Global Change Biology WILEY

Land-based climate solutions for the United States

G. Philip Robertson[1,2,3] | **Stephen K. Hamilton**[1,3,4,5] | **Keith Paustian**[6] | **Pete Smith**[7]

[1]W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, Michigan, USA

[2]Department of Plant, Soil, and Microbial Sciences, Michigan State University, Hickory Corners, Michigan, USA

[3]Great Lakes Bioenergy Research Center, Michigan State University, East Lansing, Michigan, USA

[4]Department of Integrative Biology, Michigan State University, East Lansing, Michigan, USA

[5]Cary Institute of Ecosystem Studies, Millbrook, New York, USA

[6]Department of Soil and Crop Sciences and Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, USA

[7]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, UK

Correspondence
G. Philip Robertson, W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, Michigan 49060, USA.
Email: robert30@msu.edu

Abstract

Meeting end-of-century global warming targets requires aggressive action on multiple fronts. Recent reports note the futility of addressing mitigation goals without fully engaging the agricultural sector, yet no available assessments combine both nature-based solutions (reforestation, grassland and wetland protection, and agricultural practice change) and cellulosic bioenergy for a single geographic region. Collectively, these solutions might offer a suite of climate, biodiversity, and other benefits greater than either alone. Nature-based solutions are largely constrained by the duration of carbon accrual in soils and forest biomass; each of these carbon pools will eventually saturate. Bioenergy solutions can last indefinitely but carry significant environmental risk if carelessly deployed. We detail a simplified scenario for the United States that illustrates the benefits of combining approaches. We assign a portion of non-forested former cropland to bioenergy sufficient to meet projected mid-century transportation needs, with the remainder assigned to nature-based solutions such as reforestation. Bottom-up mitigation potentials for the aggregate contributions of crop, grazing, forest, and bioenergy lands are assessed by including in a Monte Carlo model conservative ranges for cost-effective local mitigation capacities, together with ranges for (a) areal extents that avoid double counting and include realistic adoption rates and (b) the projected duration of different carbon sinks. The projected duration illustrates the net effect of eventually saturating soil carbon pools in the case of most strategies, and additionally saturating biomass carbon pools in the case of forest management. Results show a conservative end-of-century mitigation capacity of 110 (57–178) Gt CO_2e for the U.S., ~50% higher than existing estimates that prioritize nature-based or bioenergy solutions separately. Further research is needed to shrink uncertainties, but there is sufficient confidence in the general magnitude and direction of a combined approach to plan for deployment now.

1 | INTRODUCTION

Efforts to curb emissions of CO_2 and other greenhouse gases (GHGs) have fallen well short of those needed to meet the international goal of limiting warming to 1.5 or even 2°C by the end of the century (IPCC, 2018). Consequently, we now face an urgent need for negative emissions technologies (NETs) capable of removing GHGs from the atmosphere. NETs fall into three broad categories (Field & Mach, 2017): improved ecosystem stewardship or nature-based solutions, whereby more carbon is stored in ecosystems via practices like reforestation and afforestation, conservation agriculture, and wetland restoration; biological carbon capture with geologic storage as in bioenergy with carbon capture and storage (BECCS) and ocean fertilization; and non-biological technologies such as enhanced rock weathering and direct air capture. Several NETs, including conservation agriculture and bioenergy, can also contribute to GHG avoidance by substituting renewable inputs for fossil fuel use. Socioeconomic projections of end-of-century concentrations of atmospheric GHGs—IPCC Shared Socioeconomic Pathways (IPCC, 2021)—show that all scenarios with a reasonable probability of meeting the 1.5°C target require the global removal of some 100–1000 Gt of CO_2e by 2100 (IPCC, 2018; Rogelj et al., 2018).

NETs vary dramatically in their technical maturity, requirements for land, GHG removal intensities, financial and environmental costs, and delivery of co-benefits such as pollution abatement and biodiversity conservation (Smith et al., 2016), and any single NET is unlikely to sustainably meet end-of-century removal goals (Minx et al., 2018). Nor, of course, are NETs alone a viable solution—deep mitigation also requires decarbonization and non-CO_2 GHG emission reductions (Anderson et al., 2019). Land-based mitigation approaches have the potential to contribute to both negative emissions and decarbonization, and fast action is urgently needed in order to minimize a mid-century temperature overshoot (IPCC, 2022); a plan that includes and assesses the mitigation potential of proven technologies that are available now—notably those related to agriculture, forestry, and bioenergy—seems crucial.

Recent analyses of potentials for land-based mitigation to contribute to end-of-century climate change goals underscore the importance of the food system in general (Clark et al., 2020) and agriculture and forestry in particular (Griscom et al., 2017) for creating the avoided and negative emissions necessary to meet 2100 climate change targets. Bioenergy in particular is used in all successful 1.5°C scenarios (Rogelj et al., 2018), and can be used to decarbonize transportation by producing liquid fuel or electricity (Field et al., 2020; Gelfand et al., 2020), and the co-production of non-fuel chemicals from biomass can as well help to decarbonize the substantial number of chemical products today produced with fossil fuels (Huang et al., 2021).

