The Implications of Alternative Biofuel Policies on Carbon Leakage

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Abstract

We show carbon leakage depends on the type of biofuel policy (tax credit versus mandate), the domestic and foreign gasoline supply and fuel demand elasticities, and on consumption and production shares of world oil markets for the country introducing the biofuel policy. The components of carbon leakage – market leakage and emissions savings – are counteracting: carbon leakage increases with market leakage but decreases with emissions savings. We also distinguish domestic and international leakage where the latter is always positive, but domestic leakage can be negative with a mandate. The IPCC definition of leakage omits domestic leakage, resulting in biased estimates. Leakage with a tax credit always exceeds that of a mandate, while the combination of a mandate and tax credit generates lower leakage than a tax credit alone. In general, a gallon of ethanol (energy equivalent) is found to replace 35 percent of a gallon of gasoline – not 100 percent as assumed by life-cycle accounting. This means ethanol emits 13 percent more carbon than a gallon of gasoline if indirect land use change (iLUC) is not included in the estimated emissions savings effect and 43 percent more when iLUC is included.

Key words: biofuels, tax credit, mandate, market leakage, carbon leakage, emissions savings, domestic leakage

JEL: Q27, Q41, Q42, Q54

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1. Introduction

The issue of carbon leakage – where greenhouse gas (GHG) emissions reductions by an environmental policy are partially or more than offset because of market effects – is often raised as an issue that will undermine environmental policies. Leakage has been extensively studied in the case of indirect land use change (iLUC) generated from biofuels policies (e.g., Searchinger et al. 2008).[1] The controversy over iLUC has been whether or not biofuels fulfill a sustainability threshold (e.g., a 20 percent reduction in carbon emissions for U.S. corn-ethanol relative to gasoline it is *assumed to replace*). However, leakage has also been a criterion to determine the eligibility of biofuels for carbon offsets in the Clean Development Mechanism of the Kyoto Protocol.

What has not been studied to date is the indirect output use change (iOUC) in the fuel market itself where the addition of biofuels always causes a reduction in world gasoline market prices.[2] This paper develops a formal analytical framework to analyze the carbon leakage due to alternative biofuel policies, namely biofuel consumption subsidies (like the U.S. blender's tax credit or a fuel tax exemption at the retail pump in many other countries) and mandates, and the combination of a subsidy and a mandate. We identify two components of carbon leakage: the "market leakage effect" and the "emissions savings effect". The former refers to the resulting market effect of biofuels in *displacing* gasoline and other oil consumption[3] while the latter is the relative carbon emissions of biofuels *versus* gasoline.

We distinguish "domestic" versus "international" leakage. This differs from the methodology used by the IPCC, where domestic leakage is implicitly netted out. Because world gasoline prices decline with either biofuel policy, international leakage is always positive, as is domestic leakage with a tax credit. But domestic leakage with a mandate can be negative under some market conditions, making it possible that total (domestic plus international) leakage can be negative. For plausible parameter values we, however, find that, in reality, this is not the case as international leakage is much bigger than domestic leakage.

Nevertheless, the level of market leakage for either policy depends on two key market parameters: (a) the elasticities of gasoline supply curves and fuel demand curves; and (b) consumption and production shares of the country introducing the biofuels. But leakage is found empirically to be more sensitive to elasticities than to market shares, and especially to changes in market parameters of the country not introducing biofuels.

Domestic leakage becomes more important relative to international leakage as the Home country consumes more gasoline and/or the relative demand elasticity of the Home country increases. Our empirical results show that domestic leakage is less important for total market leakage compared to the case of carbon leakage – a result driven by the emissions savings effect. Therefore, were the IPCC methodology applied to the issue addressed in this paper, the estimates of carbon leakage would be biased.

The economics of a consumption mandate is shown to be more complex than that of a tax credit because the former generates a U-shaped fuel supply curve. However, for the same

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[1] There are numerous studies on iLUC. See Al-Riffai, et al. (2010) for a survey.

[2] The term "indirect output use change" (iOUC) was coined by de Gorter and Just (2009b) to emphasize how arbitrary the emphasis on iLUC was while not analyzing iOUC.

[3] Life-cycle accounting that underpins the 0,1 sustainability thresholds, like the U.S. requirement that corn-ethanol reduce GHG emissions by 20 percent relative to gasoline, assumes one gallon of ethanol (gasoline equivalent) *replaces* one gallon of gasoline.

amount of ethanol, market leakage due to a tax credit is always greater than that due to a binding consumption mandate. We also find that the combination of a binding consumption mandate and a tax credit produces greater leakage than with a mandate alone. If in combination with a mandate, the leakage due to the tax credit alone is infinite.

