The fuel market effects of biofuel policies and implications for regulations based on lifecycle emissions

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Abstract
The absence of a globally-consistent and binding commitment to reducing greenhouse emissions provides a rationale for partial policies, such as renewable energy mandates, product emission standards, etc to target lifecycle emissions of the regulated products or services. While appealing in principle, regulation of lifecycle emissions presents several practical challenges. Using biofuels as an illustrative example, we highlight some outstanding issues in the design and implementation of life cycle-based policies and discuss potential remedies. We review the literature on emissions due to price effects in fuel markets, which are akin to emissions due to indirect land use change, but are, unlike the latter, ignored under all current life cycle emissions-based regulations. We distinguish the current approaches to regulating indirect emissions into hard and soft approaches and discuss their implications.

Keywords: indirect emissions, lifecycle, fuels, regulation

1. Introduction
The absence of a globally-consistent and binding commitment to addressing global externalities, such as greenhouse emissions, provides a rationale for partial policies, such as renewable energy mandates, product emission standards, etc to target lifecycle emissions of the regulated products or services. Under lifecycle based regulations a single entity in the supply chain is responsible for emissions throughout the lifecycle of the product. For instance, under the US Renewable Fuel Standard II (RFS2) regulations, suppliers of corn ethanol are required to ensure that lifecycle GHG emission intensity of their product is 80% or lower relative to a given lifecycle GHG intensity of gasoline (EPA 2009). In the case of the California’s Low Carbon Fuel Standard (LCFS) fuel suppliers are required to reduce the average lifecycle GHG intensity of their products by a specified amount (ARB 2011). While simple in principle, regulating lifecycle emissions presents several practical challenges. Using biofuels as an illustrative example, we highlight some outstanding issues in the design and implementation of lifecycle-based policies and discuss potential remedies.

A basic question arises as to what is meant by lifecycle emissions or what is the relevant system boundary for calculating lifecycle emissions? To address this, we begin with a breakdown of lifecycle emissions based on where they may occur relative to the point of regulation. We can classify emissions into two broad categories as follows. For illustrative purposes, let us consider the point of regulation in the lifecycle is the fuel producer such as an oil refiner or a biorefiner.

• Direct emissions. This refers to emissions directly occurring in the supply chain or during final use of a given product. This can disaggregated further into three sources of emissions, namely,
  * On site emissions. This refers to emissions at the point of regulation. In our case, this refers to emissions at the...
oil refinery or a biorefinery due to combustion of fuels for process heat, captive power generation, etc.

- Upstream emissions. This refers to emissions from activities that take place upstream of the point of regulation, and which are directly attributable to the intermediate inputs to the final product. In the case of biofuels, this would include emissions from application of fertilizers in a farm, emissions during production of fertilizers etc.

- Downstream emissions. Emissions downstream of the point of regulation, and which are directly attributable to the consumption of the product of the regulated entity. For instance, if the point of regulation were the refinery gate, this would include emissions during transportation and distribution or during final consumption for passenger or commercial transport.

- Indirect emissions. This refers to the change in emissions in any of the unregulated markets that are affected by a change in the aggregate output from the regulated sector. In the case of biofuels, one manifestation of indirect emissions is the emissions associated with the expansion of agriculture, which occurs as a consequence of an increase in aggregate demand for agricultural commodities. This is the so-called ‘indirect land use change’ (ILUC) emissions due to biofuel expansion. Indirect emissions are unintended consequences. They arise from the inter-linkages between the different sectors within a region and the inter-connectedness of markets in different regions, which is increasing due to globalization.

The early literature on GHG impact of biofuels relied on attributional LCA of the biofuel production chain. This literature suggested that biofuels have a lower GHG footprint relative to fossil fuel substitutes (Macedo 1998, Sheehan et al 1998, Farrell et al 2006, Liska et al 2009). Using an economic simulation model to predict the impact of US biofuel policies for global land use, Searchinger et al (2008) predict that emissions from land use change may lead to a net increase in GHG emissions for several decades in the future before net emission reduction due to avoided gasoline consumption would accrue. The studies by Hertel et al (2010) and Tyner et al (2010) using the GTAP computable general equilibrium model and database also predict that ILUC emissions are positive but their estimates are approximately 1/4th and 1/10th of the estimates of Searchinger et al (2008) respectively. More recent studies suggest that LUC emissions for biofuel produced from perennial, low-input energy crops grown on marginal lands would be smaller or even negative and result in net soil carbon sequestration (Cai et al 2010, Dunn et al 2013, Gelfang et al 2013, Kim and Dale 2011, Tyner 2012, Scown et al 2012).

