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OPINION

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Land-based climate solutions for the United States

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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).

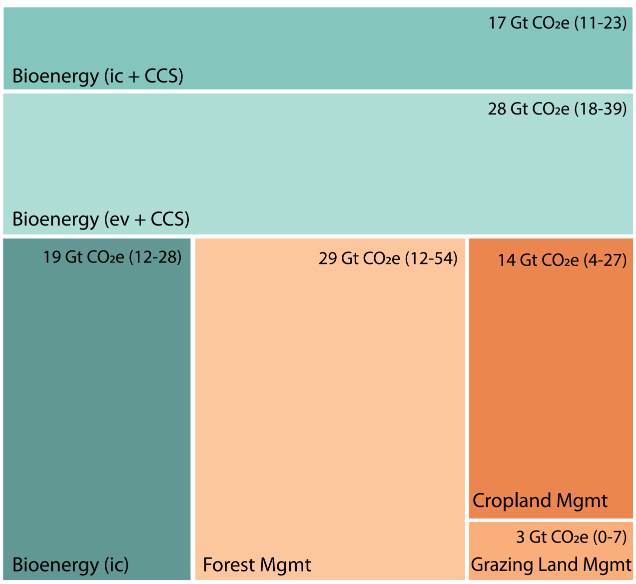

FIGURE 1 Mitigation potentials for U.S. land-based approaches totaling 110 Gt CO2e to 2100 (95% confidence interval: 57–178 Gt CO2e). Forest management includes afforestation and reforestation, and bioenergy is for light vehicle transportation. Bioenergy from 2050 includes carbon capture and storage 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.

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

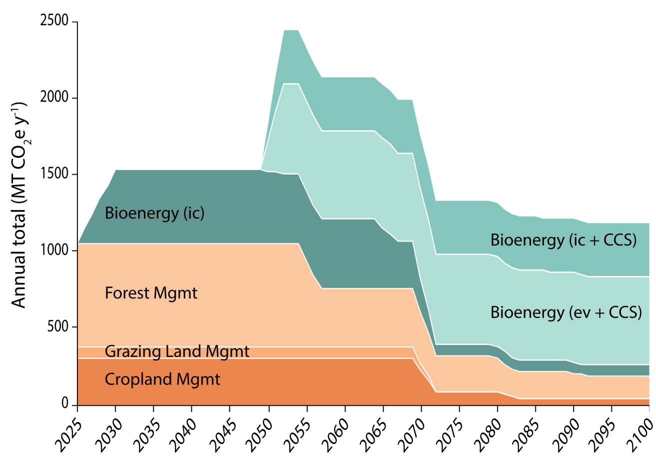

FIGURE 2 Annual mitigation potentials through 2100 for different emissions categories considering the strengths and durations of various sinks (Table S1), and the presumed availability of geologic carbon capture and storage beginning ca. 2050. The steep declines in nature-based sinks (soil organic carbon 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 sequester soil carbon or avoid existing GHG emissions include cover crops and reduced tillage, diversified crop rotations, nitrogen fertilizer management, rice water management, and the restoration 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 average; Table S1) and their potential extent (35–83 Mha) on available 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 rotations away from continuous corn and 2-year corn-soybean cropping 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 production, 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 nationwide 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 better 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 estimates with reasonable confidence. Genetic improvements to bioenergy 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 better 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 inhibitors 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 production 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 production, 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 attention, 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 generally 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.

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DATA AVAILABILITY STATEMENT

All data in supplementary materials are available in Dryad (https://doi.org/10.5061/dryad.ghx3ffbr1).

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SUPPORTING INFORMATION

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

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Supplementary Materials for

Land-based Climate Solutions for the United States

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Contents

Supplementary Text

Table S1 summarizes the magnitude of negative emissions available from changes in U.S. land management. The mitigation values presented are based on literature values for rates of carbon accretion or greenhouse gas emission reductions due to a given land management practice, the extent of the land base available for each practice, and the duration over which that practice provides quantitative mitigation (as described in notes below the table). Both rates and extents are expressed as mean, minimum, and maximum values, reflecting response variability in the case of rates and the areal extent of likely adoption in the case of land base extent. Mean values for rates are weighted towards long-term studies with broad geographic coverage, in most cases summarizing earlier reviews and meta-analyses with similar weighting; mean values are thus not necessarily the average of minimum and maximum values. Values for extent are selected to avoid double counting exclusive practices, i.e., practices that if implemented would exclude the adoption of another practice (e.g., assigning cropland to cellulosic bioenergy production excludes that land from consideration for cover crops or reforestation). Extent also considers adoption – for example, cover crops are assumed to be adopted on only 80% of eligible land, reflecting marginal abatement costs and landowner resistance to adoption, even with appropriate policy incentives. All practices and extents are limited to those that other analyses (1-11) have identified as available for less than US$100 per Mg CO_2e based on marginal abatement cost analyses.

