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Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum

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Abstract
The global warming intensities of crop-based biofuels and fossil fuels differ not only in amount but also in their discharge patterns over time. Early discharges, for example, from market-mediated land use change, will have created more global warming by any time in the future than later discharges, owing to the slow decay of atmospheric CO_2. A spreadsheet model of this process, BTIME, captures this important time pattern effect using the Bern CO_2 decay model to allow fuels to be compared for policy decisions on the basis of their real warming effects with a variety of user-supplied parameter values. The model also allows economic discounting of climate effects extended far into the future. Compared to approaches that simply sum greenhouse gas emissions over time, recognizing the physics of atmospheric CO_2 decay significantly increases the deficit relative to fossil fuel of any biofuel causing land use change.

Keywords: biofuels, greenhouse gas emissions, life cycle assessment, land use change

1. Introduction

Performance-based regulations under development in several jurisdictions promote transportation fuels with lower life cycle greenhouse gas (GHG) emissions than petroleum-based fuels. For this comparison, they use a performance metric that aggregates each fuel's direct and indirect GHG emissions into a global warming intensity (GWI). Recent studies of the effects of expanding biofuel feedstock production find large GHG emissions from land use change (LUC) for biofuels that compete for land with other uses such as the production of food. Changes in land use are transmitted across global markets linked by commodity substitutability and competition for land. These market-mediated LUC emissions are not only separated from the biofuel production process by several economic links and physical distance, but also follow a time profile very different from the direct emissions from fossil and biofuel use, being released quickly upon expansion of biofuel production [19].

To obtain a GWI, previous analysts average the total indirect emissions over the total fuel produced during a predicted production period and add these to the direct emissions, implicitly treating a unit GHG emission released today as though it has the same consequences as one released decades in the future. This 'straight-line amortization', for example, is proposed for the California Air Resources Board's implementation of that state's Low Carbon Fuel Standard [3]. Economic discounting can in principle be used to compare costs and benefits over time, but annual GHG flows are, in general, a poor proxy for economic costs: most GW costs are imposed by GHG *stocks* in the atmosphere. Furthermore, consideration of long time frames requires realistic predictions

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about technological innovation and land use changes over that timeframe, including post-cultivation changes in land use.

We define a framework to aggregate GHG emissions and other radiative forcing effects that occur over a significant span of time into a GWI metric that better represents the climate effects of fuel substitution, applicable to any estimate of discharges that are not uniform over time. Our framework accommodates changes in the duration of the production period and post-production LUC, and converts physical effects to economic damages that can properly be discounted. These corrections to previous practice increase the relative importance of early emissions, and in turn the GWI of biofuels that cause LUC.

1.1. Treatment of time in life cycle assessment

In life cycle assessment (LCA), emissions of pollutants are typically summed without regard for when or where these emissions occur [10]. For well-mixed greenhouse gases, it is appropriate to ignore the location of the emissions, as these are global pollutants. However, for long-lived pollutants, summing emissions over time masks potentially important differences among processes, especially if effects are measured at a fixed target date. In these situations, early emissions are in the environment longer relative to the target date, and thus cause greater environmental damage.

In the case of greenhouse gases (GHGs), global warming effects are usually aggregated by summing emissions of three gases (CO_2, CH_4, and N_2O) weighted by their respective global warming potentials (GWP). GWP is the measure of the cumulative radiative forcing (CRF) over a fixed time horizon (e.g., 20 or 100 years) of a pulse of some gas compared to the CRF of an equal mass of CO_2 over the same period [7]. Most LCAs use the 100 year GWPs published by the IPCC [7].

In an LCA, it is appropriate to sum GWP-weighted GHG emissions for a process whose emissions are largely coincident with production and use. Summing GWP-weighted GHG emissions also makes sense in a national emissions inventory for a single year, because over the standard 100 year time horizon the specific release date *within* the inventory year is inconsequential to the total CRF. In both of these cases, emissions are implicitly summed or compared using a consistent integration period.

Since LCAs are defined in terms of a functional unit (e.g., emissions per MJ of fuel) [14], emissions from preparatory processes, such facility construction, must be allocated over the assumed lifetime of the facility to place these emissions in terms of the functional unit [1]. In practice, these amortized emissions are generally assumed negligible and ignored in LCA, resulting in a well-recognized 'truncation error' [9].

