Biofuels and Carbon Management

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ABSTRACT

Public policy supports biofuels for their benefits to agricultural economies, energy security and the environment. The environmental rationale is premised on greenhouse gas (GHG, "carbon") emissions reduction, which is a matter of contention. This issue is challenging to resolve because of critical but difficult-to-verify assumptions in lifecycle analysis (LCA), limits of available data and disputes about system boundaries. Although LCA has been the presumptive basis of climate policy for fuels, careful consideration indicates that it is inappropriate for defining regulations. This paper proposes a method using annual basis carbon (ABC) accounting to track the stocks and flows of carbon and other relevant GHGs throughout fuel supply chains. Such an approach makes fuel and feedstock production facilities the focus of accounting while treating the CO_2 emissions from fuel end-use at face value regardless of the origin of the fuel carbon (bio- or fossil). Integrated into cap-and-trade policy and including provisions for mitigating indirect land-use change impacts, also evaluated on an annual basis, an ABC approach would provide a sound carbon management framework for the transportation fuels sector.

INTRODUCTION

Biofuels have entered the transportation energy portfolio for several reasons including reduction of dependence on petroleum imports (Duffield and Collins 2006). This energy security rationale dovetails with other policy goals of bolstering markets for farm commodities, lowering the need for crop support programs and fostering rural economic development (Brown 2008). Biofuels have also been promoted for environmental reasons, including reduction of greenhouse gas (GHG) emissions, but that issue has become controversial. Differences in view regarding net energy and GHG benefits compared to petroleum fuels were reviewed by Farrell et al. (2006), for example, who concluded that corn ethanol had modest net GHG benefits based on a meta-analysis of traditional fuel lifecycle analysis (LCA) studies. LCA methods have since been adapted for the purpose of regulating GHG emissions in fuel policy, as seen in California's Low-Carbon Fuel Standard (LCFS; CARB 2009), the U.S. Renewable Fuel Standard (RFS; EPA 2010) and the European Union's Renewable Energy Directive (RED; EU 2009).

The sufficiency of standard fuel LCA methods, which only count direct, supply-chain impacts, has been questioned, however. As U.S. regulators noted, "it has become increasingly apparent that this type of first order or attributional lifecycle modeling has notable shortcomings" (EPA 2009: 25021). Attributional LCA does not count indirect, economically induced impacts that occur as a consequence of commodity market effects. It therefore misses the emissions due to indirect land-use change (ILUC) and the associated release of carbon stocks (Searchinger et al. 2008; McCarl 2008). This leakage effect is worrisome for tropical forests, which are falling under expansions of land use for settlement, forestry and agriculture as driven by multiple factors (Geist and Lambin 2002). Regulators have therefore broadened the scope of LCA, expanding its boundaries both spatially and temporally (CARB 2009; EPA 2009, 2010). Such consequential LCA incorporates aggregate estimates of global commodity market interactions. As applied in regulation to date, it entails assumptions about discounting and how long it takes to pay back the "carbon debt" associated with land-use change (Fargione et al. 2008; Gibbs et al. 2008).

This more expansive form of LCA entails not only difficult-to-verify (and often unverified) assumptions about numerous critical aspects of GHG emissions associated with feedstock and fuel production, but also inherently unverifiable assumptions about future impacts pertaining to land-use effects and carbon uptake. Nevertheless, such methods underpin the use of biofuels for compliance with U.S. carbon-related fuel policies including the U.S. RFS and California LCFS. Although not yet part of the European Union's RED, consequential LCA results for ILUC are being considered for expanding that policy's sustainability guidelines.

These issues highlight the limitations of conventional energy policy thinking regarding renewable versus fossil fuels. The biofuels conundrum can be seen as part of the broader challenge of jointly managing the carbon dioxide (CO_2), nitrous oxide (N_2O) and other GHG impacts from stocks and flows in coupled energy and land-use systems globally (Wise et al. 2009; Melillo et al. 2009). From the perspective of resource economics, it is not obvious that LCA is the right tool for regulation. A policy analytic justification for regulatory application of LCA is strikingly absent from the literature, although criticisms are starting to appear (Holland et al. 2009). Proponents simply have asserted that policy should be based on LCA (e.g., DeCicco & Lynd 1997; Sperling & Yeh 2009), apparently assuming that its utility as a technology assessment tool implies its value as a regulatory tool.