For a range of plausible elasticities and 2009 U.S. market shares, we find market leakage to be in the order of 60 to 65 percent for all three policy options (a tax credit, a mandate, and their combination), i.e., one (gasoline-equivalent) gallon of ethanol replaces only 0.35 to 0.40 gallons of gasoline and the rest (0.60 and 0.65 gallons, respectively) is displaced. This combined with the effect of iLUC makes one gallon of ethanol emit 1.43 times more carbon than one gallon of gasoline. Note that the EPA in its evaluation of iLUC using life-cycle accounting assumes a one-to-one replacement of gasoline with ethanol. On the other hand, the magnitude of carbon leakage is lower when iLUC is not taken into account, 20 to 25 percent, (because the emissions savings effect is strong) but significantly higher, 190 to 210 percent, when the effect of iLUC is considered that weakens the emissions savings effect. Carbon leakage due to iLUC is therefore not as important as that due to iOUC.

The remainder of this paper is organized as follows. The next section defines leakage and explains two components of carbon leakage – market leakage and emissions savings. In Section 3, we analyze market leakage due to a blender's tax credit. The discussion includes implications for how country size on world oil markets affects leakage. In Section 4, we investigate market leakage under a binding consumption mandate and discuss the leakage effects of adding a blender's tax credit to the mandate. Numerical estimates of leakage are provided in Section 5. The last section provides some concluding remarks.

2. Market and Carbon Leakage Defined

Whenever a 'clean' biofuel is subsidized or mandated relative to a 'dirty' source like gasoline, carbon leakage occurs - the actual carbon savings may be more or less than the intended savings (from biofuel consumption). Carbon leakage is a result of two, typically, counteracting effects: the "emissions savings" effect and the "market leakage" effect in the fuel market.[4] To define the former, denote carbon emissions per unit of energy from a dirty (e.g., gasoline) and clean (e.g., biofuel) source by e_d and e_c, respectively. Define the emissions savings effect ξ to be the relative difference between e_d and e_c:

$$\xi = \left(e_d - e_c\right)/e_d$$

The interpretation of ξ is straightforward. A value of $\xi = 0.20$ means that gasoline emits 20 percent more carbon relative to the same amount (gasoline equivalent) of the biofuel.

While the emissions savings effect depends solely on technical properties of the two fuel sources, the market leakage effect results from market forces in the fuel market after the introduction of biofuels. To show this, the initial world consumption of fuel from gasoline is:

$$C_0 = C_{H0} + C_{F0}$$

where H and F denote Home and Foreign country, respectively. In the new equilibrium with E units of biofuels, world fuel consumption is given by:

$$C_1 = E + C_{H1} + C_{F1}$$

Market leakage due to the introduction of E units of biofuels is the change in world fuel consumption (in absolute terms):

$$\Delta C = C_1 - C_0 = E + C_{H1} + C_{F1} - C_{H0} - C_{F0} = E + \Delta C_H + \Delta C_F$$

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[4] The two effects act in the same direction if market leakage is negative.

where ΔC_H and ΔC_F represent a change in consumption of gasoline in the Home and Foreign country, respectively.

In relative terms, the market leakage effect is given by:

$$L_M = \Delta C / E = \left(E + \Delta C_H + \Delta C_F\right) / E$$

For example, if $L_M = 0.7$, then one unit of biofuel replaces 0.3 units of gasoline while total fuel use has increased by 0.7 units.

The same logic of market leakage also applies to the formula for carbon leakage: divide the expected change in carbon emissions due to the introduction of a clean fuel by the intended reduction in carbon. The formulae for the market leakage and emissions savings effects can be combined to derive an expression for carbon leakage L_C:

$$L_C = \left[(1-\xi)e_d E + e_d\left(\Delta C_H + \Delta C_F\right)\right] / (\xi e_d E) = (1-\xi)/\xi + (\Delta C - E)/(\xi E)$$

$$= (1-\xi)/\xi + \Delta C/(\xi E) - E/(\xi E) = \Delta C/(\xi E) - 1$$

which can be rewritten into a simple and intuitive form:[5]

$$L_C = L_M / \xi - 1 \tag{1}$$

Equation (1) clearly identifies the two driving forces of carbon leakage: the emissions savings and the market leakage effects. Depending on the relative value of the emissions savings and market leakage effects, carbon leakage can be positive, zero, or even negative.

