Environmental Science & Technology

pubs.acs.org/est

Article

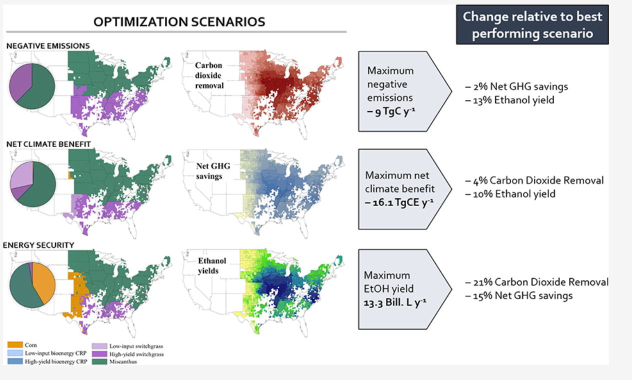
Climate vs Energy Security: Quantifying the Trade-offs of BECCS Deployment and Overcoming Opportunity Costs on Set-Aside Land

Elena Blanc-Betes, Nuria Gomez-Casanovas, Melannie D. Hartman, Tara W. Hudiburg, Madhu Khanna, William J. Parton, and Evan H. DeLucia*

Cite This: https://doi.org/10.1021/acs.est.3c05240

Read Online

ABSTRACT: Bioenergy with carbon capture and storage (BECCS) sits at the nexus of the climate and energy security. We evaluated trade-offs between scenarios that support climate stabilization (negative emissions and net climate benefit) or energy security (ethanol production). Our spatially explicit model indicates that the foregone climate benefit from abandoned cropland (opportunity cost) increased carbon emissions per unit of energy produced by 14–36%, making geologic carbon capture and storage necessary to achieve negative emissions from any given energy crop. The toll of opportunity costs on the climate benefit of BECCS from set-aside land was offset through the spatial allocation of crops based on their individual biophysical constraints. Dedicated energy crops consistently outperformed mixed grasslands. We estimate that BECCS allocation to land enrolled in the Conservation Reserve Program (CRP) could capture up to 9 Tg C year^{-1} from the atmosphere, deliver up to 16 Tg CE year^{-1} in emissions savings, and meet up to 10% of the US energy statutory targets, but contributions varied substantially as the priority shifted from climate stabilization to energy provision. Our results indicate a significant potential to integrate energy security targets into sustainable pathways to climate stabilization but underpin the trade-offs of divergent policy-driven agendas.



KEYWORDS: *climate change, carbon dioxide removal, carbon intensity, land use change, life cycle analysis, soil carbon, negative emissions, payback time, carbon debt, Conservation Reserve Program*

1. INTRODUCTION

Keeping global warming within 2 °C above preindustrial levels—a politically agreed-upon benchmark to prevent dangerous anthropogenic interference with the climate system[1]—requires immediate and unprecedented rates of decarbonization.[2−4] In this context, bioenergy with carbon capture and storage (BECCS) is being put forward by most integrated assessment models as a cost-effective strategy to achieve net-negative emissions targets while providing clean energy, moving away from fossil sources.[2,5] However, the blueprint of BECCS deployment to guarantee sufficient and sustainable negative emissions is still being debated.[6−9]

At present, there is a marked dissociation between IPCC low-carbon representative concentration pathway (RCP) scenarios that rely on sustained net-negative emissions and the emissions reduction pledges that lead international action on climate crisis.[9−11] Furthermore, while the carbon dioxide removal (CDR; i.e. physical removal of CO_2 from the atmosphere) potential is generally deemed the most valuable aspect of BECCS,[12] uncertainty in effective removal rates[5,6,13,14] and the political appeal of energy independence may make energy targets more marketable, prioritizing ethanol yields in climate action portfolios. Sociopolitical and economic considerations may, therefore, urge agendas to support either climate stabilization or energy security, the trade-offs of these inherently different priorities being, for the most part, overlooked in strategic pathways to implementation.

Despite accounting for 90% of biomass availability in 2020,[15] alternative resources (e.g., crop residue, woody biomass and residuals) are estimated to contribute less than 30% of US potential CDR from BECCS in 2040.[16] The adoption of BECCS at meaningful scales will therefore require a significant expansion of dedicated energy crops (i.e., purpose-grown bioenergy feedstocks), raising concerns over land displacement, compensatory agricultural expansions (i.e., indirect land use change), and the derived toll on emissions savings.[17] Indirect land use change can be minimized by targeting energy

Received: July 9, 2023
Revised: October 4, 2023
Accepted: October 5, 2023

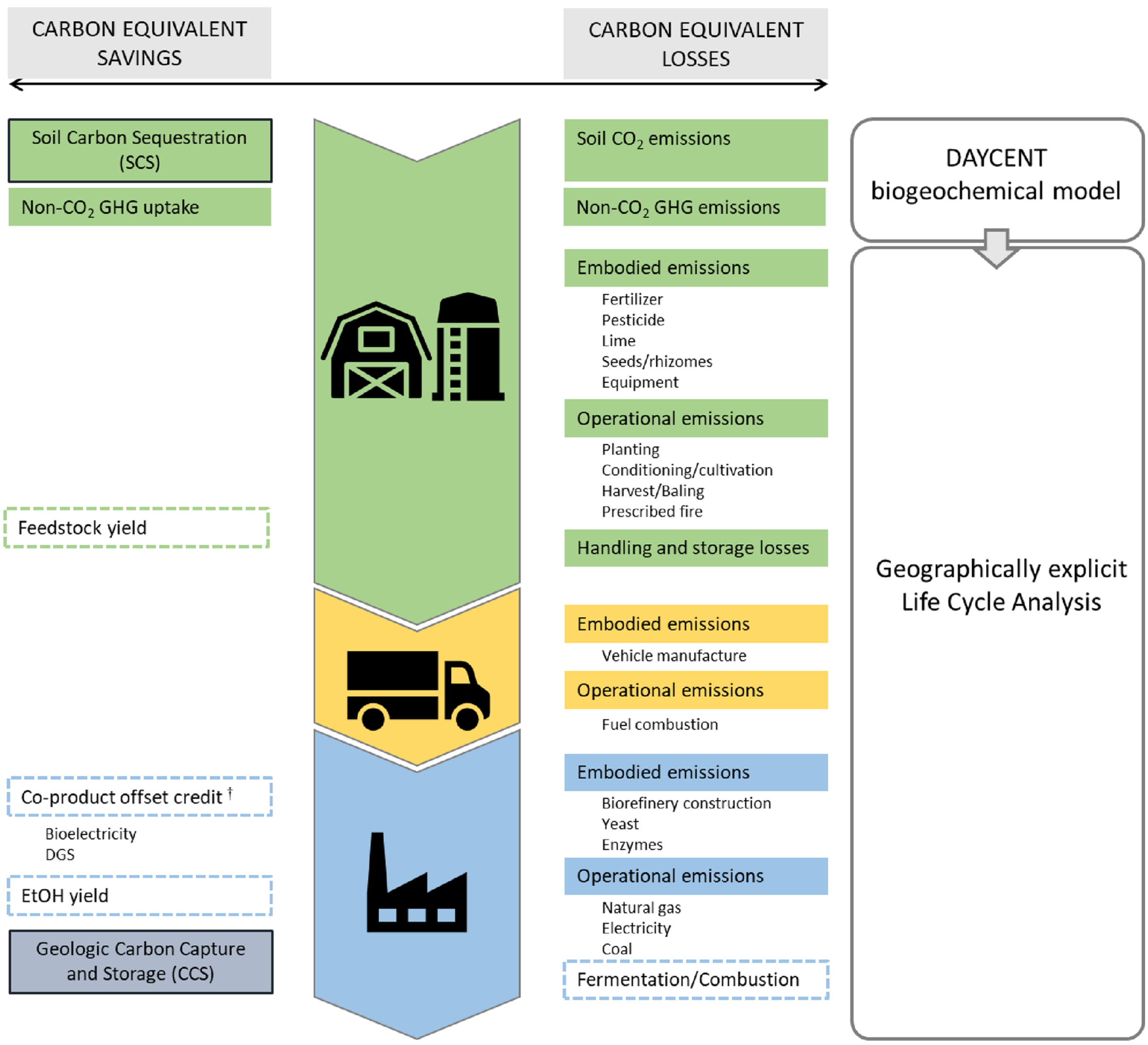


Figure 1. System boundary of farm-to-fuel analysis depicting the carbon equivalent savings (credits) and losses (costs) of the life cycle inventory encompassing: (i) feedstock production (green), (ii) transportation (yellow), and (iii) conversion (blue). Dashed lines indicate carbon that is part of a closed cycle based on the premise that carbon released during conversion and combustion processes equals carbon captured into biomass upon regrowth.[54] Solid lines indicate carbon temporarily or permanently taken out of the carbon cycle generating negative emissions.[26] Embodied emissions account for upstream emissions from the manufacturing of chemicals and equipment associated with feedstock production, transport, and conversion to ethanol. Operational or embodied emissions of geologic carbon capture and storage are not included. All contributions to the life cycle inventory are explained in detail in the Supporting Information.

feedstock production on set-aside (a.k.a. marginal) land.[18] A major caveat is that the concept of marginal land is notoriously vague, with several definitions based on principles ranging from economic return to constraints for agricultural use.[19−21] In the absence of a clear definition of marginal land, effective assessments of potential allocation to energy crops remain elusive.[21,22] This uncertainty creates inconsistencies about the role that such strategies may play on climate stabilization and energy provision.[23] In contrast to marginal land, land enrolled in the Conservation Reserve Program (CRP)—a US government program to incentivize the retirement of environmentally sensitive land from agricultural production—is clearly defined and represents an alternative for BECCS deployment, sidestepping the drawbacks of indirect land use change.

Questions remain, however, if energy feedstocks can be sourced without incurring self-defeating emissions from land use change (LUC), including disturbance emissions (i.e., carbon debt), and foregone greenhouse gas (GHG) emission savings from the displaced system (i.e., opportunity cost), that must be repaid by future savings to generate a climate benefit.[17,24] The ability of BECCS to achieve sizable rates of fuel production and CO_2 removal at tenable breakeven times (i.e., payback times) has profound implications for policy and depends on the crop of choice and the conditions of its deployment.[14] Developing sustainable low-carbon scenarios, therefore, requires careful consideration of the land use implications of bioenergy feedstock allocation,[5,13,25,26] and the explicit acknowledgment of all up- and downstream emissions associated with bioenergy production and the carbon (C) capture chain.[27,28]

The role of set-aside land on the effective deployment of BECCS at scale remains controversial. Previous studies report a mitigation potential of cellulosic ethanol production severalfold greater than grassland restoration[29] or reforestation,[30] whereas others contend that the C debt and opportunity costs of land conversion largely offset the net

https://doi.org/10.1021/acs.est.3c05240
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

climate benefit of bioenergy.[17,31] Much of the conflict arises from the use of inconsistent system boundaries of life cycle analyses (LCAs),[28] the accounting of single-crop or generic crop yields and C sequestration rates, and standard crop requirements that disregard regional heterogeneity.[32,33]

Recognizing markedly different physiologies and interactions with the environment among energy feedstocks, previous research suggests that observing the biophysical constraints of energy corps may help minimize the C debt and potentially overcome the opportunity costs of land conversion.[13,34−36] A few studies have integrated the spatial heterogeneity of some attributes (e.g., biomass yields and changes in soil C) into the LCA of bioenergy production.[37,38] However, these studies focus on contributions to bioenergy production therefore excluding CCS from the system boundary and neglect to account for local impacts on operational costs, which may account for >70% of the C equivalent costs at the farm gate.[39] Other studies assess near-term deployment opportunities for BECCS and provide a picture of optimal allocation of resources.[16,40] However, these studies lean heavily on biomass availability, and while for the most part, they account for the direct impacts of LUC, conversion losses are generally derived from standard coefficients and neglect the toll of opportunity costs on effective negative emissions. In all instances, previous studies give an indication of cost-optimal roadmaps for bioenergy or BECCS allocation, but these may deviate substantially from climate or energetically optimal pathways of deployment.

Here, we developed an integrated biogeochemical−life cycle emissions framework coupling DAYCENT with a spatially explicit farm-to-fuel LCA (Figure 1) to estimate the C debt and payback time of diverting CRP land to dedicated energy crops, evaluate the toll of opportunity costs on effective climate mitigation, and examine potential climate and energy trade-offs of large-scale deployment of BECCS. To examine climate versus energy trade-offs, we examined the impact of growing different combinations of energy crops on CRP land under three different optimization scenarios: (i) a negative emissions (NE) scenario that relies on CDR rates outlined by pathways for stabilization of radiative forcing (RCP 4.5 and below)[5,14,41]; (ii) a net climate benefit (NCB) scenario that targets emission reductions and leans heavily on fossil fuel displacement led by policy incentives[11,42]; and (iii) an energy security (ES) scenario that prioritizes ethanol (EtOH) yields led by energy statutory targets[43] (Table 1).

2. MATERIALS AND METHODS

2.1. Scenario Development, Scope, and Constraints.

We generated optimized land use scenarios for land enrolled in the CRP targeting three key sustainability goals: (i) an NE scenario led by CDR rates including both biologic (i.e., soil carbon sequestration; SCS) and geologic (i.e., the deliberate capture and storage of released CO_2 at the biorefinery into subsurface geological formations; CCS) C removal; (ii) an NCB scenario defined by the net GHG balance accounting for all C equivalent (CE) gains and losses up- and downstream the EtOH production pipeline including displaced fossil emissions (avoided emissions); and (iii) an ES scenario driven by energy yields including displaced energy from both EtOH and coproduct generation (Table 1).

Table 1. Summary of Optimization Scenarios

optimization scenario	leading goal	feedstock allocation optimized by
negative emissions (NE)	climate stabilization	total carbon dioxide removal (CDR). Sum of soil carbon sequestration (SCS) and geologic carbon capture and storage (CCS) (Figure 1)
net climate benefit (NCB)	climate stabilization	net balance of all carbon equivalent (CE) costs and credits (Figure 1)
energy security (ES)	energy security	energy yields (Figure 1)

To ensure the economic viability of alternative land uses and avoid additional pressure on freshwater resources, all scenarios were subject to a no-irrigation constraint, limiting the scope of the assessment to CRP land within the US rainfed region. To minimize the emission costs of conversion in line with the CRP conservation goals, only grassland area currently enrolled in CRP was considered available for BECCS. This limited the area of conversion to 3.6 Mha across the US rainfed region (Figure S1).

Mixed grasslands were assumed to represent the predominant land use on CRP land (conservation CRP), and we considered six alternative energy crops including a technologically and logistically consolidated first-generation EtOH feedstock (corn; *Zea mays*)[44,45] and three, arguably more end-use efficient yet relatively immature, second-generation bioenergy feedstocks.[29] Cellulosic feedstocks considered for second-generation EtOH production included grassland mixtures (bioenergy CRP) that avoid the direct impacts of LUC,[46] switchgrass (*Panicum virgatum*), a seminative perennial grass with a range of hybrids for optimal allocation,[29,47] and miscanthus (*Miscanthus* × *giganteus*), an inherently low-input high-yielding, albeit geographically constrained perennial[47,48] (Figure 2). Observing potential pressure on nutrient resources and sensitivities of both yields and ecosystem, and operational GHG emissions to fertilizer additions,[49−52] we included low-input (i.e., nutrient replacement to sustain long-term productivity) and high-yielding (i.e., fixed recommended fertilization rates to maximize productivity) management of bioenergy CRP and switchgrass cropping systems (Figure 2).

For each alternative land use and location, we estimated potential NE, NCB, and energy yields (Table 2). Observing the strict privacy policies of the Economic Research Service of the USDA that restrict data disclosure of CRP acreage at higher resolution, all simulations were performed at the county level. Data driving modeling efforts were therefore aggregated to provide weighted averages representative of CRP acreage for each county. Contributions to net emissions from EtOH production were normalized and expressed in carbon intensities (CI; CE emissions per unit of energy produced) for direct comparison among alternative feedstocks.