For N_2O and CH_4 impacts, values are converted to CO_2e using IPCC AR4 100-year global warming potentials (GWPs), which are currently required for UNFCCC national greenhouse gas reporting inventories (12, 13) and assume values of 25 for CH_4 and 298 for N_2O. More recent values from IPCC AR5 (14) (28 for CH_4 and 265 for N_2O without climate feedbacks) will change the estimated impacts of CH_4 and N_2O by 12% and -11%, respectively. These differences affect mainly the rice water management and avoided N_2O emissions categories (Table S1), which are minor overall sources of abatement in this analysis (~2%). Use of the superior and more dynamic GWP* approach (15) would likewise not much affect overall mitigation potentials.

Where minimum or maximum rates were within ±50% of mean rates, minimum and maximum values were adjusted to be 0.5 and 1.5 times mean values, respectively, in order to more conservatively capture uncertainty. For areal extents, maximum rates were the lesser of 1.5 times mean values or the extent of land available for that category, as noted in Table S1 notes. For duration, minimum and maximum values are based on the difference between when a practice might be implemented (e.g., in 2050 for carbon capture and storage; CCS) and either a) the end of the century or b) the likely duration of a sink before it becomes saturated (e.g., soil organic carbon). Mean, minimum, and maximum values for rate, extent, and duration are then used to calculate a probable mean value per source category with 95% confidence intervals using a Monte Carlo simulation (16) with 50,000 iterations; the range of responses is conservatively assumed to reflect a lognormal distribution, typical for biogeochemical pools and fluxes.

A dynamic spreadsheet, requiring the purchase of a Monte Carlo plug-in to run (16), is available at Dryad (https://doi.org/10.5061/dryad.ghx3ffbr1). A web-based version not requiring purchase will also be available.

Table S1. Total mitigation potentials for the contiguous U.S. for land management practices known to result in negative CO_2e emissions. For any given practice, probable annual rate (Mt CO_2e y^{-1}) is based on a Monte Carlo simulation of local rate and likely areal extent; end-of-century (probable Y2100 total) potential is based on a simulation that additionally includes duration. Lower 95% and upper 95% refer to 95% confidence intervals. Notes refers to sections below the table. SOC = soil organic carbon, N_2O = nitrous oxide, CH_4 = methane, and CRP = USDA Conservation Reserve Program. Within a category, annual rates and Y2100 total sequestration values are based on Monte Carlo estimates rather than direct multiplication of mean values for local rate, areal extent, and duration.

		Local rate			Likely areal extent			Probable annual rate			Duration			Probable Y2100 total		
Emissions category	Notes	Mean	Min	Max	Mean	Min	Max	Mean	Lower 95%	Upper 95%	Mean	Min	Max	Mean	Lower 95%	Upper 95%
		t CO_2e ha^{-1} y^{-1}			Mha			Mt CO_2e y^{-1}			y			Gt CO_2e		
Cropland Management																
Winter cover crops	a	1.8	0	4.3	74	35	83	130	28	252	40	30	50	5.2	1.1	10.4
Tillage management																
continuous no-till adoption	b	1.1	0.0	3.5	51	42	84	73	13	155	40	30	50	2.9	0.5	6.4
reduced tillage	c	0.7	-0.3	1.6	20	10	34	14	0	33	40	30	50	0.6	0.0	1.3
Rotation changes																
reduced summer fallow	d	0.4	-0.3	1.1	15	10	20	6	-2	14	50	40	60	0.3	-0.1	0.7
diversified crop rotations	e	0.7	-0.2	1.6	20	10	30	15	2	31	50	40	60	0.7	0.1	1.6
Advanced nutrient management																
excess manure additions	f	2.6	0.2	5.1	9	7	11	22	7	39	50	40	75	1.2	0.4	2.2
improved fertilizer efficiency																
avoided N_2O emissions	g	0.5	0.4	0.6	43	32	54	22	17	27	75	65	75	1.6	1.2	2.0
avoided CO_2e–fertilizer production	h	0.2	0.2	0.3	43	32	54	10	8	12	75	65	75	0.7	0.6	0.9
Rice water management for CH_4	i	2.0	0.1	5.3	1.0	0.5	1.0	2	1	4	75	65	75	0.2	0.0	0.3
Wetland Histosols restoration	j	13.4	6.7	20.1	0.8	0.6	1.2	11	7	17	75	65	75	0.8	0.5	1.2
Subtotal advanced cropping practices								305	79	585				14.2	4.3	27.0
Grazing Lands Management																
Extensive grazing lands																
improved stocking rates	k	0.4	0.0	1.0	87	43	130	36	7	79	40	30	50	1.5	0.3	3.2
interseeding improved grass species	l	0.3	0.0	1.1	87	43	130	37	6	83	40	30	50	1.5	0.2	3.4
Pasture lands																
improved stocking rates	m	0.4	-3.0	4.7	4	2	6	2	-9	15	40	30	50	0.1	-0.4	0.6
interseeding legumes	n	0.9	0.6	1.3	2	1	4	2	1	3	40	30	50	0.1	0.0	0.1
Subtotal grazing lands management								78	5	180				3.1	0.2	7.3

(continued next page)

