



# Revisiting “Additional Carbon”: Tracking Atmosphere–Ecosystem Carbon Exchange to Establish Mitigation and Negative Emissions From Bio-Based Systems

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Climate stabilization plans rely heavily on advanced bioenergy and bioproducts for substitution of fossil-based energy sources and materials, and increasingly, for negative emissions via the direct sequestration of biogenic carbon. Yet, there remain persistent, largely unresolved critiques of bioenergy assessment methodology, particularly in the areas of land use and biogenic carbon accounting. The concept of “additional carbon” calls for evaluating the climate performance of bio-based systems by whether feedstock production creates measurable new local agro-ecosystem uptake of carbon from the atmosphere. This concept is challenging to operationalize for first-generation biofuels, and has largely been advanced as a negative critique. However, carbon additionality is more straightforward to establish—and less critical to overall system mitigation performance—in advanced bioenergy systems. In this Perspective, I review the additional carbon critique, and why it is analytically challenging to address in first-generation biofuel systems based on conventional food crops with large existing markets. Next, I make a case that carbon additionality (1) is more readily achievable with cellulosic feedstocks, (2) is more directly observable for dedicated biomass crops, and (3) is not a strict requirement for achieving net mitigation in carbon-negative bio-based systems. I end by discussing how centering atmosphere–ecosystem carbon exchanges in bio-based system assessment could create new opportunities for enterprise-scale performance monitoring and verification, augmenting and diversifying the current reliance on model-based life-cycle assessment approaches.

**Keywords:** biogenic carbon, biofuels, additional carbon, life-cycle assessment, bioproducts, BECCS, mitigation, negative emissions

## INTRODUCTION

While electrification and renewable electricity generation have made great headway in recent years, more than a quarter of all energy-related emissions will likely require a different decarbonization approach (Davis et al., 2018). Additionally, after years of accelerating greenhouse gas (GHG) emissions, most scenarios for achieving the temperature targets of the Paris Agreement now also

include the wide-scale deployment of negative emissions (Vuuren et al., 2018). It is expected that biomass will play a key role in climate stabilization as a feedstock for renewable transportation fuels (Fulton et al., 2015), industrial heat and power (Butnar et al., 2020), carbon-negative energy production (Fuss et al., 2014), and bio-product manufacturing (Fuhrman et al., 2020) in some combination.

Biofuels and bioenergy production are among the most well-studied bio-based systems, and have been a leading topic of life-cycle assessment (LCA) research and methodological development for more than four decades (Silva et al., 1978). However, there remains significant controversy around the climate change mitigation value of such systems, particularly with respect to land use and feedstock production (DeCicco and Schlesinger, 2018). Conventional LCA is a bottom-up approach that seeks to tabulate all cradle-to-grave GHG emissions associated with the supply chain of providing a good or service. If the total life-cycle emissions of bioenergy production and use are less than that of the competing conventional fossil-derived energy source, then emissions savings (mitigation) are inferred when bioenergy use replaces the fossil energy source. Emissions of biomass-derived “biogenic” CO<sub>2</sub> from bioenergy conversion and end use are often assumed to be carbon-neutral *a priori* (DeCicco et al., 2016), on the grounds that such carbon was recently fixed from the atmosphere during feedstock production, and an equivalent amount of carbon will be fixed again when the feedstock is subsequently re-grown. Changes in land use or land management for feedstock production are accounted for in terms of changes in above- or belowground ecosystem carbon stocks (Sheehan et al., 2003; Fargione et al., 2008), but biogenic carbon fluxes from the atmosphere into the feedstock and then back to the atmosphere during conversion and use are usually presupposed, or excluded from emissions accounting entirely.