Values reported are weighted averages accounting for the CRP acreage distribution within the US rainfed region. Model uncertainty was calculated using the error propagation equations described in the 2006 IPCC guidelines.[53] Parameter uncertainty was estimated for each land use considering variance over 30-year simulations, and the error was propagated across 30 randomized weather iterations to integrate climate variability.

Optimization scenarios were developed based on best-performing land uses for each key trait (i.e., negative emissions, NCB, or energy yields) at each location, and potential contributions to sustainability goals were computed from annual means observing feedstock allocation.

https://doi.org/10.1021/acs.est.3c05240
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

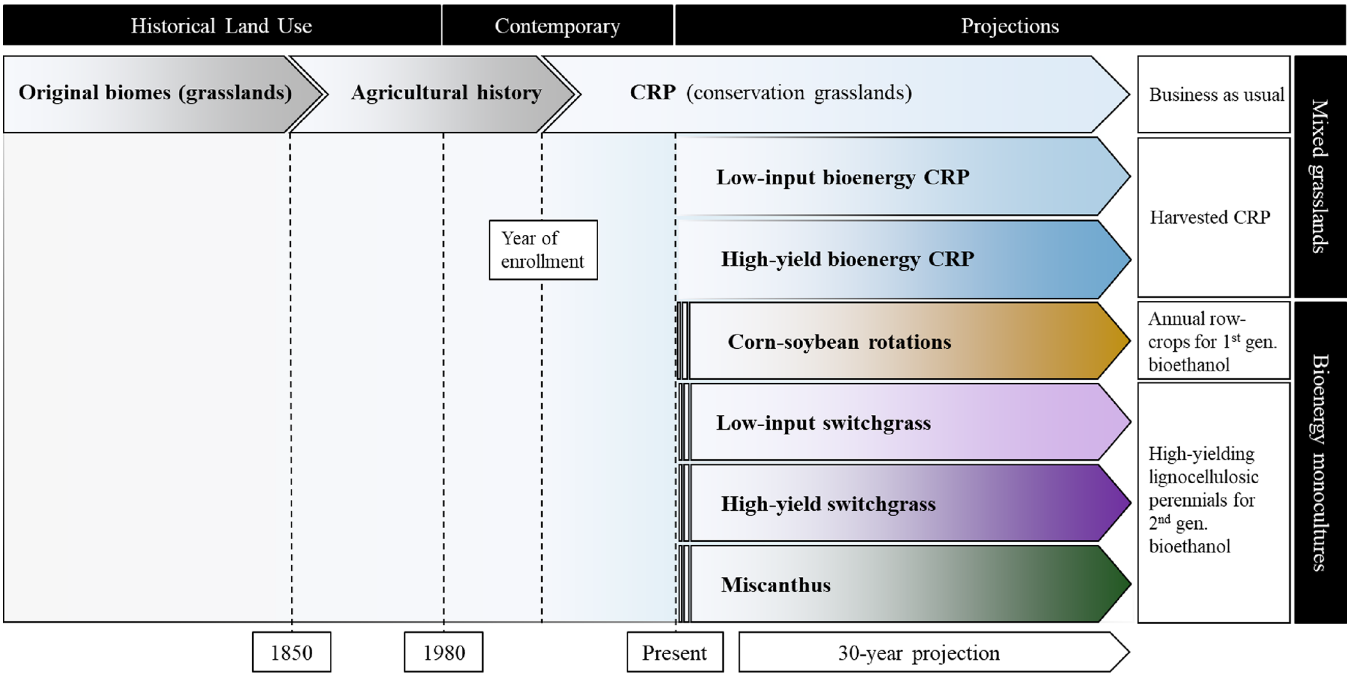


Figure 2. Schematic summary of DAYCENT simulations of alternative land uses on land enrolled in the Conservation Reserve Program (CRP).

The scope of this work is attributional.[54] As such, the LCA presented here does not consider indirect effects arising from changes in the relationships between demand for inputs, price elasticities, supply, and market effects of coproducts.[54] Similarly, market effects on CRP acreage (e.g., petroleum or land price changes resulting from increased fuel EtOH production) are beyond the scope of this study. All scenarios propose the deployment of otherwise unused land as bioenergy feedstock. Impacts from indirect LUC are therefore avoided[41] and not included in this study.

2.2. Lifecycle Inventory of GHG Emissions. The area of interest (AOI) in this study encompasses >1900 counties within 23 states of the US rainfed region, encompassing nine different plant hardiness zones. Local environmental (e.g., precipitation, temperature, daylight, soil texture, soil pH) and technological and infrastructure (e.g., electric grid supplier, primary fuel blend) attributes influence land productivity, management, and operational costs. A major challenge was to reproduce the circuitry that links local variables to CE costs (losses) and credits (gains) of EtOH production. To capture spatial variation, we developed a spatially resolved biogeochemical–LCA-coupled model that used local parameters to estimate biogenic fluxes (i.e., ecosystem productivity, soil organic carbon dynamics, and ecosystem GHG emissions) for the later assimilation into a geographically explicit assessment of all direct and embodied emissions of the bioenergy industry pipeline (Figure 1).

The system boundary of this research is from field to fuel (Figure 1). The field-to-fuel pipeline can be divided into three major phases: (i) feedstock production, (ii) transportation, and (iii) conversion. All GHG sinks and sources were expressed in carbon equivalents (CE). Non-CO_2 emissions were converted to CE using the IPCC 100-year horizon (factors of 25 for CH_4 and 298 for N_2O).

(i) Feedstock Production. There are three main contributors to the GHG footprint of feedstock production: *biogenic fluxes* (ecosystem productivity and emissions), *embodied emissions from agronomic inputs* (upstream emissions for the manufacturing of chemicals and farming machinery), and *operational emissions* (direct emissions from farm management including fossil fuel combustion during farm operations) (Figure 1).

Biogenic Fluxes. We used DAYCENT to estimate biomass yields, changes in ecosystem C storage, and ecosystem non-CO_2 emissions (i.e., CH_4 and N_2O) for business-as-usual and alternative land uses (see above) on CRP acreage within the US rainfed region at the county level (Figure S1). DAYCENT is a process-based biogeochemical model that simulates C, nutrient, and trace gas exchange at the atmosphere–plant–soil interface as a function of light, temperature, and water and nutrient availability on a daily time step.[55,56] DAYCENT successfully reproduces the dynamics of plant productivity and soil biogeochemistry as affected by changes in land use, alternative management practices, and changes in climate and has been repeatedly used to simulate the productivity, soil organic matter and nutrient dynamics, and trace gas fluxes of grasslands and croplands, including high-yielding lignocellulosic perennials, at local, regional, national, and global scales.[34,37,57−64]

Crop modules were parametrized to capture physiological responses to environmental factors and reproduce phenological and developmental cycles reported in the literature.[36,48,50,61,65−81] Model descriptors (e.g., planting/seeding date, and harvesting, cultivation, and fertilization time and intensity) were adjusted according to predominant vegetation cover and location based on published data and observing plant hardiness zones.[36,48,50,65,70−72,77,82−87] Soil attributes were parametrized using weighted averages from location-specific values (CRP acreage) extracted from the Soil Survey Geographic database (SSURGO) aggregated at the county level.[88]

Initialization of soil C and nutrient levels was conducted through the historical reconstruction of original biomes based on Olson et al.[89] followed by agricultural history driven by

https://doi.org/10.1021/acs.est.3c05240
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

climate reconstructions aggregated at the county level of historical daily weather records from CRU-NCEP (1901–1979)—an NCEP reanalysis 2.5 × 2.5° 6 h time step from 1948 onward that uses observed variability to estimate daily values between 1901 and 1947.[90] Historical land uses included corn, soybean, alfalfa, and winter and spring wheat, managed under historical fire, harvest, fertilization, and tillage practices.[91−95] Crop productivity and baseline soil organic carbon (SOC) were calibrated using NASS agricultural statistics[96] and SSURGO soil C data.[88] Because DAYCENT estimates SOC from the turnover of soil organic matter pools, defined by inputs of dead plant material associated with productivity and decomposition rates in a given environment, accurate predictions of SOC stocks are an indicator of the robustness of model baseline simulations.[55,57] Contemporary simulations built on historical land uses and integrated input data from county-specific CRP acreage including current management, and county-specific average year of enrollment provided and Daymet daily records (1980–present).[97] CRP grasslands (conservation grasslands) were simulated as cold- and warm-season grasslands according to predominant distribution and plant hardiness zone, and minimal management was assumed to optimize ecosystem services, including initial soil pH and nutrient restoration, and periodic soil conditioning seeding and prescribed fire to maintain biodiversity and prevent encroachment.[98]

Resulting baseline simulations were extended with continuation of conservation grasslands (business-as-usual scenario) or conversion to alternative land uses driven by factorial randomizations of 15-year weather records (1995–2010) looped over 30 years to integrate interannual variability. Bioenergy CRP land uses were simulated as harvested conservation grasslands and avoided conversion costs (Figure 2). *Low-input bioenergy CRP* reproduced minimal management consistent with CRP conservation goals but added routine low nitrogen (N) fertilization (56 kg N ha^{-1} $year^{-1}$) to compensate harvest removal.[99] *High-yield bioenergy CRP* assumed intensive nutrient management to optimize productivity, with N fertilization rates varying between 84 and 112 kg N ha^{-1} $year^{-1}$ based on location and initial levels.[49,52,81] Conversion to bioenergy monocultures (Figure 2) was simulated assuming brush mowing, disking, and cultivation followed by soil conditioning. Corn yield simulations reflected increases in grain-to-residue ratio and nutrient use efficiency over the past two decades.[69,100,101] Annual corn grain yields resulted from corn-year yields derived from double simulations reproducing corn–soy and soy–corn at each location. Model descriptions dynamically allocated net primary productivity to grain or leaf/stem according to temperature and water stress, with maximum grain allocations set to 0.6.[37] Fertilization rates reproduced state averages integrating interannual variability over the past decade.[96] Switchgrass simulations allocated upland and lowland varieties based on best performance as a function of latitude.[102,103] We assumed single after frost-kill harvests (excluding planting year) depending on variety[104] and field tilling and replanting every 10 years, and new model domains were developed to replicate stand age effects matching developmental, establishment, and maturity stages.[48,76] Switchgrass productivity increases with N additions,[105] with optimum fertilization rates ranging from 56 to 150 kg N ha^{-1} y^{-1} depending on location, developmental stage, and harvest time.[48−50,52,105,106] Annual N fertilizer application varied according to developmental requirements, with no fertilizer applied on the first year followed by a 100 kg N ha^{-1} $year^{-1}$ on the second year and a conservative[49] (56 kg N ha^{-1} $year^{-1}$) or an intensive[48−50,105] (84–112 kg N ha^{-1} $year^{-1}$ based on location and developmental stage) fertilization regime for the duration of the rotation aiming the conservation goals of *Low-input switchgrass* or the productivity goals of *High-yield switchgrass*, respectively. *Miscanthus* simulations assumed a single after frost-kill harvests (excluding planting year) and field tilling and replanting every 15 years, and model domains were developed to reproduce productivity across developmental stages.[48,76,107−109] Observing high rates of N retranslocation to rhizomes at senescence (up to 90%),[67,73] fertilization of miscanthus was kept at replacement levels to sustain long-term productivity.[48,105]

DAYCENT parametrizations were validated against baseline SOC pools and historical records of county annual yields of mixed grasslands, corn, switchgrass, and miscanthus from published data across a wide temperature and precipitation gradient within the US rainfed region (Figures S2 and S3).

Embodied Emissions from Agronomic Inputs. Embodied emissions account for upstream emissions from the manufacturing of chemicals and farming machinery associated with feedstock production. Embodied emissions were calculated based on usage rates according to management scenarios and feedstock- and location-specific traits (Table S1) and emission factors from major agronomic inputs (Table S2). Emission factors integrate emissions from the manufacture, transport, and storage of agronomic inputs.

Liming rates were calculated from crop-specific target pH (optimum soil pH for feedstock development) (Table S1) and location-specific initial soil pH and texture.[110]

$$\text{lime}_{\text{appl}} = (\text{sand}_{\text{frac}} \times \text{sand}_{\text{coef}}) + (\text{silt}_{\text{frac}} \times \text{silt}_{\text{coef}}) + (\text{clay}_{\text{frac}} \times \text{clay}_{\text{coef}}) \quad (1)$$

where $\text{Lime}_{\text{appl}}$ is the lime application rate (kg ha^{-1}); $\text{sand}_{\text{frac}}$, $\text{silt}_{\text{frac}}$, and $\text{clay}_{\text{frac}}$ are descriptors of soil texture; and $\text{sand}_{\text{coef}}$ (1220.7 kg ha^{-1}), $\text{silt}_{\text{coef}}$ (3662.0 kg ha^{-1}), and $\text{clay}_{\text{coef}}$ (4,882.7 kg ha^{-1}) are the amount of lime required to increase soil pH by 1 level.

Subsequent soil pH adjustments were calculated to account for soil pH drift associated with nitrogen fertilizer (N_{fert}) application,[111,112] and lime application rate was computed to maintain optimum pH considering location specific soil texture (eq 2).

$$\text{pH drift} = (N_{\text{fert}} \times 11.21)/0.1 \quad (2)$$

Soil nutrients (phosphorus and potassium) were assumed to be restored in full preceding conversion to conservation grasslands (CRP), and at a 25% rate every 4 years thereafter to maintain soil health and sustain productivity (Table S1). For all alternative scenarios, we assumed minimum required inputs aligned with the CRP sustainability goals, and nutrient application rates were therefore recalculated according to feedstock-specific replacement rates based on annual yields subject to local properties (Table S1). We assumed the herbicide application preceding the establishment of conservation grasslands. Following conversion to bioenergy monocultures, we assumed pre- and postemergence herbicide applications at recommended rates on planting year, and annual postemergence application for the rest of the rotation (Table S1). For mixed grassland systems, we assumed the recommended seeding rate applied in full on the first year after

https://doi.org/10.1021/acs.est.3c05240
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

conversion and postburn 10% reseeding in 4-year cycles thereafter. We estimated 10 and 25% establishment failure for switchgrass and miscanthus, respectively. Corrections were performed by a second-year 10% reseeding of switchgrass and the adjustment of planting densities of miscanthus on the planting year.

Embodied emissions in farming machinery result from periodic needs for new equipment and are calculated from the emission factor of steel based on a 12-year lifetime assumption for all farming equipment (Tables S2 and S3).

Operational Emissions. Operational emissions are fossil fuel-based emissions from the use of farm machinery. Farm operations included pre-establishment field preparation (i.e., brush mowing, tandem disking, soil finishing and lime, herbicide, and fertilizer applications), planting, periodic soil conditioning (nutrient and soil pH restoration), harvesting, and baling according to feedstock needs and best management practices.[104,113−120] A full relation of all considered operations and associated parameters can be found in Table S4.