Upon reflection, policy is best defined using current-period accounting of carbon stocks and flows, ideally with direct, measurement-based, verifiable tallies of GHG emissions from the production and use of all fuels and feedstocks. Reflecting the rubric, "what gets measured, gets managed," it would motivate all entities in fuel supply chains to minimize the emissions under their control, i.e., within the scope of their operations, but avoid regulating entities for impacts beyond their control. The policy should also mitigate any remaining emissions, such as leakages caused by market-induced ILUC that no particular entity controls. In short, it should establish a carbon management paradigm that provides incentives to minimize emissions from both fuel production and fuel consumption regardless of what the fuel is called.

Although fully establishing this ideal will not be possible initially, climate protection is best served by putting its elements in place from the inception of a policy regime rather than using approaches such as LCA that are poorly grounded in the principles of sound environmental management. Careful carbon accounting has been the presumed basis of cap-and-trade programs as envisioned by the Kyoto Protocol and advocated as the best approach for national climate policy (Stavins 2007). Although the approach discussed here is ideally suited for use within a cap-and-trade program, the principles also apply to other forms of policy, such as direct regulation (e.g., under the U.S. Clean Air Act), carbon taxation, or a sectoral hybrid policy that might combine approaches (e.g., Nordhaus & Danish 2003).

CARBON ACCOUNTING ISSUES

Effective carbon management must ultimately rely on in situ measurement of stocks and flows on a regular basis with what can be termed annual basis carbon ("ABC") accounting. Here "carbon" refers to all GHGs of concern and "annual" means yearly or other relatively short period, e.g., five years for tracking changes in carbon stocks and analyzing data over multiple growing seasons. Such a system would be "count as you go," without society assuming risks of carbon debt based on judgments about discount rates and acceptable payback times.

ABC accounting underpins cap-and-trade policy as defined to date for fossil CO_2 emissions. Applying it is straightforward for stationary sources, such as power plants and industrial facilities, and for end-use CO_2 from transportation fuels, where simple chemistry enables accurate measurement through points of fuel distribution in lieu of vehicle tailpipes. Emissions inventories are tied to real sources rather than to the LCA abstraction of "carbon footprint," and greater clarity is afforded to the question of which entities can be reasonably held accountable for what emissions.

ABC accounting with appropriate reporting periods can also apply for managing carbon stocks and sinks (Reilly & Asadoorian 2007). Although these issues are treated by more complex methods under the Kyoto Protocol, the result is erroneous carbon accounting for bioenergy (Searchinger et al. 2009) and other inconsistencies (Reilly et al. 2007). The need to rethink climate policy for biofuels relates directly to the need to rethink it more broadly with respect to the inherent coupling of land use to energy systems involved when substituting biological resources for fossil resources (Wise et al. 2009). Although measuring terrestrial impacts is difficult, attempting to handle these issues through LCA rather than ABC accounting does not avoid the difficulties. However, it can confuse matters by fostering debates about what and how to model and, perhaps more seriously, by tempting policymakers to rely on negotiated modeling results rather than developing sound measurement programs.

Traditional methods of energy policy analysis, including fuels LCA, neglect the linkage of energy systems, both fossil and renewable, to land, with its implications for the global carbon cycle and, more broadly, to nitrogen, water and other terrestrial cycles affecting climate (Delucchi 2010). Nevertheless, these incomplete methods have shaped public thinking and policymaking to date. A key defect is the automatic crediting of biogenic carbon, that is, the assumption that biofuel use directly emits no net CO_2 because its molecular carbon was recently absorbed from the atmosphere. That convention looks narrowly at energy-related fluxes while neglecting carbon stocks.

By assuming automatic crediting, GHG emissions caps as proposed to date cover only the fossil-based carbon in fuels. Although some production-phase biofuel emissions are covered, such as those from fossil fuels and fossil-derived inputs used by farms and biorefineries, failing to cover use-phase biogenic CO_2 creates an incentive for biofuels regardless of their actual climatic impacts. Automatic crediting is also used in lifecycle-based regulation as applied in California's LCFS and the expanded RFS. Having omitted biogenic CO_2 emissions from end-use consumption, these LCA-based policies attempt to account for production and indirect emissions through an expansive regulatory reach, asserting that all emissions can be addressed through the single metric of fuel carbon intensity (e.g., gCO_2eq/MJ). Such an expansion of system boundaries from attributional analysis into what of necessity becomes a consequential analysis is then subject to criticism as a marked departure from International Standards Organization (ISO) guidelines for LCA (Dale 2009).

