Greenhouse Gas Accounting Procedures in Low Carbon Fuel Policies Lead to Undervalued Benefits of Miscanthus-based Sustainable Aviation Fuel

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Abstract

Low carbon fuel policies such as the U.S. Renewable Fuel Standard (RFS), Canada Clean Fuel Regulations (CFR), and California Low Carbon Fuel Standard (LCFS) are intended to reduce the greenhouse gas (GHG) emissions from transportation. Cellulosic feedstocks, optimized biorefineries, and favorable farming locations can significantly reduce biofuel carbon intensity (CI). Despite the emergence of field-to-fuel GHG monitoring technologies that could verify such benefits, programmatic constraints in CI accounting procedures may limit fuel producers' ability to capitalize on these opportunities. To elucidate the implications of this challenge, this work examines a miscanthus-to-sustainable aviation fuel (SAF) pathway (i) to demonstrate how program provisions drive estimates of biofuel CIs and (ii) to explore potential CI and financial benefits of spatially explicit life cycle assessment (LCA). In comparing policy-based vs. spatially explicit CI scores (estimated via DayCent and BioSTEAM) for SAF production from miscanthus via alcohol-to-jet (ATJ), programmatic CI accounting requirements underestimated GHG benefits in 60-99% of simulated scenarios. These underestimates result in policy-induced SAF price differentials of -1.19 [(-)3.46 to (-)0.23], -0.07 [(-)1.06 to (+)0.37], and -0.48 [(-)2.46 to (+)0.16] $\$\cdot L^{-1}$ for the RFS, CFR, and LCFS, respectively. Ultimately, this work demonstrates the importance of LCA methodological specifications in low carbon fuel policies.

Introduction

Low carbon fuel policies such as the U.S. Renewable Fuel Standard (RFS), Canada Clean Fuel Regulations (CFR), and California Low Carbon Fuel Standard (LCFS) are intended to reduce the greenhouse gas emissions associated with transportation. The RFS is unique among these three programs because of its pathway-based fuel carbon intensity (CI) reduction threshold categorization structure (sometimes referred to as a "technology mandate"). If fuel producers verify they utilized a certain feedstock and production process to produce a certain fuel, the fuel is assigned to the corresponding fuel category (referred to with a "D code") and effectively assigned a predetermined CI (e.g., a D code of 3 or 7 signifies that the fuel was produced from a cellulosic feedstock and achieves a 60% CI reduction compared to a petroleum baseline fuel[1]). The CFR and LCFS are "performance-based," and allow fuel producers to calculate unique CIs for their own production pathway. Relative to a technology mandate, a fuel's performance in these programs has the potential to be more closely (but still not fully) tied to the actual CI reduction achieved by the fuel. The LCFS is credited with reducing the CI of California's transportation fuel pool by approximately 15%,[2] and U.S. bioethanol production has increased roughly 8-fold over the past two decades to meet RFS requirements.[3] However, cellulosic biofuel production targets set by the RFS have never been met, thus preventing the realization of the additional benefits of these fuels compared to conventional fuels (e.g., improved biodiversity in agricultural landscapes,[4] sequestration of atmospheric carbon in soils,[5] reduced human health externalities[6]). Critiques of the RFS suggest that the technology mandate does not properly incentivize the production of fuels that achieve lower CIs.[7] However, even performance-based programs may not necessarily account for production decisions that affect a fuel's CI at all stages of biofuel production.

The CFR is performance-based, yet requires the use of a single value for the CI of crop production for many feedstocks, regardless of the location where production took place or the methods employed (and despite data that underly the CFR illustrating that the CI of crop production varies widely across Canada for many crops[8–10]). The LCFS also does not allow fuel producers complete flexibility to determine a unique field-level feedstock CI by accounting for field-specific biogeochemistry. However, yield and soil carbon sequestration by miscanthus, a perennial grass energy crop that can produce significant biomass with few chemical inputs, have been estimated to vary from approximately 7 to 22 megagrams per hectare and -1.0 to 1.5 megagrams of carbon per hectare-year, respectively, across the rainfed U.S.[5]

Life cycle assessment (LCA) is a quantitative methodology regularly used to evaluate the environmental impacts of biofuel production, including as part of low carbon fuel policies and tax credits. In short, LCA entails combining quantities of material and energy flows in a product or process system (e.g., fertilizers, electricity, and biofuels in the case of biorefineries) with information on their likely environmental impacts to determine the overall environmental impacts of the product or process (e.g., according to ISO Standards[11,12]). Depending on the goal and scope of a LCA and data availability, the assessment may utilize emissions data from different scales (e.g., national averages vs. regional vs. state-level). There is, however, a recognition that assessments conducted using low-granularity (i.e., not site-specific) data may not properly elucidate differences in environmental impacts that inevitably occur across individual production sites.[13] Thus, there has been movement toward using more site-specific (e.g., "spatially explicit", "location-specific", "field-level") data in LCAs, particularly for analyses of bioenergy crops, biorefining technologies, and bioproducts. Simultaneously, improved technologies to facilitate field-level measurements of important parameters are being developed to support these analyses (i.e., improved measurement, monitoring, reporting, and verification [MMRV]). For example, a proposed combination of field-specific modeling and sensing and big data analytics has the potential to more accurately quantify agricultural greenhouse gas (GHG) outcomes.[14] Given the continued interest in emerging fuel production pathways (e.g., miscanthus to sustainable aviation fuel [SAF] as a means to decarbonize medium- and long-haul aviation travel[15–18]), there exists a need to evaluate the implications of such field-specific data for biofuel CI quantification and, in particular, a comparison to CIs calculated based on existing policy guidelines. Understanding the flexibility of policy-specified CI quantifications such as those utilized by the Clean Fuel Production Credit (a tax credit also known as the 45Z credit because it is established in 26 U.S. Code § 45Z) is critical to capitalize on the benefits of biofuels and field-specific monitoring.

The overarching goal of this work is to explore how programmatic constraints may affect estimates of biofuel CIs for emerging feedstock-to-fuel pathways and to highlight the potential benefits of implementing field-specific LCAs of biofuels. To illustrate the importance of sound policy provisions and highlight the potential utility of field-to-fuel GHG monitoring technology, the carbon intensity of SAF produced from miscanthus via the alcohol-to-jet (ATJ) pathway was calculated according to specifications from three low carbon fuel policies (the RFS, CFR, and LCFS) and the 45Z tax credit and compared against spatially explicit modeling results tailored to the feedstock-to-fuel pathway. The CI for the spatially explicit analysis was compared to policy-specific CIs to illustrate how policy guidelines and current flexibility affect fuel characterization for this potential pathway. In addition to more accurately representing true environmental outcomes of biofuel production, policies that enable field-specific CI calculations could better incentivize compliance and impactful carbon mitigation measures by producers.

