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Relevance of Emissions Timing in Biofuel Greenhouse Gases and Climate Impacts

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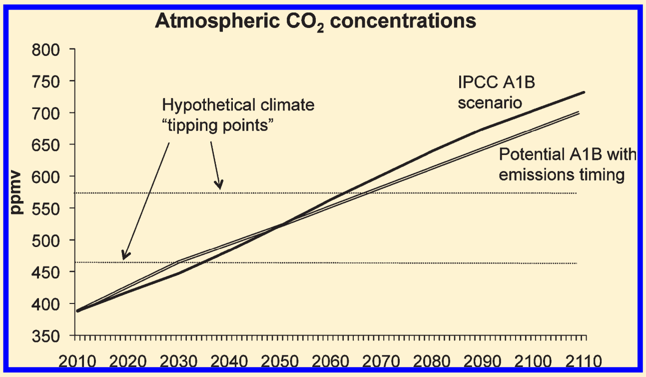
Supporting Information



ABSTRACT: Employing life cycle greenhouse gas (GHG) emissions as a key performance metric in energy and environmental policy may underestimate actual climate change impacts. Emissions released early in the life cycle cause greater cumulative radiative forcing (CRF) over the next decades than later emissions. Some indicate that ignoring emissions timing in traditional biofuel GHG accounting overestimates the effectiveness of policies supporting corn ethanol by 10−90% due to early land use change (LUC) induced GHGs. We use an IPCC climate model to (1) estimate absolute CRF from U.S. corn ethanol and (2) quantify an emissions timing factor (ETF), which is masked in the traditional GHG accounting. In contrast to earlier analyses, ETF is only 2% (5%) over 100 (50) years of impacts. Emissions uncertainty itself (LUC, fuel production period) is 1−2 orders of magnitude higher, which dwarfs the timing effect. From a GHG accounting perspective, emissions timing adds little to our understanding of the climate impacts of biofuels. However, policy makers should recognize that ETF could significantly decrease corn ethanol's probability of meeting the 20% GHG reduction target in the 2007 Energy Independence and Security Act. The added uncertainty of potentially employing more complex emissions metrics is yet to be quantified.

1. INTRODUCTION

Corn ethanol is currently the prevailing biofuel in the U.S. Domestic production increased from 1.8 to 10.6 Bgal/yr over the past decade.[1] The federal government established a mandate to blend gasoline with corn ethanol, which will increase to 15 Bgal/yr (7% of U.S. gasoline consumption) by 2016.[2] Corn ethanol is currently subsidized at $0.45/gal.[2,3] These policies are aimed toward mitigating climate change impacts from the transportation sector and to overcome the dependence on foreign oil among others.[3]

Currently, the perceived effectiveness of corn ethanol or other biofuels to mitigate climate change is mainly based on greenhouse gas (GHG) emissions. Policy makers rely increasingly on greenhouse gas accounting (GHGA) or life cycle assessment (LCA) to support complex performance evaluations of emerging technologies.[4] However, as the accounting procedures within LCA are improved to provide a better representation of reality, LCA results sometimes change significantly.[5] This can dramatically alter prior results and beliefs, influencing policies, and amending decisions that determine billions of dollars of public and private investments.

1.1. Estimating Corn Ethanol Life Cycle GHG Emissions.

GHGA or LCA of corn ethanol and other biofuels includes establishing a GHG inventory of all emissions that occur during the fuel's production and use and is usually compared to a gasoline baseline.[5] Typically, emissions are accounted for during all life cycle stages including agricultural feedstock production, conversion into liquid fuel, combustion, transportation of the feedstock and the fuel, and ancillary processes such as production of fertilizer and machinery.[6] These are sometimes referred to as well-to-wheel (WTW) emissions.[6] Other effects may be taken into account including emissions from land use change (LUC).[7]

LUC emissions can occur directly when the biofuel feedstock displaces other biomass (e.g., previous crops or forests). The above- and belowground biomass may be burned and rapidly decayed, respectively. Emissions from LUC may also be released indirectly through market-mediated effects (see the SI for details).