We estimated machinery operational emission factors of tillage equipment from energy requirements based on calculations of equipment-specific draft (kN; resistance to forward movement defined by traction) using a simplified draft prediction equation[121] and corrected by the tractive efficiency according to depth[122] and soil texture.[123−126]

$$\text{draft(kN)} = F_i \times [A + (B \times S) + (C \times S2)] \times W \times TD \quad (3)$$

where F_i is a dimensionless soil texture adjustment parameter; A, B, and C are machine-specific descriptors of the draft/speed relationship; S is field speed (km h^{-1}); W is the width of the equipment (m); and TD is the tillage depth (cm). Machine-specific parameters were from the literature.[121,124,127]

Energy requirements were then estimated from theoretical field capacity (TFC; ha h^{-1})[128]:

$$\text{energy requirements(kWh)} = (\text{draft} \times S)/(3.6 \times \text{TFC}) \quad (4)$$

$$\text{TFC} = (W \times S)/10 \quad (5)$$

Emission factors were calculated using stoichiometric-based calculations assuming predominant use of US Standard diesel (EPA reported $C_{12}H_{23}$, with 86.2% C content) and adjusting by efficiency coefficients (engine-to-wheel power) as reported by ASABE (2009).[124]

(ii) Transport to Biorefinery. Feedstock transportation includes both direct emissions from fossil fuel combustion and embodied costs in vehicle manufacture. We estimated direct emissions using the emission factor of US Standard gasoline, and assuming an average distance of 84 km[129] and a standard load capacity of 18 MgDW per truck[130,131] assuming a 12 and 15% moisture content in cellulosic biomass and corn bushel, respectively.[130,131] Indirect emissions from the manufacturing, replacement, and maintenance of the vehicles were estimated using emission factors reported in Scown et al.[132]

The harvested−to−biorefinery intake biomass ratio was 1.14 for cellulosic biomass and 1.02 for corn grain biomass due to dry matter loss during in-farm management, handling, storage and transportation.[130,131]

(iii) Conversion to Bioethanol. The corn EtOH production pathway assumes the conversion efficiencies of dry mill corn EtOH facilities, responsible of 91% of US fuel EtOH, with distillers' grains and solubles (DGS) as coproduct generation.[101] We considered an EtOH yield of 427 L per dry metric ton of grain, observing a 6.5% increase in the conversion efficiency over the past decade.[101] Biorefinery emission costs included embodied emissions in enzymes and yeast inputs,[133] and emissions derived from fossil fuel combustion were calculated based on energy requirements for EtOH (7.35 MJ L^{-1}) and DGS (0.074 MJ L^{-1}) production[39] assuming 83, 7, and 10% shares from natural gas (0.021 kg CE MJ^{-1}), coal (0.022 kg CE MJ^{-1}), and electricity (emission factor attribution based on grid-specific primary fossil source,[134,135] respectively, in the generation of EtOH, and a 100% electric energy in DGS production.[130,131] Cellulosic EtOH production assumes deacetylation and dilute acid pretreatment (DAP) with enzymatic hydrolysis and fermentation,[136] coupled with lignin combustion producing 2.294 MJ of grid-based electricity per liter of EtOH produced.[130,131] Yields of cellulosic EtOH were estimated at 302.8 L EtOH Mg DW^{-1} for switchgrass and adjusted to 318.6 L EtOH Mg DW^{-1} for miscanthus and to 288.6 L EtOH Mg DW^{-1} for mixed grasslands based on cellulose and hemicellulose content.[46,137−139] Estimated conversion efficiencies are similar to those reported in the literature for all considered feedstocks.[51,130] Biorefinery emission costs from cellulosic EtOH production incorporated embodied emissions from all biorefinery inputs, including yeast and enzymes used during DAP.[130,131,133]

Fossil fuel offset credit from coproduct generation was estimated by the displacement method, which credits the product with the emissions derived from fossil sources based on the energy required to produce a functionally equivalent quantity of the nearest substitute.[140] Coproduct-displaced emissions from DGS generation were estimated at 0.0033 kg CE per MJ of EtOH produced based on published survey data from 2019.[101] Displaced emissions from bioelectricity were estimated for each location based on published grid-specific CI from 2020.[134,135]

2.3. NE. Total NE was calculated as the sum of geologic carbon capture and storage (CCS) and SCS estimated from changes in SOC. Geologic CCS assumed a C capture efficiency of 48% of the released CO_2 from biomass at the biorefinery and 100% of captured C transported and stored in subsurface geological formations.[16,141,142] Changes in land use cause SOC content to either decrease or increase depending on the displaced and alternative land use. Conversion from mixed grasslands (conservation grasslands) to corn−soybean rotations under conventional management will decrease SOC, whereas conversion to perennial grasses creates an opportunity for SCS over time until a new equilibrium is reached.[34,35] Recent studies estimate time to SOC equilibrium after transitions to high-yielding perennials at 50 to 100 years,[143,144] providing a near-term pathway to climate stabilization beyond amortizing initial C debt and opportunity costs and avoiding the large uncertainty associated with land use and emissions over extended time horizons.[39]

3. RESULTS

3.1. Opportunity Costs and Management Significantly Affected the CI of Bioenergy Feedstock Grown on CRP Land in the US Rainfed region. CI is defined as the carbon intensity of CO_2 and non-CO_2 (CH_4 and N_2O) GHG emissions expressed as CO_2 equivalents (CO_2e) per unit energy produced. Estimates of CI integrating all up- and downstream CE gains and losses per unit of energy produced

https://doi.org/10.1021/acs.est.3c05240
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

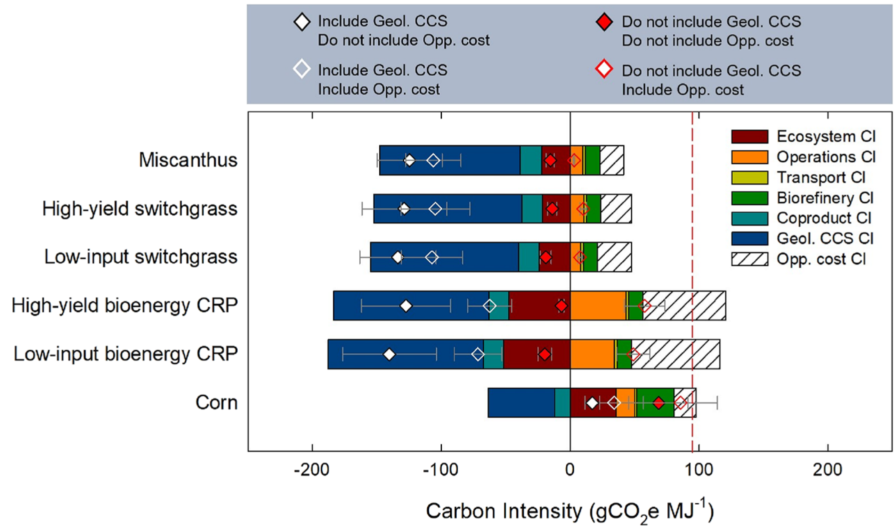


Figure 3. Contributions to carbon intensity (CI) by activity (bars) for each feedstock and calculated mean CI (diamonds) by feedstock without (red) and with (white) geologic carbon capture and storage (CCS). Open symbols include the CI of opportunity costs (Opp. cost; i.e. foregone C sequestration and non-CO_2 GHG savings from the displaced system). The dashed line indicates the carbon intensity of gasoline for reference (94 g CO_2e MJ^{-1}).[149] Ecosystem CI reflects gains and losses of CO_2 and non-CO_2 emissions from biologic sources and includes soil carbon sequestration (SCS). Operations CI includes embodied emissions in agronomic inputs and equipment, operational emissions and handling, and storage losses (Figure 1). CI estimates of corn ethanol integrate annual emissions from conventional corn−soybean rotational systems. Negative values indicate carbon equivalent (CE) credits (savings), and positive values show CE costs (losses) per unit of energy produced. Mean CI values are weighted averages observing CRP acreage distribution within the US rainfed region. Error bars integrate interannual variability.

are consistent with those reported in the literature for all feedstocks considered, both with and without geologic CCS[39,101,141,145−148] (Figure 3).

The CI of EtOH produced from bioenergy feedstocks grown on CRP land within the US rainfed region ranged from positive CI values (net CO_2e losses) for corn-based first-generation EtOH (68.6 ± 22.9 g CO_2e MJ^{-1}) to negative CI values (net CO_2e savings) of −6.8 ± 22.9 to −18.9 ± 4.2 g CO_2e MJ^{-1} for second-generation cellulosic EtOH (Figure 2). However, opportunity costs (loss of potential GHG attenuation from alternative land uses) increased the CI of corn- and mixed grass- (bioenergy CRP) based EtOH by ∼50% and by 20 and 15% in switchgrass and miscanthus systems, respectively, bringing all EtOH-producing systems grown on US rainfed CRP land to positive emissions per unit of energy in the absence of geologic CCS (Figure 3). The legacies of opportunity costs, beyond the immediate impacts of land conversion, are particularly critical on corn and bioenergy CRP, where the foregone climate benefit from the displaced system pushes CI above the standards for renewable and cellulosic biofuel (85.2 ± 28.6 g CO_2e MJ^{-1}, and 49.0 ± 12.7 to 57.9 ± 15.3 gCO_2 MJ^{-1}, respectively) relative to petroleum-based gasoline CI[39] (94 gCO_2e MJ^{-1}), making geologic CCS necessary to reach emissions reduction thresholds (20 and 60%, respectively) (Figure 3). Notably, management intensification (i.e., low-input vs high-yield) led to modest increases of the CO_2 removal (CDR) potential and EtOH yields but increased the CI of EtOH produced from bioenergy CRP and switchgrass by 18% and 33%, respectively.

3.2. Geologic CCS Dominated Negative Emissions, but Biologic Contributions Defined Breakeven Times of Bioenergy Feedstocks Grown on CRP Land. Geologic CCS dominated negative emissions, but SCS, defined as changes in SOC, significantly contributed to the total CDR (Table 2). All bioenergy monocultures incurred substantial C debt. Sustained SOC losses following conversion increased the C debt of conventional corn−soybean rotations over time, reducing the potential for negative emissions by 30.1%. Soil C gains repaid initial losses within 7 years after the establishment of switchgrass and miscanthus. However, opportunity costs extended the breakeven (payback) period to 13−15 years, respectively (Table 2). Fossil emissions displacement and geologic CCS limited the carbon equivalent (CE) debt, drastically reduced payback times to 5.7 years in the case of corn, and eliminated the CE debt within the first 2 years in the case of high-yielding perennials (Table 2).

3.3. Biophysical Constraints Led to Uneven Geographical Performance of Feedstock Contributions to Negative Emissions, NCB, and Energy Yield. Simulated feedstocks displayed distinctive geographic patterns in productivity and associated climate and energy benefits, responding to local climate and soil properties (Figures S4 and S5). The uneven distribution of CRP acreage and feedstock performance across the US rainfed region led to relatively lower weighted averages of SCS, yields, and fossil emissions displacement than previously attributed to these feedstocks.[13,37,149] Modest productivity (∼3.2 Mg DW ha^{-1} $year^{-1}$) limited CDR rates, GHG savings, and energy yields from bioenergy CRP despite the inherently low CI of mixed grass-derived EtOH (Table 2; Figure 3).

Bioenergy monocultures outperformed the potential biomass supply of mixed grasslands (bioenergy CRP) by a factor of 2.5 to 3.5. Conversion to conventional corn−soybean rotations provided the greatest EtOH yields, increasing potential contributions to national EtOH mandates by ∼6.5% relative to bioenergy CRP and providing up to 20.6 ± 2.5% of the renewable EtOH target (Table 2). However, large emissions of GHGs up- and downstream of the corn-based EtOH production pipeline increased its CI that, while lower than that of petroleum-based gasoline, led to positive emissions (Figure 2). The NCB of corn-based EtOH was derived mostly from the displacement of fossil emissions

https://doi.org/10.1021/acs.est.3c05240
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Table 2. Estimates of Mean Annual Carbon Dioxide Removal (CDR) from Both Geologic Carbon Capture and Storage (CCS) and Soil Carbon Sequestration (SCS), Net Climate Benefit, Ethanol (EtOH) Yield and Displaced Energy from Feedstock Grown on CRP Acreage in the US Rainfed Region[a]

	corn	low-input bioenergy CRP	high-yield bioenergy CRP	low-input switchgrass	high-yield switchgrass	miscanthus
Carbon dioxide removal (CDR; MgC ha^{-1} $year^{-1}$)[b]	−0.47 ± 0.25	−0.48 ± 0.07	−0.52 ± 0.04	−1.53 ± 0.21	−1.69 ± 0.22	−2.12 ± 0.24
Geologic carbon capture and storage (CCS; MgC ha^{-1} $year^{-1}$)	−0.96 ± 0.11	−0.55 ± 0.02	−0.59 ± 0.02	−1.40 ± 0.10	−1.55 ± 0.11	−1.95 ± 0.13
Soil carbon sequestration (SCS; MgC ha^{-1} $year^{-1}$)	0.49 ± 0.13	0.07 ± 0.02	0.06 ± 0.03	−0.13 ± 0.02	−0.15 ± 0.02	−0.17 ± 0.05
initial soil organic carbon debt (MgC ha^{-1})	3.4 ± 0.7	na	na	2.1 ± 0.3	2.1 ± 0.3	2.5 ± 0.7
soil organic carbon payback time (years)	> 30	na	na	15.2 ± 2.4	14.1 ± 2.1	12.9 ± 3.6
contribution to total CDR (%)	−30.1 ± 13.9	57.9 ± 4.3	54.6 ± 3.5	31.5 ± 1.3	29.5 ± 1.3	24.7 ± 2.3
Net climate benefit (MgCE ha^{-1} $year^{-1}$)[c]	−1.21 ± 0.37	−1.07 ± 0.28	−1.08 ± 0.41	−2.92 ± 0.38	−3.15 ± 0.36	−4.06 ± 0.53
initial CE debt (MgCE ha^{-1})	2.7 ± 0.8	na	na	0.19 ± 0.03	0.20 ± 0.03	1.9 ± 0.4
CE payback time (years)	5.7 ± 1.7	na	na	1.0 ± 0.1	1.0 ± 0.2	1.6 ± 0.3
EtOH yield (L ha^{-1} $year^{-1}$)	3234 ± 388	801 ± 94	851 ± 105	2082 ± 146	2297 ± 161	3010 ± 197
Potential EtOH yield from rainfed US CRP acreage (bill. L $year^{-1}$)	11.7 ± 1.4	2.9 ± 0.3	3.1 ± 0.4	7.5 ± 0.5	8.3 ± 0.6	10.9 ± 0.7
potential contribution to EtOH target (%)[d]	8.6 ± 1.0	2.1 ± 0.2	2.3 ± 0.3	5.5 ± 0.4	6.1 ± 0.4	8.0 ± 0.5
potential contribution to renewable EtOH target (%)[e]	20.6 ± 2.5	na	na	na	na	na
potential contribution to cellulosic EtOH target (%)[f]	na	4.8 ± 0.6	5.1 ± 0.7	12.4 ± 0.9	13.7 ± 1.0	18.0 ± 1.2
Energy displaced from fossil sources (GJ ha^{-1} $year^{-1}$)[g]	68.8 ± 8.6	18.9 ± 1.3	20.1 ± 1.4	49.1 ± 6.9	54.1 ± 7.6	71.1 ± 9.3

[a]Unit equivalence: 1 megagram (Mg; a.k.a. Ton) = 10^{-6} teragrams (Tg) = 10^{-9} gigatons (Gt). Soil carbon sequestration, net climate benefit, and associated debt and payback time estimates integrate opportunity costs (i.e., foregone attenuation of GHG emissions from the displaced system). Estimates are weighted averages observing CRP acreage distribution within the US rainfed region. Error term integrates interannual variability. [b]Carbon dioxide removal (CDR) integrates negative emissions from both geologic carbon capture and storage (CCS) and soil carbon sequestration (SCS) pathways. Values are expressed from the atmospheric perspective, where negative values indicate net sinks (gains) and positive values indicate net sources (losses) of carbon. Geologic CCS assumes a carbon capture efficiency of 48% of the released CO_2 from biomass at the biorefinery and 100% of captured C transported and stored in subsurface geological formations.[141] Operational and embodied emissions of CCS are not included. Values of SCS integrate opportunity costs and reflect gains and losses of soil organic carbon (SOC) relative to BAU (conservation CRP). Estimated rates of SCS from conservation CRP in the US rainfed region is 0.35 ± 0.09 Mg C ha^{-1} $year^{-1}$. Percentages of SCS reflect contributions to total carbon dioxide removal (CDR) from the feedstock alone and do not integrate opportunity costs. [c]Estimates of net climate benefit integrate the net GHG balance of all carbon equivalent (CE) costs and credits up- and downstream the EtOH production pipeline and are expressed from the atmospheric perspective, where negative values represent net CE sinks (savings) and positive values indicate net CE sources (costs) relative to BAU. Estimated rates of net CE offset from unharvested CRP in the US rainfed region is −0.32 ± 0.03 Mg CE ha^{-1} $year^{-1}$. [d]Refers to target of total ethanol from bioenergy sources produced annually in the US (136.3 billion L $year^{-1}$).[150] [e]Refers to target of ethanol from renewable sources produced annually in the US (56.8 billion L $year^{-1}$).[150] [f]Refers to target of ethanol produced from cellulosic sources produced annually in the US (60.6 billion L $year^{-1}$).[150] [g]Includes energy displaced from produced ethanol and coproduct generation (assumed DGS from corn grain and bioelectricity from the combustion of lignin content in lignocellulosic perennials).

