Biofuel debates often focus heavily on carbon impacts, with parties arguing for (or against) biofuels based solely on whether the greenhouse gas emissions of biofuels are less than (or greater than) those of gasoline. Recent studies argue that land use change leads to significant greenhouse gas emissions, making some biofuels more carbon intensive than gasoline. We argue that evaluating the suitability and utility of biofuels or any alternative energy source within the limited framework of plus and minus carbon emissions is too narrow an approach. Biofuels have numerous impacts, and policy makers should seek compromises rather than relying solely on carbon emissions to determine policy. Here, we estimate that cellulosic ethanol, despite having potentially higher life cycle CO₂ emissions (including from land use) than gasoline, would still be cost-effective at a CO₂ price of $80 per ton or less, well above estimated CO₂ mitigation costs for many alternatives. As an example of the broader approach to biofuel policy, we suggest the possibility of using the potential cost reductions of cellulosic ethanol relative to gasoline to balance out additional carbon emissions resulting from indirect land use change as an example of ways in which policies could be used to arrive at workable solutions.

Keywords: biofuels, ethanol, land use change, energy policy
The iLUC findings have sparked a spirited debate. The California Air Resources Board (CARB), charged with developing a Low Carbon Fuel Standard (LCFS) to reduce the carbon intensity of transportation fuels in California by at least 10% by 2020, has received letters from groups of scientists with opposing views. In one letter [4], CARB was urged to ignore iLUC impacts, citing a lack of empirical evidence and validation typically required of scientific findings in order to influence policy. A response [5] defended the recent iLUC findings, stating that the models and methods used to estimate iLUC impacts are widely accepted, and ignoring iLUC impacts in LCFS policy effectively assumes that the carbon impact of iLUC is zero, a value that current research estimates to be very unlikely. CARB has continued to receive letters from parties representing industry, academia, and public policy arguing for and against the inclusion of iLUC carbon impacts in biofuel policy [6]. Though important and interesting, the debate will go on for some time, while policy makers need to make decisions now.

There are some drawbacks to the types of economic equilibrium models used to generate the iLUC estimates [7]. Equilibrium models for predicting iLUC impacts rely on accurate forecasts of complex global agricultural markets, forecasts that are impacted by considerable uncertainties on both supply and demand sides. Furthermore, the response of these markets to increased biofuel production needs to be precisely modeled on a spatial level, since land use changes can have drastically different carbon impacts based on the regional characteristics of converted cropland. Future land use requirements also depend heavily on agricultural yields, which may continue to improve, especially for high feedstock prices. Issues involving the allocation of environmental impacts to biofuel co-products (a problem faced by all life cycle analyses of biofuels) are relevant to iLUC analyses as well.

The argument that recent iLUC findings should be ignored due to modeling limitations or uncertainties fails to recognize the goal of employing low carbon fuels. While accurately estimating iLUC carbon impacts may be difficult, and assigning emissions from iLUC entirely to biofuel production rather than to the agricultural production that occurs on the converted land may be controversial, the ultimate goal of the LCFS is to reduce carbon emissions, and these findings indicate that additional biofuel production may fail to accomplish that goal. Arguments for excluding iLUC emissions in biofuel policy also state that iLUC emissions are rarely considered in life cycle assessments of fossil fuels, so including them only when discussing biofuels in unfair. But fossil fuels have a higher energy density than bioenergy sources and are less likely to displace agricultural production; one preliminary study estimates that land use greenhouse gas emissions for petroleum are at least 1–2 orders of magnitude less than those estimated for ethanol [8]. Certainly, more research toward clarifying iLUC impacts is warranted, but until the scientific community is able to further address the issue, these results must be considered when making biofuel policies.