Methods

Feedstock-to-Fuel Pathway

Miscanthus is a high-yielding, perennial grass with significant potential to produce biomass for conversion to fuels because it requires little inputs of fertilizers and pesticides.[19–22] There is particular potential for miscanthus production (for eventual conversion to biofuel) east of the 100th meridian in the United States because this area can rely on rainfed agriculture.[5] Miscanthus is one of several cellulosic feedstocks that can be used to produce ethanol, though this process remains expensive.[23,24] Cellulosic ethanol can be further upgraded to SAF (potentially in the same biorefinery) to produce a more cost-competitive fuel product.[25,26] Though SAF production is in early stages in the U.S.,[27] this ATJ pathway is one of 11 SAF production pathways approved by ASTM International.[28]

Policy Provisions

Policies and Specifications for LCA

The three low carbon fuel policies evaluated in this study share similar goals: to require the blending of fuels with lower greenhouse gas emissions (RFS;[29] see § 80.2), to prevent or reduce air pollution from fossil fuels (CFR;[30] see the Registration section), and to reduce the carbon intensity of transportation fuels (LCFS;[31] see § 95480). With regard to the 45Z tax credit, one of the primary goals of the Inflation Reduction Act of 2022 (P.L. 117-169) was to address climate change by incentivizing the growth of a clean energy economy: the 45Z tax credit was included by Congress to further incentivize the production of biofuels with lower carbon scores or GHG reductions.[32] The three programs and the tax credit all specify methods to determine the CI of biofuels produced for program compliance, which includes quantifying the CI of producing the biomass feedstock used to produce the fuel (detailed in RFS § 80.1426, in CFR § 75-76, in LCFS § 95488.3, and in 45Z § (b)(1)(B)(iii)). All three programs and the tax credit utilize an LCA approach for CI quantification, with slight variations in scope; therefore, the policy, and the methods it specifies, have some influence in determining the CI that is calculated for a given biofuel from a given field. The methods specified by each policy were reviewed to highlight which policy choices might affect biofuel CI estimates. Attributes of policies considered include the use of site-specific data for each life cycle stage and any material and energy flows or other considerations that influence CI calculations.

Policy-Based Miscanthus-to-SAF CI Calculations

Policy-based SAF CIs were calculated according to methods specified by the four policies. In the case of the RFS and 45Z credit, which generally do not allow for producer-specific CIs to be used, predetermined CIs developed by program administrators were used as the policy-based CIs. For the CFR and LCFS, policy-based CIs were calculated according to the methods specified by the policies (to the greatest extent possible given current data and model availability and the use of simulated biorefinery operation data). Policy-based CIs for all four policies are detailed further in SI Section S1.1.

Farm-to-Fuel Life Cycle Assessment

Spatial Variability in Feedstock CI

CIs of miscanthus production were obtained for 36 U.S. states from Fan *et al.* (2024).[33] Fan et al. estimated the CI of miscanthus production across the rainfed U.S. using DayCent to account for spatially-varying growing conditions and weather and region-specific historical cultivation practices (detailed further in the Supporting Information for [33]). The DayCent model used parameters including precipitation, fertilizer application, land cover, and land management to calculate miscanthus yield, changes in soil organic carbon (SOC), and in-field greenhouse gas emissions associated with chemical inputs. The miscanthus CI was calculated as the sum of SOC change and in-field and upstream (scope 3) emissions associated with chemical inputs (nitrogen, phosphorus, and potassium fertilizers; herbicides; and fuel) divided by miscanthus yield.

Notably, Fan *et al.* did not vary the rate of fertilizer and herbicide application, though these parameters are likely to vary across the U.S. and from year-to-year. Additionally, there are methodological differences necessary to account for SOC compared to these non-SOC emissions (i.e., while quantities of fertilizer inputs and environmental impacts associated with their production may be measured fairly directly, long-term miscanthus-induced SOC storage must currently be estimated using biogeochemical models, as in [33]). As estimated by Fan et al., non-SOC emissions are relatively minor compared to the magnitude of carbon sequestered by miscanthus growth (15.0% [8.8-37.6%] of SOC sequestration). For transparency, the contribution of SOC and non-SOC emissions to the total SAF CI are reported separately in this study. These feedstock CIs are meant to represent the potential range of CIs that may be observed with robust field-level MMRV. The CIs of miscanthus production were incorporated into the BioSTEAM Location Specific Evaluation module (BLocS).[34,35] The median miscanthus CI was -139 kg CO_2e·dry metric ton^{-1}, indicating a net removal of carbon from the atmosphere and storage as SOC.

Transportation and Distribution CI

The CI associated with biomass and biofuel transportation and distribution was estimated by multiplying the mass of biomass or biofuel and transport distance by transportation emission factors for a diesel truck (expressed in kg CO_2e·kg-km^{-1}) from ecoinvent 3.8 and the TRACI 2.0 impact assessment methodology. Because there are only two operational SAF refineries and zero operational cellulosic ethanol refineries in the U.S.,[36] a range of biomass and biofuel transport distances (see SI **Table S1**) were evaluated to characterize the potential consequences of this parameter on the overall CI of SAF production. The median biomass and biofuel transport distances were 100 and 600 kilometers, respectively, which accounts for two trips (i.e., one full transport trip and one empty return trip). The CI of both transportation and distribution stages was added to the CI of the biomass conversion stage calculated using BioSTEAM and BLocS.

Biorefinery Design, Simulation, and LCA

Biorefinery design, simulation, and LCA were performed using BioSTEAM version 2.44.3.[37,38] BioSTEAM compiles a life cycle inventory for the biomass conversion stage based on process simulation, then combines this with user-defined emission factors to perform impact assessment. This study leveraged BLocS for location-specific LCA inputs[34] (electricity and natural gas emission factors based on balancing region and state, respectively). Life cycle inventory data for chemical inputs to the biomass conversion stage that do not contribute significantly to the total fuel CI and are unlikely to vary significantly with location (e.g., sodium hydroxide) were obtained from ecoinvent 3.8. The influence of the full range of miscanthus CIs across locations on the total fuel CI was evaluated via LCA.

The SAF model in BioSTEAM simulates the production SAF from cellulosic biomass (i.e., miscanthus) via the ATJ pathway, consistent with Wei et al.[39] The SAF production process includes two steps: ethanol production and ethanol upgrading via dehydration, oligomerization, and hydrogenation. The biorefinery uses 0.821 million metric tons of miscanthus per year and produces several hydrocarbons: SAF as the main product and gasoline and diesel as co-products. Excess electricity produced from burning waste biomass is sold to the grid.

Biofuel Combustion

The carbon intensity of biofuel combustion was excluded from consideration as part of farm-to-fuel LCA. The three low carbon fuel policies evaluated in this study consider carbon dioxide emissions from biofuel combustion to be biogenic and offset by carbon uptake during biomass production and thus exclude them from consideration, though the RFS and CFR consider other greenhouse gases associated with combustion. The CI of fuel combustion would not vary based on production location or policy participation.

