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# On mitigating emissions leakage under biofuel policies

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## Abstract

A reason for much pessimism about the environmental benefits of todays biofuels, essentially corn and sugarcane ethanol, is the so-called indirect land use change (ILUC) emissions associated with expanding biofuel production. While there exist several simulation-based estimates of indirect emissions, the empirical basis underlying key input parameters to such simulations is not beyond doubt while empirical verification of indirect emissions is hard. Regardless, regulators have adopted global warming intensity ratings for biofuels based on those simulations and in some case are holding regulated firms accountable for (some forms of) leakage. Suffice to say that both the estimates of and the approach to regulating leakage are controversial. The objective of this paper is therefore to review a wider economic in order to identify a broader set of policy options for mitigating emissions leakage. We find that controlling leakage by affixing responsibility to regulated firms lacks support in the broader literature, which emphasizes alternative approaches.

*Keywords*: Climate policy, biofuels, emissions, leakage, price effects, indirect emissions, indirect land use change, and indirect fuel market effects

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# Introduction

A basic insight of economics is that within a system of interconnected markets, a shock to one market would ripple throughout the system causing both intended and unintended effects. The latter are also referred to variously as indirect effects, spillovers, or leakage. In a pollution context, leakage is simply an increase in total pollution outside the policy jurisdiction in response to a decrease in total pollution within the jurisdiction. Leakage could be negative in that total emissions outside the jurisdiction could decline as well, but unless stated otherwise, leakage in our context refers to positive leakage. Leakage, therefore, undermines the effectiveness of policy intervention. Greenhouse gases (GHG) being global pollutants, and with global climate change policy expected to remain elusive (Diringer, 2013), it is therefore essential that leakage does not render sub-global efforts counterproductive.

Mitigating leakage presents two main challenges. The first is that quantifying leakage due to a policy, both *ex ante* and *ex post*, is shrouded in uncertainty. It is particularly so for GHGs given the ubiquitous use of fossil fuels, the global nature of commodity markets, and in the case of land uses, the heterogeneous and diffuse nature of emissions. The second is that since leakage emanates from unregulated activities, sources of leakage cannot be directly targeted. At the same time, leakage cannot simply be ignored. In the case of biofuel policies, the policy maker's response to both these issues (discussed in detail later) is controversial. (For differing of views on indirect emissions see RFA 2008, UCS 2008, Economist 2009).

A sense of pessimism towards currently commercial biofuels is palpable in the current academic and policy literature, which is rife with support for the next generation biofuels from ligno-cellulosic sources. These biofuels are predicted to provide

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substantially greater direct benefits and entail small negative spillovers(Schubert, 2006; Rubin, 2008; Campbell et al., 2008; EPA, 2009; Somerville et al., 2010; Mabee et al., 2011). One might therefore conclude that today's biofuels are in decline and with them the concerns about their unintended effects as well. However, this might be an exaggeration. According to US Energy Information Administrations projections for energy use in 2040, cellulosic biofuels account for less than 2% of total biofuel consumption with 98% still derived from current types of feedstock (EIA, 2014). Today's biofuels appear to face greater challenges from recent trends in energy efficiency, infrastructure-related constraints, innovation in shale gas and shale oil, and electric vehicles relative to that from cellulosic biofuels. Regardless, it seems prudent to continue to innovate in the technically proven and commercially mature first generation biofuels while implementing policies to manage their unintended consequences. This provides a context and motivation for this paper.

There has emerged a large literature on leakage under biofuel policies and there have also been a few recent reviews of this literature (Khanna and Crago, 2012; Rajagopal, 2013; Tokgoz and Laborde, 2014). There, however, has not been an attempt to relate either the severity of leakage from biofuels or the policies for controlling it to those in other contexts. This paper is therefore motivated by the idea that a review of the broader economic liter- ature on leakage could suggest alternative potentially less controversial and more effective approaches for controlling leakage. We focus on the following questions: 1) How do indirect emissions from biofuel-based policies compare with emission leakage under other types of policies, both in theory and the size of leakage relative to direct reduction in emissions? 2) How do current policy measures to limit indirect emissions compare with recommendations in the broader literature on leakage? Specifically, we compare leakage from biofuels to the literature on leakage under: i) environmental regulation and international trade, ii) agricultural and land-use policies, iii) energy efficiency, and iv) optimal depletion of exhaustible resources. We summarize the theoretical arguments, the quantitative estimates, and the policy insights from each area above that are applicable to biofuel policies and beyond.