## CARBON ADDITIONALITY

The concept of “additional carbon” suggests that the mitigation value of a bioenergy system is fundamentally dependent on, and should be evaluated explicitly in terms of, increased net photosynthetic uptake of atmospheric carbon in feedstock-producing agro-ecosystems (Searchinger, 2010; DeCicco, 2013; Haberl, 2013). Carbon uptake is usually understood to specifically mean net ecosystem production (NEP) (DeCicco, 2013). “A fundamental property of ecosystems” (Lovett et al., 2006) and “a central concept in C-cycling research” (Chapin et al., 2006), NEP reflects the difference between gross photosynthetic carbon uptake (i.e., gross primary production, or GPP) and carbon losses via ecosystem respiration ( $R_e$ ):

$$NEP = GPP - R_e \quad (1)$$

It can alternately be defined in terms of net primary production (NPP, i.e., net photosynthetic uptake by plants after correcting for their autotrophic respiration) and heterotrophic respiration ( $R_h$ ):

$$NEP = NPP - R_h \quad (2)$$

In systems with negligible inorganic carbon sources or sinks, NEP represents the total net CO<sub>2</sub>-C uptake from the atmosphere by the ecosystem. Note however that the net ecosystem carbon balance (NECB) of an agricultural system is also affected by removals of carbon through the harvest (*Harv*) of grain or biomass:

$$NECB = NEP - Harv \quad (3)$$

Proponents of carbon additionality assessment suggest that simplistic *a priori* assumptions of biomass carbon neutrality can mask carbon accounting baseline errors or unintended consequences from bioenergy systems. Production of first-generation biofuels from corn, soy, or sugarcane in the absence of additional NEP suggests that these feedstocks are simply being diverted from existing commodity markets. This undermines the basis of mitigation claims from such systems, and could lead to unintended consequences from compensatory agricultural extensification or intensification elsewhere [e.g., indirect land use change (ILUC)], or an overall reduction in food calorie production (Searchinger et al., 2015). Production of advanced bioenergy from cellulosic biomass feedstocks without increased NEP suggests that carbon is being “mined” from feedstock-producing ecosystems or sourced at the expense of future ecosystem carbon sequestration, and thus the benefits of reduced fossil fuel emissions are counteracted by a reduced ecosystem carbon sink (Searchinger et al., 2017; Schlesinger, 2018).

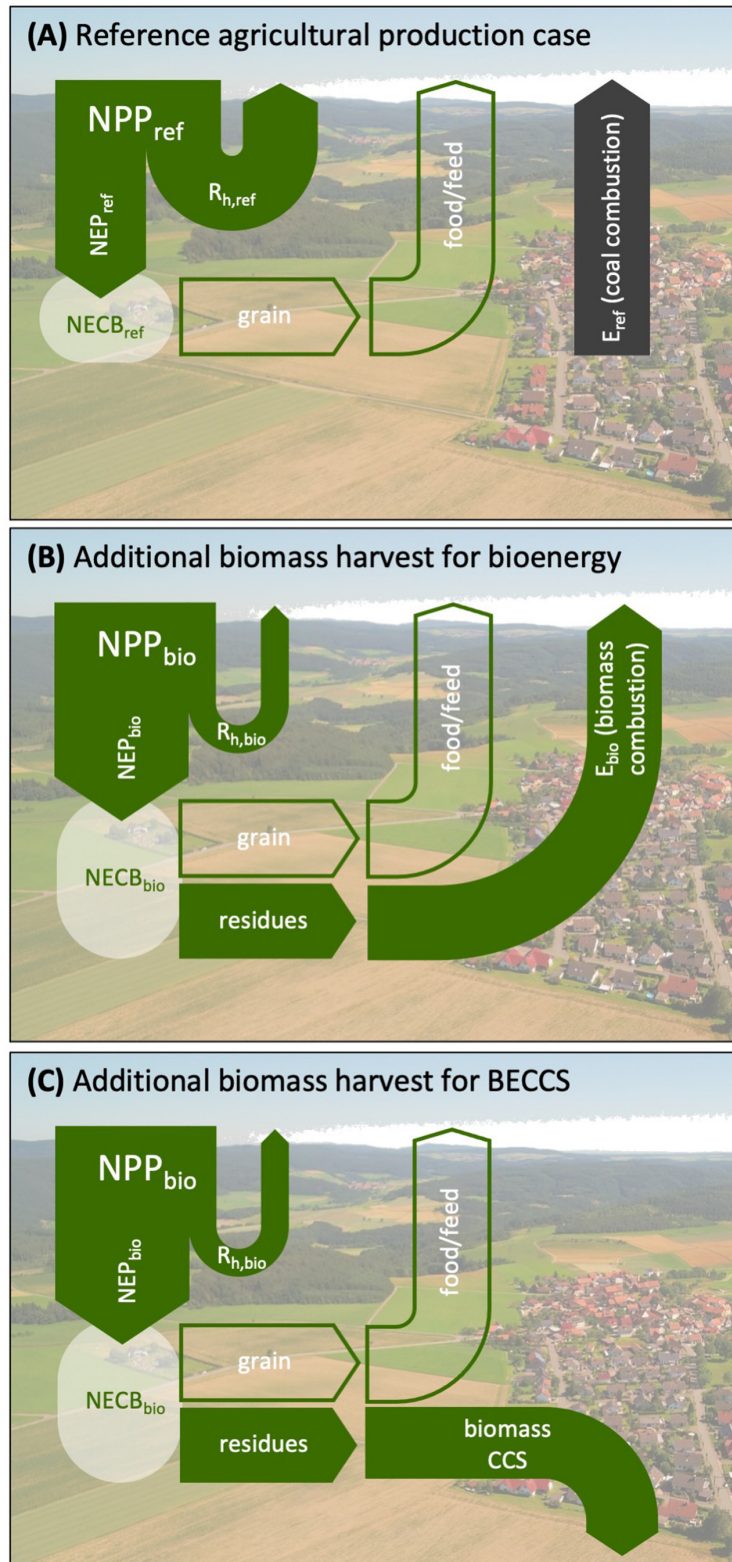
The concept of carbon additionality is illustrated in **Figure 1** by comparing reference-case (“ref”) agricultural land management and fossil coal combustion for energy (**Figure 1A**) to an alternative bioenergy scenario (“bio”) where coal is displaced by biomass sourced from agricultural residue collection (**Figure 1B**). Carbon fluxes associated with grain harvest and use for food or animal feed are assumed to be unchanged between the reference and stover-bioenergy scenarios, and thus are excluded from the accounting below for simplicity. The remaining relevant exchanges of carbon with the atmosphere in the reference case ( $\Delta C_{atm,ref}$ ) consist of point-source emissions from coal combustion for energy ( $E_{ref}$ ) and net carbon uptake by agro-ecosystems during business-as-usual agricultural production ( $NEP_{ref}$ ):