Uncertainty

While uncertainty in biofuel LCA was considered when developing the three low carbon fuel policies, none of the programs allow participants to report a biofuel CI with an uncertainty range. Under the LCFS, fuel producers are encouraged to report a slightly higher CI than they calculate to account for uncertainty in biorefinery performance (because they are penalized if the actual fuel CI is determined to be higher than what they report to the program). Uncertainty was considered for all life cycle stages (except fuel combustion; detailed in SI **Tables S1-2**) (1) to provide a more accurate estimate of the total fuel CI and (2) to illustrate the potential range of fuel CIs that are currently unaccounted for under program provisions. Latin hypercube sampling was used to generate samples for Monte Carlo simulation. Ten-thousand samples were generated for the analysis.

Influence of Policy Specifications on Fuel Characterization

Techno-Economic Analysis (TEA)

BioSTEAM and BLocS were also used to estimate the minimum SAF selling price via techno-economic analysis (TEA). BLocS contains state-specific economic parameters (e.g., miscanthus prices, tax rates, capital cost factors) that are incorporated into TEA by BioSTEAM. Miscanthus prices in BLocS were obtained for 31 U.S. states from Lee et al. (2023).[5] The influence of the full range of miscanthus prices across locations on the minimum SAF selling price was evaluated via TEA.

Policy-Induced Fuel CI and Price Differentials

To illustrate the influence of low carbon fuel program provisions on biofuel CI determination, the policy-induced CI differential was calculated by subtracting the CI calculated according to program specifications from the CI calculated via spatially explicit LCA (**Equation 1**). Therefore, a negative CI differential indicates that the policy overestimates the fuel CI, and vice versa.

$$differential_{CI}\ [g\ CO_2e \cdot MJ^{-1}] = CI_{LCA}[g\ CO_2e \cdot MJ^{-1}] - CI_{policy}\ [g\ CO_2e \cdot MJ^{-1}] \qquad \textbf{Equation 1}$$

To further illustrate the effect of program provisions on fuel characterization and valuation, the policy-induced price differential was calculated by multiplying the policy-induced CI differential by the policy-specific credit selling price and adjusting units using the lower heating value (in MJ·kg^{-1}) and density (in kg·L^{-1}) of SAF (**Equation 2**). A negative price differential indicates that policy provisions contribute to an undervaluation of a fuel, and vice versa.

$$differential_{price}\ [\$ \cdot L^{-1}] = differential_{CI}\ [g\ CO_2e \cdot MJ^{-1}] \times credit\ price\ [\$ \cdot g\ CO_2e^{-1}] \times 44.15\ [MJ \cdot kg^{-1}] \times 0.7507\ [kg \cdot L^{-1}] \qquad \textbf{Equation 2}$$

RFS credit selling prices (i.e., renewable identification number [RIN] selling prices) were obtained from the EPA.[40] LCFS credit prices were obtained from the California Air Resources Board.[41] Because the CFR was only established in 2022, the credit market is nascent and no price information is available. LCFS credit prices were used to estimate the CFR-induced price differential due to the relative similarity of the programs. The ranges of credit selling prices from the years 2014 through 2023 (adjusted to 2023 dollars, detailed in SI **Table S3**) were used to calculate the price differentials.

Results & Discussion

Comparison of Low Carbon Fuel Program Provisions and LCA Scopes

U.S. Renewable Fuel Standard

The U.S. Renewable Fuel Standard (RFS) was originally created in 2005 by the Environmental Protection Act and was amended and expanded in 2007 by the Energy Independence and Security Act. The RFS mandates that certain amounts of biofuels are blended with conventional fossil fuels used for transportation in the U.S., with the obligation to use biofuels placed on refiners producing gasoline or diesel fuel. These so-called obligated parties are required to submit proof of biofuel blending as renewable identification numbers (RINs), which are associated with batches of biofuels when they are produced and separated upon blending. RINs may also be traded between obligated parties with surpluses and deficits, and this trading creates a RIN market that determines the selling price. The extra profits from sales of RINs are meant to incentivize the production of biofuels, with the overall purpose of the RFS program being to reduce the greenhouse gas emissions associated with transportation fuels. In actuality, the RIN market has been extremely volatile and production goals for biofuels from cellulosic feedstocks have never met RFS mandates. The majority of biofuel produced for RFS compliance has been ethanol from corn grain, which has dubious environmental benefits.[42]

The RFS is unique among the three programs considered here in that, for a given feedstock and fuel production pathway, it categorizes fuels based on their achievement of CI reduction thresholds rather than their actual, producer-specific CI (**Table 1**). For example, all ethanol produced from cellulosic feedstocks is considered to achieve a 60 percent reduction in CI compared to gasoline. These thresholds are based on LCAs performed by the EPA.[43] The EPA states that its feedstock analyses are "country-neutral" and apply regardless of the growing practices used at individual farms because the environmental impacts of feedstock production "are likely to be the same regardless of which farm grows the specific feedstock used for biofuel production."[44] However, critiques of the RFS cite this threshold-based system as not properly incentivizing the production of biofuels that achieve a greater reduction in CI (i.e., because two cellulosic biofuels that achieve a 60% reduction and a 80% reduction, respectively, are considered identical in terms of program compliance).

Canada Clean Fuel Regulations

The Canada Clean Fuel Regulations (CFR) were established in 2022 under the authority of the Canadian Environmental Protection Act of 1999. Similar to the RFS, the CFR requires producers of gasoline and diesel, referred to as primary suppliers, to lower the overall CI of fuels they produce by utilizing biofuels. Biofuel producers also generate compliance credits that can be traded to create a market to further incentivize biofuel production. The CFR was implemented to prevent or reduce air pollution from the combustion of liquid fossil fuels.[30]

The CFR differs from the RFS in that producers have the option to calculate a CI for a unique fuel production pathway via LCA. Calculations to determine the CI of fuels produced for CFR compliance must be performed in the Government of Canada's Fuel LCA Model,[45] which is based in the openLCA software.[46] However, while biomass conversion processes may readily be customized based on the producer's unique methods, the CFR requires the use of a single CI for biomass feedstocks including corn, sorghum, sugarcane, and corn stover, among others (**Table**

1).[47] While it is possible for a new feedstock CI to be approved for use in calculations, the Fuel LCA Model guidance currently states: "Feedstock production in a subregion of a region included in the [Fuel LCA Model] Data Library is not an eligible criterion for submitting a new pathway application."[47] Thus, the CIs for these crops available to use in the Fuel LCA Model are weighted averages of several provincial-level CIs for each crop.[48] Miscanthus is not a feedstock currently included in the Fuel LCA Model, though fuel produced from this crop would be eligible for a new pathway application including the unique crop CI. However, given the treatment of other crop CIs by the CFR, a CI for miscanthus production included in the Fuel LCA Model would likely represent the average CI of production, across the U.S., for example.

