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Methodological and Ideological Options

On market-mediated emissions and regulations on life cycle emissions

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ABSTRACT

We analyze the use of life cycle assessment (LCA) as a regulatory tool using biofuel regulations as an illustrative example. A regulatory context calls for a consequential LCA (CLCA) of a policy as opposed to an attributional LCA (ALCA) of a product. In performing CLCA, issues of scale, price effects, technology and policy in the counterfactual state of the world, strategic behavior, policy horizon etc. need consideration. This appears to increase both uncertainty in estimates and the cost of performing LCA. We suggest heuristics for determining vulnerability to harmful indirect effects at an early stage in the policy process and discuss alternative policies to limit harmful indirect effects without engaging in the full effort of computation and selection of a central estimate for uncertain outcomes.

1. Introduction

Economic theory says that the cost-effective approach to addressing global climate change is through a globally consistent greenhouse gas (GHG) policy (Stern et al., 2006). Political consensus for such a policy appears elusive (Bodansky, 2010). Governments worldwide are, however, adopting policies to reduce GHG emissions. In a globalized world, partial measures that target emissions from a subset of polluting activities or regions could prove ineffective or even counterproductive. For instance, reducing automobile GHG emissions by replacing oil with biofuels increases emissions from land use. This provides a rationale for policies that target reduction in emissions associated with the life cycle of a product. The US Renewable FuelStandard (RFS), United Kingdom's Renewable Transport Fuel Obligation (RTFO) and the California Low Carbon Fuel Standard (LCFS) are examples of regulations that seek to reduce the life cycle GHG emission intensity of transportation fuels (Brander et al., 2009; CARB, 2009).

Life cycle assessment (LCA) is a technique for computing the total environmental burden associated with the production, use, and end-of-life of a product or service (Hendrickson et al., 1998; Joshi, 2000; Lave et al., 1995). A life cycle based regulation is implemented by holding one entity in the supply chain, typically the supplier of the final consumer good, accountable for total emissions attributable to the product's life cycle. It is expected that the regulated firm would adjust its inputs in a manner that maximizes its profits while ensuring compliance with the regulation. The suppliers of inputs would, in turn, choose their inputs and their suppliers so as to respond to changing demand under the regulation. This will then induce adjustments by the next higher up entity in the supply chain and so on. A benefit of this approach, when direct and economy-wide policies are infeasible, is that it reduces monitoring and enforcement costs while offering regulated firms the flexibility to choose the least-cost approach to achieve compliance. Although this approach is generally being discussed in the context of renewable fuel mandates and fuel emission intensity standards, it could, in theory, also be implemented under regulations using fees or quotas.

Targeting supply chain emissions may still prove inadequate when the goal is global emission reduction. Biofuels are a case in point. Whereas process-LCA of the supply chain, also known as attributional LCA (ALCA), suggests that biofuels such as corn ethanol and cane ethanol are less GHG intensive than fossil fuels (de Carvalho, 1998; Farrell et al., 2006), economic models predict that biofuel policies will lead to greater GHG emissions for several decades in to the future (Dumortier et al., 2009; Havlik et al., 2011; Hertel et al., 2010; Melillo et al., 2009; Searchinger et al., 2008). An LCA that analyzes the consequences of a decision, say a policy decision to mandate a new technology, is referred to as consequential LCA (CLCA) (Brander et al., 2009; Earles and Halog, 2011; Ekvall and Andrae, 2006).

CLCA differs from ALCA in that it accounts also emissions that are not directly traceable to the supply chain of a product. Such emissions are referred to as market-mediated or "indirect" emissions. The system boundary of CLCA therefore extends beyond the supply chain and may potentially encompass the global economy. Another distinction is that whereas the ISO 14040 and 14044 standards provide guidelines for ALCA, such guidelines do not exist for CLCA. Different

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studies employing different system boundaries, different sources of data, and different modeling approaches seem to provide widely varying estimates of the benefits of a technology. Furthermore, supply chain emissions and indirect emissions present different challenges from a regulatory standpoint, with the latter proving particularly controversial (NFA, 2008; UCS, 2008).[1]

This paper has two main objectives, namely, to outline various economic phenomena that require consideration in a policy-focused CLCA and to discuss alternative strategies for mitigating harmful unintended consequences of life cycle based policies. Although LCA aims to quantify all types of environmental burdens, here, we focus on LCA as a technique for computing a given environmental burden, specifically GHG emissions. This, however, does not restrict the generality of our conclusions which relate broadly to indirect emissions. For illustrative purposes we mainly cite evidence from the biofuel literature although the conceptual insights apply to CLCA in general. The rest of the paper is organized as follows. Section 2 outlines the various considerations relevant to a policy-focused CLCA. Section 3 discusses different modeling techniques for computing indirect effects. Section 4 describes different strategies for addressing indirect effects. Section 5 concludes the paper.