It is the use of biofuels as a substitute for gasoline that gives rise to the many potential sizes and signs of carbon leakage. The magnitude of carbon leakage also depends critically on the value of the emissions savings effect. For example, total carbon emissions could increase if coal were replaced with oil; but very likely decrease were the former replaced with natural gas. To illustrate the sensitivity of carbon leakage to the size of the emissions savings effect, we note that the direct emissions of corn-ethanol (as measured by life-cycle accounting) are 52 percent less than emissions from gasoline. (EPA 2010). In this case, the magnitude of market leakage is multiplied by two (i.e., 1/0.52, as per equation (1)). But if indirect land use change (iLUC) is taken into account, then corn-ethanol only saves 21 percent relative to gasoline (RFA 2010). The magnitude of the market leakage is multiplied by five (1/0.21) in this case (as per equation (1)).

The formula for carbon leakage given by equation (1) is also very general; it accommodates both autarky and international trade cases, allows for any type of policy that affects the introduction of biofuels on the market, and it requires some estimate of the emissions savings effect ξ to determine the magnitude of carbon leakage. It also indicates that carbon leakage can only be positive if market leakage is positive. On the other hand, there can be situations when carbon leakage is negative even though market leakage is positive. This may happen when the market leakage is sufficiently small and/or a biofuel has substantially lower carbon emissions relative to gasoline.

Implicitly embedded in equation (1) is the fact that the existence of market leakage undermines the emissions savings effect. Therefore, a question arises as to what the true emissions savings of ethanol compared to gasoline are when the two effects are combined. The induced carbon emissions of a gallon of ethanol that was introduced in the market are given by:

$$\left[(1-\xi)e_d E + e_d\left(\Delta C_H + \Delta C_F\right)\right] / E = \left(1 - \xi + L_M\right)e_d$$

Therefore, the true emissions savings of ethanol versus gasoline are:

$$\left[e_d - \left(1 - \xi + L_M\right)e_d\right] / e_d = \xi - L_M$$

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[5] Here we assume no "technical leakage", i.e., the emissions intensities of dirty energy source are the same in both countries.

This result is very intuitive – in the presence of market leakage, emissions savings of ethanol relative to gasoline are lowered by the counteracting market leakage effect. An implication of the finding above is that if the market leakage effect is stronger than the emissions savings effect, then consumption of ethanol does not reduce global carbon emissions, but increases them.

Although one would expect the value of the emissions savings effect to be more precise, including market effects with iLUC can make it as difficult to compute as the market leakage effect in the fuel market itself as both market leakage effects depend on uncertain market parameters such as supply and demand elasticities. The theoretical analysis to follow evaluates only market leakage in an international trade framework as carbon leakage can be readily calculated using equation (1).

3. Market Leakage with a Blender's Tax Credit

Consider a competitive gasoline market in Figure 1 where the Home country (H) is an importer and the Foreign country (F) an exporter of fuel. The initial fuel price P_{w0} is where excess demand ED_H equals excess supply ES_F. Initial fuel consumption is C_{H0} and C_{F0} in the Home and Foreign country, respectively. Similarly, Q_{H0} and Q_{F0} denote Home and Foreign country's production of gasoline.

Suppose there is a consumption subsidy (a blender's tax credit) for ethanol in the Home market that generates a positive level of E units of ethanol production along the ethanol supply curve (not shown). The tax credit-induced ethanol is an exogenous (taxpayer-financed) increase in fuel supply and can be depicted as a shift in S_H to S_H' by the distance E in the first panel of Figure 1. As domestic supply of fuel increases, excess demand shifts down to ED_H', creating a new world fuel price P_{w1} that is less than P_{w0}.

With an exogenous increase in fuel supply due to ethanol production, fuel prices decline and total fuel consumption increases. The latter is market leakage (*displacement* of gasoline) and hence, unlike that assumed with life-cycle analysis, a gallon of ethanol (in gasoline equivalent) *replaces* less than a gallon of gasoline. With international trade, there are two components of market (and also of carbon) leakage. The first is *domestic* leakage, represented by an increase in fuel consumption in the Home country (distance $C_{H0}C_{H1}$), while *international* leakage is defined as an increase in fuel consumption in the Foreign country (distance $C_{F0}C_{F1}$) (de Gorter 2009). With a blender's tax credit, both leakages are always non-negative because each country faces the same decrease in the gasoline price.

