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The Implications of Alternative Biofuel Policies on Carbon Leakage

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The Implications of Alternative Biofuel Policies on Carbon Leakage

Dusan Drabik, Harry de Gorter and David R. Just

Abstract

We show how leakage differs, depending on the biofuel policy and market conditions. Carbon leakage is shown to have two components: a market leakage effect and an emissions savings effect. We also distinguish domestic and international leakage and show how omitting the former like the IPCC does can bias leakage estimates. International leakage is always positive, but domestic leakage can be negative. The magnitude of market leakage depends on 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. Being a small country in world oil markets does not automatically imply that leakage is 100 percent or above that of a large country. We show leakage due to a tax credit is always greater than that of a mandate, while the combination of a mandate and subsidy generates greater leakage than a mandate alone. In general, one gallon of ethanol is found to replace only 0.35 gallons of gasoline – not one gallon as assumed by life-cycle accounting. For the United States, this translates into one (gasoline-equivalent) gallon of ethanol emitting 1.13 times more carbon than a gallon of gasoline if indirect land use change (iLUC) is not included in the estimated emissions savings effect and 1.43 times more when iLUC is included.

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

JEL: Q27, Q41, Q42, Q54

The Implications of Alternative Biofuel Policies on Carbon Leakage

1. Introduction

The issue of carbon leakage – where 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.[1] Leakage has been extensively studied in the cases of cap and trade policies (e.g., Frankel 2009),[2] reduced deforestation and land degradation - REDD (e.g., Murray et al. 2004, 2009; Murray 2008) and indirect land use change (iLUC) generated from biofuels policies (e.g., Searchinger et al. 2008; Hertel et al. 2010; Tyner et al. 2010).[3] Each source of leakage has created its own controversy. For cap and trade, green tariffs and producer rebates have been studied extensively as remedial measures[4] while the Kyoto Protocol has been reluctant to include REDD because of concerns over leakage and additionality (Murray 2008). In the case of biofuels, the issue 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.[5]

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.[6],[7] 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.[8] In so doing, 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 (domestic non-transportation and international oil) consumption[9] while the latter refers to the relative carbon emissions of biofuels *versus* gasoline. A positive market leakage (which always occurs with a tax credit that expands fuel consumption) does not necessarily imply a positive carbon leakage but a negative market leakage (that is possible with a mandate) always implies a negative carbon leakage.[10]

We distinguish "domestic" versus "international" leakage which differs from the methodology used by the IPCC, where domestic leakage is implicitly netted out.[11,12] 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 (gasoline plus biofuel) 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.

We show that a small importer (exporter) of oil facing a perfectly elastic excess supply (demand) curve does not automatically generate 100 percent market or carbon leakage. We also show that, under some market conditions, a country whose biofuel policies have a smaller impact on world oil prices can see lower leakage compared to a country that lowers world oil prices more significantly.

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 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.

If the tax credit is equal to the price premium that is necessary to generate the mandated amount of ethanol, then the tax credit exactly offsets the reduction in gasoline consumption due to the mandate if the country has no effect on world oil prices. However, if the country with the biofuel policy can affect world oil prices, then the tax credit more than offsets the reduction in gasoline consumption due to the mandate.

For most 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. We show that iLUC is not as important relative to iOUC.

Leakage under "autarky" can be interpreted as a measure for when all countries participate in the environmental policy (a biofuel policy in this case). We find that both the market and carbon leakage are lower by 'expanding the coalition' but not significantly so with the possible exception of carbon leakage with mandates but only when the emissions savings effect is sufficiently strong.

The remainder of this paper is organized as follows. The next section defines leakage and explains two components of carbon leakage – market leakage and the emissions savings effect. 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 and their sensitivity analyses 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.[13] 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:

$$\xi = \frac{e_d - e_c}{e_d}$$

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, we write the initial world consumption of fuel from gasoline as:

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

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):

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

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:

$$L_M = \frac{\Delta C}{E} = \frac{E + \Delta C_H + \Delta C_F}{E}$$

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. Contrast this, for example, with life-cycle accounting that assumes gasoline is replaced by the biofuels gallon-for-gallon (gasoline equivalent).

The same logic of market leakage also applies to the formula for carbon leakage: divide the observed change in carbon emissions due to the introduction of 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:

$$L_C = \frac{(1-\xi)e_d E + e_d(\Delta C_H + \Delta C_F)}{\xi e_d E} = \frac{1-\xi}{\xi} + \frac{\Delta C_H + \Delta C_F}{\xi E} = \frac{1-\xi}{\xi} + \frac{\Delta C - E}{\xi E}$$

$$= \frac{1-\xi}{\xi} + \frac{\Delta C}{\xi E} - \frac{E}{\xi E} = \frac{1}{\xi}\frac{\Delta C}{E} - 1$$

which can be rewritten into a simple and intuitive form:[14]

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

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, three cases can be distinguished to determine the magnitude of carbon leakage. First, carbon leakage is zero, i.e., total emissions have not changed, if $L_M = \xi$. In this case, the carbon savings effect of biofuels is completely offset by an increase in fuel consumption which results in higher emissions. Second, carbon leakage is positive whenever $L_M > \xi$. In this instance, total emissions either decrease by an amount that is smaller than the originally planned amount; or the total emissions can even increase. The latter situation occurs if and only if $L_M > 2\xi$. This condition is both necessary and sufficient for a policy to increase carbon emissions. Finally, in the event that $L_M < \xi$, carbon leakage is negative, i.e., more emissions are actually saved than initially planned (e.g., a possibility with a mandate as we will explore below).

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).[15] 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 (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.

There are competing methods to derive an estimate for the value of emissions savings ξ for a biofuel. First, one can compare the instantaneous amounts of carbon released when a fossil fuel and biofuel are combusted. In this case, the biofuel emits a different amount of CO_2 relative to the fossil fuel.[16] Second, some argue that biofuels are by and large net zero as the amount of CO_2 absorbed through the process of photosynthesis in growing the crop is equal to that when the biofuel is combusted.[17] In this case, $\xi = 1$ for any biofuel compared to a fossil-based fuel. Third, the life-cycle accounting approach measures all carbon emissions from "well-to-wheel" for fossil fuels and from "field-to-tank" for biofuels, which might yield yet another value for ξ (e.g., 52 percent saving with corn-ethanol relative to gasoline (RFA 2010)). The fourth option is to add iLUC to the life-cycle value for ξ (e.g., 21 percent savings with corn-ethanol relative to gasoline (EPA 2010)).

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:

$$\frac{(1-\xi)e_d E + e_d(\Delta C_H + \Delta C_F)}{E} = (1-\xi+L_M)e_d$$

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

$$\frac{e_d - (1-\xi+L_M)e_d}{e_d} = \xi - L_M$$

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).

In the analysis to follow, the market leakage effects of a blender's tax credit (or a tax exemption at the retail gas pump as in Europe) are compared to a consumption mandate. In the numerical example, we also provide leakage estimates when a tax credit is combined with a mandate.

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 Appendix 1):

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

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. Decomposing leakage into a domestic L_M^D and international L_M^I component, the relative share of domestic leakage depends on consumption shares and demand elasticities in both countries, but not on fuel supply elasticities as leakage occurs only along demand curves:

$$\frac{L_M^D}{L_M^I} = \left(\frac{\rho}{1-\rho}\right)\frac{\eta_{DH}}{\eta_{DF}} \quad (3)$$

Inspection of (3) reveals that domestic leakage becomes more important relative to international leakage as (*i*) the share of gasoline consumption of the Home country increases, and (*ii*) the relative demand elasticity of the Home country becomes higher. Therefore, if a country (or a coalition of countries) producing ethanol consumes a substantial share of world gasoline, the bias of market leakage estimates when ignoring domestic leakage might be substantial. Likewise, if the domestic demand for fuel is more elastic and attention is only paid to international leakage, then the estimated magnitude of market leakage is likely to be an underestimate of its true value.

How sensitive is market leakage to changes in market parameters?

From equation (2), we are in a position to analyze the effects of the key market parameters on market leakage due to a blender's tax credit. The partial derivatives of (2), summarized in Table 1, show that market leakage decreases, *ceteris paribus*, as demand for fuel in either country becomes less elastic and supply of fuel becomes more elastic in either country. An implication is that countries heavily dependent on oil, such as the United States, that introduce biofuels are more likely to see market leakage of their green (biofuel) policies abroad rather than at home.

On the other hand, market leakage increases (decreases) with a higher consumption share of the Home country if the demand for fuel in that country is more (less) elastic than it is in the Foreign country. Similarly, market leakage increases (decreases) as the Home country becomes a larger gasoline producer provided that the supply elasticity in the Home country is smaller (bigger) than it is in the Foreign country. The above suggests that the attempts of countries to be less dependent on oil (i.e., decrease their oil consumption share) by progressively consuming more ethanol are likely to increase market leakage if the domestic consumers are less price sensitive in comparison with the consumers in the rest of the world.