Briefly, the following findings emerge. Rigorous econometric estimates of leakage on a global scale is hard and such estimates are either non-existent or likely highly uncertain at best. Therefore, simulation-based approaches are currently the principal method for quantifying global leakage. Such estimates for biofuel policies, while they suggest a possibility of policy backfire, they are also wide-ranging and uncertain. Despite significant resources having been expended in quantifying leakage from biofuels, uncertainty is not declining. Policies employing a point estimate of leakage estimate are, not surprisingly, controversial. Different from past experience, some current regulations aim to control leakage from biofuels by directly penalizing regulated firm while ignoring some important indirect effects. We therefore explain why controlling leakage in this manner is better avoided and suggest alternative strategies, which merit further exploration.

The next section reviews a diverse literature on leakage, following which we discuss current approaches to control leakage from biofuel expansion. We conclude by discussing alternative leakage control policies that deserve further consideration.

## Quantifying leakage

We focus on GHG leakage, which is, but one unintended consequence of biofuel expansion. Reduction in food supply, greater demand for farm chemicals, and biodiversity effects of agricultural expansion are a few other unintended consequences, which are beyond our scope. We also do not discuss the issue of "problem shifting" from one type of burden to another such as a reduction in GHG emissions that inadvertently causes an increase in water pollution. Following Tinbergen (1952), in principle, each such unintended effect could be addressed by attaching at least one policy instrument targeting each such effect.

## Indirect emissions of biofuel policies

Figure 1 provides a graphical intuition to price effects and leakage using biofuel shocks as an example. Leakage, more commonly indirect emissions in this literature, from biofuels began receiving serious attention following Searchinger et al.'s Searchinger et al. (2008) predictions of land use change impacts of US ethanol mandates. The basic idea is that biofuel expansion increases demand (a shifting out of the demand curve) for cropland. This increases the price of agricultural land causing landowners to cultivate more land (a movement along and up the supply curve) by diverting land from its next best use. This in turn affects the returns to land in those uses and so on the effect ripples through until ultimately forested land is converted. These conversions lead to release of terrestrial carbon, referred to as Indirect Land Use Change (ILUC) emissions. "Indirect" here implies that emissions occur from land that may not directly be under cultivation for biofuel production. There is now a large literature predicting ILUC effects (Melillo et al., 2009; Lapola et al., 2010; Hertel et al., 2010; Tyner et al., 2010; Beach et al., 2012; Laborde and Valin, 2012). Whereas Searchinger et al. (Searchinger et al., 2008) concluded that average ILUC emissions per megajoule (MJ) of corn ethanol was 108 gram $CO_2$eq, Hertel et al. (Hertel et al., 2010) and Tyner et al. (Tyner et al., 2010) predict 27 and 12 gram $CO_2$eq per MJ respectively. According to Searchinger et al.'s just the ILUC emissions are 10% greater the total lifecycle GHG emissions per gasoline. If one includes the supply chain emissions of ethanol production, then it is almost twice the lifecycle GHG emissions intensity of gasoline. Hertel et al. and Tyner et al.'s estimates suggest corn ethanol expansion is much less vulnerable to backfire in the long-run. Expansion of sugarcane ethanol production in Brazil is also predicted to backfire on GHG mitigation efforts Lapola et al. (2010). It should be pointed out ILUC associated with deforestation causes an instantaneous and one-time large increase in emissions. And so the average ILUC emission intensity is a metric derived by amortizing such emissions over an assumed project lifespan of 30 years or more. This the idea of the carbon debt, which means that certain biofuels provide positive net emission reduction only after a certain period, which may be in the order of decades (Fargione et al., 2008). It is a matter of another debate as to how to treat the benefits of emissions reduction which begin to accrue only after a few decades various damage from ILUC emissions are immediate (Melillo et al., 2009; O'Hare et al., 2009).

Following ILUC, studies on leakage in the global market for transportation fuels, an indirect fuel use effect (IFUE) began to appear (Rajagopal et al., 2011; Hochman et al., 2011; de Gorter and Drabik, 2011; Rajagopal, 2013). Similar to ILUC, the IFUE effect arises because biofuel supply reduces the demand for oil depressing its world price. This leads to a partial rebound in the consumption of oil such that there is a less than 1:1 replacement of oil products with biofuel, which is a type of leakage. Rajagopal and Plevin (2013) show how different oil products are affected differently under an ethanol and biodiesel policies. Studies suggest that IFUE effect by itself could lead either to positive or negative leakage. This was followed by studies analyzing the combined effect of ILUC and IFUE (Bento et al., 2013; Chen and Khanna, 2012; Huang et al., 2013; Rajagopal and Plevin, 2013). Another indirect effect termed as the Indirect Food Effect (IFE), which refers to a net reduction in food consumption and hence avoids emissions associated with food production, has been argued to contribute to additional emissions reduction (Zilberman et al., 2013). Aggregate leakage, calculated by adding estimates of individual effects from different partial equilibrium analyses or estimated consistently in a multi-market or computable general equilibrium (CGE) framework could, in theory, be net positive or negative.