While Figure 1 depicts market leakage in its absolute form, an expression representing the market effect as a relative number makes it possible to identify its determinants, namely, supply and demand elasticities for gasoline and production and consumption shares in the gasoline markets in both countries. The formula for market leakage due to tax credit-induced production of ethanol in the Home country is given by (see Drabik, de Gorter and Just 2010):

$$L_M^{\tau} \approx \frac{\rho\eta_{DH} + (1-\rho)\eta_{DF}}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \phi\eta_{SH} - (1-\phi)\eta_{SF}} \tag{2}$$

where τ denotes a blender's tax credit, ρ stands for a share of the Home country in world gasoline consumption, ϕ denotes a share of the Home country in world gasoline production; and η denotes an elasticity. The first subscript D and S in each term signifies demand and supply, respectively and the second subscript (H and F) denotes country, e.g., η_{DH} denotes the elasticity of fuel demand in the Home country.

4. Market Leakage with a Consumption Mandate

The economics of a biofuels consumption mandate is different from that of a tax credit. It is because unlike a tax credit, which is a taxpayer-financed subsidy on ethanol production, ethanol produced to meet the mandate is financed by a money transfer from oil producers and (under some circumstances) fuel consumers (de Gorter and Just 2008; Lapan and Moschini 2009). With a consumption mandate, there are four distinct agents in the market: ethanol producers, gasoline producers, fuel blenders, and fuel consumers. We first explain the basic economics of a consumption mandate under autarky and then analyze leakage effects of this policy with international trade. For a more comprehensive treatment of the consumption mandate see de Gorter and Just (2008).

Consider the first panel in Figure 2. If a consumption of E gallons of ethanol is mandated, the ethanol market price (P_E) is read off the ethanol supply curve S_E. The produced ethanol essentially shifts the gasoline supply curve S_T horizontally to the right by the amount of E, represented by the curve S_T'. The U-shaped fuel supply curve S_F^* represents marginal costs for the blender (see de Gorter and Just 2008 for details on how S_F^* is derived).

A blender equilibrates the marginal cost with the market price for fuel which is read off the demand curve D_H. The intersection of D_H with S_F^* constitutes a market equilibrium with a fuel price P_{F1} and fuel consumption of C_{H1}. In the new equilibrium, less gasoline is demanded by blenders because a fixed amount of ethanol is mandated to be consumed. This results in a lower gasoline price received by gasoline producers P_{G1} and so gasoline production declines. Total fuel consumption can either decrease or increase, depending on the position of the fuel demand curve.

How is it possible that total fuel supply can go up? Think of a consumption mandate as a tax on the gasoline market. Gasoline consumers pay a higher price for gasoline (to pay for high ethanol price) and gasoline producers obtain a lower price. So the mandate is at once acting as a monopolist against gasoline consumers and a monopsonist against gasoline producers. It is possible that the revenues extracted from gasoline producers are so high (inelastic gasoline supply curve) that total fuel production (and hence consumption) goes up (fuel price goes down). Consumers still pay a higher price for gasoline but with ethanol supply, a lower fuel price.

The economics of a consumption mandate with international trade is analogous to the autarky case above (with a slight change in notation). The Home country is assumed to be an importer.[6] Prior to the policy, fuel demand in the Home country faces total gasoline supply S_T) given by the horizontal sum of domestic S_H and Foreign excess supply curve of gasoline S_F - D_F. When a consumption mandate is imposed, the total gasoline supply in the Home country shifts to the right by the amount E (depicted by S_T'). An intersection of the demand for fuel in Home country D_H and the fuel supply, S_F^* defines the fuel price paid by fuel consumers in the Home country P_{F1}. World fuel price is given by P_{G1}. Since this is lower than the fuel price in the initial equilibrium, fuel consumption in the Foreign country goes up by C_{F0} C_{F1} (international leakage). Fuel consumption in the Home country can decrease (as shown in Figure 2), stay unchanged, or increase, depending on where D_H intersects S_F^*.

So depending on whether domestic fuel consumption decreases with a consumption mandate or not, total leakage may be negative provided that an increase in gasoline consumption in the Foreign country is more than offset by a reduction in domestic fuel

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[6] This parallels the U.S. case, as the United States is the world's largest ethanol producer; is an oil importer and has a consumption mandate.

consumption. We also note that even if domestic fuel prices go up with a mandate, GHG emissions can increase provided that total market leakage is positive and the emissions savings effect is sufficiently small. It can also be the case that even if the domestic fuel prices decline, global GHG emissions can decline as well, provided that the total market leakage is positive and the emissions savings effect is strong enough. Therefore, a reduction in the fuel price is not a sufficient condition for GHG emissions to increase.