2. From ALCA to CLCA

ALCA is concerned with emissions traceable to processes linked to the supply chain, the use-phase and end-of-life of a product or service at a given point in time, and on average for an industry or for a specific firm. The concern from a policy standpoint is economy-wide and global (for global pollutants) emissions resulting from a policy-induced substitution of one product with the product in question. We summarize below the various issues to consider when comparing future emissions under alternative scenarios, some among which might be partially addressed using ALCA while the others require a more expansive framework. Although some of these are already recognized in the LCA literature (Brander et al., 2009; Earles and Halog, 2011; Ekvall and Andrae, 2006; Weidema, 2011), our discussion reiterates those in a consistent policy context, namely, a biofuel regulation, and highlights others.

1. Change in supply chain emissions over time: These changes may either be exogenous or be induced by the policy under consideration itself and may manifest in several ways.
   (a) Technical change: Historical experience suggests that productivity improves over time due to scale economies; learning by doing (Nemet, 2006); improvements in the quality of inputs (Hillman and Sanden, 2008), etc. Such phenomena may manifest in the form of more efficient energy-conversion technologies (Newell et al., 1999), better quality seeds (Evenson and Gollin, 2003), etc. For instance, corn yield per acre has been growing at an average rate of about 1.7% per year between 1978 and 2008 and is expected to reach 11.1 tons/ha (t/hec) by 2019–20,[2] which is 27% higher relative to the 8.8 t/hec assumed by tefarrell2006ethanol.
   (b) Input substitution and fuel switching: The relationships between inputs and output, which one observes either for a specific firm, or, on average for an industry, are not merely technical. They reflect behavior such as profit maximization or cost minimization. Under reasonable assumptions of limited substitutability in the short term and full substitutability in the long term between various inputs (say, energy and capital) or between different energy inputs, say coal and natural gas, a change in relative prices of different inputs will cause producers to adjust the optimal combination of inputs, affecting supply chain emissions. For instance, the ALCA of corn ethanol is sensitive to the assumption of whether coal or natural gas is used in corn processing.
   ALCA estimates can be derived for any exogenous level of efficiency, fuel shares or any other technical parameter (or for any given distribution of these parameters across firms). However, simulating price-induced change in such parameters, would require a broader framework.
2. Emissions due to joint production: Industrial production often yields multiple products. For instance, corn ethanol is jointly produced with distillers grains (DG) — a substitute to raw corn grain as feed for livestock operations, the distillation of crude oil yields multiple products, including gasoline, diesel, jet fuel, naptha, coke, etc. It is therefore a common practice in ALCA to allocate a fraction of the supply chain emissions to each co-product. For instance, assuming that DG substitutes corn grain in animal feeding operations, and if each kilogram (kg) of corn processed into ethanol yields approximately x kg of DG, ALCA's of corn ethanol have allocated x% of the total ethanol supply chain emissions to DG (Farrell et al., 2006; Liska et al., 2008; Wang, 1999). However, the substitutability of a co-product may change with scale of production, say due to saturation of demand for co-products because of technical or economic reasons. This suggests that apportioning emissions from joint production to each individual product can be a complex task.
3. Impact on input producing sectors: By breaking down the life cycle into a series of sequential phases such as raw material extraction, processing, use phase and end of life, ALCA accounts for emissions across the vertical supply chain. In doing so it ignores the horizontal linkages arising from competition for intermediate goods. For instance, allocation of farmland to biofuel crops reduces supply of food and increases demand for land for food. Thus, expanding biofuel production increases demand for farmland which results in land use conversion towards farming, a phenomenon referred to as indirect land-use change (ILUC), which amplifies GHG footprint of biofuels (Dumortier et al., 2009; Havlik et al., 2011; Hertel et al., 2010; Melillo et al., 2009; Searchinger et al., 2008).
4. Impact on final-output sector: It is often implicitly assumed that a new technology will simply displace an equal amount of its substitutes and that total consumption of this basket of substitutes remains unchanged. However, increasing the supply of a new and cleaner substitute reduces the demand for the dirtier technology whose price declines. In a globalized market, this will lead to a partial rebound, i.e. an increase in consumption of the dirtier technology such that total global consumption increases (Chen and Khanna, 2012; Thompson et al., 2011). Similarly, Ekvall and Andrae (2006) predict that the benefit of eliminating lead use in soldering applications may be partially offset by the accompanying fall in lead prices and therefore increased use of lead in batteries and other products. Rebound effects may even lead to an unintended increase in total emissions.
5. Strategic behavior: Hochman et al. (2011) model the behavior of the Oil Producing and Exporting Countries (OPEC) cartel in response to biofuel mandates and show that a model of the world oil market, which assumes perfect competition, underestimates the reduction in global oil consumption relative to a model which assumes non-competitive behavior by OPEC. The competitive model also therefore underestimates the impact of biofuels on greenhouse gas emissions from the fuel sector.
6. Time path of emissions: Similar to cash flow under an investment, emissions tend to be higher before net emission reduction begins to accrue, and so entail a carbon payback period. Different technologies may exhibit different time path of emissions. Whereas the carbon payback time of solar panels is estimated to be in the

[1] Hearing To Review Low Carbon Fuel Standard Proposals, U.S. Congressional Record, 111th Congress, Serial No. 111-15, May 21 2009, http://www.gpo.gov/fdsys/pkg/CHRG-111hhrg52330/html/CHRG-111hhrg52330.htm

[2] USDA Maize Outlook 2010 http://usda.mannlib.cornell.edu/usda/ers/94005/2010/Table18.xls

order of a year (Palz and Zibetta, 1991), the payback period for biofuels is reported to be in the range of decades (Fargione et al., 2008; Havlik et al., 2011). O'Hare et al. (2009) suggest that simple payback undervalues the environmental cost of land-use change emissions relative to the valuation of benefits from fuel switching.