$$\Delta C_{atm,ref} = E_{ref} - NEP_{ref} \quad (4)$$

Conventional bioenergy systems seek to mitigate climate change through displacing fossil energy use with alternative biologically-derived energy sources. In the alternative bioenergy case, excluding upstream supply chain emissions (e.g., emissions associated with fertilizer production or farm operations) for simplicity, bioenergy feedstock production affects ecosystem carbon uptake ( $NEP_{bio}$ ), and coal emissions are replaced with emissions of biogenic carbon from biomass combustion ( $E_{bio}$ ):

$$\Delta C_{atm,bio} = E_{bio} - NEP_{bio} \quad (5)$$

As described previously in Field et al. (2020), achieving net climate change mitigation (i.e., net reduction in atmospheric



**FIGURE 1** | Carbon exchanges with the atmosphere in the production of conventional and carbon-negative bioenergy (“bio”) from new agricultural residue harvest, as compared to a reference case (“ref”). Fluxes of photosynthesis-derived “biogenic” carbon are shown in green; fossil carbon emissions from fossil fuel use in black. Net *(Continued)*

**FIGURE 1** | carbon exchange between the atmosphere and the agricultural landscape (net ecosystem production, or NEP) reflects the difference between net primary production (NPP) and heterotrophic respiration ( $R_h$ ). **(A)** The reference case includes atmosphere–ecosystem fluxes from business-as-usual agricultural grain production, plus coal combustion for energy. **(B)** Conventional bioenergy production from biomass sourced from new agricultural residue collection, which displaces reference-case coal combustion. **(C)** A bioenergy with carbon capture and storage (BECCS) variant of scenario B, in which biogenic  $\text{CO}_2$  from biomass combustion is geologically sequestered.

**TABLE 1** | Illustrative example of changes to ecosystem–atmosphere and energy system–atmosphere carbon fluxes in response to corn stover collection for bioenergy production.