		Local rate			Likely areal extent			Probable annual rate			Duration			Probable Y2100 total		
									Lower	Upper					Lower	Upper
Emissions category, cont.	Notes	Mean	Min	Max	Mean	Min	Max	Mean	95%	95%	Mean	Min	Max	Mean	95%	95%
		t CO_2e ha^{-1} y^{-1}			Mha			Mt CO_2e y^{-1}			y			Gt CO_2e		
Forest Management																
Reforestation of abandoned cropland																
SOC accretion	o	1.3	0.6	1.9	22	0	56	30	6	63	60	45	75	1.8	0.4	3.9
woody biomass accretion	p	4.9	1.1	11.6	22	0	56	131	22	322	75	65	75	9.6	1.6	23.7
Windbreaks, riparian plantings to trees																
SOC accretion	q	1.3	0.6	1.9	4	3	5	5	3	7	40	30	50	0.2	0.1	0.3
woody biomass accretion	r	11.8	6.3	17.3	4	3	5	47	28	68	50	40	60	2.3	1.4	3.5
Urban forestation	s	7.0	5.9	9.1	3	3	4	22	18	28	40	30	50	0.9	0.7	1.2
Improved natural forestland																
SOC accretion	t	0.8	0.2	1.4	123	109	218	111	50	185	40	30	50	4.4	1.9	7.7
woody biomass accretion																
longer harvest intervals	u	2.2	1.9	2.5	123	109	218	298	232	399	25	20	30	7.4	5.5	10.3
fire suppression	v	1.1	-0.3	2.5	17	9	20	17	1	36	75	65	75	1.3	0.1	2.6
Improved tree plantations																
longer rotations	w	0.4	0.4	0.4	31	16	37	12	8	15	50	30	50	0.5	0.4	0.7
Subtotal forest management								673	367	1122				28.5	11.9	53.8
Cellulosic Bioenergy																
Internal combustion (IC) of liquid fuel (ethanol or an equivalent drop-in hydrocarbon) by light transportation vehicles																
On existing grain ethanol lands																
pre-SOC equilibration	x	6.1	3.0	9.1	10	6	13	58	34	87	40	30	50	2.3	1.3	3.6
post-SOC equilibration	x	2.5	1.2	3.7	10	6	13	24	14	35	30	20	40	0.7	0.4	1.1
N_2O avoided by conversion	y	1.6	0.8	2.4	10	6	13	15	9	23	70	60	70	1.0	0.6	1.6
Avoided CO_2e by fertilizer savings	z	0.6	0.4	0.7	10	6	13	5	4	7	70	60	70	0.4	0.3	0.5
On existing CRP lands																
pre-SOC equilibration	aa	6.1	3.0	9.1	5	3	6	28	16	41	20	10	30	0.5	0.3	0.9
post-SOC equilibration	aa	2.5	1.2	3.7	5	3	6	11	7	17	50	40	60	0.6	0.3	0.9
On abandoned cropland																
pre-SOC equilibration	ab	4.2	2.1	6.3	41	36	46	172	108	238	40	30	50	6.9	4.2	10.0
post-SOC equilibration	ab	3.1	1.5	4.2	41	36	46	122	80	163	30	20	40	3.7	2.2	5.4
From corn residue	ac	2.1	1.6	2.6	23	12	23	45	33	55	70	60	70	3.0	2.3	3.8
Subtotal bioenergy internal combustion								479	304	665				19.1	11.7	27.7

(continued next page)

Emissions category, cont.	Notes	Local rate Mean	Local rate Min	Local rate Max	Likely areal extent Mean	Likely areal extent Min	Likely areal extent Max	Probable annual rate Mean	Probable annual rate Lower 95%	Probable annual rate Upper 95%	Duration Mean	Duration Min	Duration Max	Probable Y2100 total Mean	Probable Y2100 total Lower 95%	Probable Y2100 total Upper 95%
		t CO_2e ha^{-1} y^{-1}			Mha			Mt CO_2e y^{-1}			y			Gt CO_2e		
Additional mitigation from internal combustion vehicles were biorefinery CCS available from 2050																
On existing grain ethanol lands	ad	5.2	2.6	7.8	10	6	13	50	29	74	50	40	50	2.4	1.4	3.6
On existing CRP lands	ad	5.2	2.6	7.8	5	3	6	24	14	35	50	40	50	1.1	0.7	1.7
On abandoned cropland	ad	5.0	2.5	7.5	41	36	46	205	129	284	50	40	50	9.9	6.2	13.7
From corn residue	ad	3.4	2.5	4.2	23	12	23	71	53	88	50	40	50	3.4	2.5	4.3
Subtotal bioenergy IC + CCS								349	225	480				16.8	10.8	23.3
Additional mitigation from the substitution of electric vehicles (EV) for IC vehicles were CCS available from 2050																
On existing grain ethanol lands	ae	9.6	4.8	14.4	10	6	13	92	54	137	50	40	50	4.4	2.6	6.7
On existing CRP lands	ae	9.6	4.8	14.4	5	3	6	44	26	65	50	40	50	2.1	1.2	3.1
On abandoned cropland	ae	7.9	3.9	11.8	41	36	46	322	202	446	50	40	50	15.5	9.7	21.6
From corn residue	ae	5.8	4.0	7.7	23	12	23	124	88	159	50	40	50	6.0	4.2	7.7
Subtotal bioenergy EV + CCS								581	370	807				28.0	17.8	39.1
Overall Total								2,465	1,350	3,840				109.8	56.7	178.3