7. The counterfactual: The predicted impact of a policy depends on the counterfactual level of emissions. The International Energy Agency (IEA, 2008) predicts that more than 75% of the increase in demand for liquid fuel between 2006 and 2030 will be met by liquids from unconventional sources such as oil sands etc., whose life cycle GHG intensity is higher than conventional petroleum. Such a scenario increases the relative benefits of non-fossil fuels. Alternatively, under a future cap on global carbon emissions, the emission benefits of renewable energy would be lower. In the case of biofuels, Searchinger (2010) argues that, by using crops that would grow regardless, biofuels do not lead to any additional carbon removal than would otherwise result. If emissions from combustion of biofuels, which have thus far been completely discounted in ALCA studies of biofuels, are accounted then biofuels are more GHG intensive than gasoline. Searchinger therefore argues the GHG benefits of biofuels, if any, ought to accrue via indirect effects such as reduced crop consumption, biofuel-induced improvements in productivity etc.
8. The policy instrument: The environmental impact of introducing a new technology is a function of the policy in question. Lapan and Moschini (2009) show that renewable energy mandate will yield higher benefits when enforced in conjunction with pollution taxes than without. By extension, mandates implemented without subsidies lead to better environmental outcomes relative to mandates with subsidies. Therefore, policy makers cannot assume the life cycle performance of a technology as given for it is an endogenous variable in the policy selection problem.

These factors highlight differences between ALCA of a product and CLCA of a policy-induced change. Brander and Wylie (2011) argue that, in essence, ALCA is about inventorying actual emissions, while the focus in a policy context is on avoided emissions. We thus need to distinguish between the current footprints as revealed by a comparison of the ALCA of two technologies and the likely future impact of replacing one technology with another on a large scale under different policy regimes.

3. On Approaches for Computing Indirect Effects

There exist several complementary concepts and frameworks to assess the impact of human activities on the environment. A comprehensive survey of all such approaches is beyond the scope of this paper. However, we discuss briefly some relevant frameworks and highlight their similarities and differences relative to LCA.

One type of analysis that predates LCA is energy analysis or embodied energy analysis (EEA), which aims to quantify the direct and indirect consumption of commercially produced energy (and associated emissions) within an economy to produce a given final good or service (Bullard and Herendeen, 1975; Lenzen, 1998). One approach to EEA is to build on national (or regional) economic input–output accounts (Leontief, 1986), which allow simultaneous estimation of direct and indirect value flows associated with a given final household consumption of a product and from which estimates of direct and indirect energy flows associated with that demand are derived. This is also the approach behind Economic Input Output-based LCA (EIOLCA) (Hendrickson et al., 1998). Metrics such as net energy and energy return on energy invested (EROI), are but measures of embodied energy, and which are particularly relevant when the final product is energy. Another type of analysis is emergy analysis, which is an abbreviation for Energy Memory analysis (EMA). Whereas the focus in energy analysis is generally on commercial energy, and exclusively so when relying on input–output accounts, emergy analysis tracks the cumulative solar energy, which is the ultimate source of the energy in fossil fuels, required to deliver commercial goods or services (Brown and Herendeen, 1996). It estimates the total solar energy required to produce a unit of given output.

Whereas the unit of analysis in LCA, EEA, and EMA is typically a product or service, such as kilowatt-hour of electricity or passenger-mile, ecological footprinting is an approach whose unit of analysis is typically a region (Wackernagel and Rees, 1998; Wackernagel et al., 1999). It focuses on estimating the total land area required to meet a region's consumption of various goods such as food, fuel, fiber, timber etc. by harvesting renewable resources. If the area required exceeds the available supply, it implies that the region's activities stress nature beyond its natural regenerative capacity leading to an ecological deficit. ALCA can play a role in ecological footprinting to determine the total resource burden of any given final good if some part of the supply chain, use or end-of-life of that good may occur outside the border of a region. Another approach with a narrower focus but whose unit of analysis also tends to be a large region, such as a nation, is embodied emissions in trade analysis. This aims to provide an estimate of leakage of emissions from importing to exporting regions (Burniaux and Martins, 2012; Muradian et al., 2002; Peters and Hertwich, 2008; Weber and Matthews, 2007). Analysis of energy flows, particularly solar energy, also lies at the heart of different techniques to measure the health of an ecosystem, which can be estimated either directly using metrics such as gross primary productivity, normalized difference vegetation index etc., or indirectly, through measurement of emergy, exergy etc. See Campbell et al. (2004) for a review of energy indicators of ecosystem health.