Scenario	Ecosystem fluxes							Energy system fluxes			Net
	NPP	$R_h$	NEP	Harv	NECB	$\Delta \text{Harv}$ ( $\text{Harv}_{\text{bio}} - \text{Harv}_{\text{ref}}$ )	$\Delta \text{NEP}$ ( $\text{NEP}_{\text{bio}} - \text{NEP}_{\text{ref}}$ )	Harvested biomass LHV	Avoided coal emissions ( $E_{\text{ref}}$ )	Biomass emissions ( $E_{\text{bio}}$ )	Atmosphere C balance change ( $E_{\text{bio}} - E_{\text{ref}} - \Delta \text{NEP}$ )
	Mg C $\text{ha}^{-1} \text{y}^{-1}$							GJ $\text{ha}^{-1} \text{y}^{-1}$	Mg C $\text{ha}^{-1} \text{y}^{-1}$		Mg C $\text{ha}^{-1} \text{y}^{-1}$
ref: Grain harvest only	13.9	8.3	5.6	5.3	0.3	–	–	–	–	–	–
bio1: Near-term grain and stover harvest	12.7	8.3	4.4	8.7	–4.3	+3.4	–1.2	137	3.3	3.4	+1.3
bio2: Long-term grain and stover harvest	13.9	4.6	9.3	9.9	–0.6	+4.6	3.7	185	4.5	4.6	–3.6
bio3: Near-term grain and stover harvest w/CCS	12.7	8.3	4.4	8.7	–4.3	+3.4	–1.2	137	3.3	0	–2.1
bio4: Long-term grain and stover harvest w/CCS	13.9	4.6	9.3	9.9	–0.6	+4.6	3.7	185	4.5	0	–8.2

Reference case is shown in gray highlight.

carbon load) from such a system implies:

$$\Delta C_{\text{atm, bio}} < \Delta C_{\text{atm, ref}} \quad (6)$$

$$E_{\text{bio}} - \text{NEP}_{\text{bio}} < E_{\text{ref}} - \text{NEP}_{\text{ref}} \quad (7)$$

Coal combustion releases  $\text{CO}_2$  to the atmosphere at a rate of  $24.4 \text{ g C MJ}^{-1}$  on a lower heating-value basis as per the GREET model (Wang, 1996). Combusting corn stover produces  $\text{CO}_2$  at a roughly equivalent rate ( $25 \text{ g C MJ}^{-1}$ , based on data from Tanger et al., 2013). Because energy system emissions are roughly equivalent in both cases ( $E_{\text{bio}} \approx E_{\text{ref}}$ ), Equation (7) simplifies to:

$$\text{NEP}_{\text{bio}} > \text{NEP}_{\text{ref}} \quad (8)$$

In other words, any net mitigation from a bioenergy system is dependent on increased NEP flux from the atmosphere to the agricultural landscape where the biomass feedstock is produced. As per Equation (3), if the increase in carbon removal from new biomass harvest exceeds the increase in net carbon uptake by the system (NEP), then the biomass carbon is not fully “additional” but rather comes at the cost of reduced ecosystem carbon storage (NECB). Thus, carbon additionality refocuses assessment from tracking changes in ecosystem carbon stocks to tracking equivalent changes in atmosphere–ecosystem carbon flux.

An illustrative quantitative example is developed in **Table 1**. Reference-case ecosystem fluxes associated with corn grain production (“ref”) are taken from Cates and Jackson (2019) for a 3-year experiment in Wisconsin. That study estimates a NEP value of  $5.6 \text{ Mg C ha}^{-1} \text{y}^{-1}$  and grain export of  $5.3 \text{ Mg C ha}^{-1} \text{y}^{-1}$  averaged across all cover crop treatments, which together imply a small positive residual NECB ( $0.3 \text{ Mg C ha}^{-1} \text{y}^{-1}$ ). A whole-plant silage harvest treatment from the same study is analogous to the case of adding stover harvest for bioenergy production (“bio1”). NPP was reduced slightly ( $-1.2 \text{ Mg C ha}^{-1} \text{y}^{-1}$ ) under that management system, but carbon harvest increased by  $3.4 \text{ Mg C ha}^{-1} \text{y}^{-1}$ . The measured heterotrophic respiration rate was unchanged compared to the reference case over this relatively short experimental timeframe, which implies no increase in NEP (in fact a small decrease). Over this short time horizon, there is no system-level benefit to the atmosphere from trading coal emissions for stover biomass emissions, since that stover production was not associated with additional net agro-ecosystem carbon uptake (i.e., no carbon additionality), but rather came at the cost of reduced NECB (i.e., reduced litter and soil carbon in the system).