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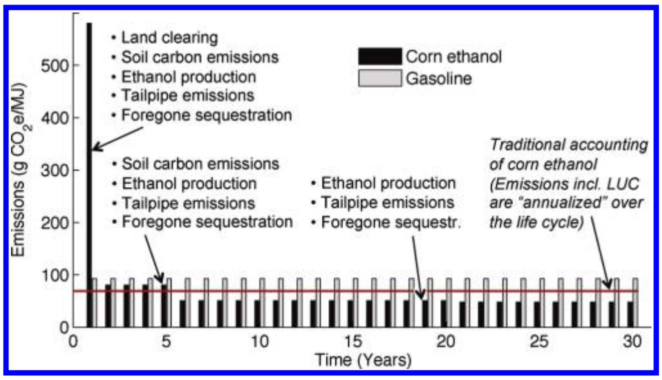

Figure 1. Illustrative GHG emissions of corn ethanol and gasoline (all EPA data). Ethanol emissions are shown for both the emissions time profile and annualized emissions (traditional GHG accounting).

Throughout this paper, we only distinguish WTW emissions and LUC emissions (direct plus indirect LUC).

Quantifying biofuel emissions from LUC is a challenging endeavor, which leads to high uncertainty in LUC estimates. Literature values for LUC from corn ethanol range from 500 to 5100 g CO_2-equivalent (CO_2e) per MJ of additional biofuel production capacity.[8] Assuming a 30-year life cycle means 17 to 170 g CO_2e/MJ emissions per year. EPA's mean estimate of corn ethanol WTW emissions is 46 g CO_2e/MJ emissions per year.[5] Thus, LUC may increase the life cycle GHG emissions by 37 to 370%. EPA has estimated mean LUC emissions at 28 g CO_2e/MJ per year.[5,7−10]

In LCA, the sum of all WTW emissions is weighted by the GHG specific global warming potentials, and LUC emissions are added after dividing by the total amount of fuel produced over the life cycle.[5] The time horizon of the life cycle can be determined by the corn ethanol project time.[6] This is the number of years the feedstock (i.e., corn) is produced on a given piece of land before the land is used for other purposes (e.g., conversion to pasture). A time horizon of 30 years is often used in LCA, but this is not an empirical value.[7] In 2010, EPA found the mean life cycle GHG emissions to be 74 and 93 g CO_2e/MJ for corn ethanol and gasoline, respectively (see the SI for details).[5] This translates into a GHG balance of −20%. The GHG balance, the prevailing performance metric regarding climate change mitigation, describes how much more or less GHG emissions corn ethanol releases relative to gasoline.[6]

1.2. Emissions Timing and the GHG Balance. Emissions from LUC occur in the first years of the life cycle until all new acreage from increased feedstock demand is converted to corn and indirect LUC has ceased through market equilibrium.[5] A hypothetical emissions time profile in Figure 1 describes the CO_2e emissions released at any year of the fuel's life cycle for the functional unit, i.e., 1 MJ of fuel. The profile is illustrative for EPA emissions data and includes emissions from land clearing, soil carbon, and foregone sequestration.[5]

Section 2.1 provides details regarding the methods to estimate the emissions time profile. The GHG emissions of corn ethanol follow a different time pattern than those of gasoline because, in the model presented here, gasoline has no analogous large upfront emissions. The construction of the ethanol factory or the oil refinery, which may also cause early GHG emissions, is not considered. We refer to the varying emissions release over the corn ethanol life cycle as the emissions time profile. It is important to note that the GHG balance used by EPA and others does not address emissions timing because it allocates all LUC emissions evenly over time, i.e., emissions are annualized over the life cycle. EPA also considered a scenario in which emissions are discounted at 2% over 100 years to address emissions timing (see discussion in the SI).

1.3. The Significance of Early Emissions. Releasing GHG emissions today may be more harmful than emissions in the future for two reasons. First, climate change poses the risk of potentially irreversible damages to humans and ecosystems, which calls for policies to mitigate climate change impacts from GHG emissions over the next decades.[11] As a result, reducing GHG emissions today may be more valuable than a reduction in the future. Substituting gasoline with corn ethanol, however, is conceptually the opposite, i.e., reducing GHG emissions in the future but increasing emissions today due to LUC.

Second, atmospheric CO_2 decays over a period of several centuries,[12] causing emissions today to contribute to the greenhouse effect several hundred years in the future. Consider the difference between emitting CO_2 today and in 20 years. Over the next century, the cumulative climate impact of the former is greater than that of the latter. The GHG balance approach masks this difference in timing, possibly conveying fewer impacts than those actually occurring. As a result, ignoring emissions timing may whitewash the effectiveness of policies that support corn ethanol or other biofuels.