Using the system of national economic accounts and some additional assumptions specific to each type of analysis, approaches such as EIOLCA, energy analysis, emergy analysis, ecological footprinting or embodied emissions in trade analysis can each be used to estimate both the direct and indirect flows (of energy, materials and emissions). The discussion in Section 2 of the limitations of ALCA suggests that this an important attribute of CLCA. Input–output tables, however, represent the structure of an economy at a given instant time and at a time in the past (for instance, the frequency with which such tables are produced is once every five years in the US). Therefore projecting future emissions using such a table implies assuming a fixed coefficient between inputs and outputs in all economic activities and therefore technical processes. However, as we argued in Section 2, these coefficients change over time, and rapidly so for new technologies, which are also poorly represented in national accounts. Hence this approach may be suitable for small changes and for mature industries. Furthermore it implies that there are no resource constraints and that expanding output in one sector does not affect resource availability for other sectors.

Another top-down modeling approach but one that relaxes the assumption of fixed-proportion in production and consumption, and contains explicit supply constraints, is computable general equilibrium (CGE) modeling (Rose, 1995; West, 1995). CGE models have a long tradition of use in policy settings for ex ante analysis of the impact of government policies on variables such as income distribution, government finances, and employment (Dixon and Parmenter, 1996). A growing application of this approach is to analyze the impact of environmental policies, such as carbon tax and tradable emission quotas on emissions and other variables mentioned above. A strength of such models is that they incorporate more realistic microeconomic assumptions and also macroeconomic feedbacks unlike models based on physical-flows and economic models based on Leontief structure. One approach that is often used is to improve the technical richness of top-down models is to have higher level of disaggregation in one or few sectors of interest and use a fixed-proportion relationship between different technologies in those sectors, while describing the technical possibilities in other sectors at an aggregate level using an elasticity of substitution. See Bohringer and Loschel (2012) for an application of this approach to renewable electricity policies in European Union. A similar approach is used to allocate the total global land use change under biofuel policies predicted by the GTAP model across different types of land in different parts of the world and it is the estimates of GHG emissions using this approach that forms the basis for ILUC rating of different biofuels under the Low Carbon Fuel Standard (CARB, 2012).

If only a limited number of inter-industry interactions are relevant to the product in question, then a simpler alternative to CGE is a multi-market, partial equilibrium model focusing on linkages between a small number of markets, which are strongly linked either on the supply side or the demand side (Sadoulet and De Janvry, 1995). By focusing on a small number of sectors, multimarket models allow for a richer specification of the technology and market structure in the relevant sectors. For instance, the U.S. EPA has adopted the FAPRI/CARD modeling system, which is a partial equilibrium model of global trade in agricultural commodities, and FASOM, which is an optimization model of the U.S. forest and agricultural sectors, for estimating ILUC emissions of different types of biofuels (EPA, 2009).

Estimates of indirect emissions differ with the modeling approach and are also to be sensitive to the parametric assumptions for any given computational model. For biofuels, studies based on the FAPRI/CARD model predict that depending on assumptions about the rate of increase in agricultural productivity, extent of deforestation, etc., the average ILUC emission intensity may range from 31.5 g of carbon dioxide CO_2 per mega joule (gCO_2/MJ) to 124 g CO_2/MJ (Dumortier et al., 2009). Studies using the GTAP CGE model predict values in the range of 13.9 to 30 g CO_2/MJ (Hertel et al., 2010; Tyner et al., 2010). Using a reduced form approach and considering various probability distributions for different factors that influence ILUC, Plevin et al. (2010) predict the 95% confidence interval for ILUC emissions as 21 to 142 g CO_2/MJ.

Rajagopal et al. (2011) describe one theoretical difference between partial and general equilibrium frameworks. Consider the case of a clean energy subsidy. Whereas the subsidy benefits consumers, it increases government expenditure. Therefore, in general equilibrium analysis, if one imposes the constraint of a balanced government budget while holding government provision of public goods and services fixed, then the subsidy will have to be accompanied by an (endogenous) increase in taxation on one or more other sectors, which will reduce consumption in those sectors. Alternatively, if the tax rate is fixed, the subsidy reduces government provision of other goods and services, which, albeit lowering emissions, will also have adverse distributional impacts. Partial equilibrium analyses overlook such economy-wide effects.

Summarizing several papers that attempt to combine the microeconomic realism and macro-economic completeness of top-down models with the technological richness of bottom-up models, Hourcade et al. (2006) conclude that developing a single hybrid model with each of these strengths presents the "greatest challenge in terms of theoretical consistency, mathematical complexity and empirical estimation" and that "it nonetheless represents an objective that some modelers might aspire to, and has been colloquially referred to as the Holy Grail." For a more detailed discussion of the various modeling efforts in this regard, which is beyond the scope of this paper, we refer to a special issue of The Energy Journal titled "Hybrid Modeling: New Answers to Old Challenges".

Another criticism of neoclassical techniques such as CGE is the use of the neoclassical production function that assumes smooth substitution between inputs, say, between capital and labor or between capital and energy. The reality is often more complex. One formalization of this idea is the putty-clay approach, which distinguishes between ex-ante and ex-post production functions (Johansen, 1972). According to this approach, switching from one technology to another requires costly capital investment. Therefore producers have limited flexibility to adjust to change in the relative price of an input, such as one type of energy. In the short run a given firm operates with a fixed coefficient production function just as assumed in LCA. When the price of variable inputs rises such that variable cost is not recoverable from revenues, firms will stop using certain capital goods. It may also lead to investment in new capital goods with higher input-use efficiency of the costlier input. So, for example, when the price of coal increases relative to the price of natural gas (say, due to market conditions or due to environmental regulations), some power producers will stop using coal and invest in gas-based generation. But, this process will be gradual because of heterogeneity among power producers in terms of the technological coefficients.