However, over longer time-frames we would expect  $R_h$  rates to drop as soil organic matter levels reach a new equilibrium in response to stover removal (Kim et al., 2018). To construct



a hypothetical longer-term equilibrium stover removal scenario (“bio2”) we assume no reduction in long-term productivity with stover harvest, and that only 20% of the carbon in harvested stover would have been stabilized as soil organic matter had it been retained. The remaining 80% of the harvested stover carbon is “additional” since it would otherwise be respired back to the atmosphere during stover decomposition, and its harvest increases agro-ecosystem NEP by decreasing  $R_h$  (Searchinger, 2010). When used for energy production, the harvested biomass carbon displaces a roughly-equivalent amount of carbon from coal combustion, and the net atmosphere carbon load is decreased by approximately the amount of long-term NEP increase from feedstock production. Note that carbon additionality is distinct from the idea of ecosystem carbon sequestration, and feedstock production can be partially additional, i.e., lead to increased local agro-ecosystem carbon uptake from the atmosphere (NEP) despite some reduction in ecosystem carbon storage (NECB, as is illustrated in the “bio2” case).

## CARBON ADDITIONALITY CHALLENGES FOR FIRST-GENERATION BIOFUELS

NEP and net ecosystem exchange (NEE, which is equivalent to NEP, but calculated from the perspective of the atmosphere and thus uses the opposite sign convention) have been measured in variety of bioenergy feedstock-producing landscapes via eddy covariance techniques (Skinner and Adler, 2010; Gelfand et al., 2011; Zeri et al., 2011, 2013; Drewer et al., 2012; Bernier and Paré, 2013; Zenone et al., 2013; Wagle et al., 2015; Sharma et al., 2017; Abraha et al., 2018). However, such data is seldom used directly in life-cycle assessments or other estimates of system-level GHG mitigation in bio-based systems. Though the concept of additional carbon is straightforward, its assessment in first-generation biofuel systems is not necessarily so.

Corn, soy, and sugarcane are fungible food commodities with large global markets, subject to large-scale supply and demand trends and market perturbations independent of biofuel production (De Kleine et al., 2017). As such, any changes in cultivation area, management intensity, or agricultural technology development associated with the scale-up of biofuel production must first be isolated from those background trends and perturbations in food and feed markets before they can be attributed to the biofuel sector. This requires detailed market analysis and modeling (Oladosu et al., 2011; Khanna et al., 2020), and the resulting estimates of biofuel performance are very heavily influenced by the conditions of a fundamentally unobservable “no-biofuel” counterfactual reference case (Babcock, 2009; Koponen et al., 2018). In addition, much of the crop mass used in first-generation biofuel production ends up in useful co-products such as corn oil, distillers grains, or soy meal, further entwining biofuel production with existing markets and introducing more dependencies around the arbitrary choice of co-product allocation method (Finnveden et al., 2009; Malça and Freire, 2010). Thus, establishing carbon additionality in such systems

is more an economic and LCA attribution problem (relying on economic modeling, trade analysis, LCA allocation conventions, etc.) than an issue of carbon cycle measurement *per se*. As such, previous studies of carbon additionality from first-generation biofuels are necessarily coarse in their spatial and temporal scale, limited by model resolution and data availability to evaluating regional- or national-scale trends over multi-year periods. While this can shed light on the sustainability of the industry as a whole, it has limited value for the design, optimization, or verification of individual bioenergy systems.