The notion of ILUC highlights a risk that a lifecycle approach that focuses only on direct lifecycle emissions and ignores indirect emissions might prove counterproductive to the policy goal of reducing emissions. Awareness about ILUC has led policy makers to modify policy formulations to account for ILUC emissions. However, although indirect effects can occur in multiple sectors, existing regulations tend to focus exclusively on ILUC.

In this letter, we review more recent literature that is concerned with an effect analogous to ILUC, and which affects the global market for liquid transportation fuels. We will refer to this indirect effect as the indirect fuel use effect (IFUE). It should be noted that different studies refer to this effect using different but equivalent definitions. We then discuss some practical challenges in both estimating indirect emissions and regulating indirect emissions.

2. The microeconomics of IFUE

A fundamental motivation to study IFUE is the fact that oil is a global commodity and that there exists substantial trade also in oil products such as gasoline and diesel. Therefore, a shock to oil demand in one-region, especially one that is large, such as the US or European Union (EU) will be transmitted to world market for oil, affecting prices and consumption both in the policy region and beyond. As a consequence, a unit increase in biofuel in the policy region may not lead to a unit reduction in global oil consumption.

Ethanol policies reduce demand for gasoline, while biodiesel policies reduce the demand for diesel. In the longer-run biofuels are considered a potential substitute to jet fuels and kerosene. These products comprise 75% by volume of all refined produced in the USA; for the EU the equivalent metric is 65% (Venkatesh et al 2011) and can be assumed to drive the demand for oil. A reduction in demand for these products, will therefore lead to reduction in demand for oil and to a fall in oil price. The fall in oil price will in turn trigger a partial rebound in oil consumption. The rebound effect mitigates net fossil fuel displacement. Biofuel policies may therefore lead to less than 1:1 replacement of fossil energy with renewable energy on a global scale, which has implications for net GHG impact.

The impact of higher supply of biofuel on consumption of different oil products is product-specific. An increase in the supply of ethanol lowers the demand for gasoline. Gasoline price therefore declines. The price of ethanol-blended gasoline may either increase or decrease (Rajagopal and Plevin 2013). However, under an ethanol policy, the demand for non-gasoline oil products is unaffected but oil supply decreases, resulting in less supply of such products, which leads to their higher price and lower consumption. An increase in biodiesel supply will have an analogous effect in the diesel market, lowering diesel price while increasing the price of non-diesel oil products. The net impact of these changes in consumption of different products in the different regions on global energy use is a function of parameters such as the elasticity of supply and demand etc.

2.1. Alternative measures of IFUE

Although one could compute IFUE specific to each type of oil product, since our concern is with aggregate energy use
and GHG emissions, we discuss IFUE as the change in total energy embodied in the two primary products, namely oil and biofuel. There exist two different but equivalent metrics that are reported in the literature, which can be used to communicate IFUE.

One approach is to compute the rebound effect, \( R \), one definition of which is,

\[
R = \left( \frac{\Delta E_{\text{oil}} + \Delta E_{\text{biofuel}}}{\Delta E_{\text{biofuel}}} \right),
\]

where \( \Delta E \) is change in energy in megajoules.

A 1:1 replacement of fossil energy with renewable energy means that \( \Delta E_{\text{oil}} = -\Delta E_{\text{biofuel}} \), and therefore the rebound effect \( R = 0 \). A positive rebound effect, i.e., \( R > 0 \) implies a less than one to one replacement of fossil energy with renewable energy and that global energy use increases. A negative rebound effect, i.e., \( R < 0 \), implies that a unit increase in renewable energy causes a greater than 1 unit decrease in fossil energy. This may result when policies mandate a renewable fuel that is significantly more costly relative to fossil fuels causing total energy consumption to decline by a large amount.

An alternative metric is net oil displacement factor, which Rajagopal and Plevin (2013) defined as

\[
\text{NODF} = -\left( \frac{\Delta E_{\text{oil}}}{\Delta E_{\text{biofuel}}} \right),
\]

where \( \Delta E \) is change in energy in megajoules.