We argue that a path through the competing arguments is achievable by returning to the various reasons that biofuels are being proposed. Biofuel discussions could be reframed by expanding the argument beyond carbon emissions. Consider cellulosic ethanol as an example. Assuming a feedstock cost of $25–$50 per dry ton and ethanol yields near 90 gallons per ton, NREL estimates the production cost of cellulosic ethanol using either biological conversion [9] or thermochemical conversion [10] to be roughly $1.00–$1.35 per gallon. After adding distribution costs (estimated to be $0.15–$0.20 per gallon when shipped primarily by rail [11]) and adjusting for the difference in energy density between ethanol and gasoline, the cost of cellulosic ethanol could be between $1.75 and $2.25 per gallon of gasoline equivalent energy. Future technological advances, such as enhanced sugar yields from cellulose and hemicellulose, could push these cost estimates lower. For a mature cellulosic ethanol industry in which feedstock costs account for two-thirds of total production costs (a figure in line with other mature commodities), cellulosic ethanol could be produced for as little as $1.00 per gallon gasoline equivalent [12]. These cost estimates would make cellulosic ethanol competitive with gasoline, despite the recent drop in petroleum prices resulting from current economic conditions.

Cellulosic ethanol’s potential for significant cost reductions compared to gasoline, and partial protection against wild petroleum price fluctuations due to global market forces, should not be ignored when considering biofuel policies. Instead, policy makers should consider the tradeoffs between different impacts of biofuels to decide on policies that are most socially beneficial. Figure 1 provides an example of how to consider both economic and greenhouse gas impacts of cellulosic ethanol relative to gasoline in light of recent LUC research.

Figure 1 compares the social costs of gasoline and cellulosic ethanol. Cellulosic ethanol can result in substantial net social benefits for modest gasoline prices, even after impacts of indirect land use change (iLUC) are taken into account. Ethanol cost estimates taken from Aden [9], GHG emissions for both cellulosic ethanol and gasoline are reported in Searchinger [2].
of CO2 emitted, and could be represented by the value of a carbon tax, the price of a carbon allowance in a cap and trade system, or simply the estimated social valuation of externalities caused by additional carbon emissions. The social cost for each fuel, shown on the y-axis, is normalized by the amount of energy contained in a gallon of gasoline. Three lines are shown on figure 1, representing gasoline, cellulosic ethanol without iLUC carbon impacts, and cellulosic ethanol with iLUC carbon impacts taken into account.

Life cycle CO2 emissions used to generate figure 1 were taken from Searchinger [2], where iLUC was estimated to shift cellulosic ethanol from a 70% reduction to a 50% increase in greenhouse gas emissions compared to gasoline. Note that this assumption represents a very pessimistic scenario for cellulosic ethanol, where (a) cellulosic feedstock production displaces other crops and induces land use change at the rate estimated in Searchinger and (b) cellulosic ethanol is held responsible for all of the resulting CO2 emissions. Since life cycle CO2 emissions for each fuel are assumed to be positive, each line is upward sloping, with the social costs increasing as the cost of carbon increases.

The colored regions in figure 1 illustrate the social cost reduction of cellulosic ethanol relative to gasoline. The entire colored region between the (upper) gasoline boundary and the (lower) cellulosic ethanol boundary represents the per gallon social cost reduction of cellulosic ethanol in the absence of iLUC impacts (or, alternatively, if iLUC impacts were assumed to be zero). The red region represents the portion of this cost reduction consumed by including the current estimates of social costs of carbon resulting from iLUC, and the blue region represents the remaining social cost reduction of cellulosic ethanol.

From this example, for a carbon shadow price of $80/ton CO2 or less, cellulosic ethanol results in social cost reductions relative to gasoline, even after subtracting the cost of iLUC soil carbon impacts. As the carbon shadow price increases, the cost reduction steadily decreases, finally disappearing at the ‘breakeven’ CO2 price of $80/ton, where both fuels would have identical social costs. For carbon prices above this breakeven price, cellulosic ethanol would not be socially beneficial, since the increased greenhouse gas emissions resulting from iLUC would outweigh the reductions in fuel cost. (Note that this analysis only explicitly considers the cost and greenhouse gas impacts of cellulosic ethanol and gasoline. Cellulosic ethanol could still benefit society for higher CO2 prices due to factors such as energy security, increased domestic economic activity, etc.) Though this social cost reduction may seem small on a per gallon basis, the macro-level impacts are significant. Considering the 16 billion gallons of cellulosic ethanol required per year by 2022 by the Energy Independence and Security Act of 2007, this reduction in social cost would amount to at least $5 billion per year for carbon prices of $30/ton CO2 or less for this particular combination of biomass feedstock and gasoline prices.