Despite these challenges around verifying carbon additionality in first-generation biofuel systems, steady improvements in bioenergy production technology are paving the way to advanced system designs that might circumvent much of this ambiguity. Biofuel production from non-edible woody and herbaceous “cellulosic” biomass has been a major area of research since the US Renewable Fuel Standard was expanded in 2007 (Steiner and Buford, 2016; Peters, 2018). Compared to first-generation biofuels, advanced bioenergy systems have a) multiple routes to increased NEP, b) more identifiable atmosphere-ecosystem feedstock fluxes, and c) more opportunities for direct enterprise-level carbon sequestration. While these ideas are developed below in the context of bioenergy, there are many commonalities for the production of bio-plastics, mass timber, and other elements of the wider developing bioeconomy.

## MULTIPLE ROUTES TO INCREASED NEP IN CELLULOSIC BIOMASS PRODUCTION

There are multiple potential routes to feedstock production in existing agricultural landscapes that increase NEP while avoiding wide-scale indiscriminate land use change. As per Equation (2), NEP can be increased via increasing NPP, decreasing  $R_h$ , or a combination thereof. These are consistent with the concept of “sustainable intensification,” which seeks to increase the per-area productivity of agricultural systems through increased crop growth and/or reduced waste (Tilman et al., 2011; Heaton et al., 2013; Yang et al., 2018; Mouratiadou et al., 2020).

Input intensification (e.g., greater use of fertilizers and irrigation) and adoption of higher-yielding crop varieties are conventional routes to increased agricultural NPP, though Heaton et al. (2013) review additional opportunities for bioenergy-focused sustainable intensification. They define temporal intensification as cultivating additional crops during the fallow portion of existing crop rotations, for example, growing winter oilseeds within conventional cotton-based rotations in the southeastern US (Kumar et al., 2020). Such approaches can have important co-benefits including reduced erosion, increased soil carbon, and reduced nutrient losses (Tonitto et al., 2006; Jian et al., 2020). Spatial intensification of agricultural landscapes involves converting under-utilized or unsustainably-cultivated land to dedicated energy crops. This might include “marginal” land of intermediate productivity (Gelfand et al., 2013) or agricultural land that has previously been degraded (Tilman et al., 2006), abandoned (Campbell et al., 2008), or placed into conservation easements (Gelfand et al.,

2011). This could also include sub-field scale integration of perennial energy grasses in areas of problematic topography or soils, which currently produce negative economic returns under conventional crops and contribute disproportionately to erosion and nutrient leaching (Brandes et al., 2018). Perennial grasses can achieve higher NPP than many annual crops due in part to a longer growing season (Dohleman and Long, 2009). Eddy flux covariance studies have observed dedicated energy grasses such as *Miscanthus* and switchgrass to have approximately double the average annual NEP of conventional corn–soy rotations (Zeri et al., 2011, 2013) or continuous corn cultivation (Abraha et al., 2018). However, such NEP results are highly sensitive to prior land use and time since energy crop establishment (Abraha et al., 2018), and some studies show substantially lower NEP values for those crops (Skinner and Adler, 2010; Drewer et al., 2012), suggesting significant regional- and site-level variability.

Alternately, cellulosic feedstocks can be produced from harvesting agricultural residues such as corn stover (Dominguez-Escribá and Porcar, 2010; Heaton et al., 2013; Mouratiadou et al., 2020) that would otherwise largely be respired back to the atmosphere. Such feedstocks are additional to the extent that they increase agro-ecosystem NEP by reducing  $R_h$  (Searchinger, 2010). Stover removal is not completely additional as it does lead to some reduction in soil carbon levels (Xu et al., 2019), particularly in the short-term as demonstrated by both modeling studies (Kim et al., 2018) and carbon flux measurements (Cates and Jackson, 2019). Soil organic matter is foundational to soil health and fertility (Campbell et al., 2018), and extreme organic matter loss can compromise agricultural system function (Tiessen et al., 1994). Erosion control and soil moisture management impose further constraints on the amount of residue that can be sustainably removed in different settings (Graham et al., 2007). However, these constraints might be lessened to some degree with the co-adoption of complementary conservation practices such as tillage intensity reduction or winter cover-cropping (Kim et al., 2018; Qin et al., 2018).