However, when considering indirect LUC caused by land-competitive biofuels, the assumptions that (i) emissions are largely coincident with production and use, or (ii) that preparatory emissions are negligible, no longer hold. The up-front iLUC emissions from land-competitive biofuels must be allocated over (that is, causally linked to) a quantity of fuel produced over decades, and the biofuel must be compared with a petroleum fuel with relatively small up-front emissions. When we compare processes with very different emission profiles over decades, the simple summation approach is no longer valid because it incorrectly sums the CRF of releases measured over overlapping, but distinct, integration periods. This is not the same as summing the CRF of these releases over a consistent, short time horizon during which all emissions occur. Discounting emission flows, as some have proposed, only compounds the error, since GWPs apply no discounting within their defined time horizon, and 100% discounting beyond the time horizon.

We recognize that GWPs represent an imperfect compromise in their treatment of time, but this compromise has been broadly accepted. Comparing the CRF as implemented in our model of two processes with different emission profiles, over a single time horizon, is consistent with the use of GWPs in national inventories, and therefore it is an appropriate approach for use with policies intended to mitigate climate change.

1.2. Time horizons

Estimating LUC GW effects for biofuels requires careful distinction of three characteristic time periods often confused in political discourse. The first of these is the *analytic horizon*, the period over which consequences are 'counted' in analysis. This may be one hundred years or more. The second is the *production period*, the time during which the analysis assumes a biofuel will be produced and displace fossil fuel. The appropriate production period is no longer than the time until the biofuel will be economically displaced by other fuels or cease production for other reasons. This value is very important for GWI estimation because it affects how long biofuel production has to 'pay back' its initial LUC emissions [8, 6], and because it determines when post-production LUC must be considered.

The third important period runs from the present to a *policy target date*. For example, the California low carbon fuel standard (LCFS) requires a 10% reduction in transportation fuels' average GWI by 2020, and the US Energy Independence and Security Act of 2007 (EISA) requires 21 billion gallons (80 GL) of 'advanced renewable fuels', that achieve a 50% GWI reduction compared to their petroleum counterparts, to be used by 2022 [4, 2]. However, neither policy specifies the date at which measurement of the GWI should be taken. The standard approach used in life cycle assessment, summing GHG emissions weighted by their global warming potential (GWP) regardless of when they occur in time [10], is incoherent (as noted earlier) and it underestimates the climate effects of LUC. A flawed protocol for calculating fuel GWI could inadvertently drive a wedge between the policy and its larger purposes, causing increased global warming rather than less. Our analysis focuses on assuring that GWI calculations implementing a biofuels policy will advance the goal of mitigating climate change.

2. Conceptual framework

To determine whether substituting a particular biofuel for petroleum increases or decreases global warming requires

decisions about the analytic and production timeframes, and whether only physical quantities, or their costs and benefits in social and economic terms, are to be assessed. Our analysis proceeds first from discharges to warming consequences, and then (prospectively) to improved benefit/cost assessment.

2.1. Physical approach

Fuel production and use increases climatic warming not only via the release of GHGs but also by direct perturbation of the earth's energy balance through land use changes that alter biophysical land surface properties such as albedo and evapotranspiration. These effects can be aggregated into a time-dependent annual radiative forcing term attributable to fuel i's use, $\mathrm{RF}_i(t)$.

$$\mathrm{RF}_i(t) = \sum_j a_j G_{ij}(t) + B_i(t) \tag{1}$$

$G_{ij}(t)$ is the additional atmospheric abundance of GHG j at time t attributable to the use of fuel i, a_j is the radiative efficiency of GHG j. Given the projected time profile of discharges for fuel i and GHG j, the time-dependent abundance, $G_{ji}(t)$, is obtained using models such as the Bern carbon cycle model [15, 7]. $B_i(t)$ represents all non-GHG radiative forcing effects of fuel i at time t.