We use the results in Table 1 to examine the sensitivity of market leakage to changes in its determinants. Here we present a selection of the possible pairwise comparisons. For example, market leakage is more sensitive to the demand elasticity of the Home country compared Foreign country if the former consumes more than a half of world gasoline ($\rho > 1/2$) (see (4)). Likewise, the magnitude of market leakage will react more to changes in the Home country's supply elasticity relative to the Foreign country, if the former covers more than a half of the world supply of gasoline ($\phi > 1/2$).This is a result of the country size effect, i.e., market changes in the large country have a bigger impact (in absolute terms) in that country than in the small one. This suggests that the United States with values of $\rho = 0.22$ and $\phi = 0.07$ will have market leakage that is more sensitive to market elasticities abroad. However, if we analyze groups of countries at a time (e.g., members of the Kyoto

Protocol), then the situation can be reversed and the Home parameters can be more influential in affecting the market leakage outcome.

$$
\begin{aligned}
&(a)\ \ (\partial L / \partial \eta_{DH})/(\partial L / \partial \eta_{DF}) = \rho/(1-\rho) \\
&(b)\ \ (\partial L / \partial \eta_{SH})/(\partial L / \partial \eta_{SF}) = \phi/(1-\phi) \\
&(c)\ \ (\partial L / \partial \rho)/(\partial L / \partial \eta_{DH}) = (\eta_{DH} - \eta_{DF})/\rho \\
&(d)\ \ (\partial L / \partial \rho)/(\partial L / \partial \eta_{DF}) = (\eta_{DH} - \eta_{DF})/(1-\rho) \\
&(e)\ \ (\partial L / \partial \phi)/(\partial L / \partial \eta_{SH}) = (\eta_{SH} - \eta_{SF})/\phi \\
&(f)\ \ (\partial L / \partial \phi)/(\partial L / \partial \eta_{SF}) = (\eta_{SH} - \eta_{SF})/(1-\phi)
\end{aligned} \tag{4}
$$

The four remaining rows of (4) (equations (c) to (f)) provide an explanation for why changes in world gasoline consumption (production) shares typically have a less significant effect than do domestic supply and demand elasticities. For consumption (production) shares of the world gasoline market to have a more significant impact, the absolute difference in respective demand (supply) elasticities has to be bigger than a consumption (production) share. But this is less likely to occur as demand elasticities are similar across countries.

In order to get more insights into market leakage due to a tax credit, we analyze the key parameters at their limiting values. The findings are summarized in Table 2. If the Home country is the only fuel consumer ($\rho = 1$), ethanol production decreases the world fuel price and generates higher domestic fuel consumption, thereby resulting in higher domestic leakage. Note that even though leakage in this case is by definition all domestic, it is not the same thing as autarky leakage ($\phi = 1$ would also be required). In the absence of gasoline production in the Home country ($\phi = 0$), both domestic and international leakage occur because after total fuel supply has expanded due to ethanol production, the world fuel price declines, resulting in higher fuel consumption worldwide.

If the demand curve in either country is perfectly inelastic (i.e., $\eta_{DH} = 0$ or $\eta_{DF} = 0$) then total leakage is either all domestic or international, depending on which country has the inelastic demand curve. If, on the other hand, demand for fuel in either country is perfectly elastic, ethanol does not replace any gasoline. This is because gasoline consumption has not changed, while total fuel consumption has increased by the amount of ethanol production. Market leakage in this case is therefore 100 percent. A perfectly inelastic fuel supply curve in either country leads to both domestic and international leakage. If the fuel price is fixed in the Foreign country due to a perfectly elastic fuel supply curve ($\eta_{SF} \to \infty$), then there is no market leakage (similarly if the country is an exporter).

Some of the results summarized in Table 2 are of practical relevance to countries that produce biofuels, but whose global gasoline consumption or production shares are negligible (e.g., Slovakia). Despite being implemented by small countries, biofuel policies in these countries produce international (and also domestic if no production of gasoline) leakage whose magnitude can be substantial, depending on the market parameters.

Is market leakage for a small country always 100 percent?

One would think that a biofuel policy of a small importer (exporter) in oil markets that faces a perfectly elastic excess supply (demand) curve would automatically result in 100 percent market and carbon leakage. However, this does not necessarily have to be the case and, under some conditions, a smaller country can see lower leakage of its biofuel policies compared to a larger country. We summarize this by the following proposition on the case of market leakage, with the result holding also for carbon leakage as per equation (1).

Proposition 1: Let there be two situations for the Home country, *A* and *B*, such that $\left(dP_G/dE\right)^A < \left(dP_G/dE\right)^B$, where $\left(dP_G/dE\right)^i$, $i = \{A, B\}$ represents the effect on world gasoline price of an increase in ethanol production due to a blender's tax credit in country *i*. The gasoline price is the same in both situations. Then market leakage seen by the Home country in situation *A* is lower than in situation *B* whenever

$$\eta_{DH}^B D_H^B + \eta_{DF}^* D_F^* < \eta_{DH}^A D_H^A + \eta_{DF} D_F \text{ .}$$

The stars indicate that the fuel demand elasticity and fuel consumption in the Foreign country may differ for situations *A* or *B*. Proof of Proposition 1 is in Appendix 1.

A small country in international markets faces a perfectly elastic excess supply/demand curve. Conditions under which this is the case are derived in Appendix 2. Out of the three possibilities, we analyze the one when a country faces a perfectly elastic trade curve because of its consumption and production shares.[18] In this instance, market leakage with a blender's tax credit is given by:

$$\frac{\rho\eta_{DH} + (1-\rho)\eta_{DF}}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \rho\eta_{SH} - (1-\rho)\eta_{SF}} \leq 1 \qquad (5)$$

Consider a case where fuel demand and gasoline supply elasticities in both countries are -0.3 and 0.3 respectively, then market leakage is 50 percent – half of what it would be expected for a small 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 2008a; 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 (2008a; 2009c).

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 2008a; 2009a for details on how S_F^* is constructed).

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. [19]

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.[20] 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 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 Appendix 3 takes the form:

$$L_M^\sigma = \frac{(\delta - 1)\eta_{DH}\left(\phi\eta_{SH} + (1-\phi)\eta_{SF}\right) - \rho\eta_{DH} - (1-\rho)\eta_{DF}}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho\eta_{DH} - (1-\rho)\eta_{DF}} \tag{6}$$

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 (10) 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 (10) 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 2: For the same amount of ethanol, the market leakage (and therefore also carbon leakage) due to a blender's tax credit is always greater than that due to a consumption mandate.

Proof: The proof follows immediately from the difference of equations (2) and (6):

$$L_M^{\tau} - L_M^{\sigma} = \frac{(\delta - 1)\eta_{DH}\left(\phi\eta_{SH} + (1-\phi)\eta_{SF}\right)}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \phi\eta_{SH} - (1-\phi)\eta_{SF}} > 0 \text{ because } \delta > 1$$

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, 2008a; Lapan and Moschini, 2009).[21] 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.

Proposition 3: If a binding consumption mandate is combined with a tax credit equal[22] to the price premium necessary to generate the mandated amount of ethanol with the tax credit alone, then *i.)* if the country is small in world oil markets, then the tax credit exactly offsets the reduction in gasoline consumption due to the mandate and market leakage of both policies combined is zero,

ii.) if the country is large in world oil markets, then the tax credit more than offsets the reduction in gasoline consumption due to the mandate and market leakage of both policies combined is positive.

Proof:

Denote P_F as the fuel price in the Home country with no policy. In this case $P_F = P_G$, where P_G denotes the world price of gasoline. Let P_F' be the fuel price when both policies are combined in the Home country. The change in the domestic fuel price is then:

$$\Delta P_F = P_F' - P_F = \frac{E}{C_F'}\left(\overline{P}_E - t_c^*\right) + \left(1 - \frac{E}{C_F'}\right)P_G' - P_G = \left(\overline{P}_E - P_G' - t_c^*\right)\frac{E}{C_F'} + P_G' - P_G$$
$$= \left(\overline{P}_E - P_G - t_c^* - \Delta P_G\right)\frac{E}{C_F'} + \Delta P_G$$

where C_F' denotes fuel consumption with the policies in place, $\overline{P}_E$ denotes the ethanol price determined by the binding consumption mandate of E gallons of ethanol, P_G' denotes the world gasoline price with the policies, and t_c^* denotes a tax credit equal to the price premium necessary to generate the mandated amount of ethanol with the tax credit alone, i.e., $t_c^* = \overline{P}_E - P_G$.