California Low Carbon Fuel Standard

The California Low Carbon Fuel Standard (LCFS) was implemented in 2011 pursuant to the California Global Warming Solutions Act of 2006. The LCFS is a state, rather than national, program meant to reduce the carbon intensity of transportation fuels used in California.[31] As with the RFS and CFR, so-called fuel reporting entities are required to demonstrate that they produced and blended biofuels by retiring compliance credits. However, the LCFS has often been cited as better incentivizing low-CI fuels (e.g., fuels produced from cellulosic biomass) compared to the RFS because it requires the calculation of a unique fuel CI rather than relying on reduction threshold categories (and for this reason the developers of the CFR referenced the LCFS).

The LCFS further differs from both the RFS and CFR by allowing fuel producers to input site-specific (or "pathway-specific") values for some LCA parameters related to the feedstock production stage (e.g., fertilizers; **Table 1**). Calculations to determine the CI of fuels produced for LCFS compliance must be performed in simplified calculators or using CA-GREET.[49] However, these models rely on non-site-specific assumptions for other key factors related to feedstock production (e.g., emissions of greenhouse gases such as N_2O from fertilized cropland). The LCFS may allow for further adjustment of feedstock production CIs to include site-specific biogeochemistry (e.g., Table D.2 [row 2.4] in the Tier 1 Simplified CI Calculator for Biodiesel and Renewable Diesel Instruction Manual[50] states: "if user-defined is selected [for the GHG emission factor of soybean farming], consult CARB staff to develop emission factors..."), but this option is not fully explained, guaranteed, or readily available to fuel producers.

26 U.S. Code § 45Z Clean Fuel Production Credit

The 45Z tax credit was established in 2022 by the Inflation Reduction Act and will be offered to U.S. taxpayers as of January 1, 2025.[51] The tax credit encourages the production of low emission transportation fuels by offsetting qualifying taxpayers' federal tax liability. Taxpayers interested in claiming this credit must prove to the U.S. Internal Revenue Service that they produced or sold transportation fuels with lower greenhouse gas emissions than conventional fossil-based fuels. In the case of SAF, the credit is worth 0.09 $\$\cdot L^{-1}$ or 0.46 $\$\cdot L^{-1}$, depending on whether the fuel is produced according to certain wage and apprenticeship requirements, multiplied by a factor that compares the SAF CI to a baseline fuel CI (see [52] for additional details).

Though the credit has not yet been fully implemented, it appears structured to categorize fuels and assign them predetermined CIs (published by the U.S. Secretary of the Treasury) that are not producer-specific (**Table 1**). However, in the case of SAF, the CI must be calculated in accordance with CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) or a similar methodology. Default biofuel CIs calculated for CORSIA include biomass feedstock-induced SOC storage.[53] Thus, while it does not appear that the 45Z credit will allow taxpayers to calculate unique SAF CIs for participation, the program does consider farming inputs and crop field biogeochemistry.

Table 1. Summary of the scope of LCAs for low carbon fuel policies and the 45Z tax incentive.

	Biomass production	**Biomass transportation & distribution**	**Biomass conversion**	**Biofuel transportation & distribution**	**Biofuel combustion**
RFS	all life cycle stages are included, but program performance is technology- and threshold-based and use of a site-specific CI is generally not possible				
CFR	biomass CIs based on LCAs available in CFR data library LUC effects excluded (except tillage practices and changes in summer fallow area)	distance and mode adjustable	adjustable for some fuels only hydrogen and electricity input considered for SAF denaturant is excluded	distance and mode adjustable	biofuel combustion CIs based on LCAs available in CFR data library biogenic emissions excluded
LCFS	farming inputs generally adjustable (depends on feedstock and Tier 1/2 calculator/model) biogeochemistry not adjustable LUC included	distance and mode adjustable	fully adjustable	distance and mode adjustable	zero combustion emissions
45Z	all life cycle stages are included (as is biomass feedstock-induced soil organic carbon storage), but predetermined CIs are the default and the use of site-specific CIs appears unlikely to be possible				

Biofuel CI and Relative Contributions of Production Stages

Compared to the CI of conventional jet fuel (89.0 to 124.9 g $CO_2e{\cdot}MJ^{-1}$), nearly all of these estimates represent a CI reduction. The policy-specific SAF CIs (for the conversion of miscanthus to SAF via ethanol) range from -51.3 (CFR, lowest CI of three scenarios) to 36.8 g $CO_2e{\cdot}MJ^{-1}$ (RFS; **Table 2**). The maximum SAF CIs found in low carbon fuel documentation was 100.5 g $CO_2e{\cdot}MJ^{-1}$, which was associated with the most conservative temporary LCFS pathway CI. In general, the policy-specific CIs tend to be higher than those estimated via spatially explicit LCA: -100.7, -75.5, and -8.9 g $CO_2e{\cdot}MJ^{-1}$ according to system expansion, hybrid allocation, and energy-based allocation, respectively.

The SAF CI utilized for RFS compliance (36.8 g $CO_2e{\cdot}MJ^{-1}$) represents a 60 percent reduction in greenhouse gas emissions compared to conventional diesel fuel. This reduction threshold is meant to be broadly representative of the various pathways for producing diesel and related fuels from biomass (which result in different fuel CIs, according to EPA LCAs[43]), and thus cannot be specifically representative of a miscanthus-to-SAF pathway that has the potential to result in a significantly lower CI. Two EPA LCAs[43] that were used to set the RFS compliance threshold (though they represent a vegetable oil-to-SAF pathway) estimated an average CI of 32.9 g $CO_2e{\cdot}MJ^{-1}$. Similarly to the RFS, the temporary SAF CIs (50.0 to 100.5 g $CO_2e{\cdot}MJ^{-1}$; **Table 2**) available for LCFS participation (without a new approved pathway) are meant to be representative of multiple technologies and present a very conservative estimate of emissions.[54] However, if a new pathway were approved for participation, the LCFS-based CI (-31.8 g $CO_2e{\cdot}MJ^{-1}$) could be closer to estimates following CFR methods and spatially explicit, energy-allocated LCA.

Regardless of policy provisions or fuel production scenario, the feedstock production and feedstock conversion stages are the main contributors to the total SAF CI (**Table 2**, SI **Figure S1**). According to methods specified by the CFR, the feedstock production stage contributes -10.4 g $CO_2e{\cdot}MJ^{-1}$ to the total SAF CI. This result is comparable to the results of spatially explicit LCA on a hybrid allocation basis, where this stage contributes -16.0 g $CO_2e{\cdot}MJ^{-1}$ to the total -75.5 g $CO_2e{\cdot}MJ^{-1}$ CI (median values). In all cases, the negative emissions during feedstock production stem from modeled increases in soil organic carbon. The relative similarity of the CFR-based and spatially explicit LCA CIs illustrates the benefits of accounting for key site-specific production factors (e.g., farming inputs and biogeochemistry in the case of the miscanthus CI used for these two analyses).