The methodologies used for predicting indirect effects of biofuels are principally sim- ulations of market equilibrium, which range from single-market single-region partial equi- librium to global CGE models, and mathematical programming (Khanna and Zilberman, 2012). There is a long history of application of such techniques to analyze trade policies, agricultural and energy market shocks, and climate policies. The weight of evidence from numerical models while it suggests leakage is likely positive in the short to medium term, the predictions are simply too wide-ranging, varying not only with the modeling framework but also across studies using a given computational model. See Dumortier et al. (2011) for a sensitivity of the FAPRI modeling system (Fabiosa et al., 2010) while Hertel et al. (2010) and Tyner et al. (2010) report widely varying point estimates using the GTAP model and database (Golub and Hertel, 2012). Rajagopal and Plevin (2013) do a montecarlo simulation of a simple partial model and report wide ranging predictions of leakage for different plausi- ble assumptions of behavioral and technical parameters, which any simulation model needs to assume. This literature also shows that the choice of policy instrument, the complemen- tary policies that are employed to limit land use change and the role of technical change are each crucial in determining the magnitude of indirect emissions (Bento et al., 2013; Lemoine et al., 2010).

While there exist several simulation-based estimates of indirect emissions due to biofuel expansion, the empirical basis underlying key input parameters used in those simulations is not beyond doubt while empirical verification of indirect emissions is hard. But there is some indirect evidence at hand. By econometrically estimating the elasticity of aggregate land supply with respect to land price for Brazil and the United States, Barr et al. (2011) conclude that current estimates of acreage expansion, and therefore, associated carbon emissions, from biofuels expansion may be biased upward. Data also shows that while the agricultural commodity price boom from 2006 to 2009 increased profitability per planted acre by about 64%, planted crop area increased only about 2% suggesting the landowners are more reluctant to expand crop area relative to the rate of conversion implied in simulation-based studies Swinton et al. (2011). Two recent papers also point out that existing simulation models in relying solely on yield response to higher crop prices have ignored other changes in land use at the intensive margin, such as double cropping, and a reduction in pre-existing farmland that is not under intensive cultivation (Babcock and Iqbal, 2014; Langeveld et al., 2014).

Nevertheless, different biofuels have been assigned a global warming intensity rating by regulators based on available estimates. These estimates are being used for determining compliance with existing regulations. Suffice to say that both the estimates and the approach to regulating indirect emissions are highly controversial (See RFA 2008 and UCS 2008).

# Emissions leakage in the broader literature

We review the literature on the mechanisms of leakage and their implications in four different areas of the economic and policy literature.

## International trade and environmental policy

Leakage here refers to an increase in emissions outside of the region undertaking domestic mitigation. Two distinct channels of leakage have been identified in this context (Elliott and Fullerton, 2014). One mechanism is that environmental policies that raise the domestic price of energy cause domestic producers to cede competitive advantage to producers abroad who then produce and emit more. This is termed as a terms-of-trade effect. When the policy-implementing region is large, then its policies could affect global demand for polluting resources (say, oil), which would lower the world price of those resources, causing an increase in their consumption abroad, a second mechanism of leakage. The second mechanism is believed to dominate the first (Zhang, 2012).

Quantitative estimates of leakage, which are almost entirely based on simulations of CGE models, are predicted to be 5% to 25% although particular economic sectors might be subject to large leakages (Harstad, 2012). An exception is Babiker (2005), which argues that if the structure of models estimating small leakage is extended to include features such as economies of scale, market power, and richer representations of international trade, leakage could exceed 100 percent in the worst case. On the contrary, Fullerton et al. (2011) derive conditions under which partial carbon regulation could lead to negative leakage i.e., reduction in emissions from the unregulated sectors as well and conditions exist to make this plausible in reality. Overall, this literature suggests that unilateral climate policies by industrialized countries will have small carbon leakage effects and unlikely to backfire (Mattoo et al., 2009; Burniaux and Oliveira, 2012). The focus in this literature is largely emissions from industrial activities.

The main policies suggested for mitigating competitive effects are border adjustment policies such as import tariffs and subsidies for home producers (Fischer and Salant, 2012; Zhang, 2012). While such policies may mitigate competitive effects and emissions leakage, they increase the social cost of achieving a given emissions target.