Integrating the radiative forcing term over the analytic timeframe, $0 < t < t_\mathrm{a}$, gives the cumulative radiative forcing:

$$\mathrm{CRF}_i = \mathrm{CRF}_i(t_\mathrm{a}) = \int_0^{t_\mathrm{a}} \mathrm{RF}_i(t)\,\mathrm{d}t \tag{2}$$

a physically plausible proxy for the total damage to the planet from the CO_2 emissions stream up to a particular analytic horizon t_a. The ratio of the CRF for the biofuel b to that of the reference fuel g, provides a physical *fuel warming potential,* or $\mathrm{FWP_p}$,

$$\mathrm{FWP_p} \equiv \frac{\mathrm{CRF}_b}{\mathrm{CRF}_g}. \tag{3}$$

This $\mathrm{FWP_p}$ (generally a function of t_a) is a more meaningful physical quantity on which to evaluate biofuel lifecycle emissions than the aggregated emissions over time. Moreover, $\mathrm{FWP_p}$ follows the approach of the Global Warming Potential metric, or GWP, used to convert emissions from non-CO_2 GHGs into their CO_2 equivalencies, an approach well established in policy and science [7].

2.2. Benefit–cost analysis

Uniformly allocating the initial emission from LUC across the production period treats a unit of GHG discharge now as though it is equally costly as a unit emitted twenty years from now. Specifically, it means that two fuels differing only in that one has, say, 10% of its total discharge at the end of an analytic horizon of 50 years while the other discharges 10% right away, with the remaining 90% in each case distributed uniformly over the period, would be scored as equals and treated as equally costly or beneficial on a GW basis. Policy analysis conventionally recognizes discounting as the tool with which to make distinctions like this. A discounted model counts the *net present value* (NPV) of benefits of B (also costs) t years in the future as

$$\mathrm{NPV}(B) = \left[\frac{1}{1+r}\right]^t B \tag{4}$$

where r is an annual discount rate. For example, if one knows a capital asset will wear out in about twenty years, one does not count that as the present cost of its replacement, but a smaller number, namely the amount that would have to be deposited in some sort of interest-bearing investment to attain the price of the asset twenty years from now. Discounting may also measure a pure delay effect, wherein something of value is simply worth less to us if received at a time in the future than it would be if received now. The effect on global warming decisions of economic discounting can be very large because the time spans analyzed are usually long: the present value of \$1 received twenty years in the future is only about 50c at $r = 3\%$. A current debate about the appropriate discount rate for global warming policy analysis focuses on the extremely low discount rate used in the *Stern Review* and the rapid commitment of expensive resources it implies [20, 18, 17, 22]. The controversy does *not* concern *whether* economic costs and benefits occurring over time should be discounted when calculating costs and benefits for action (though the discount rate apparently used in Stern is so low as to be nearly zero).

However, the intellectual and behavioral basis of this kind of discounting and the debate around it applies only to economic goods, in a world in which market mechanisms (like banks and contracts) exist by which goods in the future and the present can actually be traded against each other: the discounting model applies to costs and benefits, not to physical phenomena that generate them, *unless* their economic value is otherwise stable over time. Consider a simple example: let the *economic value* of a gallon of water on January 1 be W, and assume that a gallon of water will also sell for W on July 1. The net present value on January 1, by conventional discounting, of 10 gallons of water *for delivery on July 1* is then

$$\left[\frac{1}{1+0.06}\right]^{0.5} W \tag{5}$$

at 6%, or about 0.97 W.

It is tempting also to say, in January, that a *gallon* of water on July 15 is worth[5] 0.97 *gallons* of water now, but if the use of the water is known and it is not available for purchase whenever desired, this easy approximation can be entirely misleading. For example, if the water is intended for a garden that would not be planted until May, it is much *more* valuable in July than in January. And if it is to be applied to a house that is on fire on January 1, delaying delivery to July makes it pretty much worthless. In both cases, conventionally discounting a physical quantity produces absurd results for reasons more fundamental than an incorrect choice of r. If the money values of water at each time under each assumption (garden later or fire now) are

[5] The phrase *A is worth xB* in the present context does not denote a theoretical philosophical judgment, but the precise normative behavioral claim that society should be willing to actually give up A for x units of B indifferently. Policy choice is an act of exchange.

calculated, these may be appropriately discounted in the usual way, but discounting the physical quantity will not indicate these differential values for many cases, including the present one of iLUC GW estimation.