Substituting the expression for the required tax credit back to the above equation, we obtain:

$$\Delta P_F = \underbrace{\left(1 - \frac{E}{C_F'}\right)}_{+}\underset{-}{\Delta P_G}$$

where the negative sign of ΔP_G follows from Appendix 4 and we get::

$$sign(\Delta P_F) = sign(\Delta P_G)$$

Therefore, for a small country, whose policies have no impact on world gasoline prices, it must be that $\Delta P_F = 0$. This means that domestic and foreign fuel consumption does not change with the implementation of the policies and so market leakage is zero. A consumption mandate combined with a tax credit in a large country decrease the world gasoline price and therefore the tax credit more than offsets the reduction in gasoline consumption due to the mandate and world fuel consumption increases, resulting in positive leakage.

5. A Numerical Example

In this section, we estimate the magnitude of market and carbon leakage for the United States using 2009 data (see Appendix 5 for data sources). All data are in gasoline equivalents.[23] In 2009, the United States consumed 22.4 percent and produced 7.4 percent of total world oil consumption.[24] The share of U.S. ethanol production represented 1.3 percent of the world gasoline consumption. Baseline 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 (see Appendix 5 for details). 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 3 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.

We begin our discussion on total leakage with international trade. The first column of Table 3 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).[25] All ethanol is assumed to be consumed domestically.

Total leakage with a tax credit is 0.65 (i.e., 65 percent, when multiplied by 100) 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 3 and equation (3) suggest that the domestic share is lower in countries like Canada. On the other hand, recall that it is very possible for 'small' exporting countries to have a higher total leakage than the United States, depending on how elastic the fuel demand curve in the rest of the world is and how big the consumption share of the exporting country is relative to that of the United States.

With a mandate, on the other hand, domestic leakage is negative (total fuel 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 3 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 3 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, for given parameters and an intended reduction in carbon emissions in absolute terms, ethanol instead of reducing carbon emissions actually produces twice as much of them.

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).[26] However, looking at the last set of results in the first column of Table 3, 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 in the emissions savings parameter.

Another unique feature of the results in Table 3 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 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 3 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 3.

In the third column of Table 3, 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.

We now turn to the fourth column of Table 3 that presents estimates of autarky leakage. We present autarky leakage as an estimate of what leakage would be if all countries in the world adopted the biofuel policy. The first thing to note is that market leakage under autarky (where the United States in this case adopts the biofuel policy) does not differ very much from that of total market leakage under international trade – the difference being only 10 percentage points.[27] Therefore, "expanding the coalition" is not a critical issue in the case of biofuel policy and climate change (unlike for cap and trade or REDD – Murray 2008). Only in the case of high values for the emissions savings effect does carbon leakage drop significantly for autarky leakage (compare first and last columns of Table 3 for last three rows). This is because a higher emissions savings effect makes, the carbon and market leakage measures diverge. In this case, the emissions savings effect, which always reduces carbon leakage, almost completely offsets the market leakage effect, resulting in a very low carbon leakage.

Previous studies analyzing the impact of a tax credit and/or a mandate on leakage assume autarky (de Gorter and Just 2008a; 2009a; Holland et al. 2009). With a consumption mandate, they find both positive and negative market leakage for plausible elasticity values. In our simulations (not reported), leakage is almost always underestimated assuming autarky when U.S. supply is assumed to be more elastic but it is likely to be overestimated (for a fixed value of the demand elasticity) when the U.S. demand for fuel is assumed to be more elastic. The U.S. biofuel policies certainly have an impact on international markets. Therefore, modeling leakage assuming autarky biases the results.

Finally, in the fifth and sixth column of Table 3, we present the "true carbon savings" of ethanol relative to gasoline, when the effect of iOUC is included for the case of international trade and autarky. 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 also the market leakage effect, corn-ethanol emits more carbon emissions than does gasoline. For example, the value of -0.43 in the fifth column means that one (gasoline-equivalent) gallon of ethanol emits 1.43 times more carbon than 1 gallon of gasoline.

Sensitivity analysis on the changes in key parameters affecting the magnitude of leakages is presented in Tables 4a and 4b. The organization of data is identical in both tables: values of elasticities are changed one at a time, keeping other parameters at their baseline levels (baseline leakage values are highlighted).[28] In Table 4a, we assume a scenario that includes indirect land use change (iLUC) while in Table 4b, iLUC is ignored. Since the carbon emissions savings parameter only influences carbon leakage, we do not report the magnitudes of market leakage in Table 4b to avoid repetition.

Consistent with the theoretical predictions in Table 1, leakage decreases as the gasoline supply curve in both countries becomes more elastic and increases as the elasticity of demand for fuel increases. Elasticities in the Foreign country have a bigger impact on leakage relative to the domestic ones because the United States consumes and produces less than a half of world's gasoline. With inelastic demand and supply curves (which is most likely the case in reality), carbon leakage typically exceeds 100 percent when we assume an emissions savings parameter of U.S. corn-ethanol of 21 percent compared to gasoline. On the other hand, if the emissions savings parameter is much higher (e.g., $\xi = 0.52$ as in most recent EPA estimate of direct emissions using life-cycle accounting that excludes iLUC), then U.S. corn-ethanol is likely to reduce global carbon emissions substantially (Table 4b). Comparing Table 4a to 4b for carbon leakage, we observe that the odds that a more-than-expected amount of carbon will be saved increases as the emissions associated with ethanol declines (9 negative carbon leakage values in Table 4a *vs* 26 in Table 4b).Therefore, in order to evaluate the effects of ethanol production on the global carbon emissions, we not only need reliable estimates of how much lower ethanol emissions are compared to gasoline, but also agreement on whether to include iLUC or not.[29]

6. Conclusions

Leakage is a measure of the ineffectiveness of an environmental policy and is frequently discussed in the context of combating global climate change. We develop an analytical framework to analyze the carbon leakage due to alternative biofuel policies, namely consumption subsidies and mandates (and their combination). We identify two components of carbon leakage: 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. Despite being overlooked by the IPCC, domestic leakage, under plausible assumptions, can be a significant factor of total leakage. With numerical simulations, we show why domestic leakage should be included in leakage estimates of various policies and what biases result from not doing so. 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 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. We demonstrate that 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. We also find that being a relatively smaller country in world oil markets does not automatically imply a lower leakage.

For the same amount of ethanol, market leakage due to a tax credit is always greater than that due to a binding consumption mandate while the combination of a binding mandate and a tax credit produces greater leakage than a mandate alone. A tax credit equal to the price premium that is necessary to generate the mandated amount of ethanol combined with a binding mandate exactly offsets the reduction in gasoline consumption due to the mandate if the country has no impact on world oil prices, but more than offsets the reduction if the country does impact oil prices.

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 translates into the carbon leakage of 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 a policy and whether or not iLUC is considered.

The empirical evidence presented in this paper suggests leakage from biofuel policy could be substantial. Leakage from biofuels policies is difficult to address in policy design because a mandate does not help much due to international leakage overriding a potential negative domestic leakage. Leakage from biofuel policies is also a special problem from a policy standpoint because, unlike with leakage in a cap and trade or REDD scheme, the problem is not always solved by having all countries adopt a biofuels policy because all leakage will be “autarky” (i.e., “domestic” if the coalition is expended to all countries adopting a biofuels policy) but this will likely result in little savings compared to the case if the United States was the only country with the biofuels policy. There is one possible exception: if the emissions savings effect ξ is high enough (i.e., if iLUC is ignored and ξ is around 0.50), then if every country adopts a mandate, there can be negative carbon leakage worldwide.

The framework advanced in this paper on leakage assumes the supply curve for gasoline is fixed. But an emerging literature on the Green paradox suggests that the introduction of biofuels shifts the gasoline supply curve down as owners of non-renewable resources worry about the rate of capital gains on these resources and so are motivated to extract their stocks of oil more rapidly in order to convert a larger portion of their wealth into cash and securing it as financial capital (Sinn 2008; 2009; Eichner and Pething 2009; Hoel 2008; Grafton et al. 2010). So the estimates of leakage in this paper may be underestimated if aspects of the Green paradox are not included.