The gradual replacement of capital goods and changes in coefficients can be addressed in two ways. In many cases, empirical estimates of production functions actually provide elasticities of substitution between energy and capital that reflect behavioral considerations and heterogeneity among producers, as argued by Johansen (1972) as well as Fuss (1977). So, instead of simple analysis based on average behavior at a given point in time, estimating coefficients of a production function that is based on actual data may lead to more realistic assumption about substitution between technologies as relative cost of energy changes. Another option is to develop probabilistic models of technology adoption recognizing that changes in prices of inputs are likely to lead to adoption of technology that economizes use of the more expensive input. These models can be used to estimate the relative market share of two goods that are substitutes as functions of relative cost, and other attributes can be used to estimate changes in shares in response to changes in cost. Whereas the literature on adoption within the context of environmental policy (Jaffe et al., 2003), agriculture (Sunding and Zilberman, 2001), and automobiles (Brownstone et al., 2000), provides estimates of the likelihood of transition among technologies, a larger empirical base is required to fully incorporate adoption probabilities within LCA studies, especially in cases of new product categories.

Although the linking of engineering-accounting-based ALCA with behavioral-economic models makes CLCA more relevant in a policy context, this approach introduces additional weaknesses. Reliable estimates of parameters that tend to be key inputs to economic models such as the elasticities of substitution or elasticities of supply and demand etc. tend to be lacking. Unlike with technical parameters such as the heating value of a fuel or its carbon content, behavioral parameters such as price elasticities tend to vary from one region to another, vary depending on whether they represent short-run or long-run behavior, and also depend on other assumptions imposed during econometric estimation. Relying on different estimates in the literature, different modelers tend to assume different values for such parameters. For a global model involving several economic sectors and multiple regions, the number of such parameters can range in the tensor even hundreds. Furthermore, different studies that use the same computational model, say FAPRI/CARD, but employ different assumptions, say relating to the counterfactual technology or policy, tend to yield different estimates of emissions (see Dumortier et al., 2009).

In summary, the need to model market-mediated effects renders a policy-focused CLCA methodologically complex relative to ALCA. Although the system boundary and modeling framework suitable for CLCA is likely to be product- and policy-specific, an area for future research is to explore the possibility of developing general guidelines for CLCA.

4. On Approaches for Controlling Indirect Effects

With a cap on global GHG emissions, indirect GHG emissions of biofuel policies such as ILUC would not lead to an increase in global GHG emissions and can therefore be excluded from CLCA. Such a situation might however altogether obviate LCA. Otherwise, indirect emissions are policy relevant. We discuss some challenges to regulating indirect emissions and discuss different strategies for reducing the unintended consequences, which merit further research.

4.1. Policy Strategies for Indirect Emissions

Ideally, a policy would be chosen after a thorough assessment of risks and benefits. However, such efforts notwithstanding, new information about unintended negative consequences may become available subsequent to policy implementation. For instance, the literature on land use impacts of biofuels emerged subsequent to the adoption of biofuel mandates and subsidies. The regulatory approach to indirect emissions under both the RFS, which specifies volumetric targets for different types of ethanol, and the LCFS, which mandates reduction in the average GHG intensity of transportation fuels, is to include indirect emissions as part of the GHG rating of biofuel. For instance, corn ethanol is assigned a rating of 27 g CO_2/MJ for ILUC emissions under the LCFS (CARB, 2012). This approach is controversial given the uncertainty associated with quantifying indirect emissions and since penalizing firms for emissions, which they, at best, only partially influence, is viewed by some as unjustified (Zilberman et al., 2011).

From a product regulation standpoint, supply chain emissions and emissions due to indirect effects differ in some important ways. Emissions from the supply chain, which are the focus of ALCA, are attributable to a firm and can be assigned a firm-specific value. Firms have control over their own emissions and exercise some control over emissions in their supply chain. For instance, they could adopt a more efficient technology or switch from dirty to cleaner inputs. Indirect emissions, however, arise from the interaction of total supply and demand in a large number of inter-connected markets. They are not attributable solely to a few regulated firms, which may account for a small portion of the broader economic and policy landscape that gives rise to indirect effects. A basic principle of sound policy making would suggest that individuals should be held accountable for their own actions rather than outcomes due to indirect effects. Therefore, regulating indirect emissions by assigning an average emission intensity to each unit of biofuel consumed under the regulation, appears to contradict this principle. At the same time, estimating indirect effects specific to each firm will increase the complexity of the regulation several fold.