The purely physical assessment of radiative forcing can be amended to incorporate social preferences typically included in policy analyses, the simplest being the preference to have benefits sooner rather than later as reflected by computing a net present value (NPV) using a discount rate r. However, discounting is correctly applied only to economic rather than physical quantities, so before such economic analysis can be meaningfully pursued the relationship between physical and economic quantities must be established. This relationship can be described in a *damage function,* $D(\mathrm{RF}_f(t), t)$. A complete and realistic damage function is beyond the scope of this paper. However, among the relevant physical quantities discussed above, the radiative forcing $\mathrm{RF}(t)$ is the most appropriate starting point, since this is the most straightforward measurement of the extra heat absorbed by the planet as a result of biofuel use, and it is this heat that drives many of the damages caused by climate change [7, p 210]. A highly simplified approximate damage function, $D(t)$, treats economic damage as directly proportional to $\mathrm{RF}(t)$ with a proportionality constant that is invariant in time such that:

$$D(t) \cong d\mathrm{RF}(t) \tag{6}$$

where d is the damage proportionality constant[6]. Using this damage function, an especially appropriate approximation for the small increments and decrements in GHG emission associated with fuel policies, and an appropriate discount rate allow computation of a net present value (NPV):

$$\mathrm{NPV} = \int_0^{t_a} \frac{d\mathrm{RF}(t)}{(1+r)^t}\,\mathrm{d}t. \tag{7}$$

We emphasize that discounting a stream of *emissions* with long residence times is not a satisfactory approximation. Comparing the NPV of the biofuel case b and reference gasoline case g over the analytic time horizon allows for the computation of an *economic* $\mathrm{FWP_e}$

$$\mathrm{FWP_e} \equiv \frac{\mathrm{NPV_b}}{\mathrm{NPV_g}}. \tag{8}$$

For the simple cost function discussed above, the damage proportionality constant d cancels out of the $\mathrm{FWP_e}$ calculation. For the limiting case $r = 0$, $\mathrm{FWP_e} = \mathrm{FWP_p}$.

For use in regulations based on ratings measured in g CO_2e MJ^{-1}, either FWP can be scaled by the GWI of the baseline petroleum fuel to produce a commensurate biofuel *fuel warming intensity* (FWI):

$$\mathrm{FWI}_x = \mathrm{FWP}_x \times \mathrm{GWI_{baseline}} \tag{9}$$

where x is either p or e to specify a physical or economic fuel warming intensity.

[6] The authors do not suggest that the true damage is adequately captured by such a simple expression, especially the implication that the damage constant is constant over time. Reductions in radiative forcing that occur after irreversible calamities—such as the failure of the Gulf Stream, or the Greenland ice cap melting or sliding into the sea—may be described with time-dependent damage functions more complex than ours.

3. Methods

To demonstrate the importance of the differences between biofuel and petroleum-based GHG discharge profiles, we have developed the *Biofuels Time Integrated Model of Emissions* (BTIME)[7]. BTIME can be easily parameterized by users with values corresponding to different LUC model results. We present it here with parameters distilled from iLUC modeling results based on the GTAP model [12, 11] and ecosystem carbon data from Woods Hole Research Center [19, supporting online materials] to generate a CO_2 emissions scenario for maize ethanol and gasoline[8].

Emissions over time are estimated for the following streams:

(1) Immediate loss of above-ground biomass carbon.
(2) Loss of 25% of below-ground carbon in the top 1 m of soil. Of this 25%, 80% (20% of the total) is lost in the first 5 years, and 20% (5% of the total) is lost over the subsequent 20 years [5]. The model can be adjusted to reflect other emission profiles for below-ground carbon.
(3) Foregone sequestration. Following Searchinger *et al* [19], we assume that the conversion of forest to cropping results not only in loss of sequestered carbon, but in the loss of future sequestration that *would have* occurred had the forest been left standing. These are treated as 'emissions' occurring over a variable number of years, depending on model parameters.