Table S1 Notes

a. Adding winter cover crops to a rotation can add 1.17 (0 to 3.67) tCO_2e ha^{-1} y^{-1} of soil organic carbon (SOC) (17) depending on climate, even when combined with tillage (18), and as well save ~0.59 tCO_2e ha^{-1} y^{-1} in avoided N fertilizer use (19), for a total mitigation capacity of **1.8 (0 to 4.3) tCO_2e ha^{-1} y^{-1}**. The likely areal extent is **74.4 (34.7 to 82.7) Mha**, which reflects a suitable range of 51 to 99 Mha that excludes dry regions and winter wheat acreage (20-22), further decremented by current grain ethanol land converted to cellulosic bioenergy (see note (x)), and by land already in winter cover crops (4% of all field crops in 2018 (23), or 3.6 Mha). We assume 80% adoption of the maximum area. Poeplau and Don's meta-analysis (17) shows observed increases up to 54 years with modeled steady-state levels not achieved until 155 years; we assume a more conservative **40 (30 to 50) years** until SOC equilibrates. Multiplying local rate, areal extent, and duration via Monte Carlo simulation provides a Y2100 total sequestration probability of **5.2 (1.1 to 10.4) Gt CO_2e** with 95% confidence.

b. Long-term field experiments comparing continuous (permanent) no-till to conventional tillage on an equal soil mass basis (24) show typical no-till SOC increases of 0.4 – 2.6 tCO_2e ha^{-1} y^{-1} (25, 26) in surface soils (Ap-horizon, generally 0-30 cm); short term field experiments show less consistent SOC gains (27). Although some have suggested the potential for SOC loss in deeper no-till horizons (24, 28), the evidence is not statistically robust (29, 30). In tropical soil, SOC gains with no-till are less certain (24). For U.S. soils, West and Marland (31) estimated average rates of 1.1 tCO_2e ha^{-1} y^{-1}, a rate consistent with other syntheses (32-34) including Eagle et al. (19), who included the impact of reduced fuel use and long-term reductions in nitrous oxide (N_2O) emissions (35) in their overall estimate of 1.5 (0 to 3.5) tCO_2e ha^{-1} y^{-1}**.** In light of inconsistent N_2O emissions reductions with no-till(35) and minor fuel savings(36), we adopt the more conservative mean of **1.1 (0 to 3.5) tCO_2e ha^{-1} y^{-1}**. Areal extent is based on the availability of suitable land: Where SOC is already high, no-till has less capacity to increase SOC; no-till also has less capacity to increase SOC in cooler or wetter areas where it can sometimes reduce crop yield (37), although in the United States no-till is more often associated with small (2-5%) yield increases (37, 38). A maximum of 84.3 Mha are available for continuous no-till, representing the total acreage of field crops not in grain ethanol production (89.6 Mha; (39); see note (x)) less the ~6% (5.1 Mha) that may already be in continuous no-till (40). A conservative adoption rate of 60% of the maximum available area would enroll **50.6 (42.1 to 84.3) Mha**. Duration assumes a conservative **40 (30 to 50) years** until SOC equilibrates.

c. Reduced tillage includes any conservation tillage practice other than permanent no-till, including intermittent no-till, strip till, ridge till, and mulch till, all of which maintain residues on at least 30% of the soil surface after tillage. Eagle et al. (19) summarized the same literature as in (b) to conclude a carbon savings of **0.7 (-0.3 to 1.6) tCO_2e ha^{-1} y^{-1}**; the negative minimum rate reflects occurrences of SOC loss with reduced tillage. The maximum area available is the maximum area available for permanent no-till (84.3 Mha) less its likely extent of adoption (50.6 Mha), for 33.7 Mha; 60% adoption on this acreage provides a likely adoption extent of **20.8 (10.1 to 33.7) Mha**. Duration is same as in (b).

d. Eliminating summer fallow periods can, in the United States, sequester up to 1.1 tCO_2e ha^{-1} y^{-1} of SOC depending on climate and tillage method (41-47). Eagle et al. (19) estimated an average SOC gain of 0.6 (0.2 to 1.2) tCO_2e ha^{-1} y^{-1}. Less the CO_2e cost of the additional nitrogen fertilizer used in production cropping reduces the net benefit to **0.4 (-0.3 to 1.1) tCO_2e ha^{-1} y^{-1}**. Areal extent is based on Sperow et al.'s (22) estimate that summer fallow could be eliminated or reduced on 20 Mha; the minimum area might be half of this, leaving **15 (10 to 20) Mha** a likely areal extent. The duration of active sequestration is likely to be **50 (40 to 60) years** until SOC equilibrates (41) given a low rate of SOC accumulation.