Driven by rising public demand, private sector interest, and increasingly dire scientific assessments, legislative initiatives in the U.S. signal the government's intent to engage agriculture and forestry to meet the CO_2 drawdown commitments of the Paris Climate Agreement and COP26. Still murky, however, is the degree to which technical potentials can be met by realistic scenarios that balance available land against the relative strengths and durations of alternative carbon sequestration and emission avoidance strategies. Particularly missing from current discussions of land-based mitigation scenarios are quantitative assessments of potential solutions that include both nature-based (Fargione et al., 2018) and cellulosic bioenergy (Field et al., 2020) solutions.
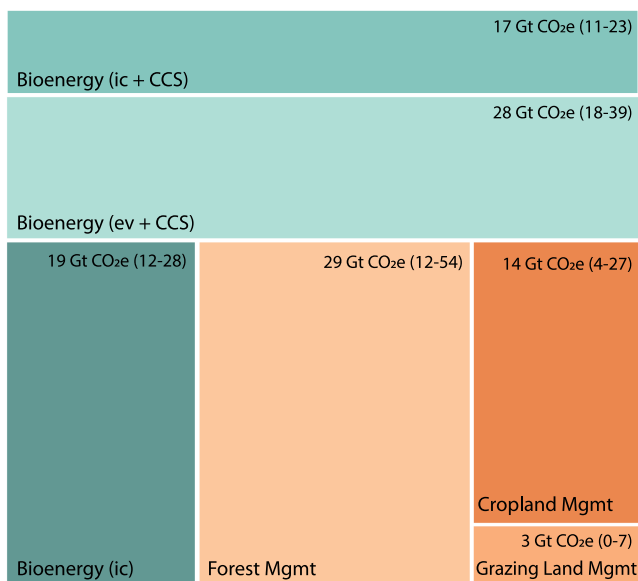
We believe this oversight deserves attention in order to provide a more complete picture of land-based climate solution potentials. And it is especially important to understand alternative land-use choices in the context of sink strength durations – the period of time over which some land-based mitigation measures will approach saturation. Most ecosystems can store only so much carbon in soils and biomass; eventually these sinks will reach some new equilibrium beyond which no more carbon will accrue. And while end-of-century targets for limiting warming to 1.5 or 2°C are aggressive (IPCC, 2018), even larger drawdowns will be necessary to return atmospheric GHG levels closer to pre-industrial concentrations (IPCC, 2019).

Top-down integrated assessment models of the capacity for land-based mitigation to avoid or remove the 100–1000 Gt of atmospheric CO_2 globally necessary to limit the global temperature increase to 1.5°C by 2100 are, by design, high level simplifications that seek to capture cost-optimized interactions among global systems but lack the sector-level detail needed for effective policy- and decision-making (NASEM, 2019). Additionally, such estimates typically consider only a subset of available land-based strategies, with an emphasis on BECCS (e.g., Calvin et al., 2019). Bottom-up efforts, on the other hand, effectively identify specific practices with substantial mitigation potentials, whether carbon capture or emissions avoidance, but struggle to capture the spatial resolution needed to avoid double-counting activities with competing land needs (NASEM, 2019), or promote one set of practices (such as reforestation) to the exclusion of others (such as bioenergy) (Fargione et al., 2018). And no efforts to derive land-based estimates capture the combined uncertainties of local practice outcomes, available land base, likely adoption rates, and the durations of different carbon sink strengths.

Recent estimates of U.S. land-based sequestration potentials suggest a maximum sequestration capacity of 1.0–2.4 Gt of CO_2 equivalents (CO_2e) per year at mid-century (NASEM, 2019), and a recent spatial analysis of potential nature-based solutions (Fargione et al., 2018) suggests an end-of-century capacity for ~74 Gt CO_2e by 2100. This estimate excludes bioenergy, however, an especially important opportunity in the United States and other countries where an available land base allows capacity to scale appreciably (Hilaire et al., 2019). That liquid bioenergy can offset fossil fuel use and thereby provide benefits immediately during the 20–30 year transition to electric vehicles (Meier et al., 2015) and for much longer for hard-to-decarbonize petroleum needs (IPCC, 2018), that biomass can be used to produce electricity (Calvin et al., 2019), and that bioenergy's mitigation potential is substantially enhanced when coupled with geologic sequestration (Klein et al., 2014; Sanchez et al., 2018), are important considerations for long-term mitigation needs.

Here we provide a quantitative assessment of the extent to which the active management of crop, grazing, and forest lands can help to meet U.S. mitigation targets by 2100. We emphasize that this is one of a number of different potential scenarios, chosen not to provide a single prescriptive solution but rather to show the mitigation potential of an integrated approach based on currently available technologies that balances competing land needs, considers the finite durations of nature-based carbon sinks, and includes a bioenergy potential constrained by expected light vehicle transportation fuel needs. We also emphasize that this U.S. example may or may not be relevant elsewhere, especially where land availability is limited. That said, the potential for restoring degraded lands while mitigating climate change through land management measures such as reforestation and perennial cellulosic bioenergy production is significant (Mosier, Córdova, et al., 2021).