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Table 1: Effect of changes in market parameters on market leakage with a tax credit			
Change in market leakage with respect to:	**Magnitude of the effect**	**Sign of the effect**	**Note**
Domestic fuel demand elasticity (η_{DH})	$-\frac{\rho\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho\eta_{DH}+(1-\rho)\eta_{DF}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}$	(-)	unambiguous sign
Foreign fuel demand elasticity (η_{DF})	$-\frac{(1-\rho)\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho\eta_{DH}+(1-\rho)\eta_{DF}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}$	(-)	unambiguous sign
Domestic gasoline supply elasticity (η_{SH})	$\frac{\phi\left(\rho\eta_{DH}+(1-\rho)\eta_{DF}\right)}{\left(\rho\eta_{DH}+(1-\rho)\eta_{DF}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}$	(-)	unambiguous sign
Foreign gasoline supply elasticity (η_{SF})	$\frac{(1-\phi)\left(\rho\eta_{DH}+(1-\rho)\eta_{DF}\right)}{\left(\rho\eta_{DH}+(1-\rho)\eta_{DF}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}$	(-)	unambiguous sign
Domestic consumption share in world gasoline consumption (ρ)	$-\frac{\left(\eta_{DH}-\eta_{DF}\right)\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho\eta_{DH}+(1-\rho)\eta_{DF}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}$	(+)	for $\eta_{DH}<\eta_{DF}$
		(-)	for $\eta_{DH}>\eta_{DF}$
Domestic production share in world gasoline production (ϕ)	$\frac{\left(\eta_{SH}-\eta_{SF}\right)\left(\rho\eta_{DH}+(1-\rho)\eta_{DF}\right)}{\left(\rho\eta_{DH}+(1-\rho)\eta_{DF}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}$	(+)	for $\eta_{SH}<\eta_{SF}$
		(-)	for $\eta_{SH}>\eta_{SF}$

Source: calculated

Table 2: Effect on market leakage with a tax credit when parameters take on limiting values*				
Limiting value of a parameter		**Magnitude of market leakage**	**Interval of magnitude**	**Location of leakage****
1.	Home country consumes all gasoline ($\rho = 1$)	$\frac{\eta_{DH}}{\eta_{DH} - \phi\eta_{SH} - (1-\phi)\eta_{SF}}$	between 0 and 1	domestic
2.	Home country consumes no gasoline ($\rho = 0$)	$\frac{\eta_{DF}}{\eta_{DF} - \phi\eta_{SH} - (1-\phi)\eta_{SF}}$	between 0 and 1	international
3.	Home country produces all gasoline ($\phi = 1$)	$\frac{\rho\eta_{DH} + (1-\rho)\eta_{DF}}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \eta_{SH}}$	between 0 and 1	domestic & international
4.	Home country produces no gasoline ($\phi = 0$)	$\frac{\rho\eta_{DH} + (1-\rho)\eta_{DF}}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \eta_{SF}}$	between 0 and 1	domestic & international
5.	Fuel demand in Home country is perfectly inelastic ($\eta_{DH} = 0$)	$\frac{(1-\rho)\eta_{DF}}{(1-\rho)\eta_{DF} - \phi\eta_{SH} - (1-\phi)\eta_{SF}}$	between 0 and 1	international
6.	Fuel demand in Home country is perfectly elastic ($\eta_{DH} \to -\infty$)	1	1	domestic
7.	Fuel demand in Foreign country is perfectly inelastic ($\eta_{DF} = 0$)	$\frac{\rho\eta_{DH}}{\rho\eta_{DH} - \phi\eta_{SH} - (1-\phi)\eta_{SF}}$	between 0 and 1	domestic
8.	Fuel demand in Foreign country is perfectly elastic ($\eta_{DF} \to -\infty$)	1	1	international

Table 2: continued					
Limiting value of a parameter		**Magnitude of market leakage**	**Interval for magnitude**	**Location of leakage**[**]
9.	Gasoline supply in Home country is perfectly inelastic ($\eta_{SH} = 0$)	$\frac{\rho\eta_{DH} + (1-\rho)\eta_{DF}}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - (1-\phi)\eta_{SF}}$	between 0 and 1	domestic & international
10.	Gasoline supply in Home country is perfectly elastic ($\eta_{SH} \to \infty$)	0	0	
11.	Gasoline supply in Foreign country is perfectly inelastic ($\eta_{SF} = 0$)	$\frac{\rho\eta_{DH} + (1-\rho)\eta_{DF}}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \phi\eta_{SH}}$	between 0 and 1	domestic & international
12.	Gasoline supply in Foreign country is perfectly elastic ($\eta_{SF} \to \infty$)	0	0	

Source: calculated

[*] Case of Home country and importer; 2., 3., 8. and 10. are only meaningful for an exporter.

[**] Based on equation (3).

Table 3: Baseline Values of Market and Carbon Leakages under Trade vs Autarky *

	International trade			Autarky	True emissions savings of ethanol**	
	(I.) Total (our definition)	(II.) Domestic share	(III.) IPCC definition	(IV.)	(V.) Trade	(VI.) Autarky
Market Leakage						
Tax credit	0.65	16%	0.61	0.57		
Mandate	0.61	-2%	0.61	0.52		
Tax credit w/ binding mandate	0.64	9%	0.61	0.54		
Carbon Leakage						
Incl. iLUC (ξ=0.21)						
Tax credit	2.09	-24%	1.72	1.69	-0.44	-0.36
Mandate	1.90	-56%	1.43	1.45	-0.40	-0.31
Tax credit w/ binding mandate	2.07	-36%	1.59	1.55	-0.43	-0.33
Excl. iLUC (ξ=0.52)						
Tax credit	0.25	-321%	0.58	0.09	-0.13	-0.05
Mandate	0.17	-619%	0.59	-0.01	-0.09	0.00
Tax credit w/ binding mandate	0.24	-408%	0.58	0.03	-0.12	-0.02

Source: calculated

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

** The values are calculated as ξ minus total market leakage (with international trade or under autarky). 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).

Table 4a: Sensitivity Analysis for Magnitude of Leakage Including iLUC (ξ=0.21): Trade *

Parameters values unless otherwise specified: $\rho = 0.224$, $\varphi = 0.074$, $\delta = 1.44$, $\eta_{SH} = 0.2$, $\eta_{SF} = 0.2$, $\eta_{DH} = -0.26$, $\eta_{DF} = -0.4$

Home supply elasticity of gasoline (η_{SH})	**0.10**	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**	**1.20**	**1.40**	**1.60**	**1.80**	**2.00**
Market leakage: Tax credit	0.66	0.65	0.63	0.62	0.60	0.59	0.57	0.56	0.55	0.54	0.53
Consumption mandate	0.62	0.61	0.59	0.57	0.56	0.54	0.52	0.51	0.50	0.48	0.47
Carbon leakage: Tax credit	2.13	2.09	2.01	1.93	1.86	1.80	1.73	1.67	1.61	1.55	1.50
Consumption mandate	1.94	1.90	1.81	1.72	1.65	1.57	1.50	1.43	1.36	1.30	1.24
Foreign supply elasticity of gasoline (η_{SF})	**0.10**	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**	**1.20**	**1.40**	**1.60**	**1.80**	**2.00**
Market leakage: Tax credit	0.77	0.65	0.49	0.39	0.33	0.28	0.25	0.22	0.20	0.18	0.16
Consumption mandate	0.75	0.61	0.43	0.32	0.25	0.20	0.16	0.13	0.11	0.09	0.07
Carbon leakage: Tax credit	2.69	2.09	1.33	0.87	0.56	0.34	0.17	0.05	-0.06	-0.14	-0.21
Consumption mandate	2.56	1.90	1.05	0.54	0.20	-0.05	-0.24	-0.38	-0.50	-0.59	-0.67
Home demand elasticity of fuel (η_{DH})	**-0.10**	**-0.20**	**-0.40**	**-0.60**	**-0.80**	**-1.00**	**-1.20**	**-1.40**	**-1.60**	**-1.80**	**-2.00**
Market leakage: Tax credit	0.62	0.64	0.67	0.69	0.71	0.73	0.74	0.76	0.77	0.78	0.79
Consumption mandate	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
Carbon leakage: Tax credit	1.97	2.05	2.17	2.28	2.38	2.47	2.54	2.61	2.67	2.72	2.77
Consumption mandate	1.90	1.90	1.90	1.90	1.89	1.89	1.89	1.89	1.89	1.89	1.89
Foreign demand elasticity of fuel (η_{DF})	**-0.10**	**-0.20**	**-0.40**	**-0.60**	**-0.80**	**-1.00**	**-1.20**	**-1.40**	**-1.60**	**-1.80**	**-2.00**
Market leakage: Tax credit	0.40	0.52	0.65	0.72	0.77	0.81	0.83	0.85	0.87	0.88	0.89
Consumption mandate	0.34	0.46	0.61	0.69	0.75	0.78	0.81	0.83	0.85	0.87	0.88
Carbon leakage: Tax credit	0.93	1.46	2.09	2.45	2.68	2.84	2.96	3.05	3.13	3.19	3.24
Consumption mandate	0.60	1.19	1.90	2.30	2.55	2.74	2.87	2.97	3.05	3.12	3.18

Source: calculated

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

Note: Shaded areas pertain to baseline.