## Slippage effects of agricultural and land use based policies

Leakage is a concern for land-use policies. For instance, the US Conservation Reserve Program (CRP) is a program that compensates landowners for setting aside agricultural lands, which lowers production and raises crop prices. This creates incentives to cultivate on land that is not enrolled in the CRP, which is termed slippage. It is estimated that less than 15 % of intended benefits of the CRP is lost to slippage (Wu, 2000; Roberts and Bucholz, 2006). Similarly, forest protection projects have also been shown to shift deforestation to unprotected areas (Wunder, 2008; Schwarze et al., 2003). However, like with the CRP, an econometric study of slippage under a Mexican forest protection program also reports low levels of leakage Alix-Garcia et al. (2012). Estimating leakage from different forest carbon sequestration activities using a combination of analytic, econometric, and sector-level optimization models, Murray et al. (2004), find leakage ranges from <10% to >90% depending on the activities affected and the project location. Urban and residential zoning has also been shown to increase demand for land in neighboring zones (Pollakowski and Wachter, 1990). Glaeser and Kahn (2010) econometrically predict that a hypothetical regulation that blocks one additional housing unit construction in San Francisco causes that activity to occur in a city whose energy mix is 50% more emission intensive. Overall, this literature implies that leakage effects, while important for various reasons, are not likely cause environmental impacts to worsen.

In terms of policies, this literature calls for superior targeting of locations for conservation in order to minimize both substitution and price effects (Wu et al., 2001). Preemptive enrollment of nearby lands that are prone to slippage is also suggested. A very different proposal is to track and control leakage at a national-level as opposed to at a project level in order to minimize transaction cost, which refers to cost associated with the design, adoption, administration, monitoring and enforcement of a program (Plantinga and Richards, 2008).

## Rebound effects of energy efficiency and conservation

Leakage, described here as “rebound” effects, refers to various mechanisms by which higher energy efficiency lowers the marginal cost of energy-consuming services, and the monetary savings get spent on activities that ultimately require energy (Greening et al., 2000; Sorrell, 2007). The total rebound effect is sometimes further disaggregated into a direct effect, which is an offsetting increase in energy use in the same service undergoing efficiency improvements, and an indirect effect which is an increase in energy use elsewhere. Given the ubiquitous use of energy, leakage from energy efficiency on a large scale manifests at multiple scales, within a single household, across different sectors within a region and across nations. As a result the indirect rebound effect is hard to quantify. Empirical estimates of rebound effect are wide-ranging varying with the application, whether direct or indirect effects are analyzed, short run versus long run, developmental state of an economy, the region of study, etc. Although the estimates of rebound are wide ranging, there are claims that risk of backfire is overstated Gillingham et al. (2013). One application with empirical evidence that the long-run rebound effect is well below 100% is personal transportation (See papers by Small and Van Dender (2007); Hughes et al. (2006)). However, drawing general conclusions about the magnitude of the rebound effect is to be avoided (Van den Bergh, 2011).

A simple response to the rebound effect is to couple it with emission pricing, either through a fee or a cap. That said, a justification for energy efficiency policies is itself the political infeasibility of this approach. Another suggestion is to target efficiency improve- ments in those services whose demand is inelastic, i.e., not price responsive, specifically, price reductions Davis et al. (2014). However, this does not ensure that the savings do not lead to a preference for bigger or more powerful products that are more energy intensive and it also does not preclude indirect rebound effects.

## Dynamics of resource use and inter-temporal leakage

A different type of leakage to the above is inter-temporal leakage, which occurs when the flow of emissions over time is altered by the policy. Cumulative emissions, however, might or might not be affected. Two hypotheses have been put forward here. Jevons (1906) wrote that more efficient utilization of a resource such as coal would create new sources of demand for that resource over time, which ultimately accelerates its depletion. Termed as the Jevons' paradox, it implies 100% leakage in that the resource is nevertheless exhausted and perhaps sooner too. A second hypothesis is that a reduction in demand for polluting resources due to policies such as carbon pricing, could lead to faster extraction those resources if owners of such resources are pessimistic about future demand. This is termed the Green Paradox (Sinn, 2008). This type of leakage is also referred to as "supply-side" leakage, one that is distinct from "demand-side" leakage, which refers to greater consumption of polluting resources in unregulated markets. In other words, even though cumulative emissions are unaffected environmental degradation accelerates under pure demand side policies such as carbon tax or tradable permits that ignore supplier behavior. When supply-side leakage occurs outside the policy jurisdiction, the more effective approach is to procure property rights to vulnerable resources to prevent their exploitation. A type of inter-temporal leakage is also discussed in the land use literature, where it is argued that conservation achieved by paying landowners are contingent on such payments being maintained (Murray et al., 2004). Biofuels are also argued to entail carbon debt on account of initial high emissions from land use change, which they pay back through reduction in fossil carbon emissions over several years or decades (Fargione et al., 2008; O'Hare et al., 2009).

Empirical evidence for inter-temporal leakage is hard to find although there are some simulation-based estimates. While the simplest of models assuming homogenous resource deposits predict 100% leakage under policies such as emission taxes and clean energy man- dates, more realistic assumptions such as rising extraction costs, suggest leakage would be lower (Fischer and Salant, 2012). Leakage is also predicted to decline with increase in strin- gency for demand-side policies.