We show a potential capacity for U.S. mitigation of 2.5 Gt CO_2e per year (95% confidence intervals: 1.4–3.8; Table S1) after mid-century vehicle electrification and deployment of geologic carbon capture and storage (CCS), which is included in all but the least energy intensive 1.5°C Shared Socioeconomic Pathway scenarios (IPCC, 2018). Our analysis provides a conservative end-of-century capacity of 110 (57–178) Gt CO_2e (Figure 1, Table S1), significantly more than that estimated by bottom-up assessments based on natural climate solutions (~74 Gt CO_2e), which exclude BECCS, and by top-down assessments based on integrated assessment models (~70 Gt CO_2e), which rely mostly on BECCS. Our land assignments
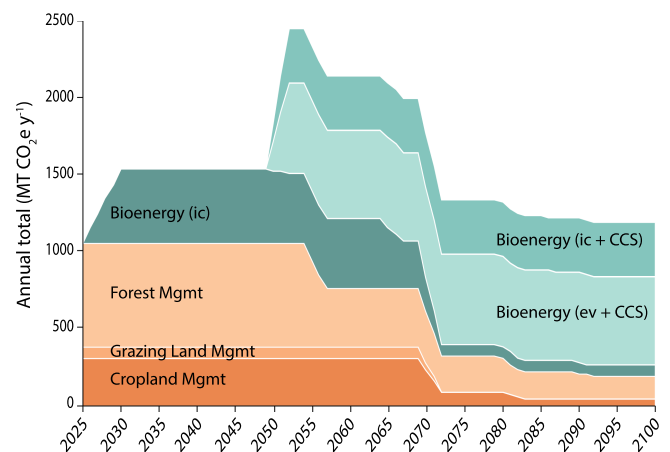
explicitly avoid double counting and involve no changes in U.S. food production, and thus avoid food-fuel conflict and should not result in indirect land use change emissions elsewhere. Explicit consideration of sink durations demonstrates how the relative importance of different potential sinks changes throughout the century (Figure 2). In general, soil carbon reaches a new equilibrium after 40–50 years in most cases, while forest biomass carbon following reforestation does not saturate until sometime after 2100; that geologic CCS is projected to become available mid-century provides an additional, indefinite sink for carbon in bioenergy feedstocks.

We identify avoided and net negative emissions in four components of the agriculture and forestry sector, which comprises most of the Agriculture, Forestry, and Other Land Uses (AFOLU) category of IPCC assessments. In rank order, these include bioenergy after CCS deployment (58% of total capacity) and forest (26%), cropland (13%), and grazing land (3%) management (Figure 1, Table S1). As noted later, significant additional land-based mitigation could be provided by demand-side shifts to plant-based diets and reduced food waste (Clark et al., 2020; Roe et al., 2019).

2 | SECTOR-LEVEL CONTRIBUTIONS

2.1 | Cellulosic bioenergy

Cellulosic bioenergy (Robertson et al., 2017), not to be confused with grain-based bioenergy (Lark et al., 2022), plays a substantial role in IPCC 1.5°C-consistent pathways both with and without CCS

FIGURE 1 Mitigation potentials for U.S. land-based approaches totaling 110 Gt CO2e to 2100 (95% confidence interval: 57–178 Gt CO2e). Forest management includes afforestation and reforestation, and bioenergy is for light vehicle transportation. Bioenergy from 2050 includes carbon capture and storage with liquid fuel + internal combustion (ic) and then electricity production + electric vehicles (ev). Values in parentheses denote 95% confidence intervals. Values by emissions category and practice change appear in supplemental materials Table S1

FIGURE 2 Annual mitigation potentials through 2100 for different emissions categories considering the strengths and durations of various sinks (Table S1), and the presumed availability of geologic carbon capture and storage beginning ca. 2050. The steep declines in nature-based sinks (soil organic carbon and tree biomass) reflect the assumption in the calculations of an abrupt termination of their effectiveness (Table S1), when in reality they would approach carbon saturation in a more gradual and asymptotic manner. The 2025 start date (2030 for bioenergy) is arbitrary but useful for comparison with other efforts; the entire timeline could be shifted to a later date with no change to the 75 years potential. See Figure 1 legend for a description of terms

(IPCC, 2018). We include here cellulosic biomass production that avoids interfering with food production to prevent food-fuel conflicts and emissions that might arise from agricultural production displaced to other parts of the world (so-called Indirect Land Use Change effects [Plevin & Kammen, 2013]) and that also avoids the conversion of carbon-dense ecosystems such as forests, wetlands, and conservation lands in order to avert long-term carbon debt and biodiversity harm (Robertson et al., 2017). Eligible feedstocks thus include purpose-grown perennial (but not annual) biomass crops and corn (*Zea mays* L.) residue (stover). We constrain land assigned to purpose-grown bioenergy production to that required to supply expected 2050 transportation fuel biomass needs not provided by waste and residue streams (U.S. Department of Energy, 2011) based on current field-scale yields of switchgrass (*Panicum virgatum* L.) and other native grasses (Gelfand et al., 2020; Robertson et al., 2011). Field-scale yields of woody crops like hybrid poplar (*Populus* spp.) could also have been used with similar results (Gelfand et al., 2020). Less land would be required for a more productive crop like giant miscanthus (*Miscanthus × giganteus*) but with considerably less biodiversity value (e.g., Williams & Feest, 2019) and potential invasiveness (Pittman et al., 2015). More land would be required for restored prairie, which is less productive but much more biodiverse (Gelfand et al., 2020).

Perennial cellulosic bioenergy lands include 41 Mha of the 70–100 Mha of former cropland still unforested (Bandaru et al., 2015; Campbell et al., 2013), planted grasslands now enrolled in the USDA Conservation Reserve Program, and lands now used to grow corn for grain ethanol production. Cellulosic biofuels from perennial crops offer >5 times the climate benefit of grain-based fuels, with CO_2e emissions reductions relative to gasoline >100% as compared to corn grain ethanol's <20%, and as well numerous co-benefits such as soil and water conservation and biodiversity enhancement (Mosier, Córdova, et al., 2021). We exclude annual biomass crops like energy sorghum (*Sorghum bicolor* L. Moench) because of their currently low GHG reduction potentials (Kent et al., 2020).