## IDENTIFYING ECOSYSTEM–ATMOSPHERE EXCHANGE WITH DEDICATED BIOENERGY CROPS

Dedicated perennial energy crops will likely be the largest source of cellulosic biomass feedstocks for a future US advanced bioeconomy (U.S. Department of Energy, 2016). Large federal research programs support the development of improved varieties of perennial energy grasses such as switchgrass, *Miscanthus*, and energycane, and short-rotation woody crops such as poplar (Steiner and Buford, 2016; Peters, 2018). Subsidies have also been offered to encourage their establishment in the landscapes around bioenergy facilities (Miao and Khanna, 2017). These dedicated bioenergy feedstock crops have often not previously been domesticated or improved, and lack large existing markets. As such, any future development and deployment of such crops can be confidently attributed to the bioenergy and bioproducts sectors.

The uniqueness of these dedicated crops also creates opportunities to cheaply and transparently monitor their growth and performance using remote sensing (RS) techniques. RS is widely used to map the extent of conventional crops in the US at fine spatial scales (Boryan et al., 2011), and has been applied to track expansion of corn cultivation during the growth of the ethanol industry (Wright and Wimberly, 2013; Wright et al., 2017; Lark et al., 2020). Differentiation of grassy land covers such as native grassland, managed pasture, hay production, and dedicated bioenergy grasses has historically been problematic for RS-based land use mapping (Kline et al., 2013). However, advanced methods show promise for identifying warm-season grasses (Wang et al., 2014, 2017) and even individual species such as *Miscanthus* (Xin and Adler, 2019) in cellulosic bioenergy production landscapes. Further refinement of such methods may enable precise, transparent, and low-cost mapping of dedicated energy crop plantings, as well as the previous land uses they replaced.

Beyond just land cover, RS is also increasingly applied to assess ecosystem carbon stocks and fluxes directly. Recent advances support using solar-induced fluorescence to sense GPP, lidar to measure standing biomass, and column  $CO_2$  concentration measurement and source/sink inversion modeling to estimate NEP (Xiao et al., 2019). Gu et al. (2012) have used RS techniques to produce high-resolution maps of NEP under current land cover, in order to identify low-productivity marginal lands to target for conversion to bioenergy crops. Many bioenergy critiques (Righelato and Spracklen, 2007; Haberl, 2013; Searchinger et al., 2017) focus not on the carbon value of current-day land use, but rather on the “opportunity cost” of producing bioenergy in lieu of reforestation or alternate land-based “natural climate solutions” (Griscom et al., 2017). However, RS approaches are also beginning to be used in the assessment and monitoring of NEP provided by such natural solutions (Gerlein-Safdi et al., 2020). Together, these methods may enable the direct observation of carbon additionality by tracking the carbon uptake of land before and after conversion to dedicated energy crops, and in comparison to alternative natural solutions. This would transform many nuanced sustainability questions that are currently subject of scenario analysis and model-based inference into a matter of direct observation and measurement at relatively fine spatial scales.

## CARBON ADDITIONALITY IN CARBON-NEGATIVE SYSTEMS

Traditional bioenergy systems aim to achieve climate benefits principally through the displacement of fossil emissions. However, advanced bioenergy and other bio-based systems increasingly target the sequestration of biogenic carbon in soils, geological reservoirs, and durable bio-based products, termed “carbon management” (Canadell and Schulze, 2014), “negative emissions,” or “carbon dioxide removal.” Perennial feedstock crop cultivation promotes sequestration of soil organic carbon (Qin et al., 2016) in amounts that significantly affect system-level climate performance (Yang and Tilman, 2020).

New research suggests that enhanced rock weathering can be widely deployed on croplands for additional sequestration of inorganic carbon (Beerling et al., 2020). A variety of “carbon negative” bioenergy production technologies have also been proposed including the co-production of biochar soil amendments (Lehmann, 2007) or pyrolysis liquids for geological sequestration (Schmidt et al., 2019), and point-source carbon capture and storage (CCS) applied to biomass power plants (Fuss et al., 2014; Sanchez et al., 2015) and biorefineries (Field et al., 2020; Gelfand et al., 2020; Hanssen et al., 2020).