Since biofuel policies aim to increase energy use from biofuels and decrease energy use from fossil fuels (and hence the negative sign so as to make NODF a positive quantity), a 1:1 replacement should suggest an NODF = 1. If NODF < 1 then there is less than 1:1 replacement and energy use increases. A negative NODF would indicate that oil consumption increases in response to biofuel policies. NODF and Rebound effect are equivalent and related as NODF = 1 - \( R \).

IFUE may be computed either on a regional basis or globally or both. The direction and magnitude of IFUE will vary accordingly. For instance, if biofuel policies cause fuel prices to increase in the policy region (P), then \( R_P < 0 \). However, since global energy use may either increase or decrease, therefore either \( R_Q > 0 \) or \( R_G < 0 \). If biofuel policies decrease fuel price in the policy region (P), then \( R_P > 0 \). Since in this case global energy use unambiguously increases, \( R_G > 0 \).

2.2. Estimates of IFUE in the literature

There is a growing literature that provides estimates of IFUE. Using a two-region partial equilibrium model of the global oil market (Rajagopal et al 2011), showed that biofuel mandates may either raise or lower the cost of biofuel-blended fossil fuels in the policy region, and correspondingly decrease or increase total fuel consumption. However, domestic policies always lower the world price of fossil fuel, which leads to an increase in fossil fuel use outside the policy region. Because they do not model the market of oil products, their numerical estimates are influenced by their extreme assumption that 1 megajoule (MJ) of ethanol is a perfect substitute for 1 MJ of crude oil. Using a similar two-region framework, de Gorter and Drabik (2011), calculate that each MJ increase in ethanol consumption in the home region leads to only a 0.35–0.40 MJ reduction in global gasoline consumption. In other words, they calculate a gasoline rebound effect of 60–65%. They however do not consider the impact on oil or other oil products.

A second set of studies account for indirect effects in both the agriculture and fuel market simultaneously. Thompson et al (2011) simulate the effect of US biofuel policies in a multi-market partial equilibrium framework, which combines the liquid fuels sector, and comprises three oil products—gasoline, diesel and residual oils—and three types of biofuels—corn ethanol, cane ethanol and soybean biodiesel—with a model of the agricultural and biofuel markets. Based on their reported results we impute a rebound effect of 45–85%. Using a similar approach that combines fuel and agricultural commodity markets and endogenously determines the price of both fuels and agricultural commodities, Bento et al (2011) also predict that rebound in fuel consumption abroad leads to a net increase in global emissions with biofuel policies than without. Although they do not report a metric similar to NODF or rebound effect, one of their findings is that global crude oil use increases by 0.1% relative to no-policy baseline. This implies a negative NODF or a rebound effect exceeding 100%. Another study to simulate biofuel policies in a multi-market framework is Chen and Khanna (2012). They calculate a global gasoline rebound effect of 39%–68%. They also provide a breakdown of total change in gasoline consumption, into substitution effect, which refers to the replacement a quantity of gasoline equivalent in energy content to the increase in quantity of ethanol, and rebound effect, which refers to the increase attributable to the fall in world price of gasoline. They further break down the rebound effect into a domestic and a global effect. Stooff (2010) reviews a number of different assessments of the US Renewable Fuel Standard and concludes that the estimates in these studies suggest a 29%–70% rebound in global oil use (or an NODF of 30%–71%).

Whereas the above studies analyze biofuel policies assuming a competitive world crude oil market (Hochman et al 2011), simulate biofuel mandates assuming OPEC behaves strategically as cartel-of-nations (CON) maximizing domestic welfare. When compared to the CON model, they show that the competitive model overestimates the reduction in world oil price, and underestimates the reduction in global oil consumption. Consequently, competitive models overestimate the global rebound effect and GHG emissions. Their CON model predicts a 50–75% rebound effect, which lies within the range of estimates derived from studies assuming perfect competition. A limitation of their study is that their model considers only ethanol and crude oil.