Growing perennial cellulosic bioenergy crops on current grain ethanol land could, with proper incentives, remove the least productive annual cropland from intensive cultivation with little to no impact on current food supplies but with substantial environmental benefit, since these lands are disproportionately prone to soil erosion and excess nutrient export. Much of this perennial cropland conversion could be focused on consistently low-yielding subfield areas that comprise up to 25% of Midwest agricultural lands (Basso et al., 2019), avoiding the need to convert entire fields to perennial cellulosic crops and ameliorating the disproportionately high global warming impacts of these patches due to their low nitrogen use efficiencies, savings that are not included in our mitigation calculations here. Alternatively, were our 10 Mha of current grain ethanol land kept in corn to meet new food demands, a portion of the co-produced corn residue could be harvested as a cellulosic feedstock to provide by 2100 about 40% of the perennial cropland conversion's climate impact (1.8 vs. 4.4 Gt CO_2e;

Table S1, note x), but without the environmental benefits of perennial systems.

Bioenergy for transportation, with CCS and electric vehicles after 2050, represents ~58% of U.S. land-based mitigation potential over the entire period (Figure 1), and by the end of the century represents ~80% of total land-based mitigation capacity once most soil carbon sinks saturate (Figure 2). We include in this analysis (Table S1) harvested corn residue, limited to corn not grown on land now producing grain ethanol (since land now growing grain ethanol is assigned to perennial bioenergy crops) and also limited to harvest of only 40% of a crop's available residue to protect soil carbon stores (Jones et al., 2018; Xu et al., 2019). We also include the CO_2e fertilizer savings from reduced nitrogen use on former grain ethanol lands. Even with the eventual saturation of soil carbon accrual by mid-century, bioenergy to meet transportation needs can provide mitigation of 19.1 Gt CO_2e (11.7–27.7) from 2030 through 2100 in the absence of CCS (Table S1). The conversion of biomass to liquid fuel provides the opportunity to capture ~50% of its carbon as CO_2, and 90% upon conversion of biomass to electricity (Klein et al., 2014), creating an additional mitigation opportunity of 16.8 (10.8–23.3) Gt CO_2e were CCS available for liquid fuel production by 2050, and additionally 28.0 (17.8–39.1) Gt CO_2e upon also electrifying the U.S. light vehicle fleet (Gelfand et al., 2020). Together this creates as much as 64 (40–90) Gt CO_2e of overall bioenergy mitigation, close to the median 70 Gt CO_2e (range: 0–136) of BECCS attributed to the U.S. by integrated assessment models that target limiting the global temperature increase to <2°C (Nemet et al., 2018).

2.2 | Forest management

In the conterminous United States, harvested natural forests cover ~218 Mha mainly in the west. Extending harvest intervals about a decade to increase the mean standing biomass over an entire growth cycle and improving stand management to increase soil carbon stores could, if implemented on about half of this acreage, capture ~11.8 (7.4–18.0) Gt CO_2e by 2100 (Table S1). This is additional to the current U.S. forest soil background carbon sink (Nave et al., 2018). Prescribed burning and thinning to suppress fires in the west together with longer rotations for eastern plantations increases the mitigation potential for harvested forests by an additional 1.8 (0.5–3.3) Gt CO_2e. A similar amount of mitigation (~11.4 [2.0–27.6] Gt CO_2e) could be provided by reforestation on 22 Mha of former croplands; this could be increased to 63 Mha (Fargione et al., 2018) were 41 Mha not already assigned to perennial bioenergy crops – a tradeoff that we bend towards the indefinite long-term mitigation potential of bioenergy. Planting trees for windbreaks and riparian buffers in cropland landscapes plus urban tree plantings could provide additional mitigation of 3.4 (2.2–5.0) Gt CO_2e by 2100. All told, improved forest management could provide ~28.5 (11.9–53.8) Gt CO_2e of mitigation by 2100 in this analysis, representing ~26% of U.S. land-based mitigation potentials to 2100.

2.3 | Advanced cropland management

Well-studied options for managing agricultural systems to se-
quester soil carbon or avoid existing GHG emissions include cover
crops and reduced tillage, diversified crop rotations, nitrogen
fertilizer management, rice water management, and the restora-
tion of cropped peatlands. Winter cover crops in mesic climates
have by far the greatest potential impact because of their high
initial rate of soil carbon capture (1.8 tons of $CO_2e\,ha^{-1}\,y^{-1}$ on av-
erage; Table S1) and their potential extent (35–83 Mha) on avail-
able cropland, capable of mitigating ~5.2 (1.1–10.4) Gt CO_2e by
2100 (Table S1). Adoption of continuous no-till captures carbon
at average rates ~40% lower than this (1.1 tons of $CO_2e\,ha^{-1}\,y^{-1}$
on average; Table S1); adoption on ~60% of available cropland (in
particular, excluding cooler and wetter areas) could potentially
mitigate ~2.9 (0.5–6.4) Gt CO_2e by 2100.

Crop rotation changes—reducing the proportion of western
farmland in summer fallow, and elsewhere diversifying crop rota-
tions away from continuous corn and 2-year corn-soybean crop-
ping cycles—could together mitigate ~1.0 (0–2.3) Gt CO_2e by 2100
(Table S1). Likewise, advanced nitrogen management, including the
redistribution of manure from many soils where it is now applied in
excess to soils now receiving no manure, and more efficient fertilizer
practices to reduce N_2O and CO_2 from fertilizer application and pro-
duction, respectively, could mitigate another 3.5 (2.2–5.1) Gt CO_2e.
In total, advanced cropland management using today's technology
could mitigate ~14.2 (4.3–27.0) Gt CO_2e by 2100, or ~13% of the na-
tionwide potential for land-based mitigation.