The analytical formula for market leakage with a consumption mandate L_M^{σ} derived in Drabik, de Gorter and Just (2010) takes the form:

$$L_M^{\sigma} \approx \frac{(\delta-1)\eta_{DH}\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)-\rho\eta_{DH}-(1-\rho)\eta_{DF}}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho\eta_{DH}-(1-\rho)\eta_{DF}} \tag{4}$$

where $\delta = \tilde{P}_E / P_{G0}$ is the ratio of the intercept of the ethanol supply curve and gasoline market price under no ethanol production. The structure of the equation (4) is very similar to that for a tax credit in (2). The parameter δ is new and relates the ethanol mandate with the gasoline market. Close inspection of equations (2) and (4) reveals that a binding consumption mandate is always superior to a blender's tax credit in terms of the magnitude of market or leakage. This is stated by the following proposition.

Proposition: For the same amount of ethanol, the market leakage (and carbon leakage) due to a tax credit is always greater than that due to a consumption mandate.
Proof: See Drabik, de Gorter and Just (2010).

Market leakage when a tax credit is added to a binding consumption mandate

If you add a blender's tax credit to a binding consumption mandate for ethanol, the tax credit simply subsidizes gasoline consumption, thus contradicting all environmental objectives (de Gorter and Just, 2008; Lapan and Moschini, 2009).[7] Leakage due to the tax credit alone in this case is infinity. The explanation is quite intuitive. A tax credit does not induce any ethanol production provided that a consumption mandate is binding. It means that no gasoline is replaced by ethanol. On the other hand, additional gasoline is consumed (displacement) as a result of combining the two policies together. Following the definition of market leakage as the ratio of what is displaced and what is replaced, the result is that the value of the fraction is infinity.

However, leakage due to a combination of the two policies will be finite. It is because ethanol generated under a mandate does replace some gasoline and so the denominator of the fraction is not zero. However, total leakage of the combination of the two policies is higher compared to a mandate alone because of the additional oil consumption induced worldwide by a tax credit.

5. A Numerical Example

In this section, we estimate the magnitude of market and carbon leakage for the United States using 2009 data.[8] All data are in gasoline equivalents. In 2009, the United States consumed 22.4 percent and produced 7.4 percent of total world oil consumption.[9] The share of U.S. ethanol production represented 1.3 percent of the world gasoline consumption. Baseline

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[7] For an original account of what happens when adding a tax credit to a blend mandate, see de Gorter and Just (2009a).

[8] The sources of the data used are reported in Drabik, de Gorter and Just (2010).

[9] In this paper, we do not distinguish gasoline consumption between transportation and non-transportation use to estimate leakage. The analysis in Drabik and de Gorter (2010) shows that such a division has little effect on leakage estimates.

parameters in this paper denote “most plausible” values, based on the sources contained on the many other studies to date on the biofuel-fuel markets. The fuel demand elasticity in the United States is assumed to be -0.26 and in the Foreign country -0.40. Elasticity of gasoline supply in both countries is assumed to be 0.2. The ratio of ethanol and gasoline prices adjusted for miles obtained is 1.44.

Using values of the most plausible market parameters (i.e., “baseline” values), estimates of market and carbon leakage are given in Table 1 for three policy options: tax credit, consumption mandate and when a tax credit is added to a binding mandate (here we use the actual tax credit which does not equal to the price premium due to the mandate). Carbon leakage uses two possible values for the relative carbon emissions intensity: with and without iLUC.

Table 1: Baseline Values of Market and Carbon Leakages under Trade*

	International trade			True emissions savings of ethanol**
	(1) Total (our definition)	(2) Domestic share	(3) IPCC definition	(4) Trade
Market Leakage				
Tax credit	0.65	16%	0.61	
Mandate	0.61	-2%	0.61	
Tax credit w/ binding mandate	0.64	9%	0.61	
Carbon Leakage				
Incl. iLUC (ξ=0.21)				
Tax credit	2.09	-24%	1.72	-0.44
Mandate	1.90	-56%	1.43	-0.40
Tax credit w/ binding mandate	2.07	-36%	1.59	-0.43
Excl. iLUC (ξ=0.52)				
Tax credit	0.25	-321%	0.58	-0.13
Mandate	0.17	-619%	0.59	-0.09
Tax credit w/ binding mandate	0.24	-408%	0.58	-0.12

Source: calculated

* Magnitudes of leakage multiplied by 100 are interpreted as percentage.

** The values are calculated as ξ minus total market leakage. For example, the value -0.43 indicates that one gasoline-equivalent gallon of ethanol emits 1.43 times more carbon emissions than one gallon of gasoline.

Baseline parameters: ρ=0.224, φ=0.074, δ=1.440, η_{DH}=-0.26, η_{DF}=-0.40, η_{SH}=0.20, η_{SF}=0.20

Domestic share figures are calculated as follows:

For market leakage: change in domestic fuel consumption is divided by change in world fuel consumption (all multiplied by 100).