The feedstock conversion stage contributes -34.5 and -39.9 g $CO_2e{\cdot}MJ^{-1}$ to total SAF CIs according to CFR and LCFS methods, respectively. The key driver for negative emissions from feedstock conversion is excess electricity production at the biorefinery. According to spatially explicit LCA and hybrid allocation, this stage contributes a median of -62.0 g $CO_2e{\cdot}MJ^{-1}$ (**Table 2**). One explanation for the difference in CIs is that the Fuel LCA Model used to calculate CIs for CFR participation uses one model for the conversion of various feedstocks (including agricultural residues, animal fats, and wood chips, among others) to SAF; users are only required to input quantities of hydrogen used for production,[47] as opposed to the more rigorous process model and life cycle inventory employed for this spatially explicit LCA (**Table 1**).

The other three life cycle stages (feedstock transportation and distribution, fuel transportation and distribution, and fuel combustion) do not contribute significantly to the total SAF CI (**Table 2**). Given the contribution of the miscanthus production stage to the overall SAF CI, the fact that low carbon fuel policies generally limit the use of field-specific feedstock CIs represents a critical challenge to capturing the anticipated benefits of this herbaceous energy crop. Regardless of rationale for this limitation, the variation in feedstock production CIs at the field level and the significance of this stage to the overall fuel CI highlights the importance of accounting for this variation via spatially explicit (or even field-specific) LCA.

Table 2. Carbon intensity (CI) of SAF derived from miscanthus (via conversion to ethanol followed by ATJ) according to various policies and methodological choices. Total CI scores include miscanthus production, biomass conversion, feedstock transportation and distribution, fuel transportation and distribution, and fuel combustion.

Relevant Policy	**Calculation and Pathway Description**	**Total CI** [g $CO_2e\cdot MJ^{-1}$]	**Miscanthus Production CI** [g $CO_2e\cdot MJ^{-1}$]	**Biomass Conversion CI** [g $CO_2e\cdot MJ^{-1}$]
--	conventional jet fuel	+124.9 [a] +87.89 [LCFS 2024] +87.9 [CFR] +89.5 [45Z]	--	--
-- *(this study)*	spatially explicit LCA, system expansion; miscanthus feedstock	-100.7 [(-)319.5 to (+)9.0][b]	-21.3 [(-)54.0 to (+)0.8][b]	-82.6 [(-)284.5 to (+)11.6][b]
	spatially explicit LCA, hybrid allocation; miscanthus feedstock	-75.5 [(-)239.5 to (+)6.8][b]	-16.0 [(-)40.5 to (+)0.6][b]	-62.0 [(-)213.3 to (+)8.7][b]
	spatially explicit LCA, energy-based allocation; miscanthus feedstock	-8.9 [(-)45.7 to (+)21.1][b]	-11.1 [(-)28.1 to (+)0.4][b]	+1.9 [(-)23.8 to (+)19.4][b]
RFS	60% reduction compared to conventional diesel	+36.8	N/A	N/A
	average of the results of 2 EPA LCAs; vegetable oil feedstocks	+32.9	*+17.7*[c]	*+14.2*[c]
CFR	Fuel LCA Model result; median U.S. miscanthus feedstock (would require new pathway application)	-42.9	-10.4	-34.5
	Fuel LCA Model result; 5th percentile U.S. miscanthus feedstock (would require new pathway application)	-51.3	-18.7	-34.5
	Fuel LCA Model result; 95th percentile U.S. miscanthus feedstock (would require new pathway application)	-36.6	-4.0	-34.5
LCFS	temporary CI; fats/oils/grease (FOG) residue feedstocks	+50	not specified	not specified
	temporary CI; plant oils (excluding palm oil) feedstocks	+70	not specified	not specified
	temporary CI; any other feedstocks	+100.5	not specified	not specified
	average of 26 approved producer pathways; waste oils, animal fats, and vegetable oils	+31.06	not specified	not specified
	GREET Aviation Module result including default SOC change; miscanthus feedstock[d]	-31.8	+5.0	-39.9
45Z	CORSIA default CI for U.S. miscanthus ethanol-to-jet (ETJ) SAF	-23.6	-38.4	+12.3

[a] This value is calculated based on the percentage of long- and medium, and short-haul flights, and the percentage and carbon intensity of the energy source.[55,56]

[b] Values shown represent median values followed by 5th and 95th percentiles (shown in brackets) of simulations across locations under uncertainty.

[c] These values are for vegetable oil feedstocks (not miscanthus), but are included here for comparison.[43]

[d] This is representative of potential CA-GREET development.

The Potential for LCA to More Accurately Quantify Field-Specific GHG Outcomes

The CI of SAF production is subject to significant variation and uncertainty based on spatially explicit LCA and tends to be overestimated by low carbon fuel policies (**Figure 1**). The SAF CI calculated via spatially explicit LCA had a median value of -100.7 g $CO_2e{\cdot}MJ^{-1}$ and 5th to 95th percentiles of [(-)319.5 to (+)9.0] according to system expansion, -75.5 g $CO_2e{\cdot}MJ^{-1}$ [(-)239.5 to (+)6.8] according to hybrid allocation, and -8.9 g $CO_2e{\cdot}MJ^{-1}$ [(-)45.7 to (+)21.1] according to energy-based allocation (**Table 2**). Thus, the CI of the median-CI locations is overestimated approximately 27 (45Z), 69 (CFR), 80 (LCFS), and 99 (RFS) percent of the time by existing policy frameworks (**Figure 1**).