2.4 | Grazing land management

The vast extent of U.S. grasslands grazed for livestock production –
~252 Mha – catapults even small changes in soil organic carbon
to nationally significant levels. Improving stocking rates by bet-
ter matching livestock foraging intensity to forage production has
been shown to increase soil carbon accrual, albeit at low rates
(0–1.0 ton of $CO_2e\,ha^{-1}\,y^{-1}$; Table S1), and current forage models
suggest accrual will occur on only ~35% of available U.S. rangeland.
Interseeding existing grasslands with improved grass species can
also increase soil carbon accrual (0–1.1 tons of $CO_2e\,ha^{-1}\,y^{-1}$) and,
together with improved stocking rates, could likely provide 3.0 (0.5–
6.6) Gt CO_2e mitigation by 2100 (Table S1). Improved stocking rates
and forage species composition on pastures—the wetter and more
intensively stocked paddocks mostly in the eastern United States—
can increase soil carbon stocks to a greater extent (e.g., Mosier,
Apfelbaum, et al., 2021), but the areal extent of these lands is low
so they do not contribute much to the total grazing lands mitigation
potential of ~3.1 (0.2–7.3) Gt CO_2e by 2100, which represents ~3%
of U.S. total land-based mitigation capacity. Ongoing research such
as adaptive multi-paddock grazing and enteric methane suppression
in ruminants may identify additional sequestration and avoidance
capacities (NASEM, 2019).

2.5 | Demand-side mitigation measures and future technologies

Missing from this analysis are demand-side measures that reduce the
need for current and future food production. Recent estimates of global
impacts suggest that shifting to plant-rich diets and reducing food waste
can amplify mitigation by land-based practices by at least 14% (Roe
et al., 2019) and that a plant-rich diet by itself might reduce total food
system emissions by ~50%, or ~678 Gt CO_2e globally (Clark et al., 2020).

Also missing are a number of land-based mitigation technologies
under active investigation but not yet sufficiently tested to allow es-
timates with reasonable confidence. Genetic improvements to bio-
energy crop productivity, for example, should soon increase rates
of bioenergy carbon capture especially on infertile soils (e.g., Casler
& Vogel, 2014), as could the potential for designing crops that bet-
ter promote soil carbon stabilization via root architecture changes
and exudates that can alter rhizosphere microbiomes and promote
soil carbon retention (e.g., Kravchenko et al., 2019). Nitrification in-
hibitors have abated soil N_2O emissions in some field studies (Rose
et al., 2018), and genetic and management improvements to crop
nitrogen use efficiency (Udvardi et al., 2021) should eventually allow
greater future savings of fertilizer-induced CO_2e emissions.

Biochar has been shown to persist in some soils, although its pro-
duction from biomass must be balanced against the diversion of land
from perennial cellulosic bioenergy production and reforestation,
each with greater and more certain mitigation potentials (Paustian
et al., 2016). Cropland reflectance of solar radiation (i.e., albedo),
already contributing to climate cooling relative to pre-conversion
reflectance (Abraha et al., 2021; Dominique et al., 2018), might be
managed to further enhance reflectance. Ruminant methane pro-
duction, already somewhat reduced by dietary changes in confined
animals (Kumar et al., 2014), may eventually be attenuated in grazed
livestock by further manipulating the rumen microbiome, thereby
enlarging the grazing land contribution to agricultural mitigation.

Not missing from this analysis, but requiring greater research atten-
tion, are the potentials for carbon accrual in forest soils and grazing lands
in particular. In contrast to a voluminous literature on soil carbon gain by
croplands under different management practices, there are few long-term
empirical studies of management-induced changes in forest soil carbon
other than soil carbon loss and recovery following forest clearing and
regrowth (Nave et al., 2018). Likewise, a lack of long-term studies of soil
carbon accretion in grasslands—especially in extensive rangelands at scale
(Teague et al., 2013)—hampers our predictions of which practices will gen-
erally increase carbon stocks (Conant et al., 2017). And missing from all
ecosystems is information on the potential for soil carbon change at depth,
that is, accrual or loss of carbon in deeper horizons, inadequately sampled
in most soil carbon accretion studies (Kravchenko & Robertson, 2011).

3 | CONCLUSIONS

The adoption of mitigation practices by land managers will involve
tradeoffs, including financial. Some options are mutually exclusive

and the least expensive options will not stay that way for long—marginal cost abatement analyses make it clear that costs differ by farm size, geography, access to technology, and other factors, such that mitigation becomes more costly as adoption rates increase (Smith et al., 2014). Moreover, a dynamic agricultural economy makes future opportunity costs hard to predict. That said, the initial costs of all practices described here are known to be well below the informal benchmark of US$100 per ton CO_2e^{-1} (Fargione et al., 2018; NASEM, 2019), and in some cases an order of magnitude lower (Smith et al., 2014). Even so, the willingness of farmers, ranchers, and other land managers to participate in mitigation opportunities is not always driven by economic returns; many landowners as well as the public place high value on other ecosystem services—biodiversity conservation, recreation, and cultural amenities, among others. In some cases, co-benefits may enhance these services, as in the case of native grasses or restored prairie for bioenergy feedstocks. Thus, although economic incentives are important, they will not alone drive adoption. Moreover, it will be crucial to establish a governance structure for fairly monitoring, reporting, compensating, and verifying participation, and as well for dissuading farmers and land managers from re-instituting practices in the future that release captured CO_2 back to the atmosphere, thereby undercutting mitigation targets.