For carbon leakage: the numerator of the ratio is equal to carbon intensity of ethanol (relative to gasoline) times quantity of ethanol plus change in domestic gasoline consumption; the denominator is equal to carbon intensity of ethanol times quantity of ethanol plus change in world gasoline consumption (all multiplied by 100).

The first column of Table 1 presents total leakage with international trade while the second column gives the domestic share. The share of domestic market leakage is the ratio of the change in Home country’s fuel consumption to the global change in fuel use (the latter represents market leakage in absolute terms).[10] All ethanol is assumed to be consumed domestically. Total leakage with a tax credit is 0.65 (i.e., 65 percent) while the share of domestic leakage is only 16 percent. Because the United States is one of the biggest consumers and importers of oil in the world, results in Table 1 suggest that the domestic share is lower in countries like Canada.

With a mandate, on the other hand, domestic leakage is negative (total fuel

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[10] We assume that all ethanol is consumed domestically which simplifies the accounting of carbon emissions when quantifying carbon leakage.

consumption declines) but domestic leakage is low while total leakage is 61 percent. Total leakage with a mandate does not differ much from that due to a tax credit because the level of domestic leakage is low relative to international leakage, the latter always being positive. This result occurs even with the United States consuming close to one quarter of total world oil consumption.

The third row in Table 1 shows the market leakage when the tax credit is added to a binding mandate and total leakage is close to that with a consumption mandate alone. This is because after the tax credit is added, the fuel supply curve does not shift down by the full tax credit, but only approximately by the share of ethanol multiplied by the tax credit.

The bottom set of results in Table 1 gives carbon leakage under two scenarios: with iLUC using the EPA's most recent estimate (where corn based ethanol emits 21 percent less CO_2 relative to gasoline) and without iLUC (where ethanol emits 52 percent less CO_2 compared to gasoline). Unlike market leakage, total carbon leakage when including iLUC (or equivalently, if one assumes a direct life-cycle accounting measure of 20 percent as all studies on biofuels have to date because the revised EPA estimates in 2010 are very recent and have not been incorporated in studies yet) is much higher for all three policy scenarios. This is because carbon leakage is a compound measure consisting of two mutually synergizing sources through which a policy generates leakage: the market leakage effect, i.e., via changes in physical quantities of fuel consumed; and the emissions savings effect where gasoline is being replaced by a biofuel with lower carbon emissions.

For example, market leakage for a tax credit is 65 percent while carbon leakage is 209 percent when carbon emissions due to iLUC are taken into account. Carbon leakage is so much higher in this case because the carbon savings of 21 percent per gallon of ethanol relative to gasoline are more than offset by a world-wide carbon increase due to higher fuel consumption. This means that ethanol doubles carbon emissions, for given parameters and an intended absolute reduction in carbon emissions.

On the other hand, total carbon leakage is much lower than market leakage when evaluating the former excluding iLUC, using the most up to date EPA estimates of direct life-cycle accounting (for new plants using specific technologies and inputs e.g., natural gas).[11] However, looking at the last set of results in the first column of Table 1, carbon leakage is much lower than market leakage when excluding iLUC. This differential effect can be explained by much stronger carbon emissions savings (52 *vs* 21 percent) of ethanol that now alleviates the generation of carbon through higher fuel consumption more significantly relative to the previous case where iLUC was not included as emissions savings.

Another unique feature of the results in Table 1 is comparing the domestic share of carbon leakage with that of market leakage. The importance of domestic carbon leakage is more pronounced and much more so when excluding iLUC. The intuition for why domestic carbon leakage, for given parameters, is negative and very high in absolute terms (especially when ξ is high) is as follows. Domestic gasoline consumption declines, regardless if a tax credit or a mandate, thereby significantly lowering domestic carbon emissions. These emissions increase again as ethanol replaces the decline in gasoline consumption but the replaced amount of emissions is lower than before because ethanol has lower emissions relative to gasoline (the more so as ξ increases).

We have shown in equation (1) that a higher emissions savings parameter for ethanol alleviates total carbon leakage. In the previous paragraph, we also explained why higher emissions savings with ethanol reduces domestic carbon emissions. Therefore, a higher value

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[11] One can view the results thus: when including iLUC, the results can also double for a what if you assumed direct life-cycle accounting emissions of 20 percent less than gasoline as all studies to date (and before the recent EPA ruling for RFS2) while the other results that include iLUC and the new EPA estimate of direct emissions are a unique situation itself.

of ξ increases domestic carbon savings (the numerator) and at the same time reduces total carbon leakage (the denominator), making the domestic share of carbon leakage much bigger (in absolute terms). Notice that total carbon leakage is nowhere negative in Table 1 and is small for $\xi = 0.52$. This is because international carbon leakage, albeit being very high, is offset by negative domestic leakage, resulting in total leakage (i.e., the sum of domestic and international leakage) reported in the bottom section of Table 1.