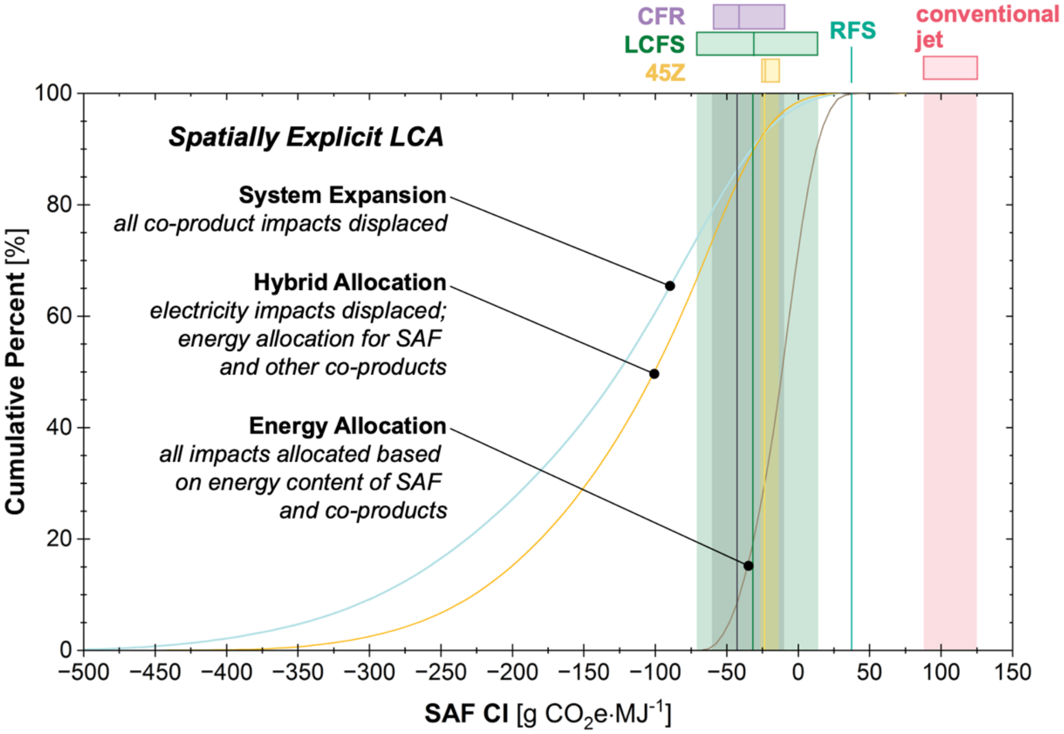

Figure 1. Distribution of SAF CI based on field-specific LCA (using system expansion, hybrid allocation, and energy allocation) compared to CIs of conventional jet fuel and calculated according to policy specifications. The line and range for each policy-based CI are based on the policy-based CI sensitivity analysis (**Section S1.1** and **S1.4** of the SI) with values for all ranges and lines reported in **Table S8** of the SI.

The overall CI of SAF production is largely dependent on co-product electricity production and the CI of miscanthus production (**Table 2**, SI **Table S2**). Thus, location-specific parameters, namely the miscanthus CI and electricity CI, are important factors governing the overall SAF production CI (**Figure 2**). States that have both a low miscanthus CI and high electricity CI, such as South Dakota, are able to achieve the lowest total SAF CI (median of approximately -160 g $CO_2e{\cdot}MJ^{-1}$) due to large amounts of soil carbon sequestration and displaced electricity from high-emissions sources. Conversely, higher total SAF CIs are likely to occur in states with higher (though still negative) miscanthus CIs and lower electricity CIs, such as New York. While varied electricity fuel sources are generally accounted for in low carbon fuel program fuel CI calculations, spatially varying feedstock CIs are generally ignored by the RFS and CFR. Given that spatially varying feedstock CIs can significantly affect the total fuel CI, they should be given appropriate consideration in low carbon fuel policies and tax credits.

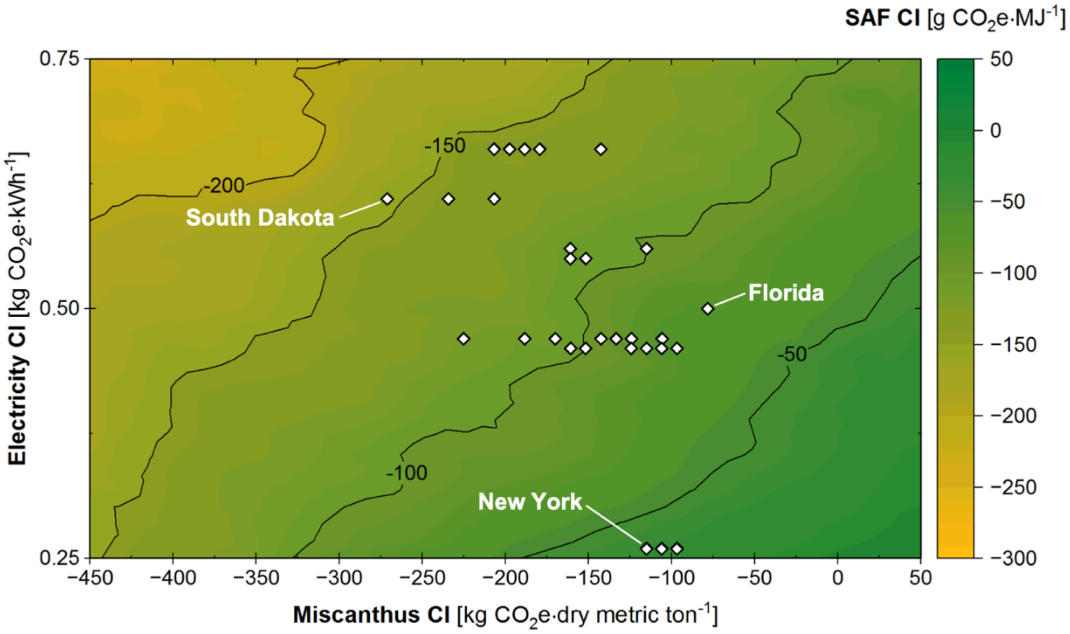

Figure 2. SAF CI across miscanthus and electricity CIs. White diamond-shaped points indicate states for which miscanthus CIs were estimated by Fan *et al.* (2024). These points indicate the median CIs for each state based on simulations over 30 years at a 4 km resolution. Vertical clustering of states was the result of differences in electricity and natural gas emission factors which were based on balancing region and state, respectively.[35] Ranges of CIs for each state are detailed in **Table S8** of the SI.

Influence of Policy Specifications on SAF Characterization and Valuation

Based on the CIs according to policies and spatially explicit LCA, the policy-induced CI differential for SAF produced from miscanthus is -137.4 g $CO_2e{\cdot}MJ^{-1}$ [(-)356.3 to (-)27.8] for the RFS, -32.6

g $CO_2e \cdot MJ^{-1}$ [(-)196.6 to (+)49.7] for the CFR, -68.9 g $CO_2e \cdot MJ^{-1}$ [(-)287.7 to (+)40.8] for the LCFS, and +14.7 g $CO_2e \cdot MJ^{-1}$ [(-)22.1 to (+)44.7] for the 45Z tax credit (**Figure 3A**). The overestimated CI on behalf of the RFS is explained by the non-producer-specific fuel pathway SAF CI used by the program (**Table 1**). The CFR overestimates and underestimates the CI similarly, but the use of a single program-based CI still cannot account for the potential variation in SAF CIs. The 45Z tax credit is the only policy that is likely to underestimate the SAF CI, because the CI is not producer-specific and estimates a higher amount of miscanthus-induced SOC storage (**Table 2**).