### Summary of leakage modeling literature

Analyzing and quantifying leakage from energy and environmental policies has a rich history in the economic literature. Emissions leakage is a concern that is not specific to any specific technology or policy instrument but arises because not all the relevant sources of pollution are affected uniformly by a technology or policy shock. The basic starting point for leakage is price effects. On account of limited past experience, our ability to econometrically predict leakage, and to verify estimates derived from numerical approaches, is limited, and biofuel policies are no exception. However, the range of numerical estimates does suggest greater vulnerability to leakage for biofuel policies relative to the other contexts. Furthermore, biofuels are a heterogeneous resource, in that there are multiple types of biofuels and any given type could be produced with varying amount of emissions depending on the agro-climatic, technical, economic and policy parameters affecting their production. The variability in the direct supply chain emissions is higher relative to other technologies.

## Controlling leakage

### Current approaches to controlling GHG leakage from biofuel policies

We discuss only approaches that go beyond a mere statement of intent to control leakage and adopt specific regulatory measures. We describe two such regulations today, both within the US, namely, the US federal Renewable Fuel Standard (RFS) and the California Low Carbon Fuel Standard (LCFS). The RFS requires fuel retailers to ensure that either biofuels sales (or an equivalent amount of purchased biofuel credits) comprise a certain minimum share of their total sales. Under this regulation, only biofuels whose total lifecycle footprint taking into indirect emissions is below an upper-limit are permitted for compliance. For a more detailed discussion of the various categories of biofuels, their target shares and their specific emission thresholds relative to gasoline refer EPA (2009). The RFS relies on a combination of FASOM (Adams et al., 1996) and FAPRI (Fabiosa et al., 2010) computational models to determine the indirect emissions intensity of each type of biofuel. The LCFS requires each regulated fuel supplier to ensure that the sales-weighted lifecycle emissions intensity of all fuels sold be below a common upper-limit. Under this regulation, the lifecycle emission intensity of each batch of fuel is the simple sum of a direct supply chain emission intensity that is specific to a fuel producer and an average global warming intensity rating for the indirect emissions intensity from each type of fuel. The latter is determined by the regulator based on the biofuel pathway used by the firm and is not specific to the regulated firm The LCFS relies on the GTAP modeling framework (Golub and Hertel, 2012) to compute indirect emissions intensity of each biofuel pathway. Neither of these regulations regulates indirect emissions other than ILUC emissions. We categorize the approach of both the RFS and LCFS to indirect emissions a micro or "firm-level" regulation of leakage.

## Arguments against firm-level regulation of leakage

A key argument here is the range of uncertainty in numerical estimates of leakage coupled with a lack of an empirical basis for any single estimate, which is necessary under this approach. If there is reason to believe that empirical evidence could become available *ex post*, then one could true-up emissions and a firm could be held accountable for it's actual level of indirect emissions, forgetting for a moment the ethical and legal implications of this approach discussed later. However, there is little rigorous evidence in the literature to suggest that there exist proven and reliable techniques to predict, ex ante or ex post, the indirect emissions of a policy, let alone at a firm-specific level. We thus also lack the tools to verify whether the firm-level approach was successful in controlling leakage and if so to what extent. Not to mention the cost of monitoring emissions to collect data for empirical investigation.

A second related argument is the inherent instability in any estimate because of dy- namic economic processes underlying the changes we observe. For instance, a historical view of agricultural development in the large economies suggests extensification as a primary mode of expanding production during initial stages of development followed by intensifica- tion during the later stages. For instance, the peak in US agricultural acreage occurred during early 1900s, and was the result of land settlement policies after agricultural inten- sification started to occur. As a result, total agricultural acreage in the US and other industrial countries has continued to decline and is now largely stable (Cochrane, 1993). Sustained high food prices have also spurred innovation whose long-run impact was a sur- feit of supply, which then led to farm subsidies for reducing food production and land re- tirement through programs such as CRP (Gardner, 1992). In response, it has also been out that in the absence of biofuels, these same dynamic processes would have returned land to nature leading to greater carbon sequestration. Resolving this requires predicting how much extra innovation would occur because of biofuels than otherwise and what is its implications for land use, which is itself an area of debate (Keeney and Hertel, 2009; Berry, 2011. http://www.arb.ca.gov/fuels/lcfs/workgroups/ewg/010511-berry-rpt.pdf; Nas- sar et al., 2011)).

A third argument is the harshness and inequity in holding a few firms who exercise little control over leakage accountable for what is a consequence of larger forces at play. The fact that leakage estimates are uncertain accentuates the problem (Eco, 2009; Zilberman et al., 2011). At best one could derive an estimate of the average indirect emissions per unit of a biofuel but a firm-specific value is unrealistic. However any average value that is chosen could force some firms to shut down for no fault of their own because despite adopting best practices compliance could be infeasible for some firms.