In the third column of Table 1, we report the magnitudes of leakage computed following the IPCC definition. We have obtained very similar values for market leakage because domestic (market) leakage, the difference between ours and the IPCC definition, is not significant in the empirical case we study here. However, the emissions savings effect renders domestic carbon leakage negative and significant in value (as explained in the previous paragraphs) and so the importance of domestic carbon leakage increases, making the difference between our definition of leakage and that of the IPCC to widen.

Finally, in the fourth column of Table 1, we present the "true carbon savings" of ethanol relative to gasoline, when the effect of iOUC is included for the case of international trade. These values were calculated by taking the difference between the emissions savings effect including (or excluding) iLUC and the magnitude of market leakage. The negative sign of the difference in all instances suggests that after taking into consideration the market leakage effect, corn-ethanol emits more carbon emissions than gasoline. For example, the value of -0.43 in the fourth column means that one (gasoline-equivalent) gallon of ethanol emits 1.43 times more carbon than one gallon of gasoline.

6. Conclusions

In analyzing carbon leakage due to alternative biofuel policies, we identify two components: the market leakage effect and the emissions savings effect. Market leakage results from a change in market prices and a subsequent displacement of gasoline and other oil uses by biofuels, while the emissions savings effect represents the relative emissions of biofuels *versus* gasoline. We find that a positive market leakage does not necessarily imply a positive carbon leakage but a negative market leakage (that may occur with a mandate) always implies a negative carbon leakage.

The international trade framework within which we analyze a blender's tax credit and a consumption mandate gives rise to a distinction between domestic and international leakage. Domestic leakage can be significant theoretically under plausible market situations but is found empirically to be relative small in the case of U.S. biofuels policy. Because world gasoline prices decline with either biofuel policy, international leakage is always positive, as is domestic leakage with a tax credit. But domestic leakage with a mandate can be negative, making it theoretically possible that total (domestic plus international) leakage can be negative.

We show that market leakages (and hence carbon leakage) with both biofuel policies depend on two groups of parameters: (1) the elasticities of gasoline supply curves and fuel demand curves; and (2) consumption and production shares of the country introducing the biofuels. Leakage is typically more sensitive to elasticities than to market shares, and is especially more sensitive to changes in market parameters of the country not introducing biofuels.

Our numerical estimates for the United States in 2009 reveal market leakage to be between 60 and 65 percent for all three policy options (i.e., tax credit, a mandate, and their combination). This narrow range suggests the benefit of a mandate over a tax credit in reducing total carbon leakage is not so important empirically in the case of the United States. Our empirical results indicate that carbon leakage ranges between 190 to 210 percent provided iLUC is taken into account and it ranges from 20 to 25 percent when excluding iLUC. We find that existing indirect output changes (i.e., market leakage) reduce the ability of ethanol to save carbon emissions relative to gasoline and the empirical results for the U.S. policies result in ethanol emitting more carbon than gasoline – between 1.09 to 1.44 times more, depending on the type of biofuel policy and whether or not iLUC is considered.

References

Al-Riffai, P., B.Dimaranan, and D. Laborde. (2010). "Global Trade and Environmental Impact Study of the EU Biofuels Mandate". Final report of an external study for the European Commission carried out by CEPII and IFPRI, March 2010. http://ec.europa.eu/energy/renewables/studies/doc/land_use_change/iluc_completed_report.pdf

de Gorter, H. (2009). "Integrating Developing Country Agriculture into Global Climate Change Mitigation Efforts." In *Non-Distorting Farm Support to Enhance Global Food Production*, eds. Aziz Elbehri and Alexander Sarris. Rome, Italy: Food and Agriculture Organization (FAO).

de Gorter, H, and D.R. Just (2008). "The Economics of the U.S. Ethanol Consumption Mandate and Tax Credit." Department of Applied Economics and Management Working Paper unpublished, Cornell University, 17 April (prepared for seminar at Cornell 1 May 2008) (paper available upon request).

_______. (2009a). "The Economics of a Blend Mandate for Biofuels". *American Journal of Agricultural Economics* 91 (3): 738-750.