Table 4b: Sensitivity Analysis for Magnitude of Leakage Excluding iLUC (ξ=0.52): Trade * **

Parameters values unless otherwise specified: $\rho = 0.224$, $\varphi = 0.074$, $\delta = 1.44$, $\eta_{SH} = 0.2$, $\eta_{SF} = 0.2$, $\eta_{DH} = -0.26$, $\eta_{DF} = -0.4$

Home supply elasticity of gasoline (η_{SH})	**0.10**	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**	**1.20**	**1.40**	**1.60**	**1.80**	**2.00**
Carbon leakage: Tax credit	0.26	0.25	0.21	0.18	0.16	0.13	0.10	0.08	0.05	0.03	0.01
Consumption mandate	0.19	0.17	0.13	0.10	0.07	0.04	0.01	-0.02	-0.05	-0.07	-0.09
Foreign supply elasticity of gasoline (η_{SF})	**0.10**	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**	**1.20**	**1.40**	**1.60**	**1.80**	**2.00**
Carbon leakage: Tax credit	0.49	0.25	-0.06	-0.25	-0.37	-0.46	-0.53	-0.58	-0.62	-0.65	-0.68
Consumption mandate	0.44	0.17	-0.17	-0.38	-0.52	-0.62	-0.69	-0.75	-0.80	-0.83	-0.87
Home demand elasticity of fuel (η_{DH})	**-0.10**	**-0.20**	**-0.40**	**-0.60**	**-0.80**	**-1.00**	**-1.20**	**-1.40**	**-1.60**	**-1.80**	**-2.00**
Carbon leakage: Tax credit	0.20	0.23	0.28	0.33	0.37	0.40	0.43	0.46	0.48	0.50	0.52
Consumption mandate	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Foreign demand elasticity of fuel (η_{DF})	**-0.10**	**-0.20**	**-0.40**	**-0.60**	**-0.80**	**-1.00**	**-1.20**	**-1.40**	**-1.60**	**-1.80**	**-2.00**
Carbon leakage: Tax credit	-0.22	-0.01	0.25	0.39	0.49	0.55	0.60	0.64	0.67	0.69	0.71
Consumption mandate	-0.35	-0.11	0.17	0.33	0.44	0.51	0.56	0.60	0.64	0.66	0.69

Source: calculated

* Market leakage is the same as in Table 4a.

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

Note: Shaded areas pertain to baseline.

Figure 1: Biofuels Leakage with a Tax Credit and Trade

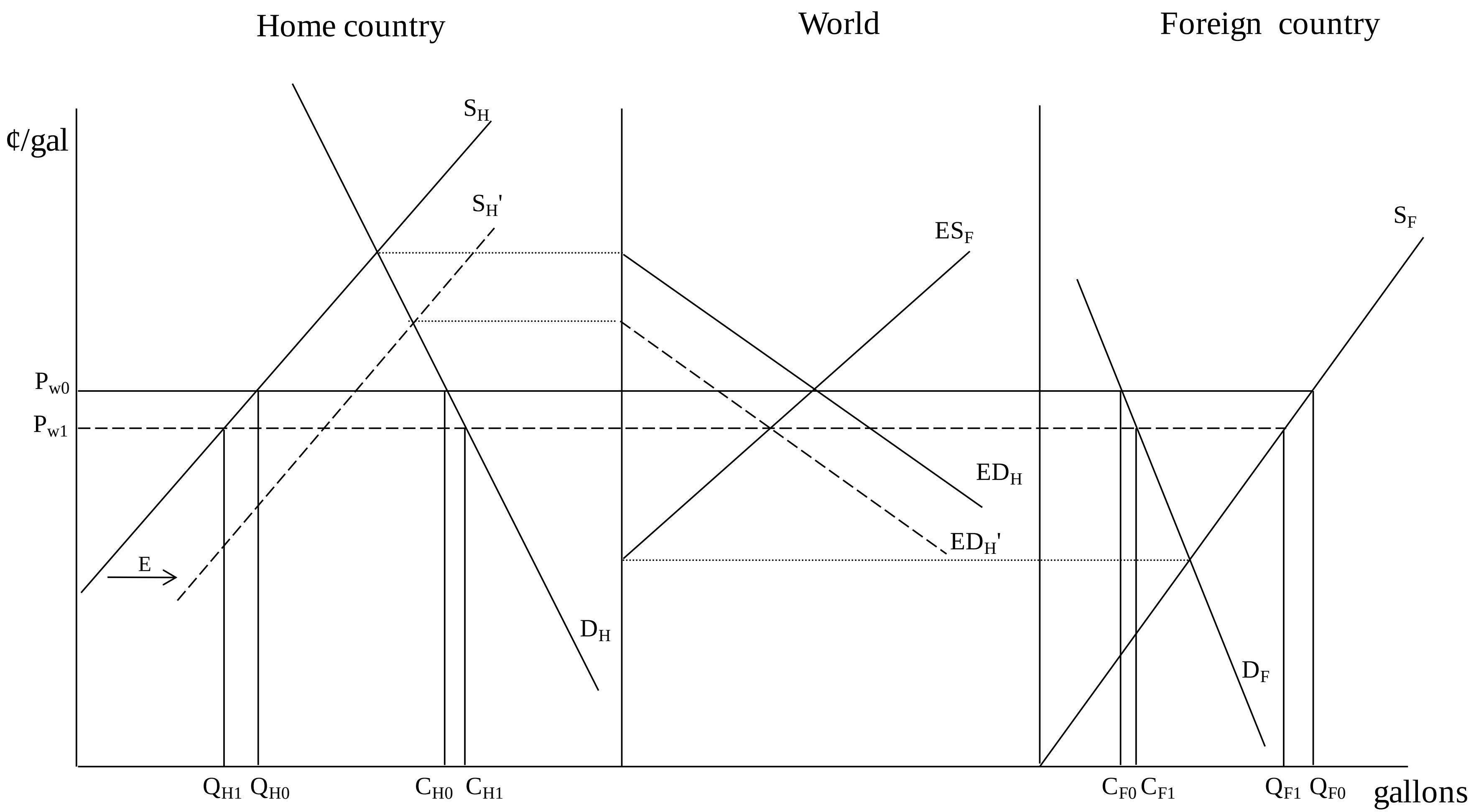
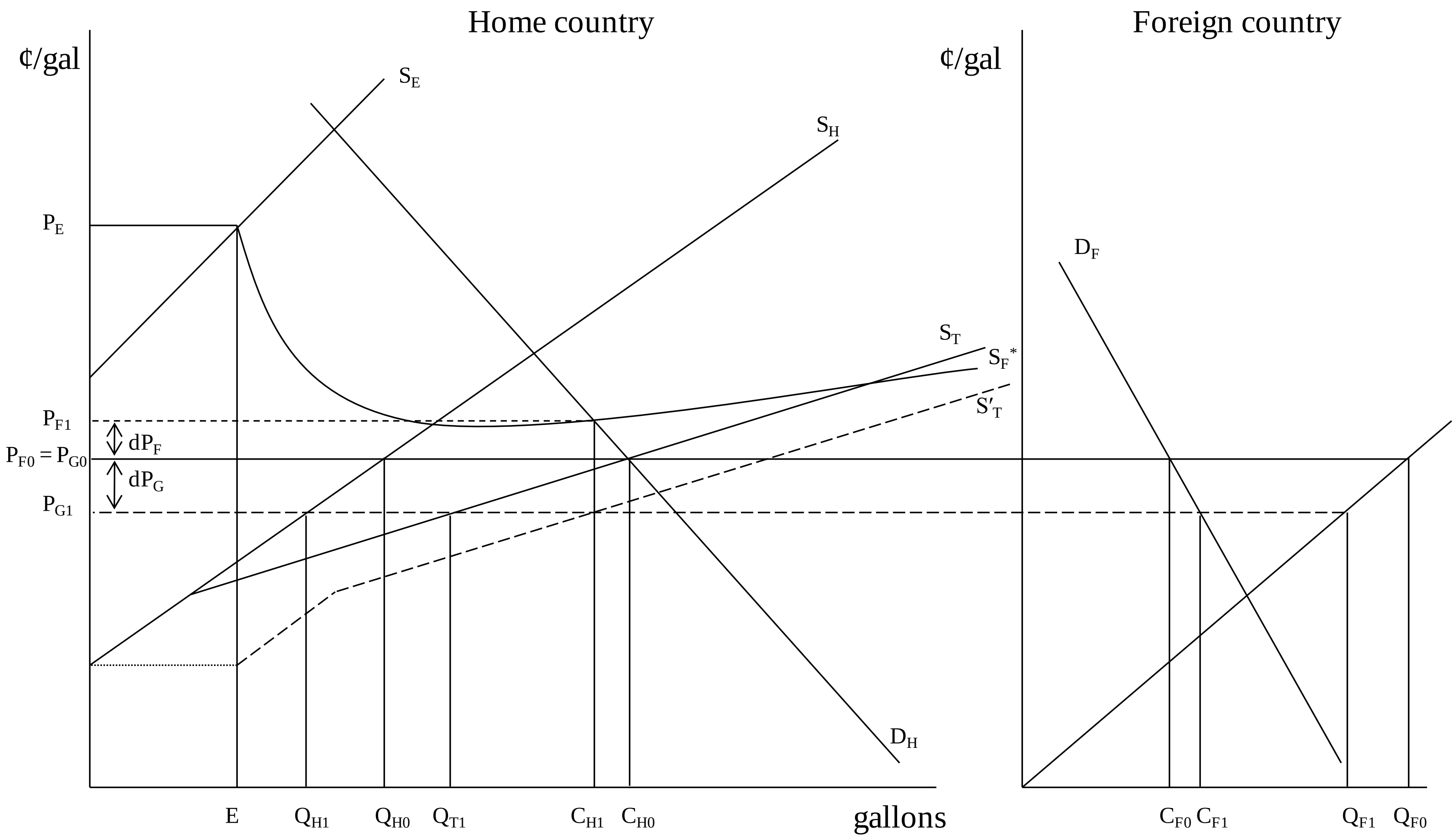