(Table 2). With sizable contributions to EtOH targets and significant GHG savings per unit of energy produced, the conversion to perennial bioenergy feedstocks holds great potential for negative emissions (Table 2; Figure 3). Miscanthus delivered the greatest CDR and GHG savings but also displayed the largest sensitivity to climatic gradients across the US rainfed region. Values ranged from maximums of productivity (31.4 ± 3.4 Mg DW ha^{-1} $year^{-1}$) and SCS (1.3 ± 0.1 Mg C ha^{-1} $year^{-1}$) in northern regions to minimum yields of 5.3 ± 0.2 Mg DW ha^{-1} $year^{-1}$ and slight SOC losses (−0.1 ± 0.06 Mg C ha^{-1} $year^{-1}$) across the southern states (Figures S4 and S5; Table 2). Switchgrass reached lower maximum productivity (20.6 ± 0.8 Mg DW ha^{-1} $year^{-1}$) and SOC accrual rates (0.9 ± 0.2 Mg C ha^{-1} $year^{-1}$) but displayed lower geographic variability and outperformed miscanthus across the southern US rainfed region (Figures S5 and S6; Table 2).

3.4. Optimized Landscapes Outperformed Single Land Use Scenarios. The strategic allocation of energy feedstocks on CRP land in the US rainfed region significantly decreased the CI of EtOH relative to single land use scenarios, achieving net-negative emissions per unit of energy produced in the absence of geologic CCS from assemblages targeting climate stabilization and reducing emissions substantially from assemblages targeting EtOH yields (Tables 2 and 3). Prioritizing CDR, the NE scenario allocated 62% of CRP land to miscanthus and 38% to high-yield switchgrass roughly distributed across the northern and southern regions of the US rainfed region, respectively (Figure 4 and Table 3).

With average CDR rates of 2.44 ± 0.3 Mg C ha^{-1} $year^{-1}$, the NE scenario increased the potential for negative emissions by 15% relative to the best-performing feedstock (Tables 2 and 3). An optimized landscape of the NCB of BECCS on CRP land (NCB scenario) maintained miscanthus presence in northern regions but allocated low-input switchgrass to the south-central US, where biophysical constraints limited responses to additional fertilization yielding marginal increases in productivity and significant increases in operations cost (Figure 4c,d). The disproportional allocation to low-input

Table 3. Potential Carbon Dioxide Removal (CDR), Net GHG Balance, Ethanol (EtOH) Yield, and Carbon Intensity from a Bioenergy Landscape on CRP Land in the US Rainfed Region Optimized for Negative Emissions (NE), Net Climate Benefit (NCB), and Energy Security (ES) Scenarios[a]

	optimization scenarios		
	negative emissions (NE)	net climate benefit (NCB)	energy security (ES)
Carbon dioxide removal (CDR; Tg C $year^{-1}$)[b]	−9.0 ± 0.56	−8.6 ± 0.65	−7.1 ± 0.71
Geologic carbon capture and storage (CCS; Tg C $year^{-1}$)	−7.5 ± 0.32	−7.7 ± 0.41	−6.8 ± 0.59
Soil carbon sequestration (SCS; Tg C $year^{-1}$)	−1.5 ± 0.25	−0.9 ± 0.22	−0.2 ± 0.10
initial soil organic carbon debt (Mg C ha^{-1})	1.7 ± 0.3	1.8 ± 0.4	3.3 ± 0.6
soil organic carbon payback time (years)	4.0 ± 0.9	5.0 ± 1.2	> 30
Net GHG balance (Tg CE $year^{-1}$)[c]	−15.7 ± 2.6	−16.1 ± 2.6	−13.9 ± 2.9
initial CE debt (Mg CE ha^{-1})	1.3 ± 0.2	1.4 ± 0.2	2.2 ± 0.5
CE payback time (years)	1.4 ± 0.2	1.2 ± 0.1	3.3 ± 0.8
Potential EtOH yield from rainfed US CRP acreage (bill. L $year^{-1}$)	11.6 ± 0.7	12.0 ± 0.8	13.3 ± 0.9
potential contribution to EtOH target (%)[d]	8.5 ± 0.6	8.8 ± 0.6	9.7 ± 0.7
Carbon intensity (CI; gCO_2e MJ^{-1})[e]			
not including geol. CCS[a]	−3.1 ± 0.6	−3.7 ± 0.61	29.3 ± 6.90
including geol. CCS[b]	−105.6 ± 17.3	−107.1 ± 21.2	−47.8 ± 11.2

[a]Shaded fields indicate best-performing scenario for a given parameter. Values are weighted averages integrating feedstock allocation. Error term integrates interannual variability. Unit equivalence: 1 megagram (Mg; a.k.a. Ton) = 10^{-6} teragrams (Tg) = 10^{-9} gigatons (Gt). [b]Carbon dioxide removal (CDR) integrates negative emissions from both geologic carbon capture and storage (CCS) and soil carbon sequestration (SCS) pathways. Values are expressed from the atmospheric perspective, where negative values indicate net sinks (gains) and positive values indicate net sources (losses) of carbon. Geologic CCS assumes a carbon capture efficiency of 48% of the released CO_2 from biomass at the biorefinery and 100% of captured C transported and stored in subsurface geological formations.[141] Operational and embodied emissions of CCS are not included. Values of SCS integrate opportunity costs and reflect gains and losses of soil organic carbon (SOC) relative to BAU (conservation CRP). [c]Estimates of net GHG balance integrate all carbon equivalent (CE) costs and credits up- and downstream the EtOH production pipeline and are expressed from the atmospheric perspective, where negative values represent net CE sinks (credits) and positive values indicate net CE sources (costs). [d]Refers to target of total ethanol from bioenergy sources produced annually in the US (136.3 billion L $year^{-1}$).[150] [e]Carbon intensity (CI) values are weighted averages integrating feedstock allocation and distribution of CRP acreage within the US rainfed region, considering opportunity costs and (a) not including and (b) including geologic CCS.

switchgrass responded to an uneven distribution of CRP acres across the US rainfed region (Figure 4b). The NCB scenario averaged 10% greater GHG savings relative to the best-performing feedstock (−4.44 ± 0.4 Mg CE ha^{-1} $year^{-1}$) (Tables 2 and 3). Under the ES scenario, the optimization of EtOH yields allocated 41% of CRP land to corn-based EtOH production mostly concentrated in the central-southern boundaries of the US rainfed region where annual row crops outperformed high-yielding perennials and reduced the shares of miscanthus and high-yield switchgrass to 56 and 3%, respectively, overall increasing potential EtOH yields by 14% relative to the best-performing feedstock (Figure 4e,f; Tables 2 and 3).

3.5. There Were Significant Trade-offs between Climate Stabilization and Energy Statutory Targets.

Under the NE scenario, BECCS could actively remove up to 9.0 ± 0.8 Tg C (1 teragram = 10^{-3} gigatons) from the atmosphere annually, with about 17% potentially stored in the soils of CRP land, reducing the SOC payback time by almost 70% relative to the best-performing feedstock while sustaining sizable climate benefits and contributions to national EtOH targets (Tables 2 and 3).

An NCB scenario targeting GHG emissions savings would lower the average CI of produced EtOH by 16% and provide a marginal increase (∼3%) of the mitigation potential of BECCS on CRP land relative to the NE scenario but would decrease the potential for CDR by 5% led by a 40% reduction of SCS (Table 3). The prioritization of EtOH yields under the ES scenario could supply up to 10% of the national EtOH mandate with substantial contributions to renewable EtOH targets (Table 3). However, a large allocation to corn-based EtOH would entail a disproportional increase in mean EtOH CI and reduce potential GHG savings by 14% and CDR by 21% relative to the best-performing scenarios (NCB and NE scenarios, respectively) (Table 3).

4. DISCUSSION

Growing energy crops on set-aside land has the potential to provide a significant energy source while simultaneously paving the way for negative emissions. However, avoiding deployment on agricultural land increased carbon emissions per unit of energy produced (CI) by 14−36%, making geologic CCS necessary to achieve negative emissions or to reach emission reduction thresholds for first- and second-generation biofuels in the case of corn and mixed grasslands, respectively. Significantly reducing the CI of bioenergy, the strategic allocation of energy feedstocks on set-aside land may help limit pressure on planetary boundaries for land displacement[150] but potential contributions to climate stabilization and energy targets are subject to trade-offs and contingent on the optimization criteria.

Integrated feedstock combinations outperformed single-feedstock landscapes in all of the optimized scenarios. Our results highlight biophysical constraints that respond to locally specific parameters and define the geographic limits of the potential biomass and energy supply. The full extent of BECCS contributions to climate stabilization and energy targets rests on optimized geographic designs as much as in crop and management amelioration.

Similarly, no single scenario attained maximum potentials on all of the optimization criteria. Of all scenarios considered, ES provided the greatest annual EtOH production on CRP land (equivalent to 10% of EtOH production target[151]) led by a large allocation to grain EtOH on the boundaries of the US rainfed region. Even with aggressive actions on the decarbonization of the transport sector, global dependence on dense liquid fuels is projected to remain high, accounting for up to

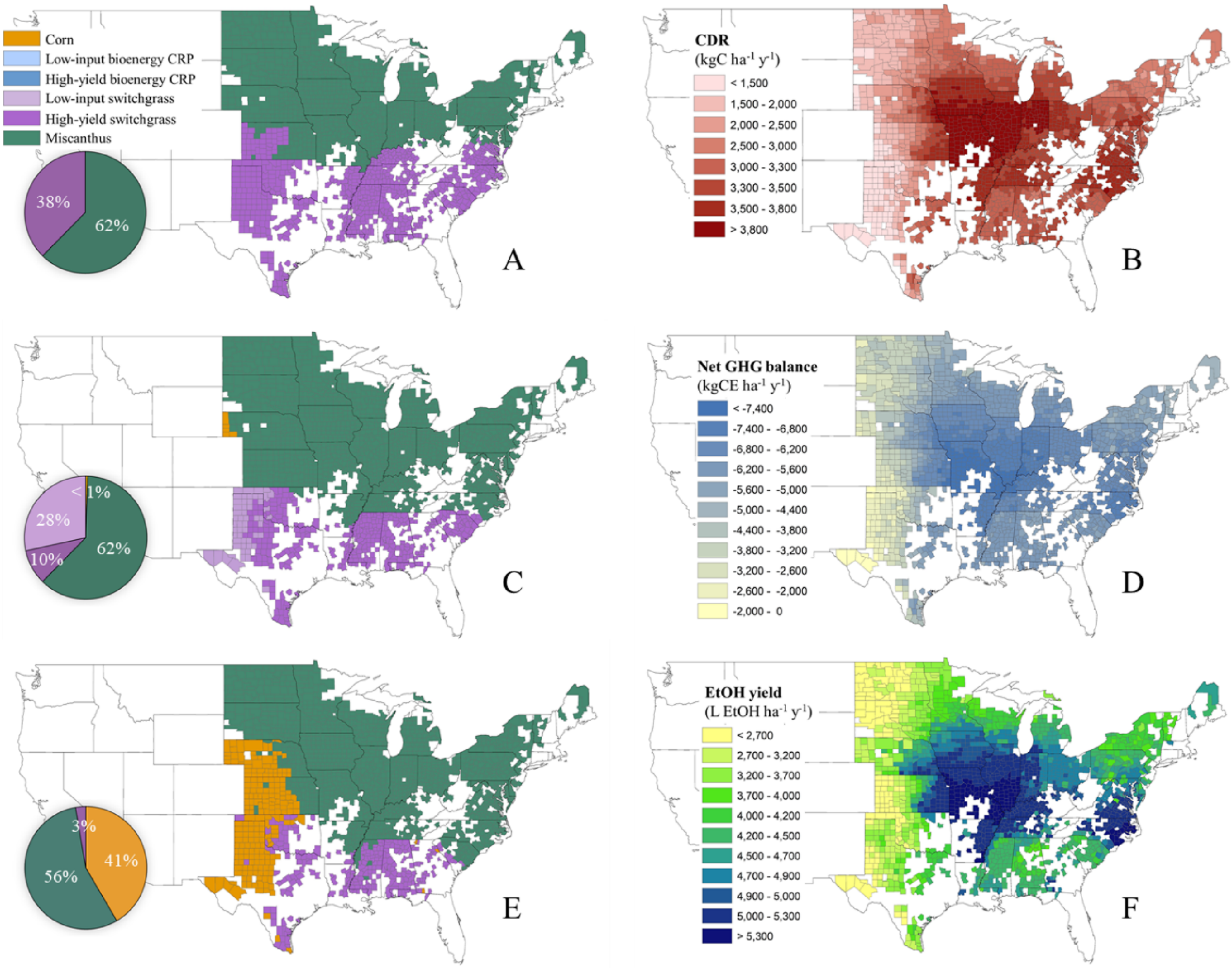


Figure 4. Bioenergy landscape on CRP land in the US rainfed region optimized for negative emissions (NE; A and B), net climate benefit (NCB; C and D), and energy security (ES; E and F) scenarios. Panels depict feedstock distribution and percentage allocation (A, C, E), and mean annual rate distribution of corresponding optimization parameters: (B) carbon dioxide removal (CDR; sum of geologic CCS and SCS), (D) net GHG balance, and (F) ethanol (EtOH) yield. Panels display feedstock allocation and annual rates on CRP acreage aggregated at county level (Figure S1). Negative values of CDR and net GHG balance indicate carbon sequestration and carbon equivalent (CE) savings, respectively.

80% of transportation fuel by the year 2050.[152] With a readily available and scalable technology[39,45] and promising contributions to national mandates, pushing an energy agenda on set-aside land holds great potential in portfolios toward energy independence and a net-zero C economy.[153] However, despite significant improvements in the efficiency of corn grain production and progressive reductions of its CI over the past two decades,[101] the generation of corn-based EtOH incurs substantial CE costs up- and downstream of the EtOH production pipeline, its climate benefit relying primarily on relatively high fossil fuel offsets and potential geologic CCS (Table 2). The introduction of corn grain EtOH into optimized scenarios disproportionally reduces the climate benefit and negative emissions of BECCS deployment on CRP land, limiting potential contributions to climate stabilization (Table 3). Climate governance fosters action with diverging criteria, whose trade-offs need to be evaluated and reflect in compensatory actions.

Among the scenarios targeting climate stabilization, NCB optimizations—led by fossil emissions displacement—displayed the greatest GHG savings, potentially offsetting close to 10% of current US agricultural emissions (0.7 Gt CO_2e year^{-1} in 2019).[154] The NE scenario achieved similar GHG savings driven by CDR rates, with considerable contributions from SCS (Table 3). Despite growing recognition,[13,155−158] SCS is still seen with skepticism as an effective C removal strategy, criticisms centered on issues of sink saturation, reversibility, or priming.[27,159] With arguably low vulnerability to reversal, geologically stored C puts BECCS among the preferred negative emissions strategies. Our simulations showed that an optimization targeting CDR (NE scenario) yielded larger, albeit more vulnerable, negative emissions, whereas the prioritization of GHG savings (NCB scenario) led to lower but more permanent negative emissions (Table 3).