While technically correct in LCA, automatic crediting of biogenic carbon obscures responsibility for the physical sources of emissions in the fuel's lifecycle. The result is a misplaced burden of proof. Fuel product suppliers and consumers are relieved of responsibility for the definite, direct CO_2 emissions at end-use. However, the responsibility for the substantial emissions (direct and indirect, CO_2 as well as N_2O and other impacts) associated with the credited carbon uptake is passed off through the long, convoluted, dynamic and currently untraceable supply chains for feedstocks and other inputs. Arguments then ensue about who is responsible for what portions of emissions and how to expand LCA system boundaries (spatially and temporally) to adequately account for all impacts. The debate has become particularly fraught for ILUC, which greatly influences estimates of GHG intensity. Not surprisingly, expansive LCA-based regulations have met strong opposition from the affected industries (Geman 2009; Guerrero 2010).

ELEMENTS OF A FUELS CARBON MANAGEMENT POLICY

In contrast to an LCA-based policy, a policy that follows principles of ABC accounting would not attempt to handle all fuel-related GHG emissions through a single mechanism. An ABC-based approach is described by DeCicco (2009), which illustrates its application with a quantitative example using data from a detailed case study of a U.S. ethanol facility. Although further analysis and development are needed, the approach can be outlined as having three main elements. These are: (1) full accounting of CO_2 emissions from fuel end-use regardless of the fuel's origin; (2) an attributional accounting protocol that relies on facilities-level GHG balances to report net CO_2 uptake and track otherwise unregulated GHG emissions throughout fuel and feedstock supply chains; and (3) a mechanism for mitigating consequential impacts, particularly the leakage due to ILUC.

Counting end-use CO_2 "emissions certain"

A foundation of sound policy is treating all CO_2 emissions that occur in the transportation sector at face value. For biofuels, this means counting their direct emissions to the atmosphere without automatic crediting of biogenic carbon. This aspect of policy design is applicable regardless of the overall climate policy whether it is carbon taxation, GHG emissions regulation using traditional source controls (e.g., "non-market" approaches under the U.S. Clean Air Act), or cap-and-trade. Implementing this element of a policy requires the correct point of regulation (POR), which cannot be located too far upstream. Because transportation fuels supplied to end users may contain components (such as ethanol, biodiesel or bio-based compounds) blended into fuel products at distribution terminals, the POR should be the point of finished fuel distribution. This POR is the same as that traditionally used for fuel properties regulation by the U.S. EPA (CFR 2009).

Abandoning an automatic credit for biogenic carbon may seem disconcerting to some analysts, but it is the only way to define a consistent GHG accounting framework without resorting to unverifiable assumptions about the extent of net carbon uptake that complicate other approaches. It is not tantamount to putting part of the agricultural sector under a carbon cap or other form of GHG regulation. Rather, it is a more accurate specification of how GHG controls apply to the transportation sector. After all, the CO_2 from vehicle tailpipes is an "emissions certain" (a well-defined quantity of molecular CO_2 entering the atmosphere) regardless of the source of the carbon in the fuel. In contrast, it is the extent of net uptake after accounting for both process emissions and leakage that is highly uncertain. Nevertheless, if all fuel carbon (biogenic and fossil) is regulated equally, biofuel suppliers will see the same market value for their product under climate policy as they see without it. Biofuel suppliers would not be competitively disadvantaged by the policy, but neither would they see the unconditional increase in value for biofuels that occurs with automatic crediting.

Tracking facility-level GHG balances

The second element of an ABC-based approach is a protocol for tracking carbon uptake and uncapped GHG emissions in biofuel and feedstock supply chains. Such a protocol would enable producers to obtain a verifiable credit for net carbon uptake in biofuel or fuel feedstock products. It would use strictly attributional accounting and entail reporting GHG balances at a local facility level, where *facility* here includes farms, managed forests or other sources of biofeedstock as well as biorefineries and processing plants.

Facility system boundaries are well defined and facility-level GHG fluxes and stock changes are in principle measurable, even though doing so is challenging for some important sources such as soil carbon and N_2O. In such cases, circumscribed models using local data could be applied to estimate GHG impacts that cannot be directly measured. This narrow use of modeling differs from its sweeping use in LCA-based regulation which, by trying to cover all options regardless of their empirical basis, ends up relying on broadly defined default values for generic feedstock-fuel pathways. The resulting adverse selection risk and other points of contrast between the approach outlined here and LCA regulation are discussed further below. For the biogenic carbon in a feedstock, measurement is straightforward and the data can be used to define the quantity of carbon uptake from which facility-level GHG emissions are debited unless they are already covered by a broader climate policy, e.g., through direct regulation, carbon taxation or allowance submission required elsewhere under a cap (as for purchased electricity).