These various negative emissions options have different implications for system-level mitigation performance. Ethanol fermentation produces a CO<sub>2</sub> byproduct, the sequestration of which creates additional mitigation beyond the fossil fuel displacement value of the main fuel product. This can be viewed as increasing the carbon efficiency of the system, i.e., achieving greater climate benefits per unit of feedstock consumed (Field et al., 2020). Further, in a bioenergy with carbon capture and storage (BECCS) system, the same mass of carbon can both displace fossil emissions via bioenergy production, and be captured and sequestered via CCS (Figure 1C), thus effectively doing double-duty from a mitigation perspective. In the simplified examples illustrated in Figure 1C and quantified in Table 1, the addition of CCS to the near-term stover removal scenario (“bio3”) prevents CO<sub>2</sub> from biomass combustion from being re-emitted back to the atmosphere. As a result, the system achieves net climate benefit compared to the reference case due to the avoidance of emissions from coal combustion, even in the absence of carbon additionality of the biomass feedstock. When CCS is applied to the carbon-additional long-term stover removal scenario (“bio4”), substantial mitigation is achieved via both displacing coal emissions, and from the geological sequestration of biogenic carbon (effectively creating a carbon pump from the atmosphere to the geosphere). Adding CCS introduces additional parasitic energy requirements that are not considered in this simplified example, though analysis of a hybrid fuel-and-power production system concept suggests that CCS integration can approximately double overall net system mitigation performance (Liu et al., 2011).

Similar logic is potentially applicable to other bio-based systems as well. For example, mass timber production may have mitigation value through both the displacement of emissions-intensive conventional building materials (steel, concrete, etc.) and via the sequestration of biogenic carbon in the timber itself.

## DISCUSSION

Bioenergy and bioproduct assessment has been heavily reliant on model-intensive LCA approaches subject to large and potentially irresolvable methodological uncertainties (Warner et al., 2013; DeCicco et al., 2016). However, as advanced bio-based supply chains become more distinct from conventional agricultural production, and more reliant on mitigation via the direct sequestration of biogenic carbon, new opportunities arise to directly observe feedstock-related carbon fluxes which

have previously been the source of much critique and controversy. Remote sensing of additional ecosystem carbon uptake at the scale of feedstock-sheds would establish a data-rich foundation for monitoring individual bioeconomy enterprises without the need for bespoke, resource-intensive studies (Field et al., 2018).

Direct observation of atmosphere–ecosystem carbon exchange does not address all feedstock-related sustainability critiques or serve as a full replacement for conventional bio-based system LCA. Those conventional approaches are still needed to calculate supply-chain emissions associated with upstream fertilizer production and farm operations, for example. However, such emissions are typically modest in cellulosic systems. In contrast, the measurement of ecosystem–atmosphere exchanges centers the more contentious issues of land availability, system scale, and biogenic emissions accounting in ways that conventional LCA cannot. There are other system-level effects such as ILUC that exist largely outside the provenance of individual feedstock producers, bioenergy companies, or even many policy jurisdictions, and which cannot directly be observed (Babcock, 2009). But even there, RS approaches can help constrain the underlying land use change modeling with observational estimates of any existing agricultural production being displaced by feedstock crops.

Climate benefits are not a guaranteed outcome of bio-based systems, but rather the result of systems thinking and design—including innovations in technology, assessment, and policy—to maximize mitigation potential while minimizing the risk of unintended consequences. Prime and even marginal arable land are a finite resource, and arbitrarily-wide deployment of any land-based mitigation approach will at some point conflict with the food system (Fuhrman et al., 2020; Stenzel et al., 2021) and/or with biodiversity preservation (Stoy et al., 2018; Seddon et al., 2019). In light of these challenges, some recommend taking a highly precautionary approach to the development and deployment of bio-based systems (Searchinger, 2010; DeCicco and Schlesinger, 2018). However, centering the observation of atmosphere–ecosystem carbon exchanges in bio-based system assessment may provide a different path. The assessment community might take inspiration from the imperative of “ecological forecasting,” which calls for a near-term iterative approach to ecological modeling that can be continuously evaluated and updated in light of the flood of new measurements becoming available in that field (Clark et al., 2001; Dietze et al., 2018). Similarly, a greater focus on observed atmosphere–ecosystem carbon exchange in bio-based system assessment could support near-term iterative performance evaluation for individual bio-based enterprises or land-use policies, in support of sustainable decarbonization.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

JF devised and wrote the manuscript.

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**Conflict of Interest:** The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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