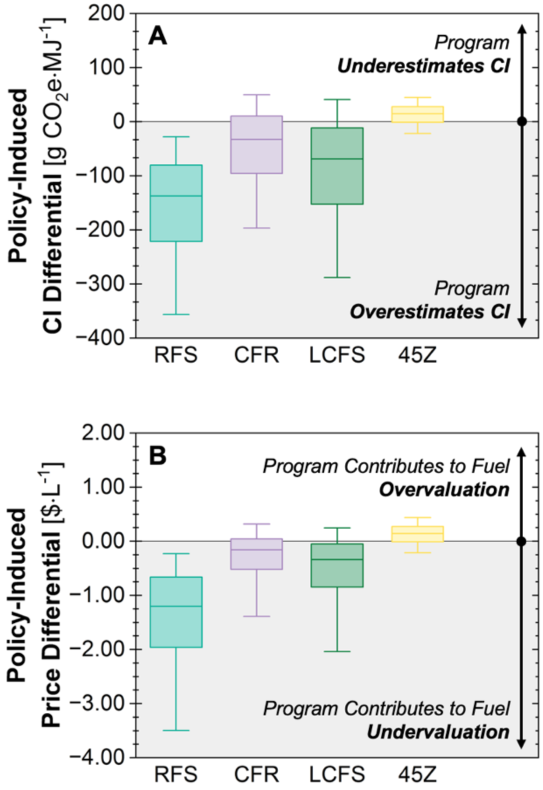

Figure 3. Policy-induced (**A**) SAF CI differentials and (**B**) SAF price differentials. Negative differentials indicate that the SAF CI is overestimated and the fuel is undervalued, respectively, by the policy, and vice versa.

Regardless of over- or underestimation, the wide range of policy-induced CI differentials highlights the limitations of using a single fuel CI for program participation (for all four policies, but particularly for the RFS and LCFS). The variation in the SAF CI estimated via spatially explicit LCA (which corresponds to the variation in CI differential in **Figure 3A**) can be attributed to multiple spatially varying and uncertain parameters along the biofuel supply chain (e.g., miscanthus CI, biomass transport distance, biomass-to-biofuel conversion efficiency). Not accounting for this variation among fuel producers and uncertainty inherent to fuel production leads to falsely precise CI quantification and broader estimates of the benefits of biofuels. Properly accounting for this variation and uncertainty (e.g., via field-specific LCA and explicit expression of uncertainty) would lead to a more accurate quantification of carbon outcomes, properly incentivize activities with the highest likelihood of reducing emissions, and help better achieve low carbon fuel policy goals overall.

Based on policy-induced CI differentials, low carbon fuel program credit selling prices, and the 45Z tax credit value, the policy-induced price differential for SAF produced from miscanthus is -1.20 $\$\cdot L^{-1}$ [(-)3.49 to (-)0.23] for the RFS, -0.16 $\$\cdot L^{-1}$ [(-)1.39 to (+)0.32] for the CFR, -0.34 $\$\cdot L^{-1}$ [(-)2.04 to (+)0.25] for the LCFS, and +0.14 $\$\cdot L^{-1}$ [(-)0.22 to (+)0.44] for the 45Z tax credit (**Figure 3B**). Given that credit selling prices have been consistently greater than zero, the monetary undervaluation of SAF is directly linked to overestimated CIs on behalf of low carbon fuel policies (**Figure 3A**). These results suggest that the RFS will almost always undervalue SAF. While the CFR-induced price differential was estimated based on LCFS credit prices, these results indicate that the program is likely structured in a way that will undervalue SAF produced from miscanthus. The 45Z tax credit is the only policy likely to overvalue SAF produced from miscanthus, due to the underestimated CI on behalf of the policy and credit value.

The consistent undervaluation of a fuel produced from a cellulosic feedstock represents one (out of many) challenges undercutting efforts to achieve cellulosic biofuel production targets set by the RFS. If biofuel production credits are not more closely linked to actual CI reductions, biofuel producers are less incentivized to undertake measures to reduce emissions. This is particularly relevant for cellulosic biofuels, which are subject to high capital costs that cannot be recovered with low fuel selling prices. Using field-specific LCA to more accurately quantify biofuel CI reductions and allowing lower CI fuels to be sold at higher prices (because of higher priced program credits) would make more money available to low-GHG technologies (including herbaceous feedstocks) and measurement tools to facilitate field-specific LCA.

The overall minimum selling price of SAF was estimated as 2.77 $\$\cdot L^{-1}$ [2.23 to 3.62], and is largely dependent on capital costs and the miscanthus price (SI **Table S2**). Thus, location-specific parameters such as the miscanthus price and location capital cost factor (LCCF, an estimate of how capital costs vary across the U.S.) are important predictors of the SAF selling price across locations (SI **Figure S2**). SAF produced from miscanthus with the lowest CI (e.g., miscanthus produced in South Dakota) will be the most undervalued by the RFS (an undervaluation of 1.35 $\$\cdot L^{-1}$ [0.31 to 3.67]; **Figure 4**, SI **Table S4**). SAF produced from the most expensive miscanthus (e.g., miscanthus produced in Florida) is less undervalued (i.e., more accurately valued, an undervaluation of 0.80 $\$\cdot L^{-1}$ [0.23 to 2.66]) because the higher production cost offsets the effect of the CI overestimation and corresponding fuel undervaluation.

An ATJ SAF biorefinery operating in South Dakota could achieve a minimum SAF selling price of 2.57 $\$\cdot L^{-1}$ [2.18 to 3.14] (SI **Figure S2**, SI **Table S4**). If the RFS were to more accurately quantify the CI of this SAF (i.e., via field-specific LCA) and the policy induced price differential of 1.35 $\$\cdot L^{-1}$ (**Figure 4**) were eliminated, the biorefinery's required SAF selling price would instead be 1.22 $\$\cdot L^{-1}$. Factors that affect farm-specific biofuel CIs should be considered in low carbon fuel policies to better promote favorable farming locations (i.e., locations that can achieve low fuel CIs) that might be subject to higher production costs, such as South Dakota.