Several authors have estimated that the GHG balance undervalues the climate impacts of corn ethanol by 9−89% due to emissions timing using different ways of modeling radiative forcing (RF).[13−15] Greenhouse gases contribute to positive RF (and increasing global surface temperature) by absorbing some of the radiation and reflecting it back into the atmosphere.[12]

These methods address the timing issue in a conceptually convincing way. However, several model limitations may potentially oversimplify real world processes, which could affect the results significantly. First, marginal emission impulses, rather than actual emissions from annually varying ethanol quantities are used to estimate RF. The former implies that all LUC from the 15 Bgal/yr occurs instantaneously, whereas in reality RF is a function of increasing ethanol production over time until full capacity is reached. Second, estimating RF from LUC emissions only, i.e., excluding WTW emissions,[13] overlooks the fact that the cumulative RF (CRF) benefits from lower WTW ethanol emissions (relative to gasoline) increase with longer impact time frames. Third, estimating the influence of timing as the difference between the CRF balance (CRF of ethanol emissions relative to gasoline) and the GHG balance (based on life cycle emissions)[14,15] may be misleading because of different underlying assumptions in the two metrics. For example, the CRF balance distinguishes two time horizons (the 30-year corn ethanol life cycle period and the year until which ethanol may be produced in the U.S.), while the GHG balance assumes both time horizons to be the same. Instead of isolating the influence of emissions timing, this approach quantifies the combined effect of emissions timing and assumed fuel quantities.

1.4. Research Objective. This work builds on the methods and arguments established by O'Hare et al., Kendall et al., and Levasseur et al. through quantifying the influence of emissions timing on the RF impacts of corn ethanol. Realizing the limitations of the existing methods, a RF model was developed in MATLAB to address these limitations and to update the results of the emissions timing effect. By modeling the total RF from actual fuel quantities, we also estimate the order of magnitude

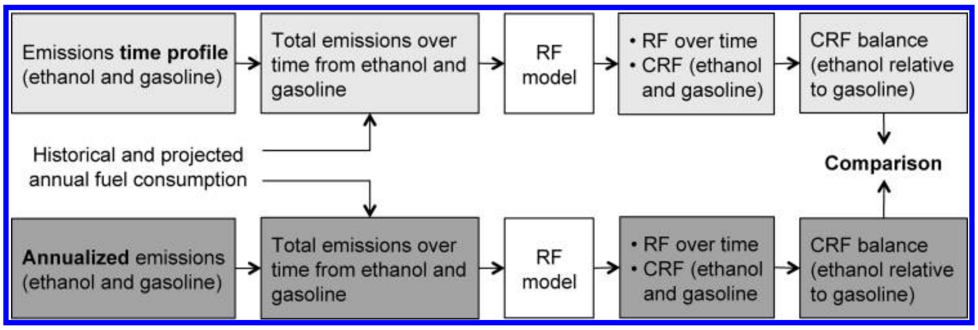

Figure 2. Overview of the analytical procedure of this research to quantify the influence of emissions timing on the RF impact of corn ethanol over a given time horizon. Fuel consumption starts at 1.8 Bgal/yr in year 2001 and reaches maximum capacity of 15 Bgal/yr in 2016 (see SI Figure 1).

effect of corn ethanol induced LUC emissions on global mean surface temperature (ΔT_s).

2. METHODS

This analysis follows the general procedure in Figure 2. In the first step, literature GHG inventories are used to generate the emissions time profile of corn ethanol and gasoline (described in section 2.1). The time profile (g CO_2e/MJ/yr) is combined with the energy contents of annual fuel consumption (MJ/yr) to estimate the total GHG emissions for each year by using the same amounts of energy for corn ethanol and gasoline.

Next, the RF model (section 2.2) estimates RF for each fuel as a function of total GHG emissions over time using the emissions time profile (upper branch). Cumulative RF for each fuel is estimated over different impact time frames. The CRF balance of corn ethanol (CRF of ethanol relative to gasoline) is estimated analogously to the GHG balance (GHG emissions of ethanol relative to gasoline).

Then, the simulation is repeated, but using the annualized emissions (lower branch), which is implied in traditional LCA (see Figure 1). Finally, the difference in CRF between the simulations for the emissions time profile and the annualized LUC emissions is used as a measure to quantify the influence of timing.