As of yet, CCS technology only exists at a pilot stage; questions remain about the geophysical limits and environmental risks of geological C storage that challenge its deployment at scale.[13,160,161] Driven by long-term climate stabilization goals, net-zero targets in isolation do not inherently call for early action, allowing the deferral of radical

https://doi.org/10.1021/acs.est.3c05240
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

upscaling of negative-emission technologies after target adoption. However, recent research suggests that early action on CO_2 would reduce warming rates, limit midterm peak and long-term temperatures, and reduce dependency on uncertain negative-emission technologies.[162−166] Climate mitigation is both input and time dependent.[167] Reflecting on the challenge of delivering ambitious CO_2 removal rates over time horizons compatible with low-carbon RCP scenarios, we suggest that climate action portfolios should integrate attainable pathways to stabilization targets. We recommend a dynamic approach to optimization criteria, switching from a NE scenario—with greater CDR rates over short time scales—in near-term actions to an NCB scenario—with greater dependence on presumably highly effective, yet still uncertain technology—in the long term.

Decision making on the large-scale deployment of BECCS toward a particular target must consider the potential of alternative scenarios to codeliver to other policy agendas. Our results indicate that an optimization driven by negative emissions holds greater potential for SOC sequestration and reduced payback times, providing an immediate and sustained GHG advantage while building resilience to climate change, reducing soil erosion and promoting soil quality, thereby contributing to food and water security.[168]

Our results indicate that BECCS from energy crops grown on CRP land could contribute significantly to climate stabilization and ES. However, despite avoiding indirect LUC, the deployment at scale poses a risk to biodiversity and freshwater use.[169,170] Worthy of note is the absence of grassland mixtures in favor of perennial monocultures in all of the optimized scenarios. The combination of routine harvest of aboveground biomass, reduced soil C sequestration, and periodic seeding, fertilization, and fire to sustain productivity and prevent woody encroachment incurs substantial opportunity and operational costs per biomass produced, reducing the energy and climate benefits of mixed grasses relative to dedicated biomass feedstocks once the initial C debt has been repaid. These results support previous research reporting enhanced climate mitigation potential from perennial biomass crops relative to grassland conservation options.[24,29,145] Although perennial monocultures have been shown to foster species richness,[171,172] transitions from native mixed grasslands may entail biodiversity losses.[173] Alternative management practices such as diversity strips, intercropping, and cover crops may enhance biodiversity[174] and should be considered as compensatory actions to ensure the sustainability of the proposed scenarios.

Similarly, water requirements to sustain crop productivity and CCS processes conflict with demand for freshwater in different sectors.[13,175] Water use differs widely among feedstocks. Long-rotation perennials (i.e., miscanthus and switchgrass) display generally larger water use efficiency (amount of CO_2 uptake per unit of water evapotranspired) than mixed grasslands or annual crops (corn/soybean rotations).[176] While unavoidable, the additional stress on water resources will largely depend on the feedstock of choice and water availability. Plant breeding for the improved efficiency and resilience of dedicated energy crops and water saving management strategies are, therefore, key for the sustainable deployment of BECCS.[177,178]

Our findings highlight biophysical constraints that define the geographic limits of potential biomass and energy supply. Realistic action portfolios require spatially explicit assessments for capturing complex dynamics and identifying the limits to implementation. Furthermore, we provide evidence of a significant potential of a BECCS landscape on set-aside land to contribute to climate stabilization and energy statutory targets but underpin the trade-offs of divergent policy-driven agendas and the repercussions for how future action portfolios will be mapped and executed.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c05240.

Aereal distribution of grasslands enrolled in the Conservation Reserve Program (CRP) within the US rainfed region; DAYCENT validations of soil carbon baselines; DAYCENT validations of annual yields across the US rainfed region; estimated mean annual yields of all considered land uses on CRP land within the US rainfed region; estimated mean annual SOC accrual rates of all considered land uses on CRP land within the US rainfed region; feedstock specific tolerance range and recommended levels of soil pH and agricultural inputs; embodied emissions from farm operations; energy and emission costs of steel manufacture; implement descriptors, draft parameters, and estimated energy requirements for agronomic equipment (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Evan H. DeLucia − *Institute for Sustainability, Energy, and Environment, Center for Advanced Bioenergy and Bioproducts Innovation, Department of Agricultural and Consumer Economics, and Department of Plant Biology, University of Illinois at Urbana−Champaign, Urbana, Illinois 61801, United States; Carl R. Woese Institute for Genomic Biology, University of Illinois at Urbana−Champaign, Urbana, Illinois 61801, United States; Leverhulme Centre for Climate Change Mitigation, Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, U.K.;* orcid.org/0000-0003-3400-6286; Email: delucia@illinos.edu

Authors

Elena Blanc-Betes − *Institute for Sustainability, Energy, and Environment and Center for Advanced Bioenergy and Bioproducts Innovation, University of Illinois at Urbana−Champaign, Urbana, Illinois 61801, United States; Carl R. Woese Institute for Genomic Biology, University of Illinois at Urbana−Champaign, Urbana, Illinois 61801, United States;* orcid.org/0000-0002-2049-4613

Nuria Gomez-Casanovas − *Texas A&M AgriLife Research Center, Texas A&M University, Vernon, Texas 76384, United States; Rangeland, Wildlife & Fisheries Management Department, Texas A&M University, Vernon, Texas 77843, United States*

Melannie D. Hartman − *Center for Advanced Bioenergy and Bioproducts Innovation, University of Illinois at Urbana−Champaign, Urbana, Illinois 61801, United States; Institute for Advancing Health Through Agriculture, Texas A&M University, Vernon, Texas 77845, United States*

Tara W. Hudiburg − *Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado 80523, United States*

Madhu Khanna − *Institute for Sustainability, Energy, and Environment and Center for Advanced Bioenergy and Bioproducts Innovation, University of Illinois at Urbana−Champaign, Urbana, Illinois 61801, United States; Department of Forest, Rangeland and Fire Science, University of Idaho, Moscow, Idaho 83844, United States;* orcid.org/0000-0003-4994-4451

William J. Parton − *Center for Advanced Bioenergy and Bioproducts Innovation, University of Illinois at Urbana−Champaign, Urbana, Illinois 61801, United States; Institute for Advancing Health Through Agriculture, Texas A&M University, Vernon, Texas 77845, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.3c05240

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was funded by the DOE Sun Grant (U.S. Department of Energy under award number 2014-3850222598) and by the DOE Center for Advanced Bioenergy and Bioproducts Innovation (U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research under award number DE-SC0018420). Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and should not be constructed to represent any official U.S Department of Energy, U.S. Department of Agriculture or U.S. Government determination or policy.

■ REFERENCES

(1) Gao, Y.; Gao, X.; Zhang, X. The 2 °C Global Temperature Target and the Evolution of the Long-Term Goal of Addressing Climate Change—From the United Nations Framework Convention on Climate Change to the Paris Agreement. *Engineering* **2017**, *3* (2), 272−278.

(2) IPCC. *IPCC, 2014; Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O., Ed.; Cambridge University Press: New York, NY, 2014.

(3) Lenton, T. M.; Rockström, J.; Gaffney, O.; Rahmstorf, S.; Richardson, K.; Steffen, W.; Schellnhuber, H. J. Climate Tipping Points — Too Risky to Bet Against. *Nature* **2019**, *575* (7784), 592−595.

(4) van Vuuren, D. P.; Deetman, S.; van Vliet, J.; van den Berg, M.; van Ruijven, B. J.; Koelbl, B. The Role of Negative CO2 Emissions for Reaching 2 °C—Insights from Integrated Assessment Modelling. *Clim. Change* **2013**, *118* (1), 15−27.

(5) Fuss, S.; Canadell, J. G.; Peters, G. P.; Tavoni, M.; Andrew, R. M.; Ciais, P.; Jackson, R. B.; Jones, C. D.; Kraxner, F.; Nakicenovic, N.; Le Quéré, C.; Raupach, M. R.; Sharifi, A.; Smith, P.; Yamagata, Y. Betting on Negative Emissions. *Nature Climate Change* **2014**, *4*, 850−853.

(6) Vaughan, N. E.; Gough, C. Expert Assessment Concludes Negative Emissions Scenarios May Not Deliver. *Environ. Res. Lett.* **2016**, *11* (9), No. 095003.

(7) Fajardy, M.; Köberle, A.; MacDowell, N.; Fantuzzi, A. BECCS Deployment: A Reality Check. *Grantham Instituted Briefing paper* 2019, *28* (https://www.researchgate.net/profile/Andrea-Fantuzzi/publication/330774659_BECCS-deployment-_a-reality-check/links/5c539d81a6fdccd6b5d87347/BECCS-deployment-a-reality-check.pdf).

(8) Creutzig, F.; Erb, K.-H.; Haberl, H.; Hof, C.; Hunsberger, C.; Roe, S. Considering Sustainability Thresholds for BECCS in IPCC and Biodiversity Assessments. *GCB Bioenergy* **2021**, *13* (4), 510−515.

(9) Smith, S. M.; Geden, O.; Nemet, G. F.; Gidden, M. J.; Lamb, W. F.; Powis, C.; Bellamy, R.; Callaghan, M. W.; Cowie, A.; Cox, E.; Fuss, S.; Gasser, T.; Grassi, G.; Greene, J.; Lück, S.; Mohan, A.; Müller-Hansen, F.; Peters, G. P.; Pratama, Y.; Repke, T.; Riahi, K.; Schenuit, F.; Steinhauser, J.; Strefler, J.; Valenzuela, J. M.; Minx, J. C. *The State of Carbon Dioxide Removal*; 1st ed.; The State of Carbon Dioxide Removal, 2023. DOI: 10.17605/OSF.IO/W3B4Z.

(10) Höhne, N.; Kuramochi, T.; Warnecke, C.; Röser, F.; Fekete, H.; Hagemann, M.; Day, T.; Tewari, R.; Kurdziel, M.; Sterl, S.; Gonzales, S. The Paris Agreement: Resolving the Inconsistency between Global Goals and National Contributions. *Climate Policy* **2017**, *17* (1), 16−32.

(11) Buylova, A.; Fridahl, M.; Nasiritousi, N.; Reischl, G. Cancel (Out) Emissions? The Envisaged Role of Carbon Dioxide Removal Technologies in Long-Term National Climate Strategies. *Front. Clim.* **2021**, *3*, 63.

(12) Sandalow, D.; Aines, R.; Friedmann, J.; McCormick, C.; Sanchez, D. L. *Biomass Carbon Removal and Storage (BiRCS) Roadmap*; LLNL-TR-815200; Lawrence Livermore National Lab. (LLNL): Livermore, CA (United States), 2021. DOI: 10.2172/1763937.

(13) Smith, P.; Davis, S. J.; Creutzig, F.; Fuss, S.; Minx, J.; Gabrielle, B.; Kato, E.; Jackson, R. B.; Cowie, A.; Kriegler, E.; van Vuuren, D. P.; Rogelj, J.; Ciais, P.; Milne, J.; Canadell, J. G.; McCollum, D.; Peters, G.; Andrew, R.; Krey, V.; Shrestha, G.; Friedlingstein, P.; Gasser, T.; Grübler, A.; Heidug, W. K.; Jonas, M.; Jones, C. D.; Kraxner, F.; Littleton, E.; Lowe, J.; Moreira, J. R.; Nakicenovic, N.; Obersteiner, M.; Patwardhan, A.; Rogner, M.; Rubin, E.; Sharifi, A.; Torvanger, A.; Yamagata, Y.; Edmonds, J.; Yongsung, C. Biophysical and Economic Limits to Negative CO2 Emissions. *Nat. Clim. Change* **2016**, *6* (1), 42−50.

(14) Fajardy, M.; Dowell, N. M. Can BECCS Deliver Sustainable and Resource Efficient Negative Emissions? *Energy Environ. Sci.* **2017**, *10* (6), 1389−1426.

(15) Langholtz, M. H.; Stokes, B. J.; Eaton, L. M. 2016 *Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy; DOE/EE-1440*; EERE Publication and Product Library: Washington, D.C., (United States), 2016. DOI: 10.2172/1271651.

(16) Baik, E.; Sanchez, D. L.; Turner, P. A.; Mach, K. J.; Field, C. B.; Benson, S. M. Geospatial Analysis of Near-Term Potential for Carbon-Negative Bioenergy in the United States. *Proc. Natl. Acad. Sci. U. S. A.* **2018**, *115* (13), 3290−3295.

(17) Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land Clearing and the Biofuel Carbon Debt. *Science* **2008**, *319* (5867), 1235−1238.

(18) Lamb, A.; Green, R.; Bateman, I.; Broadmeadow, M.; Bruce, T.; Burney, J.; Carey, P.; Chadwick, D.; Crane, E.; Field, R.; Goulding, K.; Griffiths, H.; Hastings, A.; Kasoar, T.; Kindred, D.; Phalan, B.; Pickett, J.; Smith, P.; Wall, E.; zu Ermgassen, E. K. H. J.; Balmford, A. The Potential for Land Sparing to Offset Greenhouse Gas Emissions from Agriculture. *Nature. Climate Change* **2016**, *6* (5), 488−492.

(19) Cai, X.; Zhang, X.; Wang, D. Land Availability for Biofuel Production. *Environ. Sci. Technol.* **2011**, *45* (1), 334−339.

(20) Fritz, S.; See, L.; van der Velde, M.; Nalepa, R. A.; Perger, C.; Schill, C.; McCallum, I.; Schepaschenko, D.; Kraxner, F.; Cai, X.; Zhang, X.; Ortner, S.; Hazarika, R.; Cipriani, A.; Di Bella, C.; Rabia, A. H.; Garcia, A.; Vakolyuk, M.; Singha, K.; Beget, M. E.; Erasmi, S.; Albrecht, F.; Shaw, B.; Obersteiner, M. Downgrading Recent Estimates of Land Available for Biofuel Production. *Environ. Sci. Technol.* **2013**, *47* (3), 1688−1694.

(21) Khanna, M.; Chen, L.; Basso, B.; Cai, X.; Field, J. L.; Guan, K.; Jiang, C.; Lark, T. J.; Richard, T. L.; Spawn-Lee, S. A.; Yang, P.; Zipp, K. Y. Redefining Marginal Land for Bioenergy Crop Production. *GCB Bioenergy* **2021**, *13* (10), 1590−1609.