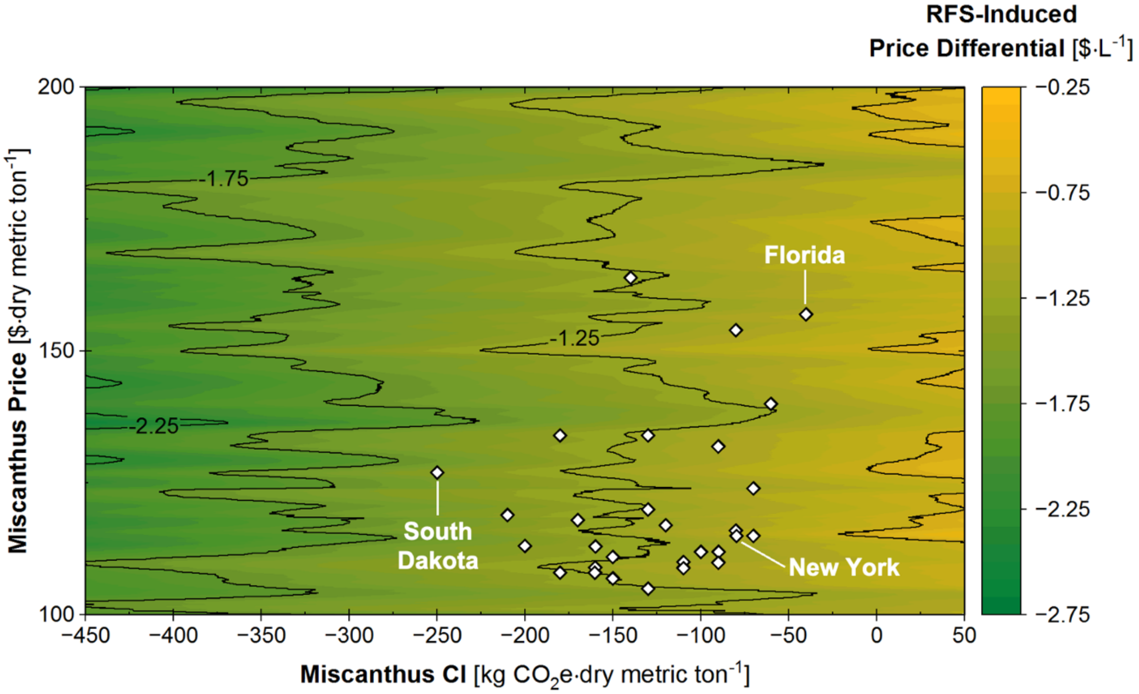

Figure 4. RFS-induced SAF price differential across miscanthus CI and miscanthus price. White diamond-shaped points indicate states for which miscanthus CIs and prices were estimated by Fan et al. (2024) and Lee et al. (2023), respectively. These points indicate the median CI and price for each state. Ranges of CIs and prices for each state are detailed in SI **Table S8**.

Feasibility and Need for Innovation

Technological Capabilities

While miscanthus has the potential to contribute to the U.S. bioeconomy,[57] this crop has not yet been widely cultivated in the U.S. (e.g., in 2022, only approximately 68,000 metric tons were produced across 9 states,[58] whereas approximately 343 million metric tons of corn grain were produced across 49 states[59]). The factors influencing the decision by individual farmers to cultivate novel energy crops such as miscanthus have been studied extensively (e.g., [60–63]). While accurate quantification of biomass feedstock and biofuel CIs is important, achieving the benefits of SOC sequestration and low carbon biofuels will also depend on farmers' transition to growing herbaceous energy crops. Cost subsidies for crop establishment[61] and payments for carbon mitigation[63] could make these novel crops more appealing to farmers and facilitate this transition.

Much of the technology needed to collect measurements used to quantify field-specific feedstock CIs is well developed. The cost of deploying the technology could be an impediment, however. For example, an eddy-covariance flux tower used to collect carbon flux data associated with biomass growth costs approximately $100,000 to install and operate.[14] If technology used to perform field-specific LCA technology is implemented, however, it seems likely that deployment costs could be recovered relatively quickly (i.e., assuming that current fuel price differentials highlighted in **Figure 4B** are negated by improved CI quantification and fuels are sold for higher prices). Further, rather than intensive monitoring on every field, a system-of-systems approach that combines in-field measurements, biogeochemical modeling, and big data analytics could enable better and more cost effective quantification of field-level carbon outcomes;[14] however, further financial investment is needed to continue to develop and prototype MMRV technologies.

The software generally used for biofuel CI calculations (e.g., GREET, openLCA) are robust LCA tools that are capable of incorporating field-specific factors and accounting for some sources of uncertainty. In general, policy provisions and LCA tools already allow for producer-specific inputs when modeling biorefinery operations (e.g., amounts of ancillary chemicals including enzymes, acids, caustic; region-specific electricity fuel sources). Given the capabilities of these LCA tools, this scope of consideration could easily be expanded to field-specific inputs (e.g., fertilizers, fuel) and biogeochemistry (e.g., SOC dynamics, given appropriate measurements and monitoring take place). The models themselves are also able to account for uncertainty (in the amounts and CIs of chemical inputs, etc.), but none of the low carbon fuel policies seem immediately capable to do so. Program administrators should consider the benefits of accounting for uncertainty in CI calculations compared to assigning false precision to carbon outcomes via single-value CI estimates.

Regulatory and Legal Precedent

The results of this study add to a body of literature (e.g., [7,42,64]) suggesting that the RFS technology mandate does not properly incentivize the production of low carbon fuels, while expanding the analysis to additional policies and a proposed pathway from a perennial grass to SAF. Field-specific LCA could better incentivize actions to meaningfully lower crop and biofuel carbon intensity and, in doing so, provide the capital necessary to implement in-field monitoring. The CFR is a more recently enacted performance-based program that appears better structured to characterize and value cellulosic biofuels (**Figure 4**). In anticipation of the continued establishment of RFS annual volume requirements, program administrators could consider restructuring the program to a performance-based standard to promote climate and financial benefits.

The Carbon Sequestration and Collaboration Act (CSCA),[65] while not yet enacted into law, indicates a desire on behalf of the U.S. Congress to better understand carbon sequestration methods. The CSCA specifically acknowledges the need to understand the variation in carbon storage potential in agricultural soil (as well as forests and geologic formations) across geographies. If enacted, the CSCA will direct the Department of Energy, the Department of the Interior, and the Department of Agriculture to establish carbon sequestration research initiatives, which could aid the development of technologies necessary to perform field-specific LCA.

Path Forward

While cellulosic biofuels present a viable option to lower GHG emissions associated with aviation, current low carbon fuel program provisions meant to incentivize their development are ineffective. Structural undervaluation of fuels that achieve lower carbon intensities in turn reduces the amount of money available to further develop these technologies. While the LCFS and CFR structurally promote the production of fuels that achieve the lowest carbon intensities (i.e., they generate program credits based on CI reductions), program methodological requirements may still lead to the mischaracterization and undervaluation of these fuels. Due to its CI threshold-based structure, the RFS does not properly incentivize the production of fuels that achieve lower CIs. Advanced energy feedstocks such as miscanthus have the potential to significantly lower the CI of SAF production, but this potential is not properly accounted for by existing program provisions. For all three low carbon fuel policies, issues with fuel characterization could be resolved by allowing fuel producers to calculate total fuel CIs that account for field-specific biomass production. Field-specific LCA presents a practicable means to more accurately quantify the outcomes of biofuel production and help society realize the benefits of cellulosic biofuels.

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Supporting Information Available

The Supporting Information includes:

> Detailed policy-specific CI calculations, description of input parameter distributions and sensitivity analysis results, description of low carbon fuel program credit prices, expanded TEA results.

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