Figure 2: Biofuels Leakage with a Consumption Mandate and Trade



Appendix 1: Formula for market leakage due to a tax credit

The equilibrium in world gasoline market with E gallons of ethanol produced due to a blender's tax credit is given by:

$$D_H(P_G) + D_F(P_G) = S_H(P_G) + S_F(P_G) + E \qquad \text{(A1-1)}$$

where D denotes demand for fuel, S supply of gasoline, P_G world price of gasoline, and subscripts H and F denote the Home and Foreign country, respectively.

Totally differentiating (A1-1), we get:

$$\frac{dP_G}{dE} = \frac{1}{D_H' + D_F' - S_H' - S_F'} < 0 \qquad \text{(A1-2)}$$

A change in Home country fuel consumption due to introduction of E gallons of ethanol is

$$\frac{dD_H}{dE} = \frac{dD_H}{dP_G}\frac{dP_G}{dE} = \eta_{DH}\frac{D_H}{P_G}\frac{1}{\left(D_H' + D_F' - S_H' - S_F'\right)} > 0 \qquad \text{(A1-3)}$$

Similarly for the change in gasoline consumption in the Foreign country:

$$\frac{dD_F}{dE} = \frac{dD_F}{dP_G}\frac{dP_G}{dE} = \eta_{DF}\frac{D_F}{P_G}\frac{1}{\left(D_H' + D_F' - S_H' - S_F'\right)} > 0 \qquad \text{(A1-4)}$$

Market leakage due to a blender's tax credit L_M^{τ} is defined as

$$L_M^{\tau} = \frac{dC_{HF} + dC_{FG}}{E} = \frac{\eta_{DH}D_H + \eta_{DF}D_F}{P_G\left(D_H' + D_F' - S_H' - S_F'\right)} \qquad \text{(A1-5)}$$

After transformation of the derivatives of the demand and supply curves into the elasticity forms, we get the final formula for market leakage with a tax credit

$$L_M^{\tau} = \frac{\rho\eta_{DH} + (1-\rho)\eta_{DF}}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \phi\eta_{SH} - (1-\phi)\eta_{SH}}$$

where $\rho = D_H / (D_H + D_F)$ and $\phi = S_H / (S_H + S_F)$. The symbol η denotes elasticity and the notation of the subscripts is the same as in (A1-1), so for example η_{DH} denoted demand elasticity in the Home country.

Proof of Proposition 1

From (A1-2) for the Home country types *A* and *B*, we have

$$\begin{aligned} \left(\frac{dP_G}{dE}\right)^A &= \frac{1}{\eta_{DH}^A \frac{D_H^A}{P_G} + \eta_{DF} \frac{D_F}{P_G} - \eta_{SH}^A \frac{S_H^A}{P_G} - \eta_{SF} \frac{S_F}{P_G}} = \frac{P_G}{\eta_{DH}^A D_H^A + \eta_{DF} D_F - \eta_{SH}^A S_H^A - \eta_{SF} S_F} \\ \left(\frac{dP_G}{dE}\right)^B &= \frac{1}{\eta_{DH}^B \frac{D_H^B}{P_G} + \eta_{DF}^* \frac{D_F^*}{P_G} - \eta_{SH}^B \frac{S_H^B}{P_G} - \eta_{SF}^* \frac{S_F^*}{P_G}} = \frac{P_G}{\eta_{DH}^B D_H^B + \eta_{DF}^* D_F^* - \eta_{SH}^B S_H^B - \eta_{SF}^* S_F^*} \end{aligned} \tag{A1-6}$$

where the star (*) in the case of country *B* signifies that the elasticities and quantities might be different from those for country *A*.

The condition $(dP_G/dE)^A < (dP_G/dE)^B$ is equivalent to

$$-\frac{\eta_{DH}^B D_H^B + \eta_{DF}^* D_F^* - \eta_{SH}^B S_H^B - \eta_{SF}^* S_F^*}{\eta_{DH}^A D_H^A + \eta_{DF} D_F - \eta_{SH}^A S_H^A - \eta_{SF} S_F} < -1 \tag{A1-7}$$

Market leakage seen by the Home country type *A* is less than by type *B* if

$$L_M^{\tau A} < L_M^{\tau B}$$

$$\frac{\eta_{DH}^A D_H^A + \eta_{DF} D_F}{\eta_{DH}^A D_H^A + \eta_{DF} D_F - \eta_{SH}^A S_H^A - \eta_{SF} S_F} < \frac{\eta_{DH}^B D_H^B + \eta_{DF}^* D_F^*}{\eta_{DH}^B D_H^B + \eta_{DF}^* D_F^* - \eta_{SH}^B S_H^B - \eta_{SF}^* S_F^*}$$

This is equivalent to

$$\frac{\eta_{DH}^B D_H^B + \eta_{DF}^* D_F^* - \eta_{SH}^B S_H^B - \eta_{SF}^* S_F^*}{\eta_{DH}^A D_H^A + \eta_{DF} D_F - \eta_{SH}^A S_H^A - \eta_{SF} S_F} < \frac{\eta_{DH}^B D_H^B + \eta_{DF}^* D_F^*}{\eta_{DH}^A D_H^A + \eta_{DF} D_F} \tag{A1-8}$$

Finally, summing (A1-7) and (A1-8) and rearranging, we get the required condition

$$\eta_{DH}^B D_H^B + \eta_{DF}^* D_F^* < \eta_{DH}^A D_H^A + \eta_{DF} D_F$$

Appendix 2: Derivation of elasticities of excess supply and demand curves

At a price p the Foreign country will export gasoline in the amount of:

$$X(p) = S_F(p) - D_F(p) \tag{A2-1}$$

Differentiating both sides of (A2-1) with respect to the price and manipulating, we obtain :

$$\begin{aligned}
\frac{dX(p)}{dp} &= \frac{dS_F(p)}{dp} - \frac{dD_F(p)}{dp} \\
\frac{dX(p)}{dp}\frac{p}{X(p)}\frac{X(p)}{p} &= \frac{dS_F(p)}{dp}\frac{p}{S_F(p)}\frac{S_F(p)}{p} - \frac{dD_F(p)}{dp}\frac{p}{D_F(p)}\frac{D_F(p)}{p} \\
\eta_{ES} &= \eta_{SF}\frac{S_F}{X} - \eta_{DF}\frac{D_F}{X} \\
\eta_{ES} &= \eta_{SF}\frac{S_F}{S_F - D_F} - \eta_{DF}\frac{D_F}{S_F - D_F}
\end{aligned} \tag{A2-2}$$

where η_{ES} denotes the elasticity of excess supply and the remaining notation is the same as in Appendix 1.

Multiplying both the numerator and the denominator of (A2-2) by $1/C_w$, where C_w is world gasoline consumption, we obtain:

$$\eta_{ES} = \eta_{SF}\frac{\frac{S_F}{C_w}}{\frac{S_F}{C_w} - \frac{D_F}{C_w}} - \eta_{DF}\frac{\frac{D_F}{C_w}}{\frac{S_F}{C_w} - \frac{D_F}{C_w}}$$

which can be re-written using the notation from Appendix 1 as:

$$\eta_{ES} = \eta_{SF}\frac{1-\phi}{\rho-\phi} - \eta_{DF}\frac{1-\rho}{\rho-\phi} \tag{A2-3}$$

Similarly, for the excess demand curve we obtain:

$$\eta_{ED} = \eta_{DH}\frac{\rho}{\rho-\phi} - \eta_{SH}\frac{\phi}{\rho-\phi} \tag{A2-4}$$

Therefore, a small importer faces a perfectly elastic excess supply curve when $\eta_{SF} \to \infty$; a small exporter faces a perfectly elastic excess demand curve when $\eta_{DH} \to -\infty$; and irrespective of the trade position, a small country faces a perfectly elastic trade curve whenever $\rho \to \phi$ (the case analyzed in the paper).