(22) Shortall, O. K. Marginal Land" for Energy Crops: Exploring Definitions and Embedded Assumptions. *Energy Policy* **2013**, *62*, 19−27.
(23) Mellor, P.; Lord, R. A.; João, E.; Thomas, R.; Hursthouse, A. Identifying Non-Agricultural Marginal Lands as a Route to Sustainable Bioenergy Provision - A Review and Holistic Definition. *Renewable and Sustainable Energy Reviews* **2021**, *135*, No. 110220.
(24) Abraha, M.; Gelfand, I.; Hamilton, S. K.; Chen, J.; Robertson, G. P. Carbon Debt of Field-Scale Conservation Reserve Program Grasslands Converted to Annual and Perennial Bioenergy Crops. *Environ. Res. Lett.* **2019**, *14* (2), No. 024019.
(25) Smith, W. K.; Zhao, M.; Running, S. W. Global Bioenergy Capacity as Constrained by Observed Biospheric Productivity Rates. *BioScience* **2012**, *62* (10), 911−922.
(26) Creutzig, F. Economic and Ecological Views on Climate Change Mitigation with Bioenergy and Negative Emissions. *GCB Bioenergy* **2016**, *8* (1), 4−10.
(27) Searchinger, T. D.; Hamburg, S. P.; Melillo, J.; Chameides, W.; Havlik, P.; Kammen, D. M.; Likens, G. E.; Lubowski, R. N.; Obersteiner, M.; Oppenheimer, M.; Philip Robertson, G.; Schlesinger, W. H.; David Tilman, G. Fixing a Critical Climate Accounting Error. *Science* **2009**, *326* (5952), 527−528.
(28) Tanzer, S. E.; Ramírez, A. When Are Negative Emissions Negative Emissions? *Energy Environ. Sci.* **2019**, *12* (4), 1210−1218.
(29) Field, J. L.; Richard, T. L.; Smithwick, E. A. H.; Cai, H.; Laser, M. S.; LeBauer, D. S.; Long, S. P.; Paustian, K.; Qin, Z.; Sheehan, J. J.; Smith, P.; Wang, M. Q.; Lynd, L. R. Robust Paths to Net Greenhouse Gas Mitigation and Negative Emissions via Advanced Biofuels. *Proc. Natl. Acad. Sci. U.S.A.* **2020**, *117* (36), 21968−21977.
(30) Evans, S. G.; Ramage, B. S.; DiRocco, T. L.; Potts, M. D. Greenhouse Gas Mitigation on Marginal Land: A Quantitative Review of the Relative Benefits of Forest Recovery versus Biofuel Production. *Environ. Sci. Technol.* **2015**, *49* (4), 2503−2511.
(31) Searchinger, T.; Heimlich, R.; Houghton, R. A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T.-H. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science* **2008**, *319* (5867), 1238−1240.
(32) Taheripour, F.; Tyner, W. E. Induced Land Use Emissions Due to First and Second Generation Biofuels and Uncertainty in Land Use Emission Factors. *Economics Research International* **2013**, *2013*, 1−12.
(33) Qin, Z.; Dunn, J. B.; Kwon, H.; Mueller, S.; Wander, M. M. Influence of Spatially Dependent, Modeled Soil Carbon Emission Factors on Life-Cycle Greenhouse Gas Emissions of Corn and Cellulosic Ethanol. *GCB Bioenergy* **2016**, *8* (6), 1136−1149.
(34) Anderson-Teixeira, K. J.; Davis, S. C.; Masters, M. D.; Delucia, E. H. Changes in Soil Organic Carbon under Biofuel Crops. *GCB Bioenergy* **2009**, *1* (1), 75−96.
(35) Anderson-Teixeira, K. J.; Masters, M. D.; Black, C. K.; Zeri, M.; Hussain, M. Z.; Bernacchi, C. J.; DeLucia, E. H. Altered Belowground Carbon Cycling Following Land-Use Change to Perennial Bioenergy Crops. *Ecosystems* **2013**, *16* (3), 508−520.
(36) Hudiburg, T. W.; Davis, S. C.; Parton, W.; Delucia, E. H. Bioenergy Crop Greenhouse Gas Mitigation Potential under a Range of Management Practices. *GCB Bioenergy* **2015**, *7* (2), 366−374.
(37) Hudiburg, T. W.; Wang, W.; Khanna, M.; Long, S. P.; Dwivedi, P.; Parton, W. J.; Hartman, M.; DeLucia, E. H. Impacts of a 32-Billion-Gallon Bioenergy Landscape on Land and Fossil Fuel Use in the US. *Nat. Energy* **2016**, *1* (1), No. nenergy20155.
(38) Chen, L.; Debnath, D.; Zhong, J.; Ferin, K.; VanLoocke, A.; Khanna, M. The Economic and Environmental Costs and Benefits of the Renewable Fuel Standard. *Environ. Res. Lett.* **2021**, *16* (3), No. 034021.
(39) Wang, M.; Han, J.; Dunn, J. B.; Cai, H.; Elgowainy, A. Well-to-Wheels Energy Use and Greenhouse Gas Emissions of Ethanol from Corn, Sugarcane and Cellulosic Biomass for US Use. *Environ. Res. Lett.* **2012**, *7* (4), No. 045905.
(40) Fajardy, M.; Chiquier, S.; Dowell, N. M. Investigating the BECCS Resource Nexus: Delivering Sustainable Negative Emissions. *Energy Environ. Sci.* **2018**, *11* (12), 3408−3430.
(41) Shukla, P. R.; Skea, J.; Calvo Buendia, E.; Masson-Delmotte, V.; Pörtner, H.-O.; Roberts, D. C.; Zhai, P.; Slade, R.; Connors, S.; Van Diemen, R.; Ferrat, M.; Haughey, E.; Luz, S.; Neogi, S.; Pathak, M.; Petzold, J.; Portugal Pereira, J.; Vyas, P.; Huntley, E.; Kissick, K.; Belkacemi, M.; Malley, J. *IPCC, 2019: Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Report; Intergovernmental Panel on Climate Change (IPCC), 2019. DOI: 10.25561/76618.
(42) Fridahl, M.; Lehtveer, M. Bioenergy with Carbon Capture and Storage (BECCS): Global Potential, Investment Preferences, and Deployment Barriers. *Energy Res. Social Sci.* **2018**, *42*, 155−165.
(43) Fajardy, M.; Dowell, N. M. The Energy Return on Investment of BECCS: Is BECCS a Threat to Energy Security? *Energy Environ. Sci.* **2018**, *11* (6), 1581−1594.
(44) Piñeiro, G.; Jobbágy, E. G.; Baker, J.; Murray, B. C.; Jackson, R. B. Set-Asides Can Be Better Climate Investment than Corn Ethanol. *Ecol. Appl.* **2009**, *19* (2), 277−282.
(45) Kato, E.; Yamagata, Y. BECCS Capability of Dedicated Bioenergy Crops under a Future Land-Use Scenario Targeting Net Negative Carbon Emissions. *Earth's Future* **2014**, *2* (9), 421−439.
(46) Tilman, D.; Hill, J.; Lehman, C. Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass. *Science* **2006**, *314* (5805), 1598−1600.
(47) Song, Y.; Jain, A. K.; Landuyt, W.; Kheshgi, H. S.; Khanna, M. Estimates of Biomass Yield for Perennial Bioenergy Grasses in the USA. *Bioenerg. Res.* **2015**, *8* (2), 688−715.
(48) Sharma, B. P.; Zhang, N.; Lee, D.; Heaton, E.; Delucia, E. H.; Sacks, E. J.; Kantola, I. B.; Boersma, N. N.; Long, S. P.; Voigt, T. B.; Khanna, M. Responsiveness of Miscanthus and Switchgrass Yields to Stand Age and Nitrogen Fertilization: A Meta-Regression Analysis. *GCB Bioenergy* **2022**, *14* (5), 539−557.
(49) Owens, V. N.; Viands, D. R.; Mayton, H. S.; Fike, J. H.; Farris, R.; Heaton, E.; Bransby, D. I.; Hong, C. O. Nitrogen Use in Switchgrass Grown for Bioenergy across the USA. *Biomass Bioenergy* **2013**, *58*, 286−293.
(50) Hong, C. O.; Owens, V. N.; Bransby, D.; Farris, R.; Fike, J.; Heaton, E.; Kim, S.; Mayton, H.; Mitchell, R.; Viands, D. Switchgrass Response to Nitrogen Fertilizer Across Diverse Environments in the USA: A Regional Feedstock Partnership Report. *Bioenergy Res.* **2014**, *7* (3), 777−788.
(51) Jarchow, M. E.; Liebman, M.; Dhungel, S.; Dietzel, R.; Sundberg, D.; Anex, R. P.; Thompson, M. L.; Chua, T. Trade-Offs among Agronomic, Energetic, and Environmental Performance Characteristics of Corn and Prairie Bioenergy Cropping Systems. *GCB Bioenergy* **2015**, *7* (1), 57−71.
(52) Kordbacheh, F.; Jarchow, M.; English, L.; Liebman, M. Productivity and Diversity of Annually Harvested Reconstructed Prairie Communities. *Journal of Applied Ecology* **2019**, *56* (2), 330−342.
(53) De Klein, C.; Novoa, R. S.; Ogle, S.; Smith, K. A.; Rochette, P.; Wirth, T. C.; McConkey, B. G.; Mosier, A.; Rypdal, K.; Walsh, M. N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application. *IPCC guidelines for National greenhouse gas inventories, prepared by the National greenhouse gas inventories programme* 2006, *4*, 1−54
(54) Schaubroeck, T. Relevance of Attributional and Consequential Life Cycle Assessment for Society and Decision Support. *Front. Sustainability* **2023**, *4*, No. 1063583.
(55) Parton, W. J.; Hartman, M.; Ojima, D.; Schimel, D. DAYCENT and Its Land Surface Submodel: Description and Testing. *Global Planetary Change* **1998**, *19* (1), 35−48.
(56) Del Grosso, S. J.; Ojima, D. S.; Parton, W. J.; Stehfest, E.; Heistemann, M.; DeAngelo, B.; Rose, S. Global Scale DAYCENT Model Analysis of Greenhouse Gas Emissions and Mitigation

Strategies for Cropped Soils. *Global Planetary Change* **2009**, *67* (1−2), 44−50.
(57) Parton, W. J. Observations and Modeling of Biomass and Soil Organic Matter Dynamics for the Grassland Biome Worldwide. *Global Biogeochem. Cycles* **1993**, *7* (4), 785−809.
(58) Del Grosso, S. J.; Ojima, D. S.; Parton, W. J.; Stehfest, E.; Heistemann, M.; DeAngelo, B.; Rose, S. Global Scale DAYCENT Model Analysis of Greenhouse Gas Emissions and Mitigation Strategies for Cropped Soils. *Global Planetary Change* **2009**, *67* (1), 44−50.
(59) Del Grosso, S. J.; Parton, W. J.; Mosier, A. R.; Walsh, M. K.; Ojima, D. S.; Thornton, P. E. DAYCENT National-Scale Simulations of Nitrous Oxide Emissions from Cropped Soils in the United States. *J. Environ. Qual.* **2006**, *35* (4), 1451−1460.
(60) Adler, P. R.; Grosso, S. J. D.; Parton, W. J. Life-Cycle Assessment of Net Greenhouse-Gas Flux for Bioenergy Cropping Systems. *Ecol. App.* **2007**, *17* (3), 675−691.
(61) Davis, S. C.; Parton, W. J.; Dohleman, F. G.; Smith, C. M.; Grosso, S. D.; Kent, A. D.; DeLucia, E. H. Comparative Biogeochemical Cycles of Bioenergy Crops Reveal Nitrogen-Fixation and Low Greenhouse Gas Emissions in a Miscanthus × Giganteus Agro-Ecosystem. *Ecosystems* **2010**, *13* (1), 144−156.
(62) Chamberlain, J. F.; Miller, S. A.; Frederick, J. R. Using DAYCENT to Quantify On-Farm GHG Emissions and N Dynamics of Land Use Conversion to N-Managed Switchgrass in the Southern U.S. *Agric. Ecosyst. Environ.* **2011**, *141* (3), 332−341.
(63) Cheng, K.; Ogle, S. M.; Parton, W. J.; Pan, G. Simulating Greenhouse Gas Mitigation Potentials for Chinese Croplands Using the DAYCENT Ecosystem Model. *Global Change Biology* **2014**, *20* (3), 948−962.
(64) Campbell, E. E.; Johnson, J. M. F.; Jin, V. L.; Lehman, R. M.; Osborne, S. L.; Varvel, G. E.; Paustian, K. Assessing the Soil Carbon, Biomass Production, and Nitrous Oxide Emission Impact of Corn Stover Management for Bioenergy Feedstock Production Using DAYCENT. *Bioenerg. Res.* **2014**, *7* (2), 491−502.
(65) Miguez, F. E.; Villamil, M. B.; Long, S. P.; Bollero, G. A. Meta-Analysis of the Effects of Management Factors on Miscanthus × giganteus Growth and Biomass Production. *Agricultural and Forest Meteorology* **2008**, *148* (8), 1280−1292.
(66) Tejera, M.; Boersma, N.; Vanloocke, A.; Archontoulis, S.; Dixon, P.; Miguez, F.; Heaton, E. Multi-Year and Multi-Site Establishment of the Perennial Biomass Crop Miscanthus × Giganteus Using a Staggered Start Design to Elucidate N Response. *Bioenerg. Res.* **2019**, *12* (3), 471−483.
(67) Heaton, E. A.; Dohleman, F. G.; Long, S. P. Seasonal Nitrogen Dynamics of Miscanthus × giganteus and Panicum Virgatum. *GCB Bioenergy* **2009**, *1* (4), 297−307.
(68) Pyter, R. J.; Dohleman, F. G.; Voigt, T. B. Effects of Rhizome Size, Depth of Planting and Cold Storage on Miscanthus x Giganteus Establishment in the Midwestern USA. *Biomass and Bioenergy* **2010**, *34* (10), 1466−1470.
(69) Scarlat, N.; Martinov, M.; Dallemand, J.-F. Assessment of the Availability of Agricultural Crop Residues in the European Union: Potential and Limitations for Bioenergy Use. *Waste Management* **2010**, *30* (10), 1889−1897.
(70) Anderson, E. K.; Aberle, E.; Chen, C.; Egenolf, J.; Harmoney, K.; Kakani, V. G.; Kallenbach, R.; Khanna, M.; Wang, W.; Lee, D. Impacts of Management Practices on Bioenergy Feedstock Yield and Economic Feasibility on Conservation Reserve Program Grasslands. *GCB Bioenergy* **2016**, *8* (6), 1178−1190.
(71) Anderson, E.; Arundale, R.; Maughan, M.; Oladeinde, A.; Wycislo, A.; Voigt, T. Growth and Agronomy of Miscanthus × Giganteus for Biomass Production. *Biofuels* **2011**, *2* (2), 167−183.
(72) Maughan, M.; Bollero, G.; Lee, D. K.; Darmody, R.; Bonos, S.; Cortese, L.; Murphy, J.; Gaussoin, R.; Sousek, M.; Williams, D.; Williams, L.; Miguez, F.; Voigt, T. Miscanthus × Giganteus Productivity: The Effects of Management in Different Environments. *GCB Bioenergy* **2012**, *4* (3), 253−265.
(73) Dohleman, F. G.; Heaton, E. A.; Arundale, R. A.; Long, S. P. Seasonal Dynamics of Above- and below-Ground Biomass and Nitrogen Partitioning in Miscanthus × Giganteus and Panicum Virgatum across Three Growing Seasons. *Glob. Change Biol. Bioenergy* **2012**, *4* (5), 534−544.
(74) Behnke, G. D.; David, M. B.; Voigt, T. B. Greenhouse Gas Emissions, Nitrate Leaching, and Biomass Yields from Production of Miscanthus × Giganteus in Illinois, USA. *Bioenerg. Res.* **2012**, *5* (4), 801−813.
(75) Smith, C. M.; David, M. B.; Mitchell, C. A.; Masters, M. D.; Anderson-Teixeira, K. J.; Bernacchi, C. J.; DeLucia, E. H. Reduced Nitrogen Losses after Conversion of Row Crop Agriculture to Perennial Biofuel Crops. *Journal of Environmental Quality* **2013**, *42* (1), 219−228.
(76) Arundale, R. A.; Dohleman, F. G.; Heaton, E. A.; Mcgrath, J. M.; Voigt, T. B.; Long, S. P. Yields of Miscanthus × Giganteus and Panicum Virgatum Decline with Stand Age in the Midwestern USA. *GCB Bioenergy* **2014**, *6* (1), 1−13.
(77) Conant, R. T.; Cerri, C. E. P.; Osborne, B. B.; Paustian, K. Grassland Management Impacts on Soil Carbon Stocks: A New Synthesis. *Ecological Applications* **2017**, *27* (2), 662−668.
(78) Hartman, M. D.; Merchant, E. R.; Parton, W. J.; Gutmann, M. P.; Lutz, S. M.; Williams, S. A. Impact of Historical Land-Use Changes on Greenhouse Gas Exchange in the U.S. Great Plains, 1883−2003. *Ecological Applications* **2011**, *21* (4), 1105−1119.
(79) Dangal, S. R. S.; Tian, H.; Pan, S.; Zhang, L.; Xu, R. Greenhouse Gas Balance in Global Pasturelands and Rangelands. *Environ. Res. Lett.* **2020**, *15* (10), No. 104006.
(80) Jarchow, M. E.; Liebman, M. Tradeoffs in Biomass and Nutrient Allocation in Prairies and Corn Managed for Bioenergy Production. *Crop Science* **2012**, *52* (3), 1330−1342.
(81) Nichols, V. A.; Miguez, F. E.; Jarchow, M. E.; Liebman, M. Z.; Dien, B. S. Comparison of Cellulosic Ethanol Yields from Midwestern Maize and Reconstructed Tallgrass Prairie Systems Managed for Bioenergy. *Bioenerg. Res.* **2014**, *7* (4), 1550−1560.
(82) NASS. *Usual Planting and Harvesting Dates for U.S. USDA Economics, Statistics and Market Information System.* https://usda.library.cornell.edu/concern/publications/vm40xr56k (accessed 2018−04−23).
(83) Sacks, W. J.; Deryng, D.; Foley, J. A.; Ramankutty, N. Crop Planting Dates: An Analysis of Global Patterns. *Global Ecol. Biogeograph.* **2010**, *19* (5), 607−620.
(84) Jarchow, M. E.; Liebman, M. Nitrogen Fertilization Increases Diversity and Productivity of Prairie Communities Used for Bioenergy. *GCB Bioenergy* **2013**, *5* (3), 281−289.
(85) Cao, P.; Lu, C.; Yu, Z. Historical Nitrogen Fertilizer Use in Agricultural Ecosystems of the Contiguous United States during 1850−2015: Application Rate, Timing, and Fertilizer Types. *Earth System Science Data* **2018**, *10* (2), 969−984.
(86) Lee, D. K.; Aberle, E.; Chen, C.; Egenolf, J.; Harmoney, K.; Kakani, G.; Kallenbach, R. L.; Castro, J. C. Nitrogen and Harvest Management of Conservation Reserve Program (CRP) Grassland for Sustainable Biomass Feedstock Production. *GCB Bioenergy* **2013**, *5* (1), 6−15.
(87) Daly, C.; Widrlechner, M. P.; Halbleib, M. D.; Smith, J. I.; Gibson, W. P. Development of a New USDA Plant Hardiness Zone Map for the United States. *Journal of Applied Meteorology and Climatology* **2012**, *51* (2), 242−264.
(88) NRCS. *NRCS. Soil Survey Geographic (SSURGO) Database for Eastern. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture.* https://websoilsurvey.sc.egov.usda.gov/ (accessed 2017−12−04).
(89) Olson, D. M.; Dinerstein, E.; Wikramanayake, E. D.; Burgess, N. D.; Powell, G. V. N.; Underwood, E. C.; D'amico, J. A.; Itoua, I.; Strand, H. E.; Morrison, J. C.; Loucks, C. J.; Allnutt, T. F.; Ricketts, T. H.; Kura, Y.; Lamoreux, J. F.; Wettengel, W. W.; Hedao, P.; Kassem, K. R. Terrestrial Ecoregions of the World: A New Map of Life on Earth: A New Global Map of Terrestrial Ecoregions Provides an