———. (2009b). "Why Sustainability Standards for Biofuel Production Make Little Economic Sense". Cato Institute *Policy Analysis* No. 647, Washington D.C. http://www.cato.org/pubs/pas/pa647.pdf

Drabik, D., and H. de Gorter. (2010). "Biofuels and Leakages in the Fuel Market". A selected paper presented at International Agricultural Trade Research Consortium: *Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security*, June 2010, Stuttgart-Hohenheim, Germany. https://iatrc2010.uni-hohenheim.de/fileadmin/einrichtungen/iatrc2010/Papers/deGorter_et_al._IATRC_Summer_2010.pdf

Drabik, D., de Gorter, H., and Just, D.R. (2010). "The Implications of Alternative Biofuel Policies on Carbon Leakage". Working Paper 2010-22. Charles H. Dyson School of Applied Economics and Management, Cornell University. November 2010 (updated December 2010). http://aem.cornell.edu/research/researchpdf/wp/2010/Cornell-Dyson-wp1022.pdf

Environmental Protection Agency (EPA). (2010). "Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis". EPA-420-R-10-006, February 2010

Intergovernmental Panel on Climate Change (IPCC). "Glossary of Terms used in the IPCC Fourth Assessment Report." http://www.ipcc.ch/pdf/glossary/ar4-wg3.pdf

Lapan, H., and G. Moschini. (2009). "Biofuel Policies and Welfare: Is the Stick of Mandates Better than the Carrot of Subsidies?" Working Paper No. 09010, Department of Economics, Iowa State University, June Ames, Iowa.

Renewable Fuels Association (RFA). 2010. "RFS Rules "Workable" - ILUC Inclusion Still Problematic". Press Release, February 3. http://renewablefuelsassociation.cmail1.com/T/ViewEmail/y/78B3C6C380747C63

Searchinger, T., R. Heimlich, R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu. (2008). "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land Use Change." *Science* 319 (5867): 1238-1240.

Figure 1: Biofuels Leakage with a Tax Credit and Trade

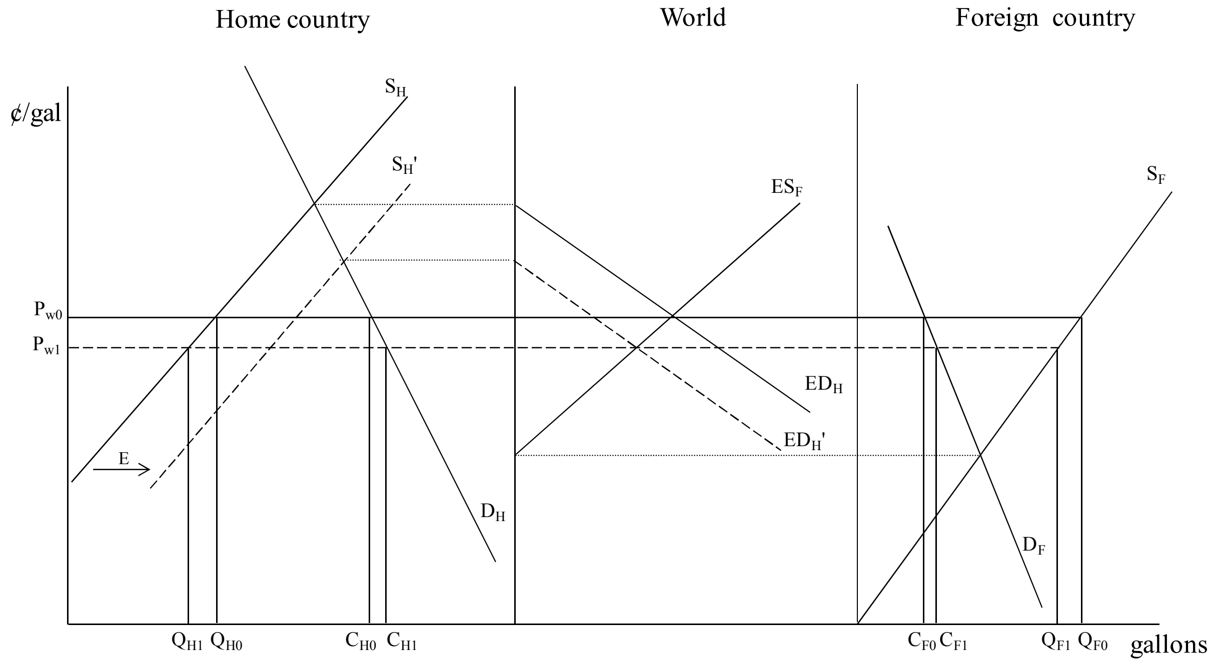

Figure 2: Biofuels Leakage with a Consumption Mandate and Trade