Furthermore, current approaches to regulating indirect emissions may not guarantee that biofuels reduce global emissions (Rajagopal and Plevin, 2013). It should also be pointed out that biofuel regulations currently only account for indirect emissions associated with global land use change, and ignore others, such as indirect emissions due to changes in global fuel consumption, changes in global food consumption, etc. Consideration of such effects will require computational approaches that are more complex and opaque, and increase the information burden on regulators. We therefore argue that explicit regulation of indirect effects as proposed under LCFS be avoided in favor alternatives that while they may also not guarantee emission decline, are simpler, transparent and less onerous.

One alternative is to lower the policy target or slow the rate of targeted growth under the policy until better information becomes available. Policy makers could limit the use of a technology that is perceived to be risky by imposing a cap, and distribute permits equivalent in volume to the cap. Another strategy is to the make the regulatory standard for supply chain emission intensity stringent enough so that there is an adequate margin for safety in ALCA emissions. For instance, the upper bound for GHG emission intensity of corn ethanol under the RFS is currently fixed at 20% below gasoline over the entire the policy horizon. This could be reduced further and required to continually decline with time. When there is heterogeneity, encouraging the adoption of technologies with greater direct benefits, reduces the quantity required of the new technology to achieve a given level of emission reduction, and this may reduce the magnitude of indirect effects relative to direct benefits. In this regard the LCFS approach of not assigning single value for corn ethanol, which is the approach under RFS seems superior. In the case of biofuels, flexible mandates that adjust to the level of grain inventory or food prices have also been proposed.[3]

To mitigate harmful land use change, incentive-based policies similar to the Conservation Reserve Program (CRP), which pays landowners to retire farmland, may be designed. Economists have estimated added pollution due to 'slippage', defined as the rebound in land use as a consequence of the CRP, in the environmental benefits of land set-aside policies. Wu et al. (2001) derive conditions under which market response to the Conservation Reserve Program (CRP), may lead to worse environmental outcomes, akin to impacts due to ILUC under biofuel policies, and suggest how the CRP may be designed to reduce the risk of such outcomes. DeCicco (2011) suggests the establishment of Land Protection Fund to finance the purchase of carbon offsets to negate ILUC while continuing to hold biofuel producers accountable for their own emissions only. Khanna et al. (2011) argue that managing land use through zoning regulations, payments for environmental services, and market-based pressures is a viable option for reducing indirect effects. With regard to global land use change, a large region, such as the US or EU or both combined, could pursue bilateral or multilateral agreements with countries such as Brazil and Indonesia to prevent harmful land use change.

With respect to fuel market effects, which unlike ILUC remain outside the purview of current regulations, eliminating subsidies for renewable energy will help reduce the vulnerability of renewable energy mandates. Trade restrictions such as the tariff on imports of sugarcane ethanol, which is considered a more cost-effective alternative to corn ethanol, too have implications for global indirect effects of biofuel mandates (de Gorter and Just, 2010). The adoption of pollution taxes will naturally further reduce risk of mandates proving counterproductive. The presence of mandates, subsidies and tariffs and the absence of pollution taxes reflect political-economic constraints. Identifying the combination of policies that satisfy such constraints without compromising environmental objectives is the policy challenge.

Another issue in both estimating indirect effects and designing policies to address them is the influence of the broader policy landscape within which an LCA based policy is being analyzed. A glance at the policy landscape indicates that renewable energy and environmental policies are simultaneously undertaken at multiple levels of government within a country and by different countries worldwide. For instance, within the US, in addition to the national RFS adopted by the federal government, state level targets for biofuels have been adopted in many states and biofuels blended to comply with state level regulations such as LCFS simultaneously also aid in complying with national target for biofuels under the RFS. The national RFS, since it is the most stringent among all biofuel regulations within the US, is the principal driver of biofuel expansion as opposed any state level policy. To cite another example, in 2007, the province of Alberta in Canada adopted a combination of GHG performance standard and carbon tax for large emitters of CO_2 emissions.[4] One compliance strategy for regulated emitters under this regulation is to purchase offset credits from other sectors that have voluntarily reduced their emissions in Alberta. Such a regulation internalizes partially the GHG externality associated with production of crude oil from oil sands, which is on average more GHG intensive than extraction of conventional crude oil (Charpentier et al., 2009). This raises the question of what is the appropriate life cycle GHG intensity of oilsands under a regulation such as the California LCFS.

Unilateral policies are often undertaken with the aim of demonstrating leadership and/or induce technical change that may deliver environmental benefits in the longer term. They may however also lead to duplication of effort by multiple regulatory agencies and dissipation of scarce public resources for research. The criteria under which it is rational for regional regulations to unilaterally target the indirect effects caused by broader policy and economic drivers and how best to address them is an area for future research.

[3] http://www.govtrack.us/congress/bills/112/hr3097

[4] http://environment.alberta.ca/01838.html

We do not suggest that it is always impractical to address indirect emissions as proposed under the LCFS or RFS, but suggest that alternative policy formulations to address indirect effects also merit consideration. As described earlier, indirect emissions depend on the policy context and therefore depend on the situation with respect to subsidies, trade policies, international agreements on land use, mandates and regulations in other regions etc. Hence, in addition to analyzing sensitivity of indirect effects to different assumptions about the uncertain parameters of the model, policy makers should also evaluate different combinations of complimentary policies that may be pursued to mitigate the potential for unintended consequences.