Estimates derived from simulation-based models are influenced by the choice of assumed values for model inputs, which includes elasticity of supply and demand for different products in different regions, the emission intensity...
of different fuels, etc. While most of the above studies have explored the sensitivity of their estimates to their model inputs, they do so by varying one or two parameters at a time, which may not capture all possible combinations of inputs. Rajagopal and Plevin (2013) employ a Monte Carlo approach in which they simulate the IFUE effect for 5000 different combinations of the model parameters. Their model also contains multiple types of petroleum and petro-products and two types of ethanol—corn and cane ethanol—but they do not model the agriculture sector and therefore rely on exogenous estimates of ILUC emissions. While their mean and median estimates fall within the range spanned by the studies above, their range of estimates is wider. It is worth pointing out that all the studies reviewed here analyze IFUE in a partial equilibrium context. We are not aware of estimates of IFUE from CGE models although CGE models such as GTAP have been widely used to model ILUC. However, these studies do not either calculate or discuss fuel market effects.

The studies discussed above also highlight the sensitivity of the rebound effect to the specific policy regime. For instance, subsidies decrease the cost of biofuel, leading to greater fuel consumption and higher emissions than otherwise under any given regulation such a mandates or emission standards (Lapan and Moschini 2009).

To summarize the literature on fuel market effects, although different studies employ different modeling frameworks with different theoretical assumptions and different specifications of supply and demand functions, and differ in the level of disaggregation of the world market for oil and oil products, they all point to a substantial rebound effect in global oil consumption, and therefore a substantially smaller than 1:1 replacement of fossil energy by renewable energy from biofuels. This suggests that the direction of impact of IFUE on lifecycle GHG benefits of biofuels is similar to that for ILUC, i.e., it amplifies the effective lifecycle GHG intensity. A limitation of the modeling studies discussed here is that they generally assume that crude oil refining yields various oil products in fixed proportion and that this proportion is fixed over time. In reality, refineries may reconfigure their processes to, say, reduce the share of gasoline and increase the share of non-gasoline oil products in response to an ethanol mandate. Ignoring such adaptation may lead to over-estimation of the reduction in crude oil consumption in response to a supply or demand shock to any single oil product. Modeling oil refinery adaptation is an area for future research.

A positive IFUE ($R > 0$ or NODF $< 1$) does not necessarily imply that total emissions increase. Whether total emissions increase or decrease also depend on the GHG emission intensity of the renewable fuel relative to the fossil fuel. A renewable fuel with a sufficiently low direct lifecycle GHG intensity might accommodate both a rebound in fossil fuel consumption and a reduction in global GHG emissions. However, the higher the renewable fuel's GHG intensity, the smaller the permissible level of rebound before total emissions increases. For the first generation biofuels, namely the currently commercial sources of ethanol and biodiesel from food crops, indirect emissions from food and fuel markets cause emissions to increase as a result of substitution of fossil fuels with such biofuels. The significance of IFUE necessitates an expansion of the system to also include the market for oil and oil products. However, while consideration of IFUE in addition to ILUC is a step forward, indirect emissions may also manifest in other markets. For instance, Zilberman et al (2013) hypothesize that the reduction in food consumption as a result of biofuel policies is an additional indirect effect (which they term as indirect food consumption effect) that needs to be taken in to account. This effect is argued to contribute to reducing GHG emissions but this may entail a high social cost.

3. Implications for regulations that target lifecycle emissions

The emergence of ILUC as a significant risk that undermines the climate benefits of biofuels has led policy makers to take serious note of indirect emissions. The current approaches to controlling indirect emissions can be classified into ‘hard’ and ‘soft’ approaches. By a hard approach we refer to explicit accounting of indirect emissions as part of the effective lifecycle GHG emission intensity of a biofuel. In other words indirect emissions are included in the GHG rating assigned or used by regulators for determining compliance with a standard or target. An example is the California LCFS, which assigns a value of 25 gCO$_2$e MJ$^{-1}$ as the average ILUC emission intensity of corn ethanol and 46 gCO$_2$e MJ$^{-1}$ as the average ILUC emission intensity of cane ethanol (CARB 2012). This average value for ILUC, which is assumed as given by any regulated firm, is then added to the firm’s own estimate of its direct emissions in order to determine an effective total GHG intensity for any given batch of fuel it sells. The LCFS regulation requires that the average of this effective total GHG intensity across all batches of fuel sold in a given year by a firm lie below the specified standard for that year. The approach to ILUC under the US RFS2 regulation can also be considered as a hard approach for it requires that the effective lifecycle GHG intensity of corn to be 80% or lower relative to the GHG intensity of gasoline taking into account ILUC emissions. There are similar limits for each of the other three classes of biofuels that the RFS identifies. However, the California Air Resources Board and the US EPA have each adopted different modeling approaches and computational tools to estimate ILUC, and therefore employ different estimates of ILUC emissions under the LCFS and RFS respectively. In contrast, by a ‘soft approach’ we mean that policy makers take cognizance of indirect emissions and declare their intent to avoid such emissions yet they refrain from explicit accounting of indirect emissions. Instead they encourage voluntary adoption of better production practices. The policies towards ILUC in the European Union, which refrain from assigning a specific number to ILUC, are some examples of soft approaches. All current regulations, however, ignore non-ILUC indirect effects.