BTIME tracks the accumulation of CO_2 in the atmosphere for maize ethanol capacity brought on-line in 2010, and the gasoline it displaces. To track how much of the released CO_2 remains in the atmosphere we use the revised version of the Bern Carbon cycle model, assuming a background CO_2 concentration of 378 ppm [13, 15]. Specifically, the decay of a pulse of CO_2 at time t is given by

$$a_0 + \sum_{k=1}^{3} a_k \mathrm{e}^{\left(\frac{-t}{\tau_k}\right)} \tag{10}$$

where $a_0 = 0.217$, $a_1 = 0.259$, $a_3 = 0.338$, $\tau_1 = 172.9$ years, $\tau_2 = 18.51$ years, and $\tau_3 = 1.186$ years[9].

3.1. Model limitations

In the model, we make several simplifications that could be corrected in a more elaborate version:

(1) The decay rate for atmospheric CO_2 assumes a constant background concentration in the atmosphere.

[7] The BTIME model is described further in the supporting materials, and can be downloaded from http://rael.berkeley.edu/BTIME.

[8] BTIME does not purport to be a complete model of the climate effects of increased biofuels production. The model does not include the full range of indirect effects (e.g., changes in methane emissions from rice and livestock production or changes in fossil fuel use), nor does it include changes in biogeophysical phenomena (e.g., albedo, surface roughness, and latent heat flux) or non-GHG emissions (e.g., black carbon, aerosols, and ozone precursors). More research is required in all of these areas. The general framework presented can accommodate these factors within the globally averaged radiative forcing term once estimates exist.

[9] BTIME tracks the decay of each term in the sum separately.

(2) We assume that the radiative efficiency of the GHG is constant.
(3) We treat iLUC and ongoing emissions as if they were entirely CO_2.
(4) We neglect non-GHG radiative forcing effects.

The radiative forcing of a pulse of a particular GHG depends both on its radiative efficiency and the quantity of gas remaining in the atmosphere. Radiative efficiency for a marginal unit of CO_2 decreases non-linearly as the background concentration of CO_2 in the atmosphere increases, while for methane and N_2O the relationship is approximately linear [7]. At the same time as radiative efficiency decreases, CO_2's residence time in the atmosphere will *increase* owing to a slowing of CO_2 removal from the atmosphere. Decreasing marginal radiative efficiency for CO_2 and a slowing decay rate for atmospheric CO_2 partially balance out [16]. Indeed, the IPCC's GWPs ignore the effect of changing background concentration as well. Both corrections are absent in our model. A more complete analysis should include both of these corrections, and should also account for GHGs other than CO_2.

The relevant non-CO_2 GHGs in the biofuels life cycle are N_2O and CH_4. N_2O releases are affected by yield intensification of crops, especially crops fertilized with nitrogen compounds, and CH_4 is especially affected by livestock production changes. Both of these changes occur as a result of market signals associated with increased or decreased production of any biofuels that compete with food for land. The current model simply converts all GHG emissions to CO_2e using GWPs from the IPCC's Fourth Assessment Report [7]. This treatment does not reflect the actual behavior of the gases in the atmosphere especially with respect to CH_4, where it underestimates effects over shorter time horizons. CH_4 has a much shorter lifetime in the atmosphere than CO_2, which partly explains the falling standard GWP value for CH_4 as the time horizon of analysis grows (75 for a 20 year time horizon versus 25 for a 100 year time horizon) [7, table 2.14]. However, according to the GREET 1.8b model, CH_4 emissions make up less than 5% of total CO_2e emissions in the maize ethanol life cycle and even less in the gasoline life cycle, so we do not expect omitting its proper treatment in the current model to significantly influence the outcome [21]. N_2O emissions, however, constitute about 25% of CO_2e emissions for maize ethanol and only 1% for gasoline [21], so its current treatment in BTIME requires explanation. The mean lifetime of N_2O in the atmosphere is approximately 114 years, not too different from the average life time of CO_2, and its GWP only changes by 3% between a 20 and 100 year time horizon [7, p 212]. Thus, while our treatment of N_2O in a CO_2e form is imperfect, the outcome would not change significantly from its correct treatment since its relative behavior compared to CO_2 does not vary significantly over the time horizons used in our model.