2.1. GHG Emissions Inventory and Time Profile for Corn Ethanol and Gasoline. Radiative forcing is estimated using GHG emissions from four different LCA studies.[5,8−10] The EPA study was used in support of the Renewable Fuels Standard 2 (RFS2). Emissions vary significantly among the studies for both LUC and WTW, i.e., the remaining life cycle emissions. A summary of data including the disaggregation of CO_2e emissions into CO_2, CH_4, and N_2O is presented in the SI. EPA data[5] were used as the base case (see SI Table 1). Emissions estimates for LUC from Hertel et al. and Tyner et al.[9,10] are used to test the sensitivity of the model. The results of a stochastic analysis of LUC uncertainty in Plevin et al.[8] were used to estimate upper and lower bounds of possible LUC values (see SI Table 2).

The allocation of emissions over time on a per MJ basis generally coincides with earlier work,[5,15] and the results are summarized in Figure 1. However, we model absolute emissions (see SI Figure 1), which allows representing the actual ramp-up in annual corn ethanol production. The annual volume increases are used as a proxy for absolute LUC occurrence over time, which distributes LUC more evenly over time compared to previous work. It is still a conservative estimate since modeled upfront emissions may be shifted more toward future years in reality, thereby reducing the share of absolute upfront emissions (see SI for details). The SI provides details regarding the choice of the biofuel project time, the sources of LUC emissions, the gasoline emissions over time, and the calculation of total emissions from a given fuel volume in a particular year. In our base case, fuel use is simulated according to historical and projected corn ethanol production[1] using data from 2001 to 2030 (see SI Figure 1). Annual fuel use increases to reach the federal mandate of 15 Bgal/yr in 2016 (Renewable Fuel portion of the RFS2) and is assumed to remain constant thereafter.[15]

We also calculated an accelerated LUC scenario, which simulates ethanol production to reach 15 Bgal/yr in the first year, rather than over the course of 16 years, which causes all LUC to occur in one year. This reflects the hypothetically highest increase in GHG concentration from LUC in a single year. In this case, no more LUC occurs in the following years assuming that corn is grown on the lands already converted to agriculture in year 1. Accelerated LUC is implied in all prior emissions timing analyses.[13−15]

2.2. Radiative Forcing over Time. A simplified RF model was developed in MATLAB based on the BERN model and recommendations given in the Fourth Assessment Report of IPCC.[12] BERN is one of the so-called simple climate models (SCM) used by IPCC. These lack the high resolution of the complex (atmosphere-ocean general circulation) models, which are used to study the fundamental processes governing climate change, and to allow projections of regional scale changes.[16] However, BERN and other SCMs "replicate the global scale average behavior of complex models",[16] which was deemed sufficient for the modeling presented here. The model estimates RF and the magnitude of ΔT_s given the emissions estimates above.

The RF model tracks the net radiative activity of the emissions over time. The only emissions considered in the RF model are from WTW (corn ethanol and gasoline) and LUC (corn ethanol only). All other anthropogenic GHG emissions are omitted because we are interested in RF effects from fuel use only.

RF is estimated for each GHG (CO_2, CH_4, and N_2O) and fuel (corn ethanol and gasoline). In each impact year t (1 to 100), RF is the result of the emissions released in t and the nondecayed fraction of emissions that occurred in all previous release years r (1 to 100). For each GHG and fuel, an r by t matrix RF_{rt} is calculated using eq 1

$$RF_{rt,\,Fuel,\,GHG} = E_{rt,\,Fuel,\,GHG} \bullet \Delta C \bullet RE_{rt,\,GHG} \bullet D_{rt,\,GHG} \tag{1}$$

where $E_{rt,Fuel,GHG}$ is the matrix of the annual emissions release of a GHG (g), ΔC is the change in atmospheric concentration of the GHG due to the release (ppmv/g), $RE_{rt,GHG}$ is the radiative efficiency matrix, i.e., the instantaneous RF of a unit increase in atmospheric GHG concentration (W/m^2/ppmv), $D_{rt,GHG}$ is the decay matrix of the GHG (unit-less), and • denotes element-by-element multiplication (as opposed to standard matrix multiplication). The details of the above matrices are described in the SI.[17−19]

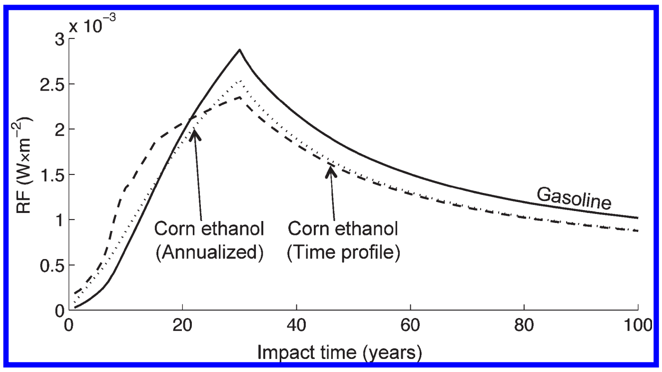

Figure 3. RF(t) of gasoline and corn ethanol (both annualized emissions and emissions time profile) using base case data (EPA, 30 years of production). See SI Figure 2 and section 3.2 for a discussion of alternative production periods.