The literature on IFUE suggests that the currently mature biofuels are not guaranteed to reduce emissions even after accounting for ILUC emissions, and this is due to the
effect of biofuels on fuel prices and global fuel consumption (Rajagopal and Plevin 2013). One interpretation of this finding is that lifecycle-based regulations should also account for IFUE. As with ILUC, one could pursue either a hard or a soft approach. To pursue a hard approach would require a computational tool(s) that can provide a reliable best estimate of IFUE emissions. However, experience with use of computational tools for modeling ILUC emissions, such as, the GTAP global computable general equilibrium (CGE) (Hertel et al 2010), the FAPRI/CARD global multi-market partial equilibrium model of world trade in agricultural commodities and (Tyner et al 2010, Dumortier et al 2011) suggests that their predictions might be wide ranging and sensitive to modelers’ assumptions about the numerous parameters such as elasticities of supply and demand in various markets etc (Plevin et al 2010). Consideration of other indirect effects such as IFUE increases the complexity and the uncertainty in estimates. One can argue that there is value to engaging in the exercise of developing and simulating models of global indirect emissions, at least in order to derive order of magnitude estimates indirect emissions. However, whether one can expect to derive an expected value of indirect emissions or a confidence interval is questionable. While there is a rich tradition of use of CGE and multi-market partial equilibrium models for economic analysis of government policies, such tools have been used mainly to derive order of magnitude estimates of economic impact and have not been relied upon as a basis for deriving precise estimates of uncertain variables for regulatory use. However, such is not the case with their application in the context of biofuel regulations.

Another challenge in precise estimation of indirect emissions is that dynamic processes govern phenomena such as land use change. The history of agriculture suggests that although acreage may expand in the short-run in response to an increase in prices, technological improvements have led to higher productivity and a contraction in the agricultural land base in the longer-run (Cochrane 1993). As a result, in highly developed regions such as the US, Canada or Western Europe, total acreage under agriculture tends to be stable. The situation may however be different in developing countries such as Brazil or Indonesia whose agricultural land base continues to expand driven by government policies. Such dynamic processes are not captured in the CGE or multi-market modeling frameworks used for ILUC. A similar limitation may apply to the literature on IFUE reviewed earlier. For instance, the impact of biofuel policies on investment in new oil capacity has not been investigated in a serious manner. Given that the global oil infrastructure is transitioning towards a greater share of more GHG intensive resources such as non-conventional petroleum, such as, oil sands and other heavy crude oils, liquids from natural gas and coal, etc (IEA 2008), static comparisons of renewable and fossil fuels tend to under-value the environmental benefits of slowing this transition.

Another concern with the hard approach relates to equity and fairness in assigning responsibility for indirect emissions to regulated firms, who comprise only a subset of polluters that contribute to indirect emissions. A hard approach to indirect emissions may amount to a virtual ban on certain technologies even though their use leads to a direct lifecycle improvement relative to either present or future business-as-usual emission intensity scenarios. Another limitation of the hard approach is that the virtual exclusion of certain technologies may prevent attainment of other objectives such as improving a region’s terms of trade, inducing learning-by-doing in infant industries etc. These latter objectives tend to be important for renewable energy policies. In fact, one could even argue that, in some instances, considerations other than pollution reduction might be the primary objective. For instance, the US Renewable Fuel Standards were enacted as part Energy Security and Independence Act 2005. This, however, is not the case with California LCFS, which is implemented as part of the state’s Global Warming Solutions Act and, which is not a biofuel policy per se. Nevertheless, when there is scope for pollution leakage, indirect emissions represent real externalities and while they might be unintended, they are a consequence of the policy and so policy makers ought to take indirect emissions into consideration. This is a challenge for analysts and policy makers.