A fourth argument is that there is little support in the literature for penalizing individuals firms on the basis of predicted leakage effects. In the international trade literature, the recommended approach is border tariffs and subsidies to domestic firms to reduce competitive effects. The slippage literature calls for superior targeting of land retirements to minimize and preemptively enrolling susceptible land parcels. The energy efficiency literature suggests subsidies target efficiency in services with inelastic demand. Finally, inter-temporal leakage is addressed by choosing the right types of policies and the right stringency of policies.

Last but not least, firms-level approaches do not guarantee that the policy will not backfire. One reason for this is that all forms of leakage may not have been considered in estimating leakage. For instance, Rajagopal and Plevin (2013) show that the LCFS regulation might backfire despite considering ILUC emissions because it ignores IFUE. In any case, as mentioned before, we also lack the tools to verify the actual effect on emissions.

## Looking ahead: Alternative strategies for limiting leakage

We now suggest approaches that obviate the need for a point estimate of leakage. The literature on their applicability to biofuel policies is scarce and therefore, is an area for further research. A targeted and effective solution to leakage is to expand the scope of the regulation to include unregulated emitters. For leakage crossing political boundaries, this requires inter- governmental environmental agreements, on which a rich literature exists and we have little to add here. Instead, we focus on adjustments that the jurisdiction in question could pursue unilaterally. Given a prediction of leakage under a proposed policy instrument, we discuss –

i) altering the stringency of the instrument, ii) adding complementary instruments, and iii) adopting an altogether different instrument. Mixing the first two strategies is of course an option as well.

In choosing from the above approaches we argue that three factors merit consideration i) the level of confidence in the estimates of leakage; ii) the severity of the problem implied by those estimates; and iii) whether the type of pollution in question is the primary objective of the policy. If leakage is estimated to a high level of confidence, and the estimates suggest a substantial risk of backfire, and if emissions reduction is the primary objective of the policy then the policy merits a complete reconsideration. If, however, any one of the above conditions is not true, then elimination of the policy altogether appears extreme.

Biofuel (and renewable energy) policies are multi-objective. For this reason we emphasize approaches that do not *de jure* or *de facto* ban any given technology on account of leakage. Typically, one or more among consumption mandates, subsidies, and performance standards have been employed as policy instruments to support the adoption of new technologies to reduce pollution. We emphasize mandates, which have been the main driver of renewable energy expansion worldwide. Much of the discussion that follows is also applicable to leakage under a broad range of policies.

The size of the mandate has a strong effect on the size of leakage. Their relationship is, however, not necessarily monotonic. Let us take the case of ILUC. A larger biofuel mandate, all else equal, implies bigger increase in land value, which implies larger land use change and emissions. Higher prices, however, also induce innovation that shrinks land use in the long run, a phenomenon with empirical support (see discussion in Section 4.2). With regard to IFUE emissions, bigger mandates would lead to higher domestic prices and lower world oil prices. This means lower domestic fuel consumption (and emissions) and higher consumption (and emissions) abroad respectively. However, under certain conditions the combined effect could be smaller leakage under a bigger mandate (Rajagopal et al., 2011). To determine the optimal size of the mandate given leakage we, however, need to again rely on those same computational models, whose calculations, we argued earlier, depend on uncertain model parameters.

A second modification to a renewable energy mandate is to limit the most risky compli- ance pathways. The firm-level approaches under the RFS and LCFS discussed above are of this type. An alternative would be to simply cap the total quantity or the share of the risky pathways and distribute permits to regulated parties up to the cap. It is worth pointing out that current RFS mandate of 15 billion gallons of first generation ethanol is a floor or and not a cap. The adoption of explicit volumetric targets for second-generation fuels under the RFS II regulations partially remedies this situation. To go further, policymakers could cap each specific type of biofuel as well. A complementary modification would be to ramp up the stringency of the mandate ever more slowly over time in order to mitigate price effects, and therefore, mitigate leakage. Another response is to index mandates to the size of grain inventory to limit adverse price shocks. The benefit of both these approaches is that they simultaneously help address leakage globally.

One suggestion from the slippage literature is to track and control leakage at a regional or national level as opposed to a project level (Plantinga and Richards, 2008). In the case of biofuels, they are but one driver of land use change in addition to demand for food, feed, timber and forestry products and supply side shocks such as weather and energy shocks. Therefore, a more direct approach would be to adopt national targets for land use patterns and pursue international agreements to limit adverse land use change abroad. Since there exist multinational programs such as the United Nations' Reducing emissions from Defor- estation and forest Degradation (REDD), one option is to further strengthen such programs in the face of additional burden from specific policies. Countries adopting biofuel mandates could commit additional funds in lieu of the additional stress they cause to existing inter- national policies and programs. These funds could be used to purchase additional set-aside land to compensate for slippage. Within the US, additional funds could be used to ensure landowners continue to enroll in the Conservation Reserve Program. This is consistent with the supply-side approach to limiting leakage that emerged from studies on the green paradox and inter-temporal leakage (Harstad, 2012).