In order to calculate the total RF for each fuel and GHG, the rows r in the RF matrix are added to yield an RF vector with t elements for each impact year t (eq 2). Next, the three RF vectors representing each GHG are added to yield the total RF vector for each fuel (eq 3)

$$RF_{Fuel,\,GHG}(t) = \begin{bmatrix} \sum_{r=1}^{100} RF_{rt,\,Fuel,\,GHG}(t=1) \\ \sum_{r=1}^{100} RF_{rt,\,Fuel,\,GHG}(t=2) \\ \vdots \\ \sum_{r=1}^{100} RF_{rt,\,Fuel,\,GHG}(t=100) \end{bmatrix} \quad (2)$$

$$RF_{Fuel}(t) = \sum_{GHG} RF_{Fuel,\,GHG}(t) \quad (3)$$

Ethanol's *CRF balance* is estimated analogously to the GHG balance, i.e., relative to gasoline. In contrast to the GHG balance, however, the *CRF balance* is a function of impact time t (eq 4)

$$CRF\ balance(t) = \frac{\sum_t RF_{Ethanol}(t) - \sum_t RF_{Gasoline}(t)}{\sum_t RF_{Gasoline}(t)} \quad (4)$$

This analysis defines the emissions timing factor *ETF* as the amount (in percent) by which the GHG balance underestimates actual RF impacts over a given t (eq 5)

$$ETF(t) = CRF\ balance_{Time\ profile}(t) - CRF\ balance_{Annualized}(t) \quad (5)$$

The magnitude of the change in global mean surface temperature (ΔT_s) is estimated from RF in eq 6 according to IPCC[12]

$$\Delta T_s = \frac{\lambda_{2xCO_2}}{\Delta F_{2xCO_2}} * (RF_{Ethanol} - RF_{Gasoline}) \quad (6)$$

where λ_{2xCO_2} is the climate sensitivity, i.e., the increase in global mean surface temperature from a doubling of atmospheric CO_2 concentration from preindustrial levels (from 280 ppmv to 560 ppmv), which IPCC estimates to be between 1.5 and 4.5 °C.[12] ΔF_{2xCO_2} is the RF response from this doubling of CO_2, commonly assumed to be 3.71 W/m^2.[12]

3. RESULTS

Radiative forcing from 30 years of corn ethanol and gasoline use was estimated over a 100-year impact time frame based on literature life cycle emissions (including LUC) and fuel use scenarios in the U.S. The base case represents LUC distributed over 16 years (2001−2016) as annual ethanol production increases over this period. This represents a phased-in agricultural land approach to increasing U.S. ethanol production, thereby illustrating historical and projected annual ethanol volumes in the U.S. from 2001 to 2030.

3.1. Radiative Forcing over Time. Figure 3 shows RF from gasoline and corn ethanol for both annualized emissions and the time profile using base case data (EPA). Ethanol production is increased to 15 Bgal/yr in 2016 according to historical and projected annual ethanol volumes in the U.S.[1] All three curves display increasing RF until year 30 because the net effect of the GHG emissions release over time is an increase in atmospheric GHG concentration. After 30 years, RF declines in all three curves because GHG emissions from fuel use cease in our base case. However, a significant RF effect remains after 100 years due to the long atmospheric lifetime of the GHGs.

Initial (year 1) RF is highest for the corn ethanol time profile curve due to LUC. After about 10 years, the slope of the time profile curve decreases gradually because 80% of the overall LUC has occurred. After about 20 years, the curves of the time profile and gasoline intersect, which means a RF reduction from substituting gasoline with ethanol thereafter. Over the first 15 years, RF from annualized corn ethanol is higher than gasoline despite lower life cycle emissions because modeled fuel volumes are initially low. As a result, annualized LUC emissions have an over proportionate leverage on overall emissions.

The fuel production increase at varying rates in the model contributes to the nonuniform slope over the first 30 years. For annualized corn ethanol, overall RF from LUC is distributed evenly over 30 years, creating a more uniform slope. The same is true for gasoline, which has no LUC effects in the model.