e. Increasing the number of crops in a rotation can significantly increase carbon stores additional to any SOC gain attributable to cover crop use (a) or fallow elimination (d). West and Post (2002) synthesized 97 paired long-term studies (average duration 25 y) that measured SOC gain attributable to rotational complexity greater than one crop but excluding corn – soybean, which lost SOC. Most of the complex rotations included either two or three crops, only 18 included perennial grasses, none included winter cover crops, and till and no-till systems behaved similarly. The overall average sequestration rate was 0.7 (±0.4) $tCO_2e\ ha^{-1}\ y^{-1}$ (41), with a range of 0.2 (±0.3) to 1.9 (±1.7) $tCO_2e\ ha^{-1}\ y^{-1}$ depending on crops and tillage systems, for an overall rate of **0.7 (-0.2 to 1.6) $tCO_2e\ ha^{-1}\ y^{-1}$** . Considering the same area available for continuous no-till of 84.3 Mha (b), but excluding the 50.6 Mha presumed converted to no-till to avoid double counting no-till effects (b), leaves 33.7 Mha; 60% adoption provides **20.2 (10.1 to 30.3) Mha** available for crop diversification. West and Post (41) calculated an average duration of **50 (40 to 60) years**, as in (d).

f. Manure applied to soil can be considered another form of crop residue return, with the residue made more recalcitrant by animal digestion. However most manure in the U.S. is already land-applied (48) so the amount available for additional SOC gain is that that is over-applied – i.e. applied at rates in excess of that needed to sequester the C in manure as SOC (e.g., (49)). In 2001, 60-70% of U.S. manure was applied in excess of crop N and P needs, mostly on large farms (50). Eagle et al. (19) suggest that this excess manure could instead be applied to an additional 6.5-10.5 Mha, mostly (85%) within the county of origin. Since the C in this manure would otherwise be released as CO_2 where applied in excess, the manure addition is a net carbon gain when applied to otherwise unmanured soil (51), assuming little additional transportation costs. Nitrous oxide impacts will be nil because the manure added will replace fertilizer N and its N_2O emissions. Estimates of SOC gain from long-term applications of livestock manure to arable soils range from 0.7 to 1.9 $tCO_2e\ ha^{-1}\ y^{-1}$ (52, 53). Eagle et al. (19) estimate **2.6 (0.2 to 5.1) $tCO_2e\ ha^{-1}\ y^{-1}$** that does not include CO_2 savings from reduced nitrogen fertilizer use, applied to **8.5 (6.5 to 10.5) Mha** of the 24.6 Mha planted to corn and soybean for animal feed in 2018 (54). We assume a duration of **50 (40 to75) years**; the world's longest-running manure addition experiment found SOC stocks still increasing after 120 years (55), with stocks equilibrating to some lower level upon cessation (56).

g. A 50% increase in nitrogen fertilizer use efficiency, from today's 50% to 75% in the future (57, 58), would lead to a 32% reduction in nitrogen fertilizer use. In 2017, U.S. cropland N_2O emissions were 162 Mt CO_2e above background levels (59), or 1.6 $tCO_2e\ ha^{-1}$ for 102 Mha of field crops (60). A 32% savings would thus conservatively (61) avoid emission of **0.5 (0.4 to 0.6) $tCO_2e\ ha^{-1}$**, on average. The likely areal extent of **42.8 (32.2 to 53.6) Mha** represents 80% of 2018 field crops (102.4 Mha) less legumes (36.1 Mha) and corn grown for ethanol (12.7 Mha; see note (x)) (23). The duration is the entire analysis period of **75 (65 to 75) years**.

h. A 32% reduction (g) in the 11.8 Mt of N fertilizer applied to U.S. field crops in 2015 (62) would result in 3.8 Mt of avoided fertilizer N use; at a fertilizer CO_2e production cost of 4 kg CO_2e per kg N (63), this equates to 15.1 Mt CO_2e or, on average, **0.2 (0.2 to 0.3) $tCO_2e\ ha^{-1}$** for the 66.3 Mha of field crops fertilized with N in 2018 (102.4 Mha less 36.1 Mha of legumes) (62). The areal extent and duration are as in (g).

i. Methane (CH_4) from flooded rice is readily controlled by periodic drainage. In the United States, Sass and Fisher (64) documented a 50% emissions reduction in Texas with a single mid-harvest drainage, and almost complete cessation with a 2-day drainage every three weeks. Others have found similar responses around the world, particularly in China (65). Eagle et al. (19) suggest a U.S. rice CH_4 mitigation potential of **2.0 (0.1 to 5.3) $tCO_2e\ ha^{-1}\ y^{-1}$** based on improved drainage practices. Maximum areal extent is based on the relatively small acreage (**1.0 Mha**) in 2019 rice production (66); duration as in (g).

j. Histosols are soils with very high (~20%) SOC contents such as those in peatlands. Estimates of C gain under restored histosols vary widely, from 2.2 to 73.4 $tCO_2e\ ha^{-1}\ y^{-1}$ (19). An average value, considering other greenhouse gas impacts such as increased CH_4 emissions, was estimated by Alm et al. (67) to be around 9.9 $tCO_2e\ ha^{-1}\ y^{-1}$ for Finnish peatlands; more recently Griscom et al. (1) suggest an average value from a global peatlands database of **13.4 (6.7 to 20.1) tCO_2e ha^{-1} y^{-1}** after adjusting for changes in CH_4 (higher) and N_2O (lower) emissions and our assuming a range of 0.5x to 2x. In 2017, the USDA paid farmers to maintain 0.8 Mha of restored wetlands through the CRP Farmable Wetlands Program (68); at least another **0.8 (0.6 to 1.2) Mha** is readily available (2, 19). The duration is the entire analysis period of **75 years** since SOC does not saturate in histosols.