One can envision several softer approaches for controlling indirect emissions that are less rigid and also entail less informational burden on policy planners. One option is for policy makers to take a ‘harder’ stance towards direct emissions. By this we mean that policy makers could require greater benefits accruing from the supply chain of a new technology. To this end, they could stipulate an upper bound on direct emissions and make the upper bound more stringent over time. Technologies with zero or very low direct emissions are less likely to prove counterproductive in spite of indirect emissions in the form of increase in energy use outside the policy regions. Another option is to impose a penalty in the form of a tax for every unit increase in emission intensity above the upper bound. Alternatively a subsidy that is indexed to the reduction in direct emissions achieved by a firm relative to a baseline could be provided. However, political feasibility might be a concern with a tax approach while, a concern with a subsidy approach is financing. Another safeguard is to limit either the market share or the absolute level of consumption of the risky technologies. To this end, a lower bound such as a biofuel mandate could be complemented with an upper bound that limits maximum allowed level of use. For instance, consumption of biofuels from food crops could be restricted following a negative supply shock or during a period of high food price inflation.

4. Conclusion

In reviewing the literature on fuel market effects of biofuel policies, we draw two main conclusions—one pertaining to the GHG impacts to biofuels and another pertaining to regulations based on lifecycle emissions. With regard to the former, we conclude that significant indirect emissions are not merely confined to agricultural and land use related sectors but might extend to other sectors. In this letter we focused
on indirect effects in the fuel sector. Some are now beginning to raise the issue of indirect food consumption effect, which might be beneficial from an emissions standpoint but at the cost of reducing food consumption. In any case, non-ILUC indirect effects remain outside the purview of current biofuel regulations. This needs to be addressed by policy makers.

The case of biofuels both provides a rationale for a regulatory approach, which accounts for the entire lifecycle and at the same time, demonstrates the practical difficulties in designing simple, transparent, lifecycle emissions regulations. A major practical challenge is the issue of indirect emissions, which, in principle, are a consequence of the policy shock, but in reality, appear difficult to estimate to any reasonable level of precision. The notion of indirect emissions, albeit having achieved prominence in context of biofuel policies, is not unique to biofuels. They need to be considered when assessing the global impact of any partial policy irrespective of whether the policy is a tax, cap and trade, renewable energy mandate, energy efficiency standards or any other type of policy. They are especially important in the context of GHGs since these are global pollutants. Indirect emissions are also difficult to regulate by assigning responsibility for such emissions to only a subset of polluters, an approach we refer to as the hard approach. A soft approach, on the other hand, while it too does not guarantee that emissions will decline relative to a business-as-usual future, is an approach that has the benefits of being less onerous on a small number of polluters, requiring less information to design, and offering the potential to induce learning-by-doing in technologies, none of which might be exploitable under a hard approach.