4. Results

We emphasize that this paper is concerned with the methodology embodied in BTIME, and not any particular estimate of LUC emissions for any particular biofuel. To illustrate the importance of this methodology, we report the effect of applying it to LUC estimates from our GTAP work [12] (which are much lower than Searchinger's). Assuming that maize ethanol is produced for 25 years starting in 2010 with direct life cycle emissions of 60 g CO_2 MJ^{-1} versus 94 for gasoline, and that the converted ecosystems revert over 30 years to hold 50% of the carbon held before cultivation, we project the annual emissions streams for maize ethanol and gasoline shown in figure 1 with dashed lines. Using the Bern carbon cycle model [7] we compute the increased abundance of CO_2 in the atmosphere over time, (solid lines).

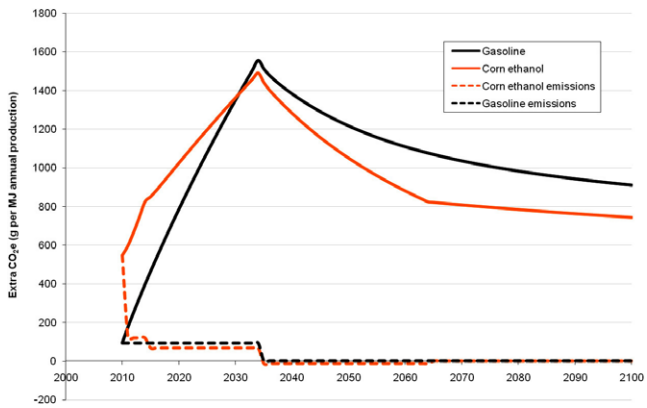

Figure 1. CO_2 emissions and resulting atmospheric abundance for gasoline (25 years at 94 g CO_2e MJ^{-1}) and maize ethanol (25 years at 60 g CO_2e MJ^{-1} plus iLUC discharge of 776 g CO_2 MJ^{-1} and foregone sequestration totaling 102 g CO_2 MJ^{-1}; post-cultivation recovery of 50% of the lost biomass carbon over 30 years).

The maize ethanol emissions stream depicted by the dashed orange line begins with a large release as land is cleared (directly or indirectly) for biofuels feedstock cultivation, followed by five years in which soil carbon is released rapidly and twenty years of slower release [5]. After the ethanol production ceases in 2035 we assume a small annual carbon sequestration through 2065 as land reverts in part to its original condition (other ways to handle post-cultivation LUC are discussed further in SOM). The emissions profile of gasoline displaced MJ-for-MJ has no initial release and fixed production/use emissions over the time in which biofuel is being produced. The solid lines show the abundance of extra CO_2 in the atmosphere for the two cases, which is the sum of new releases subject to gradual reduction through the functioning of the carbon cycle. The implicit policy choice is between obtaining the same amount of fuel energy by following the black or orange paths.

For the first 15 years of production the maize ethanol case leads to higher CO_2 abundance, and after that gasoline's is higher. This crossover should not be interpreted as a 'break-even' point, because at this crossover, the planet has been warmer for the preceding 15 years in the maize ethanol case, leading to damage that remains at the crossover point manifested in higher sea levels, more ecosystem damage, and retained heat in reservoirs like the ocean.

A physical 'break-even' occurs with equal *cumulative warming*, as is captured in the FWP and FWI metrics described below. We assume that after 25 years, the maize ethanol

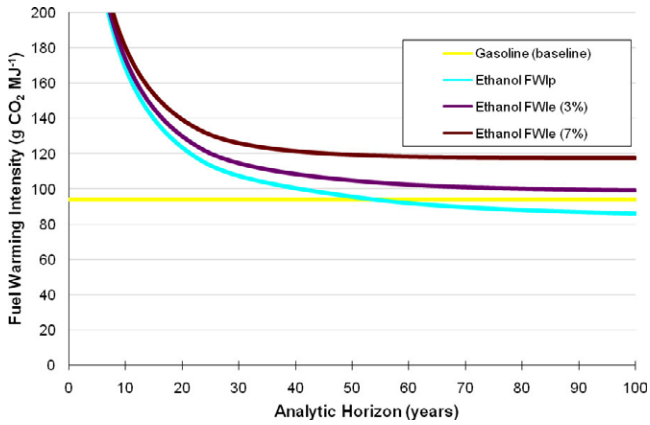

Figure 2. Fuel warming intensity (g CO_2 MJ^{-1}) versus analytic horizon.

production and the displaced gasoline emissions cease. The post-cultivation period has some recovery sequestration for ethanol and significant reductions in CO_2 abundance for both species as the carbon cycle absorbs some of the atmospheric carbon.