Finally, with regard to mandates, the combination of facts that biofuel mandates are not a pollution control policy, estimates of leakage are highly uncertain, and that large investments have already been undertaken (despite the sunk cost argument being a non-economic one), the option of altogether eliminating the mandate is likely therefore a politically infeasible option.

The implications for limiting leakage under a performance-based standard such as the LCFS are similar to that we derive for renewable fuel mandates. Performance standards are in theory technology-neutral. But if there is concern that a risky technology might comprise the principal compliance mechanism then, one response is to establish an upper-bound on the quantity or share of the risky technology as opposed to tampering with that technology's performance rating itself, which is the approach under the LCFS. Another strategy is to regulate only direct emissions, but make either the performance standard more stringent or impose an upper-bound on the direct emission intensity of the risky technologies and make the upper-bound more stringent over time. The intuition for this approach is that as the direct benefits a technology increase, a lesser quantity of that technology is required to reach a given standard, reducing its vulnerability to leakage. For leakage attributable to a subsidy policy, lowering it, eliminating it altogether, or indexing it to some measure of a performance, are direct and feasible responses. For instance, the excise tax exemption on domestic ethanol consumption and import tariffs on ethanol were both eliminated by the US federal government in 2012.

To summarize, the alternatives to firm-level regulation do not eliminate the risk of back- fire but such is the case with firm-level approaches as well. Nevertheless, by not requiring precise estimates of a highly uncertain variable the alternative approaches are simpler, and may therefore, engender less controversy and transaction costs. Furthermore, a small amount of leakage might be desirable if it improves socio-economic outcomes. For instance, avail- ability of additional to cropland allows a supply response that mitigates food price inflation.

In trying to limit the supply of the most risky technologies, care should be taken so that it does not result in an effective ban on a technology, whose performance could be improved through innovation. Such innovation can lead to the generation of new technology that could have positive spillover effects for other markets. The impact of alternative leakage control policies on innovation is an important topic for future research.

Significant time and resources have been expended in not just computational modeling but also in debating, lobbying, and litigating around various issues related to precise quantification of leakage for the purpose of regulating leakage at the firm level. In economic terms, current approaches involve high transaction costs. There are several potential alternatives to firm-level regulation of leakage that appear to be simpler, more transparent and impose low transaction costs. Further research on mitigating leakage should therefore focus on analyzing the costs and benefits such alternatives.

### Caption Figure 1

Figure 1: Graphical intuition for leakage due to price effects in the short-run for biofuels. Panels (a) and (b) depict the impact of an ethanol mandate on an input market (land) and an output (gasoline) market, respectively. The x and y axes denote quantity and price respectively. Upward sloping lines represent the supply function of a commodity and those sloping downward represent demand. An ethanol mandate is a positive demand shock to land, which shifts out. The vertical dotted line in the left panel denotes that a fixed quantity of land is demanded for producing crops that will be used to produce a mandated quantity of biofuel (not shown) and this is not a function of the price of land. The thicker downward sloping line is the aggregate demand for land for both biofuel and food. Before the biofuel mandate the equilibrium, which is the intersection of supply (*S*) and demand ($D_F^0$), is ($P_L^0$, $L_T^0$). Post mandate, the new equilibrium is at ($P_L^0$, $L_T^0$). The equilibrium price of cropland increases and total cropland used increases from ($L_T^0$, $L_T^1$). Land allocated to food production declines more than the land allocated to biofuel production such that total expansion $\Delta L_T < \Delta L_B$. This is on account of the downward slope of demand for food. To the gasoline market, biofuel is a negative demand shock. The dotted line on the right panel denotes that demand for gasoline shifts inward, which means a decrease in demand, on account of biofuel supply (not shown). Before biofuel supply the equilibrium in the gasoline market is at ($P_G^0$, $G^0$ ) and post biofuel mandate it is at ($P_G^1$, $G^1$ ). Both the equilibrium price of gasoline and quantity consumed decrease ($\Delta P_G < 0, \Delta G < 0$). However, consumption of gasoline decreases by less than the quantity of increase in biofuel i.e., $\Delta G + \Delta B > 0$. This is the basic mechanics of price effects, whose ultimate effect is that introducing (or eliminating) a fixed quantity of a new (or existing) product via a mandate (or a ban) does not reduce (or increase) an equal quantity of a substitute. Because of the price-responsiveness of supply and demand, the total quantity of the basket of substitutes is not fixed. The pollution associated with the net change is the basis of emissions leakage.

