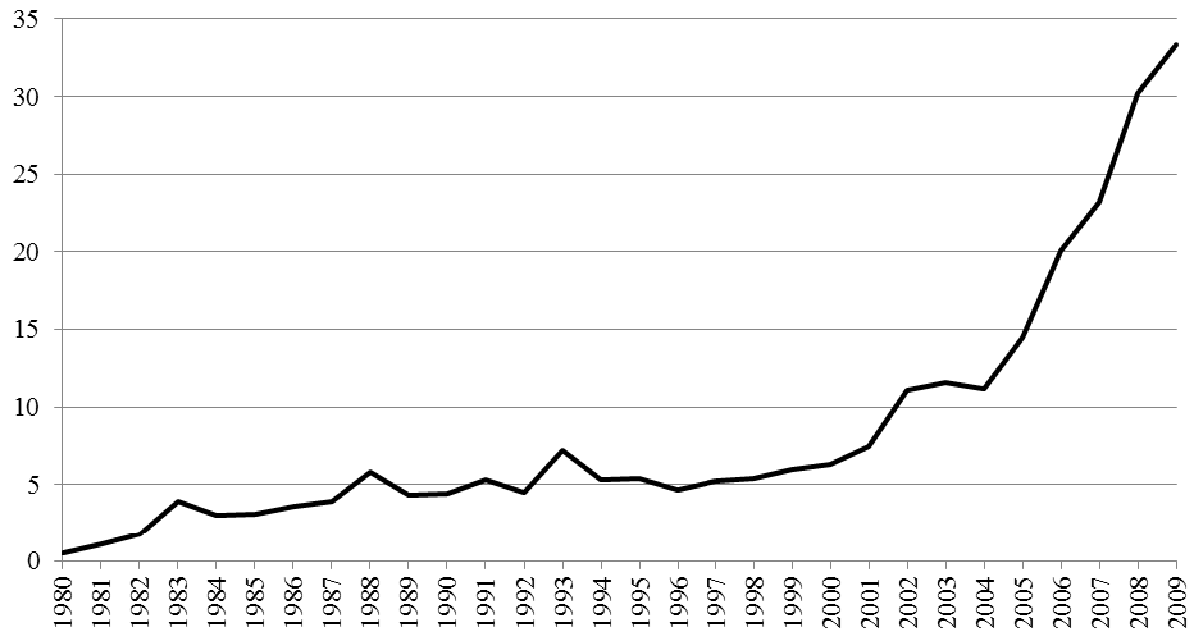
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**Figure 1. Percentage of U.S. Corn Used for Fuel Ethanol\***



\*Note that corn used for fuel ethanol in a given year comes from the previous year's crop.

Source: Earth Policy Institute