In the case of cap-and-trade and barring direct GHG regulation of agriculture (which has not been seriously proposed), climate policy will affect agriculture indirectly through carbon price impacts on fossil-based inputs and the potential for income opportunities from offsets (Adams 2009). With agriculture and forestry unregulated, net carbon uptake tracking using facilities-level

GHG balances would be voluntary. But with CO_2 uptake no longer automatically credited in regulated fuel end-use sectors, the burden of proof shifts to feedstock producers. Although producers would have an incentive to document net uptake, they would not have a reporting obligation. CO_2 uptake and uncapped emissions tracking would be required only if a producer wishes to realize credit in the carbon-constrained fuels end-use market. Although such a policy is not perfect in the sense of immediately regulating all fuel-related emissions, it does avoid the egregious problems due to automatic crediting.

Applying the net uptake crediting protocol at the facility level will reveal -- and enable policy to exploit -- real-world variability. This is another key distinction from the process-based approach of LCA regulations. For example, the U.S. RFS treats all corn the same, avoiding any look at the variability in, say, N_2O emissions for different locations, growing conditions, fertilizing practices, and so on (EPA 2009). LCA-based policies also treat biorefining according to generic process characteristics, using "check box" methods that ignore the variability in emissions for a given process at different facilities, which can vary both locally and temporally according to market conditions, changes in inputs and changes in product mix. In contrast, a protocol based on annual facility-level reporting will foster scientific GHG management, which entails observing variability to enable selection of best practices.

The stated reason for not differentiating given feedstocks within a country is that they are fungible commodities (EPA 2009: 25022). However, this need not be a barrier; data on net carbon uptake could be incorporated into commodity trading contracts, as proposed for handling broader sustainability criteria for biofuels (Mathews 2008). Developing mechanisms to track emissions impacts through supply chains will be essential for rational GHG management of liquid fuels, which are likely to remain fungible commodities regardless of the source.

Addressing emissions from indirect land-use change

The final part of a policy is a mechanism for addressing leakage, specifically emissions from ILUC. Although estimates vary, ILUC is large enough to greatly influence the net GHG impact of biofuels (Melillo et al. 2009). The many assumptions that go into estimating it result in ILUC uncertainties greatly dominating LCA-based policy results (Plevin et al. 2010; Mullins et al. 2011). It is mediated by price signals tied to demand for agricultural and forestry products. If the biofuel-related portion of this price signal were neutralized, or an equal-and-opposite signal created for protecting forests, then that would be a way to mitigate emissions from ILUC.

One option for doing so could be a Land Protection Fund (LPF) for purchasing international forest carbon offsets in proportion to the ILUC emissions estimated to occur as a consequence of biofuel production. The LPF would be administered at the national level, commensurate with the scale and type of a nation's biofuel use, and designed to leverage programs for Reducing Emissions from Deforestation and Forest Degradation (REDD) being developed internationally (Gibbs et al. 2007). REDD is based on the body of work that emphasizes the importance of financial incentives for protecting forests (Gullison et al. 2007; Mollicone et al. 2007).

The LPF should not come at the expense of other REDD funding. To the extent that biofuel production indirectly exacerbates deforestation, funds for REDD should be increased beyond what is otherwise deemed appropriate. A number of options can be explored for financing the LPF, an issue that is left for future work. The requisite mitigation levels can be estimated using same models now applied to incorporate ILUC into regulations. Applying these methods to determine ILUC mitigation needs at a national scale is arguably a more appropriate use of such highly aggregate global models than reducing their results to product-specific values for LCA-based regulations such as an LCFS or RFS.

DISCUSSION

One way to look at the approach outlined here is as a deconstruction of LCA for the purpose of practical carbon management. It enables the use of insights from LCA without encumbering policy with the liabilities of LCA, chief among which are the compounding uncertainties that result from reliance on modeling and the indeterminacy that is introduced because of the need for consequential analysis to address leakage. However, questions can be raised regarding just how much an ABC approach ultimately differs from LCA; whether the mitigation fund for addressing ILUC would enable fuel suppliers to merely "buy their way out" of enforceable emissions reductions; and the extent to which the resulting policy would provide enough incentive to bring "truly low carbon fuels" to market.