The results shown in figure 1 depend heavily on gasoline and cellulosic biomass prices, and the dramatic changes in gasoline prices in recent years caution against making policies based on narrow predictions of future prices. Additionally, cellulosic ethanol cost estimates are highly sensitive to feedstock costs, and given recent volatility in energy and food prices, cellulosic biomass prices may not be confined in the $25–$50 per dry ton range assumed here. However, even substantial increases in cellulosic feedstock prices do not eliminate the potential for cost savings from cellulosic ethanol. Should feedstock costs rise to $100 per dry ton, cellulosic ethanol cost estimates would range from $3.00–$3.50 per gallon gasoline equivalent, extrapolating from NREL’s results. These production cost estimates are still lower than the $3.60 pre-tax national average gasoline price at the end of July 2008 [13] despite increasing the price of biomass crops by a factor of 2–4 from current estimates. The 2008 gasoline price is notable since it was before the global economic downturn that led to decreases in global production and consumption of oil and price declines.

The breakeven CO2 price for cellulosic ethanol is highly sensitive to ethanol costs, gasoline costs, and iLUC emission estimates, but many potential combinations of these parameters result in high breakeven prices. For instance, assuming the same cellulosic ethanol production cost of $2.00 per gallon gasoline equivalent and the same iLUC emissions as assumed in figure 1, a gasoline price of $3.00 per gallon raises the breakeven CO2 price of cellulosic ethanol to $160 per ton. Should gasoline prices rise as high as $3.60 per gallon, cellulosic ethanol’s breakeven CO2 price would reach $260 per ton. Gasoline prices would have to fall below $2.15 per gallon for the breakeven CO2 price to fall below $25 per ton. Conversely, should ethanol production costs fall as the industry matures, the breakeven CO2 price would rise. Assuming $2.50 per gallon gasoline, a cellulosic ethanol production cost of $1.50 per gallon gasoline equivalent equals to a breakeven CO2 price of $160 per ton, while a production cost of $1.00 per gallon gasoline equivalent (in line with some long-term projections [14]) means the breakeven CO2 price would be over $240 per ton, even with modest gasoline prices. Finally, more conservative estimates of iLUC than those assumed in figure 1 would also raise the breakeven CO2 price. If cellulosic ethanol were estimated to be 25% more CO2 intensive than gasoline (rather than the 50% assumed here), then the breakeven CO2 price of cellulosic ethanol would rise from $80 to $160 per ton. In order for the breakeven CO2 price to fall below $25 per ton CO2 given a $0.50 per gallon price differential, iLUC emissions would have to make cellulosic ethanol 175% more carbon intensive than gasoline.

The potential for very high breakeven CO2 prices is a promising result for cellulosic ethanol proponents. Since cellulosic ethanol may be a low cost, high carbon alternative to gasoline in light of LUC findings, the breakeven CO2 price is essentially the cost reduction cellulosic ethanol generates in exchange for the release of an additional ton of CO2. For example, the breakeven CO2 price of $80/ton indicates that society would be indifferent between cellulosic ethanol and gasoline given a CO2 price of $80 per ton. In other words, cellulosic ethanol would reduce fuel costs by $80 for every additional ton of CO2 released, including iLUC emissions.

Put another way, the decision not to produce cellulosic ethanol and rely instead on gasoline would result in lower
total CO$_2$ emissions, since, based on assumed emissions estimates, gasoline has lower life cycle CO$_2$ emissions than cellulosic ethanol. However, compared to a future scenario with cellulosic ethanol production, using gasoline instead of cellulosic ethanol would represent a very expensive mitigation option, with a cost of mitigation, for this combination of energy prices, of $80/ton CO$_2$.