We also estimated RF and ΔT_s from electricity generation[20,21] and the transportation sector[22] as reference points of what increases may be considered "high". The details provided in the SI show that the maximum effect of 15 Bgal/yr corn ethanol on RF and ΔT_s is less than 1% that of U.S. electricity consumption. Reducing U.S. gasoline consumption by 10% decreases RF and ΔT_s by eight times the amount that RF and ΔT_s increases from 15 Bgal/yr corn ethanol.

3.2. CRF Balance. Figure 4 shows the CRF balance of corn ethanol, i.e., the ethanol-gasoline ratio of RF integrated under the curves in Figure 3 for both the annualized emissions and the time profile over different impact time frames. The CRF provides a measure of ethanol's life cycle performance based on cumulative RF up to a given impact year, as opposed to the traditional GHG balance.

Both CRF curves decrease with higher impact time frames as the RF benefits from relatively lower WTW emissions from ethanol materialize over time. The curve for the time profile is above the annualized emissions because the LUC emissions of the former cause RF over a longer period within 100 years. The difference between both curves is ETF, which indicates by how much the RF impacts are underestimated when emissions timing is ignored. In our base case, ETF is 2 and 5%age points over 100 and 50 years, respectively, and increasing for shorter time frames. Modeling relatively low WTW emissions from the

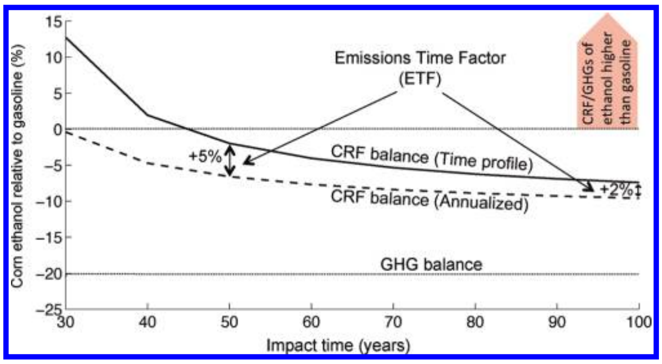

Figure 4. CRF balance of corn ethanol (both annualized emissions and emissions time profile) and ETF using base case data (EPA). The GHG balance of corn ethanol is also depicted for reference. A lower CRF balance means lower RF impacts of corn ethanol relative to gasoline.

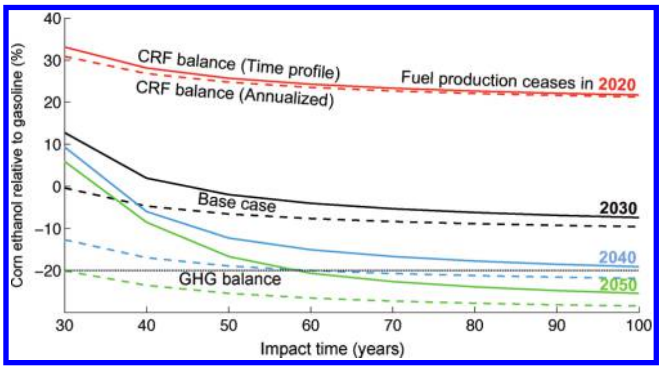

Figure 5. CRF balance of corn ethanol (both annualized emissions and emissions time profile) for varying fuel production periods using EPA data.

RFS2[5] offsets some of the ethanol CRF increases due to modeling a ramp-up in ethanol production (see SI Figure 5).

The horizontal line at −20% in Figure 4 represents the GHG balance − the commonly used GHGA metric used to compare biofuels with gasoline − as a reference to show the gap between CRF and GHG balance. Previous analyses[14,15] quantified emissions timing as the gap between the GHG balance and the CRF balance (time profile). In contrast, this method isolates the influence of (a) emissions timing due to significant upfront emissions and (b) anticipated fuel quantities on corn ethanol's climate performance. The latter is an independent policy issue, which should be addressed regardless of how harmful early emissions are to climate.

The CRF balance of the time profile is 12% to −7% (base case), which indicates that corn ethanol is 32 to 13%age points less beneficial than what the GHG balance conveys. Note that both the GHG balance and CRF balance shown in Figure 4 assume the same fuel production period of 30 years used in earlier studies[5,7,9,10,13−15] after which no more ethanol is produced to further offset early LUC emissions. Figure 5 illustrates the influence of alternative production periods on CRF. Further differences in implicit assumptions between GHG and CRF balance are illustrated in SI Figure 5.