An alternative to regulating consumer products such as gasoline or electricity based on embodied or life cycle emissions is to regulate the production of primary fossil fuels, such as coal, oil and gas, that are the source of downstream emissions, based on their concentration of carbon or other pollutants. A benefit of this is approach, in addition to being more cost-effective (as it effectively taxes emissions in all sectors consuming these regulated fuels as opposed to just one or few products), is lower cost of monitoring and enforcement, which would be required only for a smaller number of locations relative to that for downstream regulation. Bushnell and Mansur (2011) explore the relationship between the point of regulation and emissions leakage, and argue that, under certain conditions, upstream regulation of fuels, say at the point of production, based on emissions during their consumption will reduce emissions in unregulated regions and this is preferable to direct regulation of the emissions during consumption of the product. We identify two challenges to this plausible alternative that merit further research. One is that the relationship between the carbon content of a fuel and the carbon emissions from combustion of the fuel depends on several factors, such as the type of conversion process, the vintage of capital, scale economies, time of day and year when combustion occurs, etc., which make the selection of a single emission factor for each fuel challenging. Another relates to political feasibility of such an approach, given that the effect of such indirect taxes on fuels is likely to be similar to an economy-wide carbon tax or tradable emission permits.

4.2. Assessing Vulnerability to Counterproductive Outcomes

The prudent strategy is to avoid or modify counter-productive policy formulations so as to minimize such a risk. We suggest heuristic criteria for identifying at an early stage in the policy process vulnerabilities to unintended consequences, which, in our case, refer to an increase in GHG emissions. We illustrate these criteria in the context of an ethanol mandate and all comparisons of ethanol are with respect to gasoline unless otherwise noted.

1. Difference in ALCA estimates: The smaller the ALCA-based benefits of a new technology relative to an existing technology, the greater the vulnerability of a policy mandating the new technology. ALCA suggests that average GHG intensity of corn ethanol is 20% lower relative to gasoline (Farrell et al., 2006), while that for cane ethanol is more than 50% lower (Macedo et al., 2008). This suggests that a policy that encourages cane ethanol is potentially less vulnerable relative to a policy that encourages corn ethanol. We say potentially because the vulnerability to indirect effects might be higher for the former.
2. Sensitivity to coproduct credits: The more sensitive the ALCA-based GHG intensity to allocation of emissions across the different co-products, the more vulnerable the policy to indirect effects. For instance, Farrell et al. (2006)'s finding of a 20% lower GHG intensity of corn ethanol was under the assumption that coproducts account for 33% of the supply chain emissions. This highlights the need for developing a better understanding of the impact on co-product markets.
3. The magnitude of shock to input and output sectors: The input producing sectors experience a positive demand shock, while the final-output sector experiences a positive supply shock under a new technology mandate. The bigger the policy shock, the bigger the shock to the input and output sectors and therefore there will be a larger response in these markets. For instance, the US RFS target of 56.7 gigaliters (GL) or 15 billion gallons of corn ethanol by 2015 would account for 54% of the corn produced in the year 2000 and account for 8% (in energy equivalent terms) of the U.S. gasoline consumption in 2000. Furthermore, corn accounts for about 65% of nitrogen applied to crops in the U.S.[5] while fertilizers account for 20% of the ALCA emission intensity of corn ethanol. Going further up the corn supply chain, area under corn crop accounts for about 25% of the area under agriculture in the U.S.[6] These figures highlight the potential for significant shock to corn, fertilizer, land, and oil markets, among others.
4. The price elasticity of demand and supply in the affected markets: In the input producing sectors, the more inelastic the demand in competing markets, the greater will be the increase in total quantity supplied of the input ceteris paribus. For instance, a corn ethanol mandate will lead to higher global consumption of corn when corn demand for food consumption is more inelastic relative to when it is less inelastic. The increase in agricultural land use will in turn be higher when food demand is inelastic compared to when it is less inelastic, which indicates a higher vulnerability to harmful indirect effects.
   In the final-output sector, more inelastic the supply of substitutes, greater will be the rebound effect on consumption ceteris paribus. An ethanol mandate reduces the demand for gasoline, which reduces the derived demand for oil and lower oil price. More inelastic the supply of oil, smaller will be the reduction in the quantity of oil supplied.
5. The emission intensity of marginal supply in the affected markets: The impact on emissions depends on both the magnitude of supply response, which depends on the magnitude of the shock and the price elasticity, and the emission intensity of the marginal supply. The higher the emission intensity of marginal supply in the input producing sectors, the larger the increase in emissions under a positive demand shock. Therefore, for instance, ILUC emissions of ethanol are higher when the marginal land is forest land as opposed to idle farm land. On the other hand, the higher the emission intensity of marginal supplies of substitutes in the final-output sector, the larger the reduction in emissions, since total quantity of substitutes supplied declines. Therefore, for instance, fuel use market emissions are lower when the marginal oil source is oilsands as opposed to conventional crude oil.

A simple calculation seems to suggest that the GHG benefits of corn ethanol policies are vulnerable on account of indirect effects in fuel markets. If ALCA suggests that corn ethanol is only 20% less GHG intensive than gasoline, then a 20% rebound in global fuel energy use, which may accompany the reduction in world oil price due to the increased supply corn ethanol, is sufficient to negate the GHG benefits of corn ethanol.