Critics argue against the adoption of ethanol as part of a Low Carbon Fuel Standard based solely on the increased carbon emissions. However, such an argument views the social problem of carbon mitigation too narrowly. By taking a society-wide approach to the problem of carbon mitigation, cost reductions from using cellulosic ethanol could be used to fund carbon mitigation alternatives that may then make up for the additional emissions from iLUC, even if current estimates remain unchanged and biofuels are held solely responsible for these emissions. A key ingredient of such an approach is the existence of carbon mitigation technologies or practices available at a cost significantly less than cellulosic ethanol’s breakeven cost, estimated to be $80/ton CO$_2$ in figure 1. Fortunately, there are many alternatives that meet this requirement. McKinsey & Co. [15] suggests that there are 1.3 billion tons per year of potential CO$_2$ mitigation with negative costs (e.g., conservation activities such as lighting replacements), and another 600 million tons costing less than $30 per ton (such as reforestation). Even large-scale projects such as carbon capture and sequestration from coal-fired power plants could be funded for $30 to $90/ton CO$_2$ [16]. These options have long been known but not previously pursued due to lack of centralized funding. If policies are in place to capture part of the $5 billion resulting from reduced fuel costs of cellulosic ethanol, such funding could become available to more than mitigate the 65 million tons of CO$_2$ added by cellulosic ethanol when iLUC impacts are considered. Thus, if carbon mitigation is the sole objective of LCFS policies, cellulosic ethanol can still play an effective role.

Furthermore, carbon mitigation strategies could be chosen to help ameliorate other negative impacts of biofuels. For instance, biofuel-driven land use change may have detrimental effects on biodiversity. Land use change has been identified as the primary driver impacting biodiversity in terrestrial ecosystems throughout the next century, with significant changes in land use having major impacts on biodiversity across a variety of biomes [17]. Changes in biodiversity resulting from land use change may have profound economic impacts on society by altering ecosystem attributes, such as soil quality, water supply, and fire and disease vulnerability [18]. These impacts are often costly, if not impossible, to reverse. Though the relationships between biodiversity and ecosystem goods may be non-linear, non-additive, and ultimately difficult to quantify, preserving biodiversity may serve as an insurance policy against drastic ecosystem changes that could otherwise result from changes to the environment. Thus, accelerating global land use change by producing biofuels could impact biodiversity in ways that, during a time of major climate change, could lead to severe economic consequences. These consequences may be avoided by funding measures such as reforestation (estimated to cost around $30 per ton CO$_2$ [15]) that can both help sequester soil carbon and preserve biodiversity.

Effectively administrating a program that taxes biofuels in order to fund carbon mitigation options would be very challenging. It would be difficult to accurately quantify iLUC emissions from different biofuel feedstocks grown in different regions, a necessary step in determining the size of any biofuel tax. Deciding whether producers or consumers of biofuels are responsible for iLUC could also be difficult (though this issue is already being debated more generally throughout climate change policy). These challenges do not erase the fact that the cost-carbon tradeoff of biofuels may compare favorably to that of gasoline. Though policies designed to balance the carbon and cost impacts of biofuels may not be simple, biofuels should not be excluded from energy policy due solely to iLUC.

This argument has focused primarily on cellulosic ethanol produced from energy crops, but a similar line of reasoning could be applied to other fuels as well. Assuming a corn price of $5/bushel and projecting from the results of a USDA survey [19], the cost of corn ethanol is $2.00–$2.25 per gallon. Though corn ethanol could be about twice as CO$_2$ intensive as gasoline once iLUC carbon impacts are considered [2], corn ethanol would still be expected to result in social cost reductions for CO$_2$ costs below $25/ton, assuming a gasoline price of $3.60 per gallon. Fischer–Tropsch fuels produced from coal could cost $1.50–$1.85 per gallon [20], creating the potential for funds to more than mitigate their increased emissions. Cellulosic ethanol produced from sources other than energy crops, or grown on degraded land, looks particularly promising. Growing cellulosic crops on marginal or degraded land results in much lower soil carbon losses than crops grown on forest or grasslands [1] and iLUC would be avoided if no agricultural activity were displaced. Using agricultural residues (such as corn stover or wheat straw) or forest residues would avoid land use change entirely. Scenarios with lower land use emissions result in higher breakeven CO$_2$ prices for cellulosic ethanol and increase the social cost reduction relative to gasoline.

Like so many of the climate and climate mitigation debates, authors argue as if there were only black and white alternatives, when ultimately solutions will be found in the gray areas. Given the rising costs of gasoline, and other externalities such as energy security that may trump iLUC issues, we need to look for alternatives that may not be ‘optimal’ but workable. Here, we suggest using the cost reductions of cellulosic ethanol to balance out the impacts of iLUC as an illustration of ways policies can be used to arrive at workable solutions. As long as parties take a narrow approach and argue for a favorite solution, rather than looking hard for potential compromises, we fear that the scientific community may be unable to provide effective guidance for climate policy in a complex world.

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