k. Estimates of SOC gains resulting from improved stocking rates on continuously grazed rangelands range from 0.3 to 1.1 tCO_2e ha^{-1} y^{-1} (69, 70), with higher rates for the Rocky Mountains and Great Plains region. In a meta-analysis that included results from 50 paired sites, Conant et al. (71) estimated an average SOC sequestration potential for improved stocking management on extensive rangelands of 1.0 tCO_2e; however, more recent modeling based on optimal forage production (72) suggests a mean rate of **0.4 (0 to 1.0) tCO_2e ha^{-1} y^{-1}**, with soils in only the 34.5% or **86.8 (43.4 to 130.2) Mha** of U.S. non-forest rangelands (252 Mha; (73)) estimated to be responsive to improved stocking rates. Duration assumes a conservative **40 (30 to 50) years** until SOC equilibrates.

l. Conant et al. (71) report an increase of 1.1 tCO_2e ha^{-1} y^{-1} for sowing improved grass species into continuously grazed rangeland, but a low number of studies makes these results very uncertain so 30% of this rate or **0.3 (0 to 1.1) tCO_2e ha^{-1} y^{-1}** seems a more prudent estimate. The extent and duration are assumed similar to that estimated for improved stocking rates (k).

m. Pastures are grazing lands in more mesic areas of the United States, where rainfall exceeds potential evapotranspiration, generally east of the Mississippi River. Improved stocking rates on continuously grazed pastures can result in carbon gains of 0.9 tCO_2e ha^{-1} y^{-1} on average (19), spanning a range of -2.9 to 4.8 tCO_2e ha^{-1} y^{-1}. Follet et al. (74) estimated gains of 1.1 to 4.8 tCO_2e ha^{-1} y^{-1} for 10 Mha of available U.S. pastureland; more recent modeling based on optimal forage production (72) suggests a smaller mean rate of **0.4 (-3.0 to 4.7) tCO_2e ha^{-1} y^{-1}** for the 22.1% or **4.0 (2 to 6.1) Mha** of North American pastures (18.3 Mha; (73)) judged responsive. Duration as in (k).

n. Pastures inter-seeded to legumes can result in average carbon gains of **0.9 (0.6 to 1.3) tCO_2e ha^{-1} y^{-1}** after discounting for increased N_2O emissions (19, 72). Henderson et al. (72) estimated that 13.2% of U.S. pasture soils (18.3 Mha (73)) or **2.4 (1.2 to 3.6) Mha** are likely to be responsive to inter-seeding. Duration as in (k).

o. SOC accretion following reforestation of former agricultural lands in temperate regions is, on average, **1.3 (0.6 to 1.9) tCO_2e ha^{-1} y^{-1}** (75-77) over a 60 y period. Areal extent is based on the total reforested land potential identified by Fargione et al. (2): 63 Mha on average, with a range of 39 to 92 Mha, less the 41 Mha assigned in this analysis to cellulosic energy on marginal lands (see (ab) below), for a likely areal extent of **22.1 (0 to 55.8) Mha**. The duration is assumed to be **60 (45 to 75) years** (75-77).

p. Based on U.S. Forest Service yield tables (78), Fargione et al. (2) constructed a region-weighted estimate of **4.9 (1.1 to 11.6) tCO_2e ha^{-1} y^{-1}** for C captured in woody biomass by various U.S. forest types, not including SOC sequestration. This is a conservative estimate for former cropland, as 75% of abandoned cropland in the United States is in the Midwest and eastern states (79), where rates of above- and belowground biomass accumulation for hardwood forests are substantially higher at ~12.1 tCO_2e ha^{-1} y^{-1} (80). The areal extent of **22.1 (0 to 55.8) Mha** is as for SOC accretion (o), and the duration is assumed to be the entire analysis period of **75 years** since forest growth can persist for well over a hundred years.

q. SOC accretion under trees planted as windbreaks and in riparian areas is likely similar to accretion under marginal land converted to forests as noted in (p). The areal extent of **4.5 (2.5 to 5.1) Mha** is based on 80% adoption for the 5% of the 85 Mha cropland area estimated to benefit from windbreaks (4.3 Mha) and 0.8 Mha of riparian buffer areas (81). Duration assumes a conservative **40 (30 to 50) years** until SOC equilibrates.

r. Windbreaks on cropland soil can sequester 13.1 tCO_2e ha^{-1} y^{-1} in biomass and soil combined, on average (2); subtracting the soil component in (q) leaves **11.8 (6.3 to 17.3) tCO_2e ha^{-1} y^{-1}** sequestered in woody biomass for the same areal extent as in (q). Faster accretion rates than (p) reflect faster growing trees planted on more fertile soils, and a shorter duration, **50 (40 to 60) years** of tree growth, reflects this faster growth rate.

s. Fargione et al. (2) estimated that **7.0 (5.9 to 9.1) $tCO_2e\ ha^{-1}\ y^{-1}$** could be newly sequestered in **3.0 (2.6 to 4.0)** Mha of urban street, park, and residential areas over a **40 (30 to 50) year** period.