Innovative Tool for Conserving Biodiversity. *BioScience* **2001**, *51* (11), 933−938.

(90) Viovy, N. *CRUNCEP Version 7 - Atmospheric Forcing Data for the Community Land Model.* Research Data Archive at the National Center for Atmospheric Research. Boulder, CO: Computational and Information Systems Laboratory. https://rda.ucar.edu/datasets/ds314.3/ (accessed 2018−01−29).

(91) Yu, Z.; Lu, C.; Cao, P.; Tian, H. Long-Term Terrestrial Carbon Dynamics in the Midwestern United States during 1850−2015: Roles of Land Use and Cover Change and Agricultural Management. *Global Change Biology* **2018**, *24* (6), 2673−2690.

(92) Cao, P.; Lu, C.; Yu, Z. Historical Nitrogen Fertilizer Use in Agricultural Ecosystems of the Contiguous United States during 1850−2015: Application Rate, Timing, and Fertilizer Types. *Earth System Science Data Discussion* **2018**, *10*, 969−984.

(93) Yu, Z.; Lu, C. Historical Cropland Expansion and Abandonment in the Continental U.S. during 1850 to 2016. *Global Ecology and Biogeography* **2018**, *27* (3), 322−333.

(94) Cao, P.; Lu, C.; Yu, Z. Agricultural Nitrogen Fertilizer Uses in the Continental U.S. during 1850−2015: A Set of Gridded Time-Series Data. *Supplement to: Cao, P.; Lu, C.; Yu, Z. Historical Nitrogen Fertilizer Use in Agricultural Ecosystems of the Contiguous United States during 1850−2015: Application Rate, Timing, and Fertilizer Types. Earth System Science Data Discussion 2018, 10, 969−984*, 2017. DOI: 10.1594/PANGAEA.883585.

(95) Ito, A. A Historical Meta-Analysis of Global Terrestrial Net Primary Productivity: Are Estimates Converging? *Global Change Biology* **2011**, *17* (10), 3161−3175.

(96) NASS. *National Agricultural Statistics Service. Census of Agriculture Quick Stats 2.0 Beta, United States Department of Agriculture*. https://quickstats.nass.usda.gov/ (accessed 2020−01−10).

(97) Thornton, P. E.; Thornton, M. M.; Mayer, B. W.; Wei, Y.; Devarakonda, R.; Vose, R. S.; Cook, R. B. Daymet: Daily Surface Weather Data on a 1-Km Grid for North America, Version 3. *ORNL DAAC* **2016**. DOI: 10.3334/ORNLDAAC/1328.

(98) Fuhlendorf, S. D.; Limb, R. F.; Engle, D. M.; Miller, R. F. *Assessment of Prescribed Fire as a Conservation Practice. Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps*. USDA-NRCS: Washington, DC, USA 2011, 75−104.

(99) Mulkey, V. R.; Owens, V. N.; Lee, D. K. Management of Warm-Season Grass Mixtures for Biomass Production in South Dakota USA. *Bioresour. Technol.* **2008**, *99* (3), 609−617.

(100) Bentsen, N. S.; Felby, C.; Thorsen, B. J. Agricultural Residue Production and Potentials for Energy and Materials Services. *Prog. Energy Combust. Sci.* **2014**, *40*, 59−73.

(101) Lee, U.; Kwon, H.; Wu, M.; Wang, M. Retrospective Analysis of the U.S. Corn Ethanol Industry for 2005−2019: Implications for Greenhouse Gas Emission Reductions. *Biofuels, Bioproducts and Biorefining* **2021**, *15* (5), 1318−1331.

(102) Zhang, Y.; Zalapa, J.; Jakubowski, A. R.; Price, D. L.; Acharya, A.; Wei, Y.; Brummer, E. C.; Kaeppler, S. M.; Casler, M. D. Natural Hybrids and Gene Flow between Upland and Lowland Switchgrass. *Crop Science* **2011**, *51* (6), 2626−2641.

(103) Douglas, J.; Lemunyon, J.; Wynia, R.; Salon, P. Planting and Managing Switchgrass as a Biomass Energy Crop. *Natural Resources Conservation Service, US Department of Agriculture* 2009, 3, 663−674, .

(104) Mitchell, R.; Schmer, M. Switchgrass Harvest and Storage. In *Switchgrass*; Green Energy and Technology; Springer: London, 2012; pp 113−127. DOI: 10.1007/978-1-4471-2903-5_5.

(105) Chen, H.; Dai, Z.; Jager, H. I.; Wullschleger, S. D.; Xu, J.; Schadt, C. W. Influences of Nitrogen Fertilization and Climate Regime on the Above-Ground Biomass Yields of Miscanthus and Switchgrass: A Meta-Analysis. *Renewable Sustainable Energy Rev.* **2019**, *108*, 303−311.

(106) Arundale, R. A.; Dohleman, F. G.; Voigt, T. B.; Long, S. P. Nitrogen Fertilization Does Significantly Increase Yields of Stands of Miscanthus × Giganteus and Panicum Virgatum in Multiyear Trials in Illinois. *Bioenerg. Res.* **2014**, *7* (1), 408−416.

(107) Iqbal, Y.; Gauder, M.; Claupein, W.; Graeff-Hönninger, S.; Lewandowski, I. Yield and Quality Development Comparison between Miscanthus and Switchgrass over a Period of 10 Years. *Energy* **2015**, *89*, 268−276.

(108) Gauder, M.; Graeff-Hönninger, S.; Lewandowski, I.; Claupein, W. Long-Term Yield and Performance of 15 Different Miscanthus Genotypes in Southwest Germany. *Annals of Applied Biology* **2012**, *160* (2), 126−136.

(109) Larsen, S. U.; Jørgensen, U.; Kjeldsen, J. B.; Lærke, P. E. Long-Term Miscanthus Yields Influenced by Location, Genotype, Row Distance. *Fertilization and Harvest Season. Bioenerg. Res.* **2014**, *7* (2), 620−635.

(110) Hubbs, M. D. Liming to Improve Soil Quality. *Soil quality - Agronomy technical note* **1999**, *8*, 6.

(111) Anderson, N. P.; Hart, J. M.; Sullivan, D. M.; Christensen, N. W.; Horneck, D. A.; Pirelli, G. J. Applying Lime to Raise Soil PH for Crop Production (Western Oregon). 2013, *21*.

(112) Lukin, V. V.; Epplin, F. M. Optimal Frequency and Quantity of Agricultural Lime Applications. *Agric. Syst.* **2003**, *76* (3), 949−967.

(113) Barnhart, S.; Mallarino, A.; Sawyer, J. *Fertilizing Pasture*; Pasture and Forage; PM869; 2013. https://store.extension.iastate.edu/product/Fertilizing-Pasture (accessed 2022−07−07).

(114) Mallarino, A.; Sawyer, J.; Barnhart, S. *A General Guide for Crop Nutrient and Limestone Recommendations in Iowa; PM1688*; 2013. https://store.extension.iastate.edu/product/A-General-Guide-for-Crop-Nutrient-and-Limestone-Recommendations-in-Iowa (accessed 2022−07−08).

(115) Bullard, M.; Metcalfe, P. *Estimating the Energy Requirements and CO2 Emissions from Production of the Perennial Grasses Miscanthus, Switchgrass and Reed Canary Grass*; 2001.

(116) Barnhart, S.; Duffy, M. *Estimated Costs of Pasture and Hay Production*; A1−15; 2012. https://www.extension.iastate.edu/agdm/crops/pdf/a1-15.pdf (accessed 2022−07−08).

(117) West, T. O.; Marland, G. A Synthesis of Carbon Sequestration, Carbon Emissions, and Net Carbon Flux in Agriculture: Comparing Tillage Practices in the United States. *Agric., Ecosyst. Environ.* **2002**, *91* (1), 217−232.

(118) Mitchell, R.; Vogel, K.; Anderson, B.; McAndrew, T. J. Estimated Cost of Establishment and Production of "Liberty" Switchgrass. *Forage Grazinglands* **2005**, *3* (1), 1−2.

(119) Kalmbach, B.; Toor, G.; Ruppert, D. *Soil Fertility Recommendations Nitrogen Phosphorus and Potassium Requirements of Miscanthus*; EB-443; 2020. https://extension.umd.edu/sites/extension.umd.edu/files/_docs/publications/Soil%20Fertility%20Recommendations%20Nitrogen%20Phosphorus%20and%20Potassium%20Requirements%20of%20Miscanthus.pdf (accessed 2021−01−28).

(120) Hoque, M.; Artz, G.; Hart, C. *Estimated Cost of Establishment and Production of Miscanthus in Iowa*; A1−28; 2014. https://www.extension.iastate.edu/agdm/crops/pdf/a1-28.pdf (accessed 2022−07−08).

(121) Harrigan, T. M.; Rotz, C. A. Draft Relationships for Tillage and Seeding Equipment. *Appl. Eng. Agric.* **1995**, *11* (6), 773−783.

(122) Kim, Y.-S.; Kim, W.-S.; Siddique, M. A. A.; Baek, S.-Y.; Baek, S.-M.; Cheon, S.-H.; Lee, S.-D.; Lee, K.-H.; Hong, D.-H.; Park, S.-U.; Kim, Y.-J. Power Transmission Efficiency Analysis of 42 KW Power Agricultural Tractor According to Tillage Depth during Moldboard Plowing. *Agronomy* **2020**, *10* (9), 1263.

(123) Oduma, O. Effect of soil pysical propertis on performance of agricultural field machineries in the tropical region of Nigeria. *Agric. Eng. Int.: CIGR J.* **2018**, *20* (1), 25−31.

(124) ASABE. Agricultural Machinery Management Data; *ASABE Standards*; D497.6; American Society of Agricultural and Biological Engineers (ASABE): St. Joseph, MI, USA, 2009; p 2.

(125) Grisso, R. D.; Yasin, M.; Kocher, M. F. Tillage Implement Forces Operating in Silty Clay Loam. *Trans. ASAE* **1996**, *39* (6), 1977.

https://doi.org/10.1021/acs.est.3c05240
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