How this approach differs from LCA

The approach outlined here shares with LCA a common ideal of accounting for all GHG emissions associated with the production and use of fuel. However, it differs in key ways, the most important of which is rooted in the fact that it does not automatically credit biogenic carbon. Under ABC accounting, biofuel end-use CO_2 emissions are fully covered whether or not biofuel and feedstock suppliers "opt-in" to the emissions tracking protocol. Conversely, the LCFS or other LCA-based policy presumption that biofuel carbon was recently absorbed from the atmosphere sets up a serious adverse selection risk regarding the accuracy of imputed supply-chain emissions, for which verification is not required, as well as the need to address ILUC leakage through highly uncertain consequential analyses and inherently non-empirical judgments about how to amortize carbon debt.

Another way to view the difference is by contrasting the *product* focus of LCA with the *source* focus of an ABC framework. With source-based accounting, the focus is on the specific locations ("facilities" as termed above) where GHG emissions and CO_2 uptake occur (sources and sinks, respectively). Thus, an ABC approach does not account for everything in one place as does a policy based on LCA, which analytically collapses all of the sources and sinks in a product's supply chain to the single, product-focused metric of carbon intensity. Although automatic crediting of biogenic carbon is arithmetically correct for the "cradle-to-grave" abstraction of a biofuel's lifecycle, it codifies a misplaced burden of proof as previously noted.

An ABC accounting structure reflects the fact that locations of biofuel CO_2 uptake (feedstock sinks) are remote from the locations of end-use CO_2 emissions (biofuel combustion sources). Whether or not biofuel and feedstock suppliers provide verifiable data on facility-level GHG balances, biofuel end-use emissions are covered, while they are not covered in a product-focused LCA policy. Neither are they covered in cap-and-trade systems that follow the Kyoto Protocol's convention of treating bioenergy as carbon neutral; such versions of cap-and-trade are incompletely source-based because of the exception they make for bioenergy products. An ABC policy admittedly entails a very high burden of proof for biofuel net CO_2 uptake, a situation that is arguably appropriate given that agricultural and forestry systems are presently unmanaged as far as GHG emissions are concerned.

Moreover, the source-based approach of an ABC policy does not fundamentally rely on a need for baselines because it is not attempting to treat the issue as an offsets problem. Thus, it is not concerned with the *local* additionality of CO_2 uptake in biofuel feedstock. That uptake is straightforward to measure based on the chemical carbon composition of the biomass used for biofuel production. Because the policy is not product focused, a GHG *reduction* associated with the use of a biofuel product is not computed in the ABC framework, and so an additionality test is not applicable. ILUC effects, which some might view as a lack of additionality globally, are treated strictly as leakage.

That being said, important practical aspects of measuring facility-level GHG balances will involve local modeling and a need for local baselines, e.g., for estimating net stock changes in managed forests or net effects on soil carbon and other important fluxes such as N_2O emissions. Such estimates could rely on use of models such as DAYCENT (e.g., Del Grosso et al. 2008), but rather than assuming national or broad regional-scale values as now used for LCA-based policy, these techniques would be applied with local and seasonal inputs for soil type and composition, precipitation, and other key variables including management practices. This approach would encourage localized applications of such modeling as well as field work to improve the measurement basis for the modeling. It would also position regulators to accept or reject the resulting farm, forest and other facility-level GHG balance data based on its quality, as opposed to being forced to rely on defaults in the absence of localized estimates.

The distinction can also be seen in the different starting points for ABC policy versus LCA policies. The latter claim to cover all fuels, in the case of an LCFS, or all (other than grandfathered) biofuels, in the case of the U.S. RFS and EU RED, and so start with a complete reliance on default values and other sweeping assumptions for the GHG emissions associated with feedstocks and fuels. Modeled GHG reductions are thereby assumed for biofuels without any "on-the-ground" verification and involve the inherently non-empirical convention of amortizing carbon debt over future periods. In contrast, the starting place for an ABC-based policy presumes no GHG reductions from the use of biofuels. Net uptake crediting would have to be developed "from the ground up," using the facility-level GHG balances as outlined above, and as part of a system that includes an explicit mechanism for countering the market pressures that lead to emissions leakage. Such a system can be initiated at a small scale with a few producers able to prove out the procedures, permitting oversight of early efforts to develop and implement the facility-level GHG balance protocols by agencies and third-party auditors whose methods can be tested, refined and validated for broader use.