Policy should always serve to protect and enhance conservation and biodiversity services. Fortunately, all of the mitigation measures noted here, including bioenergy, have environmental co-benefits when implemented judiciously: enhanced soil fertility, drought resilience, and flood abatement derive from greater soil carbon stores; more diverse landscapes and cropping systems that favor native species promote biodiversity (IPBES, 2019; Werling et al., 2014); and advanced cropland and forest management attenuates wildfires, soil erosion, and nutrient runoff. That said, there are also tradeoffs, some insufficiently known, such as the potential for additional water requirements of CCS (Rosa et al., 2020), that will need to be carefully balanced against expected benefits.

While highly simplified, our analysis illustrates that with affordable technologies available today, advanced land management in the United States can provide ~110 (57–178) Gt CO_2e of mitigation by 2100 while protecting and enhancing the productivity and environmental benefits of crop, forest, and grazinglands. This value is ~50% greater than either prior bottom-up estimates that exclude bioenergy (Fargione et al., 2018) or top-down estimates that rely mostly on bioenergy (Hilaire et al., 2019; Nemet et al., 2018). Although not a panacea, and insufficient by itself (Anderson et al., 2019), the potential for U.S. land-based climate mitigation that includes both natural climate solutions and bioenergy is significant and deserves sensible support.

ORCID

G. Philip Robertson https://orcid.org/0000-0001-9771-9895
Stephen K. Hamilton https://orcid.org/0000-0002-4702-9017
Keith Paustian https://orcid.org/0000-0001-5262-5596
Pete Smith https://orcid.org/0000-0002-3784-1124

REFERENCES

Abraha, M., Chen, J., Hamilton, S. K., Sciusco, P., Lei, C., Shirkey, G., Yuan, J., & Robertson, G. P. (2021). Albedo-induced global warming impact of conservation reserve program grasslands converted to annual and perennial bioenergy crops. *Environmental Research Letters*, *16*(8), 084059. https://doi.org/10.1088/1748-9326/ac1815

Anderson, C. M., DeFries, R. S., Litterman, R., Matson, P. A., Nepstad, D. C., Pacala, S., Schlesinger, W. H., Shaw, M. R., Smith, P., Weber, C., & Field, C. B. (2019). Natural climate solutions are not enough. *Science*, *363*(6430), 933–934. https://doi.org/10.1126/science.aaw2741

Bandaru, V., Izaurralde, R. C., & Zhao, K. (2015). Biomass potential of switchgrass and miscanthus on the USA's marginal lands. In A. K. Bhardwaj, T. Zenone, & J. Chen (Eds.), *Sustainable biofuels: An ecological assessment of the future energy* (pp. 299–317). DeGruyter.

Basso, B., Shuai, G., Zhang, J., & Robertson, G. P. (2019). Yield stability analysis reveals sources of large-scale nitrogen loss from the U.S. Midwest. *Scientific Reports*, *9*, 5774. https://doi.org/10.1038/s41598-019-42271-1

Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R. Y., Di Vittorio, A., Dorheim, K., Edmonds, J., Hartin, C., Hejazi, M., Horowitz, R., Iyer, G., Kyle, P., Kim, S., Link, R., McJeon, H., Smith, S. J., Snyder, A., … Wise, M. (2019). GCAM v5.1: Representing the linkages between energy, water, land, climate, and economic systems. *Geoscientific Model Development*, *12*(2), 677–698. https://doi.org/10.5194/gmd-12-677-2019

Campbell, J. E., Lobell, D. B., Genova, R. C., Zumkehr, A., & Field, C. B. (2013). Seasonal energy storage using bioenergy production from abandoned croplands. *Environmental Research Letters*, *8*(3), 035012. https://doi.org/10.1088/1748-9326/8/3/035012

Casler, M. D., & Vogel, K. P. (2014). Selection for biomass yield in upland, lowland, and hybrid switchgrass. *Crop Science*, *54*(2), 626–636. https://doi.org/10.2135/cropsci2013.04.0239

Clark, M. A., Domingo, N. G., Colgan, K., Thakrar, S. K., Tilman, D., Lynch, J., Azevedo, I. L., & Hill, J. D. (2020). Global food system emissions could preclude achieving the 1.5°C and 2°C climate change targets. *Science*, *370*(6517), 705–708. https://doi.org/10.1126/science.aba7357

Conant, R. T., Cerri, C. E. P., Osborne, B. B., & Paustian, K. (2017). Grassland management impacts on soil carbon stocks: A new synthesis. *Ecological Applications*, *27*(2), 662–668. https://doi.org/10.1002/eap.1473

Dominique, C., Gaétan, P., Morgan, F., Xavier, C., & Eric, C. (2018). What is the potential of cropland albedo management in the fight against global warming? A case study based on the use of cover crops. *Environmental Research Letters*, *13*(4), 044030. https://doi.org/10.1088/1748-9326/aab650

Fargione, J. E., Bassett, S., Boucher, T., Bridgham, S. D., Conant, R. T., Cook-Patton, S. C., Ellis, P. W., Falcucci, A., Fourqurean, J. W., Gopalakrishna, T., Gu, H., Henderson, B., Hurteau, M. D., Kroeger, K. D., Kroeger, T., Lark, T. J., Leavitt, S. M., Lomax, G., McDonald, R. I., … Griscom, B. W. (2018). Natural climate solutions for the United States. *Science Advances*, *4*(11), eaat1869. https://doi.org/10.1126/sciadv.aat1869