We simulated fuel production over 20, 30 (base case), 40, or 50 years, i.e., fuel production from 2001 to 2020, 2030, 2040, and 2050, respectively. As illustrated in Figure 5, longer fuel production allocates LUC over a greater amount of fuel volume, which improves ethanol's CRF balance. In fact, the CRF balance of the

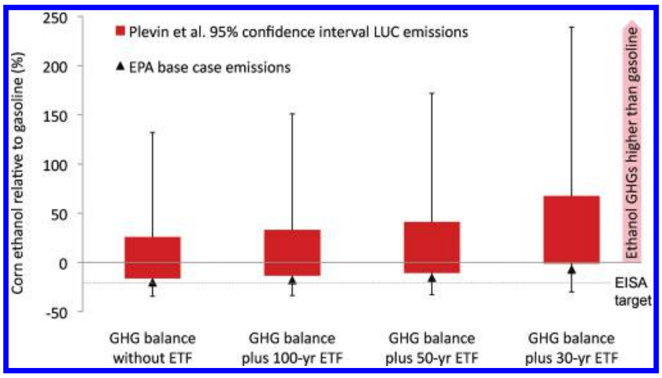

Figure 6. GHG balance of corn ethanol with and without emissions time factor (ETF) for several impact time frames. Illustrated data are EPA base case and Plevin et al. LUC uncertainty with 95% confidence intervals and min/max values (error bars). The target of the Energy Independence and Security Act 2007 (EISA) is a 20% reduction in GHG emissions relative to gasoline.

2050 scenario is below the −20% mark (GHG balance) for 60 or more years of impacts. The model assumes no additional LUC after 2016 when the maximum capacity of 15 Bgal/yr is reached. For production periods less than 30 years, the CRF is shifted to higher values. As a result, the difference between CRF balance and the GHG balance captures not only emissions timing but also the influence of produced fuel volumes. Note that the fuel production period has a significantly higher influence on ethanol's climate performance than ETF. Our model shows ETF is mainly a function of the scale of assumed LUC, the impact time frame, and the production period, and ETF is fairly insensitive to other parameters. For instance, the sensitivity analysis in SI Figure 6 shows that ETF is only 1−6% for the relatively low LUC estimates in Tyner et al.,[10] but it increases to 3−15% for higher LUC in Hertel et al.[9]

3.4. Influence of Emissions Timing on the GHG Balance. ETF may be added to the GHG balance of corn ethanol to reflect the influence of emissions timing. The value of ETF depends on the impact time frame chosen by the policy-maker. Figure 6 shows the GHG balance for several impact time frames.

The boxes with error bars pertain to LUC uncertainty values (95% confidence interval and minimum and maximum values, respectively) from Plevin et al.[8] The 95% confidence interval of −16% to 26% in Figure 5 compares to −32% to −7% in EPA.[5] The triangles correspond to EPA base case data, which do not fall within the 95% confidence interval. According to these data, there is a less than 2.5% chance that corn ethanol will meet the EISA target of a 20% reduction in GHG emissions relative to gasoline, which confirms the conclusions of Mullins et al.[22]

Considering either Plevin et al. or EPA data, corn ethanol emissions uncertainty (LUC and fuel production period) has a much greater influence on the GHG balance than the ETF, which is triggered by LUC. However, emissions timing shifts the 95% confidence interval toward higher corn ethanol emissions relative to gasoline. That is, the chance of meeting the EISA target is reduced even further.

As mentioned above, the period over which corn ethanol will be produced in the U.S. also influences the performance of corn ethanol, which is not captured in the GHG balance. This effect is displayed in SI Figure 7. It shows that the CRF balance drops slightly below the GHG balance (in favor of ethanol) if ethanol is produced until 2050 but increases significantly if production ceases in 2020.

4. CONCLUSIONS

This study was designed to understand if and how the LCA of biofuels can accurately account for the fact that LUC emissions occur early in its life cycle. Adaptations to current LCA may be appropriate if traditional GHGA underestimates the RF impacts from biofuel emissions including LUC. The emissions timing effect of biofuels has been investigated previously. This research further develops the methods to quantify the timing effect in three ways. First, this study accounts for the annual ethanol production that increases over time, thereby distributing LUC over more than a decade. Second, the analysis accounts for total RF of both WTW and LUC emissions, rather than LUC alone. This takes into account the increasing CRF benefits of lower ethanol WTW emissions (than gasoline) at higher impact time frames. Finally, the difference between the CRF balance of the time profile and the annualized emissions (traditional LCA) was calculated rather than the difference between the CRF balance of the time profile and the GHG balance. The former is necessary to isolate the effect of emissions timing from the effect of annually varying fuel volumes.