Reduction obligations vs. leakage mitigation

Because the ABC framework treats leakage as a problem to be mitigated rather than attempting to incorporate its effects as adjustments to the level of GHG reduction assigned to biofuels, it can be criticized as providing a buy-out mechanism for biofuel and fossil fuel suppliers without enforcing any actual emission reductions. This criticism can be leveled at any form of climate policy that includes a trading mechanism. The common response is that because the shared atmosphere makes the location of GHG emissions immaterial, the problem reduces to one of ensuring the integrity of trades and offsets. That is an issue that receives considerable attention of itself. This proposal's reliance on REDD for addressing ILUC leakage would exploit the ongoing effort by researchers and policymakers to maximize the effectiveness of REDD for protecting forest carbon stocks, a process that developed in recognition of the limitations of project-based approaches for terrestrial offsets.

The magnitude of ILUC and the resulting leakage tied to biofuel use is highly uncertain and a question that cuts to the heart of debates about the role of the biosphere in climate protection (Righelato & Spracklen 2007). Nevertheless, studies indicate that its magnitude is large enough to negate the GHG reduction benefits of current biofuels relative to fossil fuels over multi-decade timeframes (Gibbs et al. 2008; Melillo et al. 2009; Plevin et al. 2010). LCA-based policies finesse this problem by the accounting device of spreading the large CO_2 releases from carbon stock changes during a current period over longer periods, such as 30 years for the U.S. RFS and California LCFS policies or 20 years for recent EU analyses undertaken for the RED (JRC-IE 2010).

For example, a recent estimate for the ILUC emissions impact of U.S. corn ethanol is roughly 800 gCO_2/MJ (Hertel et al. 2010). This value is an order of magnitude greater than the direct, end-use combustion only emissions of 72 gCO_2/MJ for either ethanol or gasoline. Only through amortization, e.g., over 30 years to yield a value of 30 gCO_2/MJ as in the California LCFS, can the estimated lifecycle ILUC impacts be made numerically small enough for the biofuel to appear to offer a reduction relative to fossil fuel. As a result, such LCA-based policies provide an incentive for greater use of biofuels, exacerbating leakage while incurring a significant risk that its magnitude may be even greater than that estimated through the very uncertain modeling (Mullins et al. 2011).

In contrast, an ABC policy does not privilege biofuels in a way that risks added leakage, and so an LPF would not need to address leakages as large as those risked by LCA policies that amortize large current-period stock changes over multi-decade future periods. Biofuel use unrelated to climate policy (i.e., as mandated for other reasons regardless of GHG emissions) arguably incurs no leakage problem as such, just the same (large) problem of induced consumption-related emissions driven by growing demand for agricultural and other products in carbon-unconstrained economies globally. For example, no one claims a GHG reduction when consuming grains for food or feed, and so leakage is not an issue; the problem arises when attempting to claim an emissions reduction from grain-based biofuel. The leakage concern arises when claiming an emissions *reduction*, a problem which is in turn an artifact of using a *product*-focused as opposed to a *source*-focused framework for policy.

Some might view ILUC as only a special case of the more general problem of leakage, which occurs when consumption in a carbon-regulated economy induces carbon-intensive production in an unregulated trading partner or when regulation of carbon-intensive industries causes production to shift to unregulated locations. Thus, other mechanisms might be considered for counteracting it, such as border adjustment taxes or programs to motivate offsetting emissions reductions in countries where the emissions due to leakage occur. None of these mechanisms are problem-free, and the considerations of economic efficiency, flexibility and minimizing trade barriers tend to argue for incentive measures over border adjustments (Winchester et al. 2010). Moreover, the nature of particular leakage problems and their effects on interest groups also factor into the choice of mechanism. For example, trade-exposed industries may not be satisfied to know that the emissions leakages have been handled when they still face a competitive loss of business; they may therefore prefer mechanisms using border taxes, rebates or allowance allocations. Given that the major leakage concern for biofuels is tied to the risk to forests or other terrestrial carbon stocks, and that there are other good reasons to protect those resources, a mitigation mechanism that targets forest protection seems appropriate.

Although this paper focuses on biofuels, similar considerations apply to bioenergy in general. Note also that the direct uptake crediting protocol is not the same as treating biofuels as a carbon offset. Although it can draw on the measurement and verification techniques developed for agricultural offsets accounting, the protocol outlined here yields a direct, annual measure of net carbon uptake, rather than an emissions reduction relative to some baseline, and so avoids the need for tests of additionality and permanence.