Another calculation, which illustrates the vulnerability of corn ethanol to land use change is depicted in Table 1. Using hypothetical but representative values we calculate a GHG payback period, which is the time after which corn ethanol leads to a net reduction in GHG emissions, for corn ethanol as 14 years. Indeed, precise computation of ILUC emissions is a complex exercise requiring sophisticated models of economic and biophysical phenomena. Our estimate is within the range predicted by such models (Dumortier et al., 2009; Hertel et al., 2010; Melillo et al., 2009; Searchinger et al., 2008).

[5] www.ers.usda.gov/media/117596/err127.pdf
[6] http://www.epa.gov/oecaagct/ag101/cropmajor.html

Table 1
Calculation to illustrate vulnerability of GHG benefits of corn ethanol to land use change.

Annual corn ethanol production (in gigaliters)	a	57[a]
Conversion efficiency of corn to ethanol (in liters per ton of corn)	b	402[b]
Annual corn requirement for ethanol (in billion tons per year)	c = a / b	0.14
Fraction of corn used for ethanol that is produced by expanding corn acreage	d	0.20[c]
Average productivity of corn in the newly expanded land (in tons/ha)	e	10[d]
Increase in corn acreage (in million hectares)	f = c ∗ d / e ∗ 1000	3.5
GHG emissions due to pasture land conversion to corn farming (in tons CO_2e/ha)	g	110[e]
Total GHG emissions from land conversion (in million tons of CO_2e)	h = f ∗ g	309
Difference in ALCA emission intensity of gasoline and corn ethanol (in gCO_2e/MJ)	i	18[f]
Quantity of ethanol to be consumed to offset land use change emissions in (MJ of ethanol)	j = h / i ∗ 1e12	1.72E + 13
Energy density of ethanol in MJ/l	k	21
Quantity of ethanol to be consumed to offset land use change emissions (in gigaliters)	l = j / k / 1e9	818
Number of years of ethanol consumption to offset land use change emissions[g]	m = l / a	14

[a] U.S. renewable fuel standard target of 15 billion gal of ethanol for the year 2015.
[b] 2.7 gal of ethanol per bushel of corn.
[c] This is an assumption, which states that increased demand for corn for ethanol is only partially, in our case 20%, met by expanding corn acreage. The remaining is met by improvements in productivity.
[d] We use the U.S. average corn yield of 160 bushels/acre in 2010 (Source: U.S. Department of Agriculture Maize Outlook 2010 http://usda.mannlib.cornell.edu/usda/ers/94005/2010/Table18.xls).
[e] Average GHG emissions for pasture land conversion to crop land as reported in the GTAP database.
[f] Difference in ALCA GHG emission intensity between corn ethanol and gasoline as calculated by Farrell et al. (2006).
[g] This is an estimate of the GHG payback period of corn ethanol mandate.

An assessment along the above lines may help identify vulnerable aspects of a policy at an early stage in the policy process so that the policy formulation could be modified to reduce such vulnerabilities. For instance, our examples illustrate the vulnerability to indirect effects in land and fuel markets. Avoiding risky policies might eliminate the need for complex approaches to explicitly account for indirect effects as is the case today with certain biofuel regulations.

5. Conclusion

While there is a rich history of LCA, its application in a policy context, for instance, to compute the future long term impacts of a policy such as a renewable fuel mandate or to determine compliance of a firm with a regulation, is in its infancy. Predicting the impact of a policy on emissions requires expanding the engineering–accounting approach of ALCA to accommodate behavioral-economic considerations such as issues of scale, price effects, strategic behavior, the counterfactual state of technologies and policies, time horizon of analysis etc. While there exist different alternative approaches, they require more data and more complex computational approaches. In the case of biofuels, consideration of indirect emissions suggests the impact of biofuels on global GHG emissions is uncertain.

The task of designing effective LCA-based regulations appears complex when there are potential significant unintended negative consequences. A conclusion we derive is that LCA-based policies might be suited to situations in which the potential benefits suggested by ALCA are large enough to exceed indirect emissions. In such cases the full effort of computing indirect effects and enacting additional regulations to limit indirect emissions can be avoided. To this end, heuristics to ascertain the vulnerability of a proposed regulation to large negative indirect effects might be employed so that potentially harmful policies may be corrected at an early stage in the policy process or avoided altogether. We have identified several potential criteria that could serve as heuristics. Of course, heuristic procedures will sometimes fail.

We have also identified alternatives to the current approach under RFS and LCFS to control harmful indirect effects without engaging in the full effort of computation and selection of a central estimate for uncertain outcomes. Another conclusion we derive is that in estimating the indirect effects of a policy and considering policies to control such effects, one cannot ignore the interaction of the policy in question with the broader policy landscape. The marginal indirect effect of a policy may be small given larger national or international policy drivers. This has implications for smaller jurisdictions seeking to control indirect effects. Finally, given the knowledge gaps in the design of local policies to address global environmental problems, the importance of achieving a binding and unified global commitment for preserving global public goods, such as climate and biodiversity, cannot be overstated.

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