Appendix 3: Derivation of market leakage formula with a consumption mandate

World fuel market equilibrium with a binding consumption mandate and a blender's tax credit in the Home country is given by:

$$\begin{aligned}
C_{HF} &= D_H\left(P_F\right) \\
C_{FG} &= D_F\left(P_G\right) \\
Q_{HG} &= S_{HG}\left(P_G\right) \\
Q_{FG} &= S_{FG}\left(P_G\right) \\
E &= S_E\left(P_E\right) \\
P_F &= \frac{E}{C_{HF}}\left(P_E + t - t_c\right) + \frac{C_{HF} - E}{C_{HF}}\left(P_G + t\right) \\
C_{HF} + C_{FG} &= Q_{HG} + Q_{FG} + E
\end{aligned} \qquad \text{(A3-1)}$$

where the first subscript denotes country (H = Home, F = Foreign), the second denotes either fuel F or gasoline G. The letter E represents the amount of ethanol that is mandated. The blender's tax credit is denoted by t_c and a fuel tax by t. The remaining notation is the same as in Appendix 1.

Totally differentiating the system of equations in (A3-1), we get:

$$\begin{aligned}
dC_{HF} &= D_H{}'dP_F \\
dC_{FG} &= D_F{}'dP_G \\
dQ_{HG} &= S_{HG}{}'dP_G \\
dQ_{FG} &= S_{FG}{}'dP_G \\
dE &= S_E{}'dP_E \\
dP_F &= \frac{P_E - P_G - t_c}{C_{HF}}dE + \frac{E}{C_{HF}}dP_E + dt - \frac{E}{C_{HF}}dt_c + \frac{C_{HF} - E}{C_{HF}}dP_G - \frac{E\left(P_E - P_G - t_c\right)}{C_{HF}{}^2}dC_{HF} \\
dC_{HF} + dC_{FG} &= dQ_{HG} + dQ_{FG} + dE
\end{aligned}$$

(A3-2)

Solving the linearized system (A3-2) for dC_{HF}/dE and dC_{FG}/dE and converting the derivatives into the elasticity forms, we obtain:

$$\frac{dC_{HF}}{dE} = \frac{\eta_{DH}\frac{(P_E - P_G - t_c)}{P_F} + \frac{\eta_{DH}}{\eta_E}\frac{P_E}{P_F} - \left(1 - \frac{E}{C_{HF}}\right)\frac{P_G}{P_F}\frac{\eta_{DH}C_{HF}}{(\eta_{SH}Q_{HG} + \eta_{SF}Q_{FG} - \eta_{DF}C_{FG})}}{1 + \eta_{DH}\frac{E}{C_{HF}}\frac{(P_E - P_G - t_c)}{P_F} - \left(1 - \frac{E}{C_{HF}}\right)\frac{P_G}{P_F}\frac{\eta_{DH}C_{HF}}{(\eta_{SH}Q_{HG} + \eta_{SF}Q_{FG} - \eta_{DF}C_{FG})}} \quad \text{(A3-3)}$$

$$\frac{dC_{FG}}{dE} = \frac{\eta_{DH}\frac{(P_E - P_G - t_c)}{P_F} + \frac{\eta_{DH}}{\eta_E}\frac{P_E}{P_F} - \eta_{DH}\frac{E}{C_{HF}}\frac{(P_E - P_G - t_c)}{P_F} - 1}{\left(1 + \eta_{DH}\frac{E}{C_{HF}}\frac{(P_E - P_G - t_c)}{P_F}\right)\left(\frac{\eta_{SH}Q_{HG} + \eta_{SF}Q_{FG}}{\eta_{DF}C_{FG}} - 1\right) - \left(1 - \frac{E}{C_{HF}}\right)\frac{\eta_{DH}}{\eta_{DF}}\frac{P_G}{P_F}\frac{C_{HF}}{C_{FG}}} \quad \text{(A3-4)}$$

Let us first analyze the situation with a binding consumption mandate alone, i.e., $t_c = 0$. Evaluate the derivatives (A3-3) and (A3-4) at $E = 0$ and use the fact that the ethanol supply curve is perfectly elastic around that point.[30]

After some simplifications, we get:

$$\left.\frac{dC_{HF}}{dE}\right|_{E=0} = \frac{\left(\frac{\tilde{P}_E}{P_{G0}} - 1\right)\eta_{DH}(\eta_{SH}Q_{HG0} + \eta_{SF}Q_{FG0} - \eta_{DF}C_{FG0}) - \eta_{DH}C_{HG0}}{\eta_{SH}Q_{HG0} + \eta_{SF}Q_{FG0} - \eta_{DH}C_{HG0} - \eta_{DF}C_{FG0}} \quad \text{(A3-5)}$$

$$\left.\frac{dC_{FG}}{dE}\right|_{E=0} = \frac{\left(\eta_{DH}\left(\frac{\tilde{P}_E}{P_{G0}} - 1\right) - 1\right)\eta_{DF}C_{FG0}}{\eta_{SH}Q_{HG0} + \eta_{SF}Q_{FG0} - \eta_{DH}C_{HG0} - \eta_{DF}C_{FG0}} \quad \text{(A3-6)}$$

where the additional subscript *0* is meant to denote the initial equilibrium with no ethanol (hence also the changed notation for consumption of gasoline in the Home country, C_{HG0}) and $\tilde{P}_E$ denotes the vertical intercept of the inverse ethanol supply curve.

For a mandate to bind, it must be the case that $\tilde{P}_E / P_{G0} = \delta > 1$. Multiplying both the numerators and the denominators of (A3-5) and (A3-6) by $1/C_0$, where C_0 denotes world consumption of gasoline in the absence of ethanol, we arrive at:

$$\left.\frac{dC_{HF}}{dE}\right|_{E=0} = \frac{(\delta - 1)\eta_{DH}(\phi\eta_{SH} + (1-\phi)\eta_{SF} - (1-\rho)\eta_{DF}) - \rho\eta_{DH}}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho\eta_{DH} - (1-\rho)\eta_{DF}}$$

$$\left.\frac{dC_{FG}}{dE}\right|_{E=0} = \frac{(1-\rho)\eta_{DF}\left(\eta_{DH}(\delta-1)-1\right)}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho\eta_{DH}-(1-\rho)\eta_{DF}}$$

Since we have assumed no ethanol in the initial equilibrium, with a consumption mandate of E gallons of ethanol we must have $dE = E$. Therefore, the change in fuel consumption after the mandate has been introduces is:

$$dC_{HF} = \frac{(\delta-1)\eta_{DH}\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}-(1-\rho)\eta_{DF}\right)-\rho\eta_{DH}}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho\eta_{DH}-(1-\rho)\eta_{DF}}E$$

$$dC_{FG} = \frac{(1-\rho)\eta_{DF}\left(\eta_{DH}(\delta-1)-1\right)}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho\eta_{DH}-(1-\rho)\eta_{DF}}E > 0$$

Note that while the change in domestic fuel consumption is ambiguous, gasoline consumption in the Foreign country always increases when a consumption biofuel mandate is introduced in the Home country.

Finally, market leakage with a consumption mandate L_M^{σ} is given by:

$$L_M^{\sigma} = \frac{dC_{HF}+dC_{FG}}{E} = \frac{(\delta-1)\eta_{DH}\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)-\rho\eta_{DH}-(1-\rho)\eta_{DF}}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho\eta_{DH}-(1-\rho)\eta_{DF}}$$

It is easy to show that $L_M^{\sigma} < 1$, but it is not bounded from below, i.e., can also be negative meaning that one than one gallon of gasoline can be replaced with one gallon of ethanol. This happens whenever $(\delta-1)\eta_{DH} < \dfrac{\rho\eta_{DH}+(1-\rho)\eta_{DF}}{\phi\eta_{SH}+(1-\phi)\eta_{SF}}$.

Appendix 4: Change in the World Gasoline Price when a Tax Credit is added to a Binding Consumption Mandate

Solving (A3-2) for the change in the world gasoline price we obtain:

$$dP_G = \frac{\frac{P_E - P_G - t_c}{C_{HF}} D_H' + \frac{E}{C_{HF}} \frac{D_H'}{S_E'} - \left(1 + \frac{E\left(P_E - P_G - t_c\right)}{C_{HF}^{2}} D_H'\right)}{\left(S_{HG}' + S_{FG}' - D_F'\right)\left(1 + \frac{E\left(P_E - P_G - t_c\right)}{C_{HF}^{2}} D_H'\right) - \frac{C_{HF} - E}{C_{HF}} D_H'} dE$$

$$- \frac{\frac{E}{C_{HF}} D_H'}{\left(S_{HG}' + S_{FG}' - D_F'\right)\left(1 + \frac{E\left(P_E - P_G - t_c\right)}{C_{HF}^{2}} D_H'\right) - \frac{C_{HF} - E}{C_{HF}} D_H'} dt_c \qquad \text{(A4-1)}$$

Evaluating (A4-1) at E = 0 and t_c = 0, and noting that after introduction of ethanol $dE = E$, we get:

$$dP_G\Big|_{E=0, t_c=0} = \frac{\left(\frac{\tilde{P}_E - P_G}{C_{HF}}\right) D_H' - 1}{S_{HG}' + S_{FG}' - D_F' - D_H'} E < 0$$

which means that the world gasoline price decreases as a tax credit is added to a binding consumption mandate.