Figure 2 illustrates the difference between the physical and economic metrics, and the effect of discount rate on the result. In this figure, the y axis indicates the relative performance of maize ethanol to gasoline and the x-axis reflects different analytical horizons.

The FWI_p for maize ethanol (light blue line) shows that using this biofuel results in greater warming than does using gasoline over analytic horizons of less than 50 years. For a 30 year analytic horizon the ethanol's FWI_p is 15% higher than gasoline's. To compare this result to earlier work, note that the parameters used in our model would show biofuel emissions 5% *lower* than gasoline's if the annual emissions were simply averaged, even over 30 production years [19]. Over a 100 year analytic horizon, biofuel production shows an 8% benefit versus gasoline, and this result is highly dependent upon the assumption that the land reverts toward a natural state following biofuel production. The extent of ecosystem recovery after biofuel production ceases decades from now is unknowable, therefore crediting a biofuel with this regrowth may be inappropriate. Excluding this credit results in the FWI_p of the modeled ethanol being 4% greater than that of gasoline after 100 years.

Non-zero discount rates further degrade the benefits of projected future fuel production and reduce sensitivity to assumptions regarding post-production regrowth. With a 3% discount rate and 100 year analytic horizon, the FWI_e of ethanol is 3% greater than that of gasoline; with a 7% discount rate ethanol's FWI_e is 16% greater. Excluding land reversion increases these spreads to 11% and 20%, respectively.

5. Conclusion

5.1. Summary

We developed a model of the cumulative radiative forcing caused by the production and use of biofuels and gasoline, including emissions from biofuels-induced land use change (LUC). Our model aggregates GHG emissions that occur over a significant span of time into a global warming intensity metric that better represents the climate effects of fuel substitution.

Properly treating emissions and decay over time increases the importance of near-term emissions since the cumulative warming and associated damages from those emissions, for any finite analytic horizon, are more severe. Compared to approaches that simply sum GHG emissions over time, we show that recognizing the physics of atmospheric CO_2 decay and radiative forcing significantly increases the estimated climate effects relative to fossil fuel for any biofuel causing LUC. We also show that economic discounting is only applicable to costs and benefits, not to physical phenomena that generate them, *unless* their economic value is stable over time. Cumulative radiative forcing is a better proxy for economic damages than the sum of GHG flows, and as such is a more appropriate quantity to which to apply discounting.

We propose a new measure of the climate performance of biofuels, *fuel warming potential* (FWP), defined as the ratio of the cumulative radiative forcing caused by the life cycle GHG emissions from a biofuel relative to that of its fossil substitute. Where discounting is desired, we propose an 'economic' version of the FWP, defined as the ratio of the net present values of the cumulative radiative forcing from the two fuels. Any positive discount rate magnifies the importance of early emissions.

We also define a metric called fuel warming intensity (FWI), which simply multiplies either version of FWP by the global warming intensity of direct emissions (in units of g CO_2e MJ^{-1}) of the fossil fuel (e.g., gasoline) to produce a quantity with suitable units for use in fuel regulations.

Finally, we note that large initial GHG discharges are not unique to crop-based biofuels. Analysis of any GHG-reducing technology with large up-front capital investments (nuclear, tidal, wind, photovoltaics) should similarly account for up-front GHG discharges (for example, from cement manufacture) as we do here.

5.2. Policy considerations

To achieve real climate benefits, 'low carbon' biofuel policy must recognize the importance of early emissions, and climate policies should use performance metrics that reflect cumulative warming rather than GHG flows.

Operationalizing the approach recommended herein forces the regulator to choose values for several influential model parameters, particularly the analytic horizon. An analytic horizon extending into decades requires predictions about the expected cultivation period and post-cultivation LUC, decisions on how post-cultivation LUC emissions should be credited, and assessment of the time-value of benefits and costs. Benefit–cost analysis brings with it the need to settle on a reasonable damage function and an appropriate discount rate as well. Policymakers may find it appropriate to focus on more certain, near-term climate impacts, in which case a short horizon physical FWI is sufficient. For short analytic horizons, discounting has little effect and post-cultivation LUC occurs beyond the system boundary.

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