Field, C. B., & Mach, K. J. (2017). Rightsizing carbon dioxide removal. *Science*, *356*(6339), 706–707. https://doi.org/10.1126/science.aam9726

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. (2020). Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(36), 21968–21977. https://doi.org/10.1073/pnas.1920877117

Gelfand, I., Hamilton, S. K., Kravchenko, A. N., Jackson, R. D., Thelen, K. D., & Robertson, G. P. (2020). 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. *Environmental Science & Technology*, *54*, 2961–2974. https://doi.org/10.1021/acs.est.9b07019

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., … Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

Hilaire, J., Minx, J. C., Callaghan, M. W., Edmonds, J., Luderer, G., Nemet, G. F., Rogelj, J., & del Mar Zamora, M. (2019). Negative emissions and international climate goals—Learning from and about mitigation scenarios. *Climatic Change*, *157*(2), 189–219. https://doi.org/10.1007/s10584-019-02516-4

Huang, K., Peng, X., Kong, L., Wu, W., Chen, Y., & Maravelias, C. T. (2021). Greenhouse gas emission mitigation potential of chemicals produced from biomass. *ACS Sustainable Chemistry & Engineering*, *9*(43), 14480–14487. https://doi.org/10.1021/acssuschemeng.1c04836

IPBES. (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernamental Science-Policy Platform on Biodiversity and Ecosystem Services.* https://ipbes.net/global-assessment

IPCC. (2018). Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch/sr15/

IPCC. (2019). *Climate change and land* (P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, & J. Malley Eds.). https://www.ipcc.ch/srccl/ In press.

IPCC. (2021). *Climate change 2021: The physical science basis* (B. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. Matthews, T. Maycock, T. Waterfield, R. Yelekçi, R. Yu, & B. Zhou Eds.). https://www.ipcc.ch/report/ar6/wg1/#FullReport Cambridge University Press. In Press.

IPCC. (2022). *Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change* (P. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, & J. Malley Eds.). Cambridge, UK and New York, NY, USA: Cambridge University Press.

Jones, C. D., Oates, L. G., Robertson, G. P., & Izaurralde, R. C. (2018). Perennialization and cover cropping mitigate soil carbon loss from residue harvesting. *Journal of Environmental Quality*, *47*(4), 710–717. https://doi.org/10.2134/jeq2017.04.0177

Kent, J., Hartman, M. D., Lee, D. K., & Hudiburg, T. (2020). Simulated biomass sorghum GHG reduction potential is similar to maize. *Environmental Science & Technology*, *54*(19), 12456–12466. https://doi.org/10.1021/acs.est.0c01676

Klein, D., Luderer, G., Kriegler, E., Strefler, J., Bauer, N., Leimbach, M., Popp, A., Dietrich, J. P., Humpenöder, F., Lotze-Campen, H., & Edenhofer, O. (2014). The value of bioenergy in low stabilization scenarios: An assessment using REMIND-MAgPIE. *Climatic Change*, *123*(3), 705–718. https://doi.org/10.1007/s10584-013-0940-z

Kravchenko, A. N., Guber, A. K., Rasavi, B. S., Koestel, J., Quigley, M. Y., Robertson, G. P., & Kuzyakov, Y. (2019). Microbial spatial footprint as a driver of soil carbon stabilization. *Nature Communications*, *10*, 3121. https://doi.org/10.1038/s41467-019-11057-4

Kravchenko, A. N., & Robertson, G. P. (2011). Whole-profile soil carbon stocks: The danger of assuming too much from analyses of too little. *Soil Science Society of America Journal*, *75*(1), 235–240. https://doi.org/10.2136/sssaj2010.0076

Kumar, S., Choudhury, P. K., Carro, M. D., Griffith, G. W., Dagar, S. S., Puniya, M., Calabro, S., Ravella, S. R., Dhewa, T., & Upadhyay, R. C. (2014). New aspects and strategies for methane mitigation from ruminants. *Applied Microbiology and Biotechnology*, *98*(1), 31–44. https://doi.org/10.1007/s00253-013-5365-0

Lark, T. J., Hendricks, N. P., Smith, A., Pates, N., Spawn-Lee, S. A., Bougie, M., Booth, E. G., Kucharik, C. J., & Gibbs, H. K. (2022). Environmental outcomes of the US renewable fuel standard. *Proceedings of the National Academy of Sciences*, *119*(9), e2101084119. https://doi.org/10.1073/pnas.2101084119

Meier, P. J., Cronin, K. R., Frost, E. A., Runge, T. M., Dale, B. E., Reinemann, D. J., & Detlor, J. (2015). Potential for electrified vehicles to contribute to U.S. petroleum and climate goals and implications for advanced biofuels. *Environmental Science & Technology*, *49*(14), 8277–8286. https://doi.org/10.1021/acs.est.5b01691

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., & del Mar Zamora Dominguez, M. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 063001.

Mosier, S., Apfelbaum, S., Byck, P., Calderon, F., Teague, R., Thompson, R., & Cotrufo, M. F. (2021). Adaptive multi-paddock grazing enhances soil carbon and nitrogen stocks and stabilization through mineral association in southeastern U.S. grazing lands. *Journal of Environmental Management*, *288*, 112409. https://doi.org/10.1016/j.jenvman.2021.112409

Mosier, S., Córdova, S. C., & Robertson, G. P. (2021). Restoring soil fertility on degraded lands to meet food, fuel, and climate security needs via perennialization. *Frontiers in Sustainable Food Systems*, *5*, 706142. https://doi.org/10.3389/fsufs.2021.706142

NASEM. (2019). *Negative Emission Technologies and Reliable Sequestration: A Research Agenda.* Washington, DC, https://doi.org/10.17226/25259 The National Academies Press.