Appendix 5: Data sources

Parameter/Variable	Symbol	Value	Source/explanation
U.S. oil consumption	C_{HO}	17,491 1,000 bpd	EIA
U.S. oil production	Q_{HO}	5,783 1,000 bpd	EIA
World oil consumption	C_{WO}	78,006 1,000 bpd	EIA
U.S. ethanol production	Q_E	698 1,000 bpd	FAPRI
Gasoline production out of one barrel of crude oil	θ	0.46	θ=19.5/42
Miles per gallon of ethanol relative to gasoline *	λ	0.70	de Gorter and Just (2008b)
U.S. gasoline consumption share	ρ	0.224	$\rho = C_{HO}/C_{WO}$
U.S. gasoline production share	ϕ	0.074	$\phi = Q_{HO}/C_{WO}$
Intercept of the inverse U.S. ethanol supply curve	$\tilde{P}_E$	\$1.77/gallon	calculated following de Gorter and Just (2009d)
U.S. gasoline price	P_G	\$1.76/gallon	NEO
Ratio of the intercept of the ethanol supply curve and gasoline market price under no ethanol production	δ	1.44	$\delta = \left(\tilde{P}_E / 0.7\right) / P_G$
U.S. ethanol blender's tax credit	t_c	\$0.52/gallon	\$0.45/gallon federal + \$0.07/gallon average state
U.S. fuel demand elasticity	η_{DH}	-0.26	Hamilton (2009)
ROW fuel demand elasticity	η_{DF}	-0.40	
U.S. gasoline supply elasticity	η_{SH}	0.20	de Gorter and Just (2009a)
ROW gasoline supply elasticity	η_{SF}	0.20	assumed equal to η_{SH}
U.S. ethanol supply elasticity	η_E	1.00	calculated following de Gorter and Just (2009a)

Note: all data refer to 2009
bpd – barrels per day
* Although a gallon of ethanol has only 0.66 energy content of a gallon of gasoline, miles traveled is 0.70 (see de Gorter and Just 2008b)

Endnotes

[1] The literature uses the term *carbon leakage* to refer to an unintended increase in carbon dioxide (CO_2) and other green house gas emissions due to an environmental policy which is aimed at their reduction. We adopt this term to be consistent with the terminology, but in our paper carbon leakage is a proxy for a more general type of leakage−greenhouse gas emissions leakage.

[2] See Wooders et al. (2009) for a survey.

[3] There are endless studies on iLUC. For just a few surveys, see Fonseca et al. (2010); Al-Riffai, et al. (2010); European Commission (2010); Fabiosa et al. (2009); Plevin et al. (2010); Farrel et al. (2006); Kline et al. (2009); Lapola et al. (2010) and Edwards et al. (2010).

[4] See for example, Alexeeva-Talebi et al. (2008); Fischer and Fox (2009); Bordoff (2009); Brewer (2008); Green and Epps (2008); Pauwelyn (2007) and Winchester et al. (2010).

[5] See Vöhringer et al. (2006); Murray (2008); Muller (2009); Raymond (2010); Schneider (2007); and Schneider and Cames (2009).. The Clean Development Mechanism is also concerned with permanence. The concepts of additionality and leakage are included in the measures developed in this paper while permanence is addressed in the conclusion of this paper when discussing the implications of the emerging literature on the Green Paradox for the leakage measures developed here.

[6] 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. For further developments of this concept, see de Gorter (2010a,b,c,d) and Drabik and de Gorter (2010).

[7] However, with a biofuel mandate it can be the case that the direct emissions reduction can be even more strengthened, leading to higher carbon reductions than originally intended.

[8] In this paper, we use a partial equilibrium framework to analyze carbon leakage. For a discussion of differences between partial equilibrium and genereal equilibrium models for analysis of carbon lekakage see Karp (2010).

[9] 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.

[10] Because a mandate taxes the gasoline market, it is possible that market leakage in the fuel market is negative, possibly replacing more than a gallon of gasoline.

[11] One can implicitly assume that the "emissions reductions in Annex B countries" as referred to in the IPCC definition of leakage are the final reductions after domestic leakage has been accounted for.

[12] Unlike this paper, the IPCC defines carbon leakage as an increase in emissions outside the country divided by a decrease in emissions inside the country (Wooders et al. 2009). This definition therefore ignores domestic carbon leakage (i.e., change in domestic emissions)). In addition, it is not clear whether the change in domestic emissions is subtracted from the intended carbon reduction. Note also that the IPCC definition is not able to capture leakage under autarky, which does exist in theory and we simulate its magnitude. In comparing our leakage magnitudes with those by the IPCC, we assume that domestic leakage has been subtracted from the intended reductions in the IPCC formula. Therefore the formula for market leakage takes the form $L_{IPCC}^{M} = -\Delta C_G^F / \Delta C_G^H$ and that for carbon leakage is $L_{IPCC}^{C} = \Delta C_G^F \big/ \left((2\xi - 1)E - \Delta C_G^H \right)$ where Δ denotes change and G denotes gasoline. The remaining notation is the same as in Appendix 2.

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

[14] Here we assume no "technical leakage", i.e., the emissions intensities of dirty energy source are the same in both countries. For analytical tractability, we also assume that all clean energy (ethanol) saves the same amount of carbon relative dirty energy, e.g., corn-ethanol is assumed to emit the same amount of carbon as that produced from sugar cane.

[15] Indirect land use changes denote additional land that is converted to produce biofuels. In the process, carbon emissions incur not only by biofuels production and their combustion but also by the additional land conversion.

[16] The weight of the carbon dioxide produced by burning a gallon of gasoline is 19.56 pounds, while that produced by burning a gallon of ethanol is 12.57 pounds. The latter figure becomes 17.95 if adjusted for mileage, yielding the emissions savings effect $\xi = 0.08$.

[17] This is the approach taken by the Nobel Laureate IPCC who gives biofuels a value of zero in their accounting balance tables.

[18] A small importer faces no market leakage provided that production technology in the Foreign country exhibits constant returns to scale that render the Foreign gasoline supply curve perfectly elastic. On the other hand, a small exporter sees 100 percent market leakage, of the fuel demand curve in the rest of the world is perfectly elastic.

[19] Fuel price does also respond ambiguously to changes in the quantity of the mandated ethanol, with the result heavily depending on market elasticities and the share of ethanol in total fuel consumption:

$$\frac{dP_F}{dE} = \frac{\frac{1}{C_F}\left(\left(1+\frac{1}{\eta_{SE}}\right)P_E - \left(1-\frac{E}{\eta_{SG}Q_G}\right)P_G\right) - \frac{P_G}{\eta_{SG}Q_G}}{1+\frac{\eta_{DF}E}{C_F P_F}\left(P_E - P_G\right) - \frac{\eta_{DF}P_G}{\eta_{SG}P_F}}$$

where η_{SG}, η_{SE}, and η_{SE} are elasticities of the gasoline and ethanol supply curves, and fuel demand curve, respectively. C_F denotes fuel consumption and Q_G gasoline production. Explanation of other variables is the same as in section 4.

[20] 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.

[21] For an original account of what happens when adding a tax credit to a blend mandate, see de Gorter (2007; 2009a).

[22] If the tax credit is less than the mandate premium (which almost has to be the case in reality when the mandate binds), then the market leakage in the large country case can still be positive but may become negative if the mandate alone generates negative leakage; otherwise leakage is more positive than mandate alone.

[24] 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.

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

[26] 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.

[27] While under autarky market leakage is all domestic by definition, the domestic component of market leakage is often very small as a share of total leakage with international trade.

[28] Two columns are highlighted in Tables 4a, 4b and 5 because the baseline value of the Home fuel demand elasticity (-0.26) lies between the values presented in the tables, namely -0.20 and -0.40.

[29] For arguments not to include iLUC, see de Gorter and Just (2009b). However, there is widespread disagreement with this view so this paper presents both possibilities.

[30] We assume that the ethanol supply curve is differentiable in the neighborhood of $E = 0$ and that its slope is globally strictly positive. Then, from the definition of elasticity, it follows that $\lim_{E \to 0^+} \eta_E = \lim_{E \to 0^+} \frac{dS_E}{dP_E} \frac{\tilde{P}_E}{E} = \infty$, where $\tilde{P}_E$ denotes the intercept of the inverse ethanol supply curve with the vertical axis.