t. Kimble et al. (82) estimated that in total, U.S. forests managed for timber could sequester an additional 92 to 378 $MtCO_2e\ y^{-1}$ of SOC with improved management practices. Subtracting the current U.S. forest soil background sink of 48 to 77 $MtCO_2e\ y^{-1}$ (83) leaves a likely range of 44 to 301 $MtCO_2e\ y^{-1}$, for average sequestration rates of 0.2 to 1.4 $tCO_2e\ ha^{-1}\ y^{-1}$ based on the total extent of US forests (218 Mha; (73)). This provides a mean rate of **0.8 (0.2 to 1.4) $tCO_2e\ ha^{-1}\ y^{-1}$**, a more conservative rate than IPCC (84) estimates for temperate forests of 1.9 $tCO_2e\ ha^{-1}\ y^{-1}$. The areal extent is Fargione et al.'s (2) estimate of **123 (109 to 218) Mha** assuming a range of 0.5x to 2x, and likely duration is **40 (30 to 50) years** until SOC equilibrates.

u. Using an economic model, the U.S. Environmental Protection Agency (4) estimated that longer harvests in U.S. forests could store an additional 25 to 385 $MtCO_2e\ y^{-1}$ at carbon prices from US$1 to US$50 per tCO_2 for 100 years or more; at a conservative US$15 per tCO_2 (85) this amounts to 220 $CO_2e\ y^{-1}$. More recently, Fargione et al. (2) modeled extended harvest periods for privately managed natural forests, regionally weighted, to estimate a potential national sequestration rate of **2.2 (1.9 to 2.5) $tCO_2e\ ha^{-1}\ y^{-1}$** for improved forest management across the same areal extent as for (t) with an average duration of **25 (20 to 30) years**.

v. For the 17 Mha of U.S. forests most susceptible to burning, Fargione et al. (2) used a regionally weighted fire suppression scenario, wherein 5% of forested areas are burned per year, to estimate that protecting these forests from crown fires allows an additional 362 Mt CO_2 to be sequestered over a 20 year period as compared to current fire management, or a mitigation rate of **1.06 (-0.33 to 2.46) $tCO_2e\ ha^{-1}\ y^{-1}$** for **17 (8.5 to 20.4) Mha** of most susceptible forests assuming a range of 0.5x to 2x, and for the **75 (65 to 75) year** duration of the analysis.

w. Extending regionally weighted harvest periods slightly on privately managed plantations can increase rates of forest carbon accumulation by **0.40 (0.36 to 0.44) $tCO_2e\ ha^{-1}\ y^{-1}$** on **31 (16 to 37) Mha** that are privately managed for a duration of **50 (30 to 50) years** (2).

x. Rates of negative emissions from cellulosic bioenergy planted on existing grain ethanol lands, both pre- and post-SOC equilibration, are from Gelfand et al. (86) and based on a conservative estimate of contemporary switchgrass yields of 7.5 (±0.5 SD) $Mg\ ha^{-1}$, with yields intermediate to other cellulosic crops (miscanthus, poplar, native grasses, restored prairie) and similar to current average switchgrass yields elsewhere in the U.S. (87, 88). The mean mitigation rate is **6.1 (3.0 to 9.1) $tCO_2e\ ha^{-1}\ y^{-1}$** pre-SOC equilibration and **2.5 (1.2 to 3.7) $tCO_2e\ ha^{-1}\ y^{-1}$** post-SOC equilibration, with minimum and maximum values based on 2 standard deviations reported of the means. The areal extent is **9.6 (6.4 to 12.7) Mha**, which assumes 75% conversion of the 12.7 Mha planted to corn for grain ethanol production in 2018 (23). Duration of the pre-SOC equilibration period is **40 (30 to 50) years** as in (b); the post-SOC equilibration period is **30 (20 to 40) years** – the balance of a 70-year analysis period that begins in 2030 rather than 2025 as for other emissions categories. If these lands were not converted to perennial cellulosic crops but instead remained in corn (see main text), corn residue (stover) harvest could instead provide 1.8 Gt CO_2e mitigation by 2100, assuming the 9.6 Mha eligible for conversion has the same proportional impact (3.0 $GtCO_2$ by 2100) as the 23 Mha projected to be harvested annually for corn residue – see (ac), below.

y. In 2017, U.S. cropland N_2O emissions were 162 Mt CO_2e above background levels (59), or 1.6 $tCO_2e\ ha^{-1}$ for 102 Mha of fertilized non-leguminous field crops on average (60). N_2O emissions from cellulosic biofuel crops post-establishment are similar to natural background emissions (89, 90) when recommended N fertilizer rates of 0 to 56 kg N ha^{-1} (91); the difference between annual cropland and perennial switchgrass emissions thus provides **1.6 (0.8 to 2.4) $tCO_2e\ ha^{-1}\ y^{-1}$** of avoided emissions for the same acreage as in (x) and for the entire analysis period of **70 (60 to 70) years** as in (x).

z. In 2018 corn was fertilized at an average rate of 167 kg N ha^{-1} (92); recommended N fertilizer rates for perennial cellulosic biofuel crops range from 0 to 56 kg N ha^{-1}, representing a savings of 111-167 kg N ha^{-1}. Avoided CO_2 emissions from avoided N fertilizer production, equivalent to 4 kg CO_2 per kg N (63), thus ranges averages **0.6 (0.4 to 0.7) $tCO_2e\ ha^{-1}$**, for the same acreage as in (x) and for the entire analysis period of **70 (60 to 70) years** as in (x).