Nave, L. E., Domke, G. M., Hofmeister, K. L., Mishra, U., Perry, C. H., Walters, B. F., & Swanston, C. W. (2018). Reforestation can sequester two petagrams of carbon in US topsoils in a century. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 2776–2781. https://doi.org/10.1073/pnas.1719685115

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., Lamb, W. F., Minx, J. C., Rogers, S., & Smith, P. (2018). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, *13*(6), 063003. https://doi.org/10.1088/1748-9326/aabff4

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57. https://doi.org/10.1038/nature17174

Pittman, S. E., Muthukrishnan, R., West, N. M., Davis, A. S., Jordan, N. R., & Forester, J. D. (2015). Mitigating the potential for invasive spread of the exotic biofuel crop, *miscanthus × giganteus*. *Biological Invasions*, *17*(11), 3247–3261. https://doi.org/10.1007/s10530-015-0950-z

Plevin, R. J., & Kammen, D. M. (2013). Indirect land use and indirect greenhouse gas impacts of biofuels. In S. A. Levin (Ed.), *Encyclopedia of biodiversity* (Second ed., pp. 293–297). Academic Press.

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. (2017). Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. *Science*, *356*(6345), eaal2324d. https://doi.org/10.1126/science.aal2324

Robertson, G. P., Hamilton, S. K., Del Grosso, S. J., & Parton, W. J. (2011). The biogeochemistry of bioenergy landscapes: Carbon, nitrogen, and water considerations. *Ecological Applications*, *21*(4), 1055–1067. https://doi.org/10.1890/09-0456.1

Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlík, P., House, J., Nabuurs, G.-J., Popp, A., Sánchez, M. J. S., Sanderman, J., Smith, P., Stehfest, E., & Lawrence, D. (2019). Contribution of the land sector to a 1.5°C world. *Nature Climate Change*, *9*(11), 817–828. https://doi.org/10.1038/s41558-019-0591-9

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., … Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5°C. *Nature Climate Change*, *8*(4), 325–332. https://doi.org/10.1038/s41558-018-0091-3

Rosa, L., Reimer, J. A., Went, M. S., & D'Odorico, P. (2020). Hydrological limits to carbon capture and storage. *Nature Sustainability*, *3*(8), 658–666. https://doi.org/10.1038/s41893-020-0532-7

Rose, T. J., Wood, R. H., Rose, M. T., & Van Zwieten, L. (2018). A re-evaluation of the agronomic effectiveness of the nitrification inhibitors DCD and DMPP and the urease inhibitor NBPT. *Agriculture, Ecosystems and Environment*, *252*, 69–73. https://doi.org/10.1016/j.agee.2017.10.008

Sanchez, D. L., Johnson, N., McCoy, S. T., Turner, P. A., & Mach, K. J. (2018). Near-term deployment of carbon capture and sequestration from biorefineries in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(19), 4875–4880. https://doi.org/10.1073/pnas.1719695115

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsidding, E. A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N. H., Rice, C. W., Robledo Abad, C., Romanovskaya, A., Sperling, F., & Tubiello, F. (2014). Agriculture, forestry and other land use (AFOLU). In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Von Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 811–922). Cambridge University Press.

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., … Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, *6*, 42–50. https://doi.org/10.1038/nclimate2870

Teague, R., Provenza, F., Kreuter, U., Steffens, T., & Barnes, M. (2013). Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience? *Journal of Environmental Management*, *128*, 699–717. https://doi.org/10.1016/j.jenvman.2013.05.064

U.S. Department of Energy. (2011). *U.S. billion-ton update: Biomass supply for a bioenergy and bioproducts industry. R.D. Perlack and B.J. Stokes (Leads)*. http://www1.eere.energy.gov/biomass/pdfs/billion_ton_update.pdf

Udvardi, M., Below, F. E., Castellano, M. J., Eagle, A. J., Giller, K. E., Ladha, J. K., Liu, X., Maaz, T. M., Nova-Franco, B., Raghuram, N., Robertson, G. P., Roy, S., Saha, M., Schmidt, S., Tegeder, M., York, L. M., & Peters, J. W. (2021). A research road map for responsible use of agricultural nitrogen. *Frontiers in Sustainable Food Systems*, *5*, 660155. https://doi.org/10.3389/fsufs.2021.660155

Werling, B. P., Dickson, T. L., Isaacs, R., Gaines, H., Gratton, C., Gross, K. L., Liere, H., Malmstrom, C. M., Meehan, T. D., Ruan, L., Robertson, B. A., Robertson, G. P., Schmidt, T. M., Schrotenboer, A. C., Teal, T. K., Wilson, J. K., & Landis, D. A. (2014). Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(4), 1652–1657. https://doi.org/10.1073/pnas.1309492111

Williams, M. A., & Feest, A. (2019). The effect of miscanthus cultivation on the biodiversity of ground beetles (coleoptera: Carabidae), spiders and harvestmen (Arachnida: Araneae and Opiliones). *Agricultural Sciences*, *10*, 903–917. https://doi.org/10.4236/as.2019.107069

Xu, H., Sieverding, H., Kwon, H., Clay, D., Stewart, C., Johnson, J. M. F., Qin, Z., Karlen, D. L., & Wang, M. (2019). A global meta-analysis of soil organic carbon response to corn Stover removal. *Global Change Biology Bioenergy*, *11*(10), 1215–1233. https://doi.org/10.1111/gcbb.12631

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.