(126) Askari, M.; Khalifahamzehghasem, S. Draft Force Inputs for Primary and Secondary Tillage Implements in a Clay Loam Soil. *World Appl. Sci. J.* **2013**, *21* (12), 1789−1794.
(127) Bowers, C. G., Jr. Tillage Draft and Energy Measurements for Twelve Southeastern Soil Series. *Trans. ASAE* **1989**, *32* (5), 1492−1502.
(128) Al-Janobi, A.; Al-Hamed, S.; Aboukarima, A.; Almajhadi, Y.; Al-Janobi, A.; Al-Hamed, S.; Aboukarima, A.; Almajhadi, Y. MODELING OF DRAFT AND ENERGY REQUIREMENTS OF A MOLDBOARD PLOW USING ARTIFICIAL NEURAL NETWORKS BASED ON TWO NOVEL VARIABLES. *Eng. Agric.* **2020**, *40* (3), 363−373.
(129) Kang, S.; Önal, H.; Ouyang, Y.; Scheffran, J.; Tursun, Ü. D. Optimizing the Biofuels Infrastructure: Transportation Networks and Biorefinery Locations in Illinois. In *Handbook of Bioenergy Economics and Policy*; Khanna, M.; Scheffran, J.; Zilberman, D., Eds.; Natural Resource Management and Policy; Springer: New York, NY, 2010; pp 151−173. DOI: 10.1007/978-1-4419-0369-3_10.
(130) Wang, M.; Elgowainy, A.; Lee, U.; Bafana, A.; Banerjee, S.; Benavides, P.; Bobba, P.; Burnham, A.; Cai, H.; Gracida-Alvarez, U.; Hawkins, T.; Iyer, R.; Kelly, J.; Kim, T.; Kingsbury, K.; Kwon, H.; Li, Y.; Liu, X.; Lu, Z.; Ou, L.; Siddique, N.; Sun, P.; Vyawahare, P.; Winjobi, O.; Wu, M.; Xu, H.; Yoo, E.; Zaimes, G.; Zang, G. *Summary of Expansions and Updates in GREET® 2021*; Argonne National Laboratory; 1; Argonne, IL, 2021. https://greet.es.anl.gov/publication-greet-2021-summary (accessed 2022−07−11).
(131) Wang, M. Q. *GREET 1.5 - Transportation Fuel-Cycle Model - Vol. 1: Methodology, Development, Use, and Results.*; ANL/ESD-39 VOL. 1; Argonne National Lab., IL (US), 1999. DOI: 10.2172/14775.
(132) Scown, C. D.; Nazaroff, W. W.; Mishra, U.; Strogen, B.; Lobscheid, A. B.; Masanet, E.; Santero, N. J.; Horvath, A.; McKone, T. E. Lifecycle Greenhouse Gas Implications of US National Scenarios for Cellulosic Ethanol Production. *Environ. Res. Lett.* **2012**, *7* (1), No. 014011.
(133) Dunn, J. B.; Mueller, S.; Wang, M.; Han, J. Energy Consumption and Greenhouse Gas Emissions from Enzyme and Yeast Manufacture for Corn and Cellulosic Ethanol Production. *Biotechnol. Lett.* **2012**, *34* (12), 2259−2263.
(134) de Chalendar, J. A.; Taggart, J.; Benson, S. M. Tracking Emissions in the US Electricity System. *Proc. Natl. Acad. Sci. U. S. A.* **2019**, *116* (51), 25497−25502.
(135) EIA. *U.S. Energy Information Admisnistration. Electricity databes, analysis and projections.* https://www.eia.gov/electricity/data/state/ (accessed 2022−07−13).
(136) Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A.; Schoen, P.; Lukas, J.; Olthof, B.; Worley, M.; Sexton, D.; Dudgeon, D. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*; NREL/TP-5100−47764; National Renewable Energy Lab. (NREL): Golden, CO (United States), 2011. DOI: 10.2172/1013269.
(137) Doczekalska, B.; Bartkowiak, M.; Waliszewska, B.; Orszulak, G.; Cerazy-Waliszewska, J.; Pniewski, T. Characterization of Chemically Activated Carbons Prepared from Miscanthus and Switchgrass Biomass. *Materials* **2020**, *13* (7), 1654.
(138) Lee, W.-C.; Kuan, W.-C. Miscanthus as Cellulosic Biomass for Bioethanol Production. *Biotechnol. J.* **2015**, *10* (6), 840−854.
(139) Waliszewska, B.; Grzelak, M.; Gaweł, E.; Spek-Dźwigała, A.; Sieradzka, A.; Czekała, W. Chemical Characteristics of Selected Grass Species from Polish Meadows and Their Potential Utilization for Energy Generation Purposes. *Energies* **2021**, *14* (6), 1669.
(140) Farrell, A. E.; Plevin, R. J.; Turner, B. T.; Jones, A. D.; O'Hare, M.; Kammen, D. M. Ethanol Can Contribute to Energy and Environmental Goals. *Science* **2006**, *311* (5760), 506−508.
(141) Gelfand, I.; Hamilton, S. K.; Kravchenko, A. N.; Jackson, R. D.; Thelen, K. D.; Robertson, G. P. Empirical Evidence for the Potential Climate Benefits of Decarbonizing Light Vehicle Transport in the U.S. with Bioenergy from Purpose-Grown Biomass with and without BECCS. *Environ. Sci. Technol.* **2020**, *54* (5), 2961−2974.
(142) Klein, D.; Luderer, G.; Kriegler, E.; Strefler, J.; Bauer, N.; Leimbach, M.; Popp, A.; Dietrich, J. P.; Humpenöder, F.; Lotze-Campen, H.; Edenhofer, O. The Value of Bioenergy in Low Stabilization Scenarios: An Assessment Using REMIND-MAgPIE. *Clim. Change* **2014**, *123* (3), 705−718.
(143) Hill, J.; Polasky, S.; Nelson, E.; Tilman, D.; Huo, H.; Ludwig, L.; Neumann, J.; Zheng, H.; Bonta, D. Climate Change and Health Costs of Air Emissions from Biofuels and Gasoline. *Proc. Natl. Acad. Sci. U. S. A.* **2009**, *106* (6), 2077−2082.
(144) Jarecki, M.; Kariyapperuma, K.; Deen, B.; Graham, J.; Bazrgar, A. B.; Vijayakumar, S.; Thimmanagari, M.; Gordon, A.; Voroney, P.; Thevathasan, N. The Potential of Switchgrass and Miscanthus to Enhance Soil Organic Carbon Sequestration—Predicted by DayCent Model. *Land* **2020**, *9* (12), 509.
(145) Gelfand, I.; Sahajpal, R.; Zhang, X.; Izaurralde, R. C.; Gross, K. L.; Robertson, G. P. Sustainable Bioenergy Production from Marginal Lands in the US Midwest. *Nature* **2013**, *493* (7433), 514−517.
(146) Lask, J.; Wagner, M.; Trindade, L. M.; Lewandowski, I. Life Cycle Assessment of Ethanol Production from Miscanthus: A Comparison of Production Pathways at Two European Sites. *GCB Bioenergy* **2019**, *11* (1), 269−288.
(147) Lewandrowski, J.; Rosenfeld, J.; Pape, D.; Hendrickson, T.; Jaglo, K.; Moffroid, K. The Greenhouse Gas Benefits of Corn Ethanol − Assessing Recent Evidence. *Biofuels* **2020**, *11* (3), 361−375.
(148) Scully, M. J.; Norris, G. A.; Alarcon Falconi, T. M.; MacIntosh, D. L. Carbon Intensity of Corn Ethanol in the United States: State of the Science. *Environ. Res. Lett.* **2021**, *16* (4), No. 043001.
(149) Zhu, P.; Zhuang, Q.; Eva, J.; Bernacchi, C. Importance of Biophysical Effects on Climate Warming Mitigation Potential of Biofuel Crops over the Conterminous United States. *GCB Bioenergy* **2017**, *9* (3), 577−590.
(150) Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S. E.; Fetzer, I.; Bennett, E. M.; Biggs, R.; Carpenter, S. R.; de Vries, W.; de Wit, C. A.; Folke, C.; Gerten, D.; Heinke, J.; Mace, G. M.; Persson, L. M.; Ramanathan, V.; Reyers, B.; Sörlin, S. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, *347* (6223), No. 1259855.
(151) EISA. Energy Independence and Security Act of 2007. *Public Law. 110th Congress* 2007, *110−140.*
(152) Fulton, L. M.; Lynd, L. R.; Körner, A.; Greene, N.; Tonachel, L. R. The Need for Biofuels as Part of a Low Carbon Energy Future. *Biofuels, Bioproducts and Biorefining* **2015**, *9* (5), 476−483.
(153) Uría-Martínez, R.; Leiby, P. N.; Brown, M. L. Energy Security Role of Biofuels in Evolving Liquid Fuel Markets. *Biofuels, Bioproducts and Biorefining* **2018**, *12* (5), 802−814.
(154) US EPA, O. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990−2019.* https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019 (accessed 2022−06−04).
(155) Paustian, K.; Larson, E.; Kent, J.; Marx, E.; Swan, A. Soil C Sequestration as a Biological Negative Emission Strategy. *Front. Climate* **2019**, *1*, 1.
(156) Field, J. L. Revisiting "Additional Carbon": Tracking Atmosphere−Ecosystem Carbon Exchange to Establish Mitigation and Negative Emissions From Bio-Based Systems. *Front. Climate* **2021**, *3*, No. 603239.
(157) Griscom, B. W.; Adams, J.; Ellis, P. W.; Houghton, R. A.; Lomax, G.; Miteva, D. A.; Schlesinger, W. H.; Shoch, D.; Siikamäki, J. V.; Smith, P.; Woodbury, P.; Zganjar, C.; Blackman, A.; Campari, J.; Conant, R. T.; Delgado, C.; Elias, P.; Gopalakrishna, T.; Hamsik, M. R.; Herrero, M.; Kiesecker, J.; Landis, E.; Laestadius, L.; Leavitt, S. M.; Minnemeyer, S.; Polasky, S.; Potapov, P.; Putz, F. E.; Sanderman, J.; Silvius, M.; Wollenberg, E.; Fargione, J. Natural Climate Solutions. *Proc. Natl. Acad. Sci. U.S.A.* **2017**, *114* (44), 11645−11650.

(158) Yang, Y.; Tilman, D. Soil and Root Carbon Storage Is Key to Climate Benefits of Bioenergy Crops. *Biofuel Research Journal* **2020**, *7* (2), 1143−1148.

(159) Schlesinger, W. H.; Amundson, R. Managing for Soil Carbon Sequestration: Let's Get Realistic. *Global Change Biology* **2019**, *25* (2), 386−389.

(160) Fuss, S.; Lamb, W. F.; Callaghan, M. W.; Hilaire, J.; Creutzig, F.; Amann, T.; Beringer, T.; de Oliveira Garcia, W.; Hartmann, J.; Khanna, T.; Luderer, G.; Nemet, G. F.; Rogelj, J.; Smith, P.; Vicente, J. L. V.; Wilcox, J.; del Mar Zamora Dominguez, M.; Minx, J. C. Negative Emissions—Part 2: Costs, Potentials and Side Effects. *Environ. Res. Lett.* **2018**, *13* (6), No. 063002.

(161) Low, S.; Schäfer, S. Is Bio-Energy Carbon Capture and Storage (BECCS) Feasible? The Contested Authority of Integrated Assessment Modeling. *Energy Research & Social Science* **2020**, *60*, No. 101326.

(162) Brandão, M.; Levasseur, A.; Kirschbaum, M. U. F.; Weidema, B. P.; Cowie, A. L.; Jørgensen, S. V.; Hauschild, M. Z.; Pennington, D. W.; Chomkhamsri, K. Key Issues and Options in Accounting for Carbon Sequestration and Temporary Storage in Life Cycle Assessment and Carbon Footprinting. *Int. J. Life Cycle Assess* **2013**, *18* (1), 230−240.

(163) Sun, T.; Ocko, I. B.; Sturcken, E.; Hamburg, S. P. Path to Net Zero Is Critical to Climate Outcome. *Sci. Rep* **2021**, *11* (1), 22173.

(164) Drouet, L.; Bosetti, V.; Padoan, S. A.; Aleluia Reis, L.; Bertram, C.; Dalla Longa, F.; Després, J.; Emmerling, J.; Fosse, F.; Fragkiadakis, K.; Frank, S.; Fricko, O.; Fujimori, S.; Harmsen, M.; Krey, V.; Oshiro, K.; Nogueira, L. P.; Paroussos, L.; Piontek, F.; Riahi, K.; Rochedo, P. R. R.; Schaeffer, R.; Takakura, J.; van der Wijst, K.-I.; van der Zwaan, B.; van Vuuren, D.; Vrontisi, Z.; Weitzel, M.; Zakeri, B.; Tavoni, M. Net Zero-Emission Pathways Reduce the Physical and Economic Risks of Climate Change. *Nat. Clim. Chang.* **2021**, *11* (12), 1070−1076.

(165) Riahi, K.; Bertram, C.; Huppmann, D.; Rogelj, J.; Bosetti, V.; Cabardos, A.-M.; Deppermann, A.; Drouet, L.; Frank, S.; Fricko, O.; Fujimori, S.; Harmsen, M.; Hasegawa, T.; Krey, V.; Luderer, G.; Paroussos, L.; Schaeffer, R.; Weitzel, M.; van der Zwaan, B.; Vrontisi, Z.; Longa, F. D.; Després, J.; Fosse, F.; Fragkiadakis, K.; Gusti, M.; Humpenöder, F.; Keramidas, K.; Kishimoto, P.; Kriegler, E.; Meinshausen, M.; Nogueira, L. P.; Oshiro, K.; Popp, A.; Rochedo, P. R. R.; Ünlü, G.; van Ruijven, B.; Takakura, J.; Tavoni, M.; van Vuuren, D.; Zakeri, B. Cost and Attainability of Meeting Stringent Climate Targets without Overshoot. *Nat. Clim. Chang.* **2021**, *11* (12), 1063−1069.

(166) Matthews, H. D.; Zickfeld, K.; Dickau, M.; MacIsaac, A. J.; Mathesius, S.; Nzotungicimpaye, C.-M.; Luers, A. Temporary Nature-Based Carbon Removal Can Lower Peak Warming in a Well-below 2 °C Scenario. *Commun. Earth Environ* **2022**, *3* (1), 1−8.

(167) Sierra, C. A.; Crow, S. E.; Heimann, M.; Metzler, H.; Schulze, E.-D. The Climate Benefit of Carbon Sequestration. *Biogeosciences* **2021**, *18* (3), 1029−1048.

(168) Amelung, W.; Bossio, D.; de Vries, W.; Kögel-Knabner, I.; Lehmann, J.; Amundson, R.; Bol, R.; Collins, C.; Lal, R.; Leifeld, J.; Minasny, B.; Pan, G.; Paustian, K.; Rumpel, C.; Sanderman, J.; van Groenigen, J. W.; Mooney, S.; van Wesemael, B.; Wander, M.; Chabbi, A. Towards a Global-Scale Soil Climate Mitigation Strategy. *Nat. Commun.* **2020**, *11* (1), 5427.

(169) Heck, V.; Gerten, D.; Lucht, W.; Popp, A. Biomass-Based Negative Emissions Difficult to Reconcile with Planetary Boundaries. *Nature Clim Change* **2018**, *8* (2), 151−155.

(170) Vaughan, N. E.; Gough, C.; Mander, S.; Littleton, E. W.; Welfle, A.; Gernaat, D. E. H. J.; van Vuuren, D. P. Evaluating the Use of Biomass Energy with Carbon Capture and Storage in Low Emission Scenarios. *Environ. Res. Lett.* **2018**, *13* (4), No. 044014.

(171) Robertson, G. P.; Hamilton, S. K.; Barham, B. L.; Dale, B. E.; Izaurralde, R. C.; Jackson, R. D.; Landis, D. A.; Swinton, S. M.; Thelen, K. D.; Tiedje, J. M. Cellulosic Biofuel Contributions to a Sustainable Energy Future: Choices and Outcomes. *Science* **2017**, *356* (6345), No. eaal2324.

(172) Robertson, B. A.; Doran, P. J.; Loomis, L. R.; Robertson, J. R.; Schemske, D. W. Perennial Biomass Feedstocks Enhance Avian Diversity. *GCB Bioenergy* **2011**, *3* (3), 235−246.

(173) Lark, T. J.; Spawn, S. A.; Bougie, M.; Gibbs, H. K. Cropland Expansion in the United States Produces Marginal Yields at High Costs to Wildlife. *Nat. Commun.* **2020**, *11* (1), 4295.

(174) Tamburini, G.; Bommarco, R.; Wanger, T. C.; Kremen, C.; van der Heijden, M. G. A.; Liebman, M.; Hallin, S. Agricultural Diversification Promotes Multiple Ecosystem Services without Compromising Yield. *Sci. Adv.* **2020**, *6* (45), No. eaba1715.

(175) Smith, P.; Adams, J.; Beerling, D. J.; Beringer, T.; Calvin, K. V.; Fuss, S.; Griscom, B.; Hagemann, N.; Kammann, C.; Kraxner, F.; Minx, J. C.; Popp, A.; Renforth, P.; Vicente Vicente, J. L.; Keesstra, S. Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals. *Ann Rev. Environ. Resources* **2019**, *44* (1), 255−286.

(176) Joo, E.; Zeri, M.; Hussain, M. Z.; DeLucia, E. H.; Bernacchi, C. J. Enhanced Evapotranspiration Was Observed during Extreme Drought from Miscanthus Opposite of Other Crops. *GCB Bioenergy* **2017**, *9* (8), 1306−1319.

(177) Gomez-Casanovas, N.; Blanc-Betes, E.; Moore, C. E.; Bernacchi, C. J.; Kantola, I.; DeLucia, E. H. A Review of Transformative Strategies for Climate Mitigation by Grasslands. *Sci. Total Environ.* **2021**, *799*, No. 149466.

(178) Blanc-Betes, E.; Gomez-Casanovas, N.; Yang, W. H.; Chandrasoma, J.; Clark, T. J.; De Lucia, E. H.; Hyde, C. A.; Kent, A. D.; Pett-Ridge, J.; Rabinowitz, J.; Raglin, S. S.; Schwender, J.; Shen, Y.; Van Allen, R.; von Haden, A. C. Accelerating the Development of a Sustainable Bioenergy Portfolio through Stable Isotopes. *GCB Bioenergy* **2023**, *15* (7), 840−866.