Technology change and market transparency

The voluntary facility-level GHG balance tracking outlined here will probably only motivate reporting by producers whose verifiable net carbon uptake is large enough to make it worthwhile for them to opt into the system. Nevertheless, it will foster the beginning of measurement-based GHG management in biofuel and feedstock production. Such a policy would harness approaches like those already used to enhance agricultural productivity by engaging producers, related businesses, extension services and agricultural researchers in a search for low-GHG solutions. A net carbon uptake crediting system coupled to a cap or other form of energy sector carbon regulation will create a market pull for emerging technologies such as cellulosic processing or biotechnologies with minimal land requirements while providing an incentive to improve the "carbon efficiency" of mature technologies that exist at scale today.

Advocates of the LCFS or other LCA-based fuels policies assert its importance as a technology-forcing mechanism for "low-carbon fuels," assuming that the carbon price signal from general climate policy will be too weak to motivate technology change (Sperling & Yeh 2009). If the climate policy is in fact poorly specified, e.g., by excluding biogenic carbon, by setting the point of regulation too far upstream from actual fuel assembly and distribution processes, and by lacking a rigorous mechanism for tracking GHG impacts in the supply chain, then such concerns are justified. However, the approach outlined here tightens the policy specification, ensures transparency and avoids loopholes that would indeed enable a transportation fuel supplier to merely pass the price through to consumers without incurring a risk that a competitor will find a lower cost way to measurably limit emissions.

Moreover, given the overwhelming uncertainties and lack of transparency inherent in specifying policy through LCA, it is difficult to have confidence in the results. The ABC approach outlined here would accurately expose the fuel supply and use systems to a carbon price signal, leading to greater confidence that whatever changes are motivated, they will tangibly limit emissions. If as a result of such a policy, including its mechanism for countering leakage, more land is devoted to protecting or rebuilding carbon stocks than is used to grow feedstocks for biofuels, that may well be the superior "technological" outcome as far as climate is concerned. In short, policy should be premised on measurable emissions limitations achieved in current periods rather than wishful thinking about fuels that might someday avoid more emissions in the future than they actually cause today. Far from being technology neutral as its proponents claim, policy specified through LCA picks presumed "winners" using prospective analysis that is built upon layers of technology-specific feedstock and fuel pathway assumptions. Because it avoids automatic crediting of biogenic uptake, an ABC approach takes a precautionary stance in keeping with a principle of "above all do no harm," unlike LCA policies which entail numerous unverified assumptions and so risk harm in the form of both direct and indirect GHG emissions resulting from an expanded use of fuels qualified through assumptions.

Managing emissions instead of disputing fuels

Indeed, a perhaps surprising aspect of the approach outlined here is that it does not involve explicit comparison of fuels. With all molecular carbon treated equally as a source of CO_2 emissions certain during fuel use, attention turns to handling production phase emissions by tracking carbon uptake and unregulated GHG impacts in the supply chain in addition to an overall climate policy's presumed coverage of major industrial sources. The focus is on facilities where emissions actually occur rather than on products to which emissions are imputed through LCA. Moreover, because liquid fuels and their feedstocks are fungible commodities, it is unclear that differentiating them with a product-based metric is as effective as pricing their production-related emissions, which an ABC approach would achieve by exposing fuel supply chains to a carbon price signal whether derived explicitly from a carbon market or a carbon tax or implicitly from direct GHG regulation.

From a deeper perspective, attempting to regulate fuels through LCA can be seen as premised on a "fallacy of misplaced concreteness" (Whitehead 1927). A form of logical reification, this mistake involves treating an abstract construct (in this case, a fuel's lifecycle GHG emissions) as if it were a concrete physical property (such as a fuel's chemical composition). Seen in this light, LCA-based regulation is an unproven and radical departure from traditional environmental policy based on measured substances or impacts of concern. For biofuels, the key impacts occur at fields and facilities; those locations are the sources of physical emissions that must be measured to ensure transparency. Carbon intensity is purely notional; it cannot be measured in a repeatable way as can, for example, limits on sulfur or other chemical specifications for fuels. Although ILUC brings the issue to a head, the uncertainty and variability of many other production-related emissions are also problematic. The high degree of abstraction entailed in lifecycle GHG estimates is clear in the CARB (2009) and EPA (2009; 2010) documents, which reveal how regulatory compliance heavily depends on numerous modeling assumptions, the vast majority of which have not been verified, many of which are practically impossible to verify, and some of which (such as those for amortizing carbon debt) are inherently not empirical yet have a great influence on the results.