References

ARB 2011 Low carbon fuel standard—indirect effects Report of the Expert Working Group’s subgroup on Indirect Effects of Other Fuels (Sacramento, CA: California Air Resources Board)
Bento A M, Klotz R and Landry J R 2011 Are there carbon savings from US biofuel policies? The critical importance of accounting for leakage in land and fuel markets Agricultural and Applied Economics Association and NAREA Joint Annual Mtg (Pittsburgh, PA, July)
Cai X, Zhang X and Wang D 2010 Land availability for biofuel production Environ. Sci. Technol. 45 334–9
CARB 2012 Final Regulation Order for the Low Carbon Fuel Standard (Sacramento, CA: California Air Resources Board)
Chen X and Khanna M 2012 The market-mediated effects of low carbon fuel policies AgBio Forum. 15 1–17
Cochrane W W 1993 The Development of American Agriculture. A Historical Analysis (Minneapolis, MN: University of Minnesota Press)
de Gorter H and Drabik D 2011 Components of carbon leakage in the fuel market due to biofuel policies Bioresour. Technol. 2011 119–21
Demontier J, Hayes D J, Carriquiry M, Dong F, Elobeid A, Fabiosa J F and Tokgoz S 2011 Sensitivity of carbon emission estimates from indirect land-use change Appl. Econ. Perspect. Policy 33 428–48
Dunn J B, Mueller S, Kwon H and Wang M Q 2013 Land-use change and greenhouse gas emissions from corn and cellulosic ethanol Biotechnol. Biofuels 6 51
EPA 2009 Draft regulatory impact analysis: changes to renewable fuel standard program EPA-420-D-09-001 (Washington, DC: Environmental Protection Agency)
Farrell A E, Plevin R J, Turner B T, O’Hare M, Jones A D and Kammen D M 2006 Ethanol can contribute to energy and environmental goals Science 311 506–8
Gelfand I, Sahajpal R, Zhang X, Izaurralde R C, Gross K L and Roberson G P 2013 Sustainable bioenergy production from marginal lands in the US midpoint Nature 7433 514–7
Hertel T W, Golan A A, Jones A D, O’Hare M, Plevin R J and Kammen D M 2010 Effects of US maize ethanol on global land use and greenhouse gas emissions—estimating market-mediated responses Bioscience 60 223–31
Hochman G, Rajagopal D and Zilberman D 2011 The effect of biofuels on the international oil market Appl. Econ. Perspect. Policy 33 402–27
IEA 2008 World Energy Outlook 2008 (Paris: Organization for Economic Cooperation and Development and International Energy Agency)
Kim S and Dale B E 2011 Indirect land use change for biofuels: testing predictions and improving analytical methodologies Biomass Bioenergy 35 3235–40
Lapan H E and Moschini G C 2009 Biofuels policies and welfare: is the stick of mandates better than the carrot of subsidies? Iowa State University Department of Economics Working Paper 09010 (Ames, IA: Iowa State University)
Liska A J, Yang H S, Bremer V R, Klopfenstein T J, Walters D T, Erickson G E and Cassman K G 2009 Improvements in lifecycle energy efficiency and greenhouse gas emissions of corn–ethanol J. Indust. Ecol. 13 58–74
Macedo I C 1998 Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil (1996) Biomass Bioenergy 14 77–81
Plevin R J, O’Hare M, Jones A D, Torn M S and Gibbs K H K 2010 Greenhouse gas emissions from biofuels: indirect land use change are uncertain but may be much greater than previously estimated Environ. Sci. Technol. 44 8015–21
Rajagopal D, Hochman G and Zilberman D 2011 Indirect fuel use change and the environmental impact of biofuel policies Energy Policy 39 228–33
Rajagopal D and Plevin R 2013 Implications of market-mediated emissions and uncertainty for biofuel policies Energy Policy 56 75–82
Scown C D, Nazaroff W W, Mishra U, Stroten B, Loboschek A B, Masanet E, Santero N J, Horvath A and McKone T E 2012 Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production Environ. Res. Lett. 7 014011
Searchinger T, Heimlich R, Houghton R A, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D and Yu T H 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change Science 319 1238
Sheehan J, Camobreco V, Duffield J A, Grabowski M and Shapouri H 1998 Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus (Final Report No. NREL/SR-580-24089) (Golden, CO: National Renewable Energy Laboratory)
Stoft S 2010 Renewable fuel and the global rebound effect Research Paper No. 10-06 (Berkeley, CA: Global Energy Policy Center)
Thompson W, Whistance J and Meyer S 2011 Effects of US biofuel policies on US and world petroleum product markets with consequences for greenhouse gas emissions Energy Policy 39 5509–18
Tyner W E 2012 Biofuels and agriculture: a past perspective and uncertain future Int. J. Sustain. Dev. World Ecol. 19 389–94
Tyner W E, Taheripour F, Zhuang Q, Birur D and Baldos U 2010 Land Use Changes and Consequent CO2 Emissions due to US Corn Ethanol Production: A Comprehensive Analysis (West Lafayette, IN: Department of Agricultural Economics, Purdue University)
Venkatesh A, Jaramillo P, Griffin W M and Matthews H S 2011 Uncertainty in life cycle greenhouse gas emissions from united states natural gas end-uses and its effects on policy Environ. Sci. Technol. 45 8182–9
Zilberman D, Barrows S, Hochman G and Rajagopal D 2013 On the indirect effect of biofuel Paper Presented at the Allied Social Science Associations Annual Mtg at San Diego (San Diego, CA, Jan.)