aa. Rates of negative emissions from cellulosic bioenergy on existing USDA Conservation Reserve Program lands, both pre- and post-SOC equilibration, are as for (x) since CRP lands are formerly productive farmland. Areal extent is **4.5 (3.0 to 6.0) Mha** based on a 75% conversion rate for the 6.0 Mha of CRP acreage in 2019 not in restored wetlands or trees (68). Duration for pre-SOC equilibration is only **20 (10 to 30) years** – half the duration for existing cropland in (x) because CRP lands will have already been accumulating SOC since enrollment ~20 years earlier, on average. The post-SOC equilibration period is **50 (40 to 60) years** – the balance of the 70 year analysis period .

ab. Rates of negative emissions from cellulosic bioenergy on former cropland (sometimes called marginal lands), both pre- and post SOC equilibration, are from Gelfand et al. 2019 (86) based on switchgrass productivity of 7.3 (±0.9 SD) Mg ha^{-1} on a lower fertility soil than in (x). The mean mitigation rate is **4.2 (2.1 to 6.3) $tCO_2e\ ha^{-1}\ y^{-1}$** pre-SOC equilibration and **3.1 (1.5 to 4.2) $tCO_2e\ ha^{-1}\ y^{-1}$** post-SOC equilibration, with minimum and maximum values based on 2 standard deviations of the reported mean. The areal extent of **41 (36 to 46) Mha** is based on the 55 Mha of low-productivity land acreage required to meet 2050 liquid fuel transportation needs (93, 94), less 4.5 Mha of CRP land (aa), less 9.6 Mha of grain ethanol land converted to cellulosic bioenergy (x), with minimum and maximum ranges calculated similarly (e.g., for minimum area: 55 Mha less the maximum 6.0 Mha of CRP land (aa), less the maximum 12.7 Mha of converted grain ethanol land (x)). Duration is as described in (x) for pre- and post-SOC equilibration.

ac. Rates of negative emissions from cellulosic bioenergy derived from corn residue are from Gelfand et al. (86), based on average corn residue harvest from a moderate fertility soil (minimum rate; 3.7 Mg $ha^{-1}\ y^{-1}$, representing 27% of available residue) and a high fertility Mollisol soil (maximum rate; 6.0 Mg $ha^{-1}\ y^{-1}$, representing 52% of available residue), providing **2.1 (1.6 to 2.6) $tCO_2e\ ha^{-1}\ y^{-1}$** mitigation on average. Harvested fractions are based on quantitative modeling of the amounts of retained residue needed to maintain no-till SOC levels. Areal extent is based on 2018 acreage in corn not grown for fuel ethanol (23); duration is the entire analysis period of **70 (60 to 70) years** as in (x).

ad. Bioenergy with carbon capture and storage (CCS) provides additional carbon sequestration in geological reservoirs. Some 48% of biomass carbon used to fuel internal combustion engines can be captured in the biorefinery (95, 96), and, once additional pipeline infrastructure is in place, shipped and stored belowground. Mitigation fluxes ($tCO_2e\ ha^{-1}\ y^{-1}$) are additional to those without CCS (x to ac) as provided in Gelfand et al. (86), Table S8. The amount of additional mitigation ($tCO_2e\ ha^{-1}\ y^{-1}$) is dependent on the amount of biomass (t ha^{-1}) delivered to the biorefinery and thus is not affected by SOC equilibration status. For existing grain ethanol lands and existing CRP lands, which have similar average yields, average mitigation rates are **5.2 (2.6 to 7.8) $tCO_2e\ ha^{-1}\ y^{-1}$**. For abandoned cropland, additional mitigation rates are **5.0 (2.5 to 7.5) $tCO_2e\ ha^{-1}\ y^{-1}$**, reflecting somewhat lower yields. For corn residue, additional mitigation rates are **3.4 (2.5 to 4.2) $tCO_2e\ ha^{-1}\ y^{-1}$**. Areal extents are the same as for cellulosic bioenergy without CCS (x to ac). The duration for each category assumes deployment in 25 years (2050), then mitigation for the remaining **50 (40 to 50) years** of the analysis period.

ae. Using biomass to generate electricity for electric vehicles, rather than refining biomass to liquid fuel for internal combustion, provides, when coupled with CCS, the opportunity to capture 90% of biomass carbon at the generation facility (95-97). Mitigation fluxes ($tCO_2e\ ha^{-1}\ y^{-1}$) are additional to internal combustion vehicles with CCS (ad) as calculated from Gelfand et al. (86), Table S9. For existing grain ethanol lands and existing CRP lands, which have similar average yields, average mitigation rates are **9.6 (4.8 to 14.4) tCO_2e ha^{-1} y^{-1}**. For abandoned cropland, additional mitigation rates are **7.9 (3.9 to 11.8) tCO_2e ha^{-1} y^{-1}**, reflecting somewhat lower yields. For corn residue, additional mitigation rates are **5.8 (4.0 to 7.7) tCO_2e ha^{-1} y^{-1}**. Extents and duration are the same as in (ad).

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