In contrast, a GHG management policy using current-period, facilities-based ABC accounting does not require assumptions about emissions reductions based on abstract estimates of complex systems and their spatial and temporal behavior. Neither does it require resolving long-running debates about the climate benefits of biofuels. Rather, it acknowledges the reality of biofuels in the marketplace and the fact that neither fossil fuel supply systems nor agricultural systems have been carbon constrained to date. A cap-based policy using ABC accounting can co-exist with the RFS or other biofuel mandates while avoiding the need for GHG lifecycle regulations in an RFS or LCFS. As a rational system for carbon management, it would create incentives for lower net GHG emitting options regardless of their form and whatever their emissions may be today, recognizing that some of the most cost-effective opportunities for limiting emissions may well be found through scientific management of existing GHG-intensive systems.

While climate protection may have been a rationale for promoting biofuels, an unvarnished political analysis shows that support for biofuels rests on their value for rural economic development -- an important interest in most political systems -- amplified by concerns about energy security. Although many environmentalists promoted biofuels (e.g., NRDC 2005), climate concerns are not a foundation for biofuels policy. For example, legislation that expanded the RFS passed the U.S. Senate with a vote of 86-8 (Sissine 2007), clearly supported by many members opposed to climate policy *per se*.

CONCLUSION

While further analysis and development are needed for the approach outlined here, its paradigm of applying ABC accounting tied to a carbon cap offers a tractable climate policy not just for biofuels, but for transportation fuels generally. Cap-and-trade creates a price signal that fosters economic efficiency and, given adequate integrity and transparency, enables an extension of carbon management to uncapped sectors and sources. An ABC approach provides mechanisms for handling challenges of policy diffusion and problems of leakage due to the impossibility of imposing caps everywhere at once. It is therefore well suited for addressing biofuels, which involve uncapped sectors (agriculture and forestry) and indirect impacts in uncapped jurisdictions across international borders. Although cap-and-trade would offer the ideal framework, ABC accounting mechanisms could be adapted to other forms of policy such as direct carbon regulation or carbon taxation.

As for recently adopted policies that attempt to regulate fuel-related GHG emissions on a lifecycle basis, careful consideration reveals that specifying policy through LCA is premised on a logical fallacy. The problem is that of imputing to a product all of the emissions impacts of the complex systems involved in its production. Real-world fuel products derive from commodity and agro-industrial systems whose spatial and temporal boundaries cannot be circumscribed in ways that are at once traceable and sufficiently complete to ensure environmental integrity. Viewed through a lifecycle lens, automatic crediting of biogenic carbon uptake may appear arithmetically correct. However, the result is a misplaced burden of proof. Fuel suppliers and end-users are relieved of counting the CO_2 "emission certain" from biofuel combustion while no clear accountability is established for the production emissions (direct and indirect) that occur in the diverse and dynamic supply chains for feedstocks, fuels and their associated inputs.

While it may be discomfiting to some readers, the conclusion is that LCA is inappropriate for specifying regulations. Although LCA may be a useful research tool and can helpfully inform policy discussions, its literal application for policy specification is a mistake. Disputes over LCA regulatory outcomes are unproductive and ultimately unresolvable; defining policy with ABC accounting offers a way out of this morass. Developing ABC-based fuel-sector policies offers a near-term path forward, at least in jurisdictions such as California and the European Union that have made serious commitments to limit GHG emissions, and can begin to put in place an accounting framework that will stand the test of time as other jurisdictions face up to the climate threat. It is not feasible to establish anytime soon (if indeed ever) the type of global policy covering energy and other industrial sources as well as land suggested as ideal by Wise et al. (2009). However, it is possible to establish sound ABC accounting protocols (whether voluntary or mandatory) in successive jurisdictions, thereby guiding markets toward emissions-limiting decisions that will at least enhance the prospects for major technology and system changes that are truly climate friendly.

In summary, adherence to direct, source- and sink-based, current-period accounting provides a robust framework for handling emissions from fuels regardless of their origin. Fully including transportation fuels under a carbon cap would put the majority of the sector's emissions under carbon management. Biofuels have come to present a special problem because biogenic carbon is excluded from fossil-based caps as proposed to date even though (like most forms of bioenergy) their production is intrinsically coupled to terrestrial carbon stocks. However, these issues can be handled through an ABC approach that accounts for all fuel end-use CO_2 emissions at a well-specified point of regulation; a protocol to track carbon uptake and uncapped emissions in fuel and feedstock supply chains; and a land protection fund to mitigate leakage from ILUC. Such an approach will create a sound carbon management framework for the sector and in so doing, move policy closer to the integrated treatment of fossil energy and terrestrial GHG sources ultimately needed for effective climate protection.

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