It was found that the influence of emissions timing on RF is significantly smaller than 9−89% suggested by the previous studies.[13−15] In the base case, ETF is 2, 5, and 13% for impact time frames of 100, 50, and 30 years, respectively. Given a corn ethanol GHG balance of −20%,[5] i.e., corn ethanol emitting 20% less GHGs than gasoline, accounting for time may increase the GHG balance to −18%, −15%, and −7% with respect to the above impact time frames. The results are sensitive to the uncertainty in the LUC emissions inputs as well as the time period over which the fuel is produced.

From a biofuel LCA perspective, emissions timing adds very little to our understanding of the climate impacts of corn ethanol because the uncertainty inherent in the LUC estimates (that triggers ETF) contributes 1 to 2 orders of magnitude more to life cycle emissions uncertainty than ETF. To complicate matters, it may be inappropriate to select a single ETF for a given impact time frame because ETF depends significantly on the time period over which corn ethanol would be produced. The fuel production period is different from the life cycle period. The former is the period over which ethanol is produced in the U.S., irrespective of the location, whereas the latter is the period over which the feedstock is produced on a given piece of land (usually 30 years). The longer corn ethanol is produced at the mandated 15 Bgal/yr beyond 2016, the greater the CRF benefits from lower WTW GHG emissions. This assumes that LUC from corn ethanol is reduced dramatically for fuel produced at constant volumes, thereby avoiding an increasing demand for agricultural land. It does not account for the possibility of accumulating carbon on land dedicated to corn after reducing ethanol and corn production.

From a policy maker's perspective, emissions timing is more important because, in our model, ETF increases the chance of corn ethanol missing the EISA target of 20% GHG reduction relative to gasoline. According to the EPA LCA, the mean (and median) GHG balance of corn ethanol is −20%, i.e., there is a 50% probability that the target is met. Adding LUC induced ETF to the GHG balance in a stochastic model, such as Mullins et al.,[23] may reduce this probability significantly. Considering the Plevin et al. estimates of LUC uncertainty, there is only a less than 2.5% chance that corn ethanol meets the EISA target. In this case, accounting for ETF would not have a major influence given the already low chance to meet the target.

From a climate change mitigation perspective, the impacts from corn ethanol emissions would be a very small contributor to reducing climate change as expressed by RF units, even when considering the relatively low EPA LUC emissions estimate. Our model assumes that most of the emissions "cost" of corn ethanol has occurred over the past decade due to LUC effects from expanding ethanol production. We estimated this cost to be 0.0006 W/m^2 in our base case (15 Bgal/yr), which translates into a first order estimate of 0.0007 °C increase in ΔT_s. The model predicts a *reduction* in RF and ΔT_s at the end of the life cycle, which is in the same order of magnitude. It appears very unlikely that either temperature change (first positive, then negative) would entail increased or reduced damages of an order of magnitude that can actually be observed or quantified.

The analysis of the influence of emissions timing on biofuel GHG emissions and climate impacts may be extended to address some issues not considered here. First, employing a set of more sophisticated climate models would allow quantifying ETF based on temperature changes. This may be important to account for (1) the time gap between RF and temperature changes (in the order of a decade) and (2) the added uncertainty inherent in the climate response, both of which are masked in RF based ETF. Second, the climate model did not account for non-GHG emissions, such as aerosols and black carbon, which are also released during LUC from biomass burning. Aerosol and black carbon emissions have a negative and positive RF impact, respectively, and modeling these emissions may significantly change RF from biofuel GHG emissions. While this may be important for biofuel LCA in general, it could also increase or reduce the influence of emissions timing. However, it does not address other issues of GHG emissions, such as the acidification of the oceans.

This case study looked at relatively small emissions or emissions reductions. Changing traditional LCA methodology by accounting for emissions timing is reasonable only if timing actually impacts climate on an absolute scale. While GHG emissions clearly add up among different energy technologies, this accumulation effect is not obvious for emissions timing. Future research should explore scenarios in which different energy technologies exhibiting large upfront emissions generate significant climate impacts due to emissions timing. As an example, such scenarios could include carbon capture and sequestration or natural gas production from shale formations, whose temporal emissions patterns may vary significantly.

■ ASSOCIATED CONTENT

Supporting Information. Underlying emissions data, RF model details, alternative emissions scenario results, and sensitivity analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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