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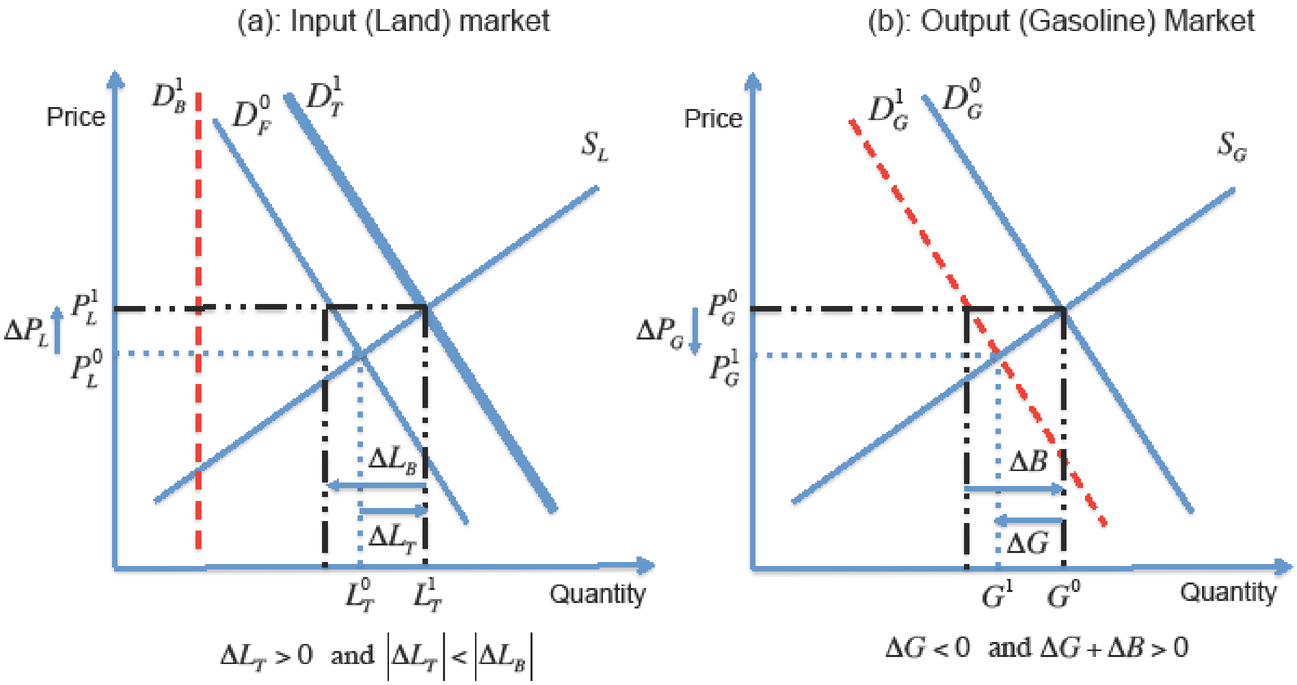
Table 1: Summary of literature predicting magnitude of leakage.

| **Context** | **Leakage terminology** | **Typical sectoral coverage of reported estimates** | **Range of estimates** | **Prediction methodology** | **Policy approaches** |
|---|---|---|---|---|---|
| Biofuels | Indirect or market-mediated emissions | Land, Fuels | Wide ranging and uncertain | Simulation | Regulated firms accountable for indirect emissions[*] |
| Environmental regulation and international trade | Positive and Negative Leakage | Economy-wide but industrial only | 5%-25% , but at least one prediction >100% | Simulation | Import tariffs and subsidies for domestic production |
| Land set aside - Agriculture and Forestry | Slippage/ Spillover | Same sector | Typically low, <10% but at least one prediction > 90% | Simulation and Econometric | Better targeting of land parcels, pre-emptive enrollment of sensitive parcels, adopt national/regional targets for land use as opposed to project level targets |
| Energy Efficiency | Rebound effect | Own sector and in some cases economy-wide | Wide ranging but generally small (in a static context) | Simulation and Econometric | Couple efficiency policy with emission pricing, target improvements in activities that are price inelastic |
| Optimal resource extraction | Leakage, supply-side leakage | Same sector | Potentially 100% | Simulation | Emission pricing, buy out rights to developing resources prone to leakage |

[*] Unlike with other contexts, for biofuels, we report the actual approach adopted by two prominent regulations – the US RFS and California LCFS.



P- price, L - Quantity of Land, G- Quantity of Gasoline, B – Quantity of Biofuel, D – Demand, S – Supply. Superscripts 0 and 1 denote pre and post biofuel mandate respectively. Subscripts F, B and T denote Food, biofuel and total land respectively