WORLD
RESOURCES
INSTITUTE

WORKING PAPER

CARBON REMOVAL IN FORESTS AND FARMS IN THE UNITED STATES

JAMES MULLIGAN, GRETCHEN ELLISON, REBECCA GASPER, AND ALEXANDER RUDEE

EXECUTIVE SUMMARY

Highlights

- The ambitious emissions reduction measures modeled in most global emissions pathways are not enough to achieve the Paris Agreement targets for limiting temperature rise. In these pathways, it is also necessary to undertake efforts to remove carbon dioxide (CO_2) from the atmosphere at the gigaton scale—billions of metric tons per year globally.
- This paper explores candidate land management approaches for carbon removal in the United States, including carbon removal in forests and farms.
- There is untapped potential to increase carbon removal in America's forests and farms. However, although marginal costs of implementation are generally below US$50/metric ton of CO_2 (tCO_2), deploying these approaches at large scale will require addressing a set of needs related to scientific uncertainty, measurement, and monitoring; mechanisms to drive landowner adoption at large scale; and public funding.
- If these needs can be addressed, the potential scale of deployment in the United States is likely on the order of hundreds of millions of metric tons of CO_2 ($MtCO_2$) per year.

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues. Working papers may eventually be published in another form and their content may be revised.

Suggested Citation: Mulligan, J., G. Ellison, R. Gasper, and A. Rudee. 2018. "Carbon Removal in Forests and Farms in the United States." Working Paper. Washington, DC: World Resources Institute. Available online at https://www.wri.org/publication/land-carbon-removal-usa.

Background

Heightened abatement of greenhouse gas (GHG) emissions is needed to achieve the goals of the Paris Agreement to limit warming to well below 2°C, with efforts to limit warming to 1.5°C, to avoid the most dangerous climate impacts. Furthermore, most scientific estimates show that to keep these goals within reach, the global emissions trajectory needs to not only reach net-zero by the second half of this century but continue downward into net-negative emissions. Global climate models therefore illustrate the need to pursue both aggressive emissions reductions and significant deployment of carbon removal. They rely upon carbon removal approaches to offset the last remaining GHG-emitting activities that are too challenging or expensive to eliminate, and to compensate for any temporary overshoot of temperature goals.

Carbon removal is the process of removing CO_2 from the atmosphere and storing it. It is distinct both from solar radiation management, which seeks to reflect sunlight to reduce warming rather than remove carbon from the atmosphere, and from carbon capture and storage (CCS) from point sources of emissions such as fossil-fuel burning power plants or other industrial facilities. Approaches to carbon removal traverse a spectrum from land management approaches to technological options, including carbon management in agricultural soils, forests, and agroforestry; bioenergy with carbon capture and storage (BECCS); direct air capture and storage (DACS); and frontier technologies such as biochar, plant breeding or engineering, enhanced weathering, and seawater capture. The intention of carbon removal is to store CO_2 in plants, soils, and oceans, as well as nonbiologically in geological formations and products (e.g., building materials), augmenting the net transfer of carbon from the atmosphere that naturally takes place as part of the carbon cycle (Minx et al. 2018) (see Box ES-1). In some cases, storage is permanent; in others the CO_2 may return to the atmosphere over time.

To date, a gap exists between the need for rapid emissions reductions to stabilize the climate at the temperature targets established in the Paris Agreement and the availability of cost-effective measures that can provide those reductions (UNEP 2017). Advancements in carbon removal can help close that gap. However, each carbon removal approach available today faces its own challenges, potential pitfalls, and limitations. The full potential of each remains uncertain. Given this uncertainty, a portfolio of approaches and technologies could yield greater opportunities for achieving large-scale carbon removal (Minx et al. 2018; Fuss et al. 2018).

Box ES-1 | Carbon Removal and the Carbon Cycle

Carbon circulates between the land, atmosphere, and ocean through various natural and human-induced processes (see Figure ES-1.1):

- Plants use sunlight and absorb carbon dioxide (CO_2) through photosynthesis, generating oxygen.
- Humans and animals inhale oxygen and exhale CO_2.
- Decomposition of organic carbon in soils, plants, and animals emits CO_2.
- CO_2 dissolves in the ocean, is consumed by phytoplankton through photosynthesis, and released back into the atmosphere.
- Fossil fuel combustion and deforestation or other land use changes emit CO_2.

Carbon removal is intended to help address global warming by reducing atmospheric concentrations of the primary greenhouse gas, CO_2, accelerating or augmenting the net transfer of CO_2 from the atmosphere (see Figure ES-1.2).

About This Working Paper

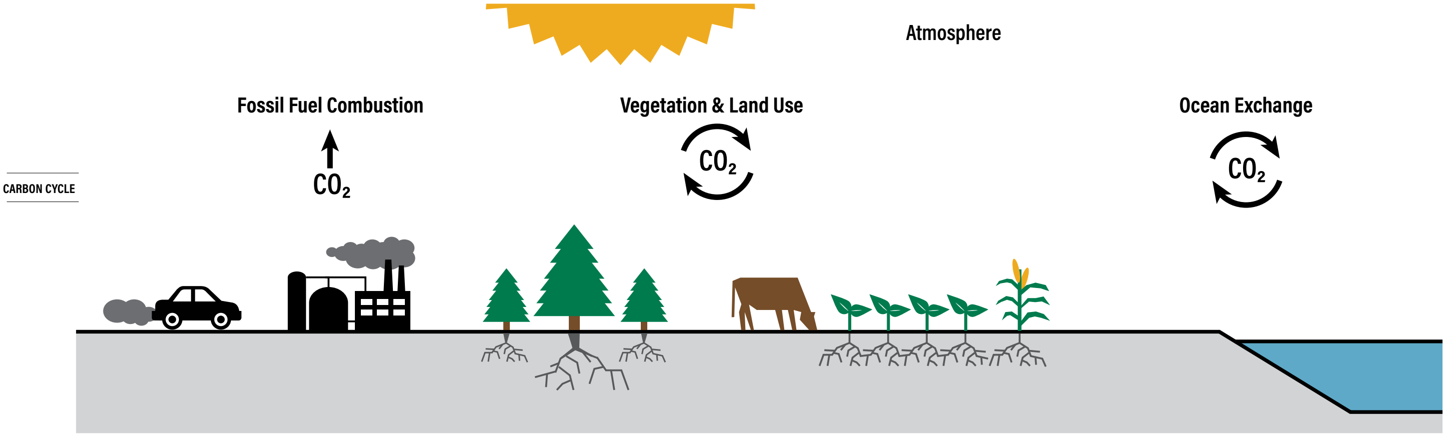
The purpose of this working paper is to explore the potential for carbon removal in forests and farms in the United States, to identify needs likely to arise on the pathway to large-scale deployment, and to consider ways to begin addressing those needs. This working paper is part of a World Resources Institute (WRI) publication series CarbonShot: Creating Options for Carbon Removal at Scale in the United States. The series presents findings from a WRI-led assessment of needs for scaling candidate carbon removal approaches in the United States, drawing on a synthesis of available scientific literature. This paper focuses on carbon removal in forests and farms.

Key Findings

There is untapped potential to increase carbon removal in America's forests and farms. However, realizing this potential will require navigating challenging dynamics related to competition for land to supply global food and fiber markets, diffuse landownership over expansive areas, persistent scientific and technological challenges related to measurement and monitoring, and still-limited public funding for carbon-beneficial land management.

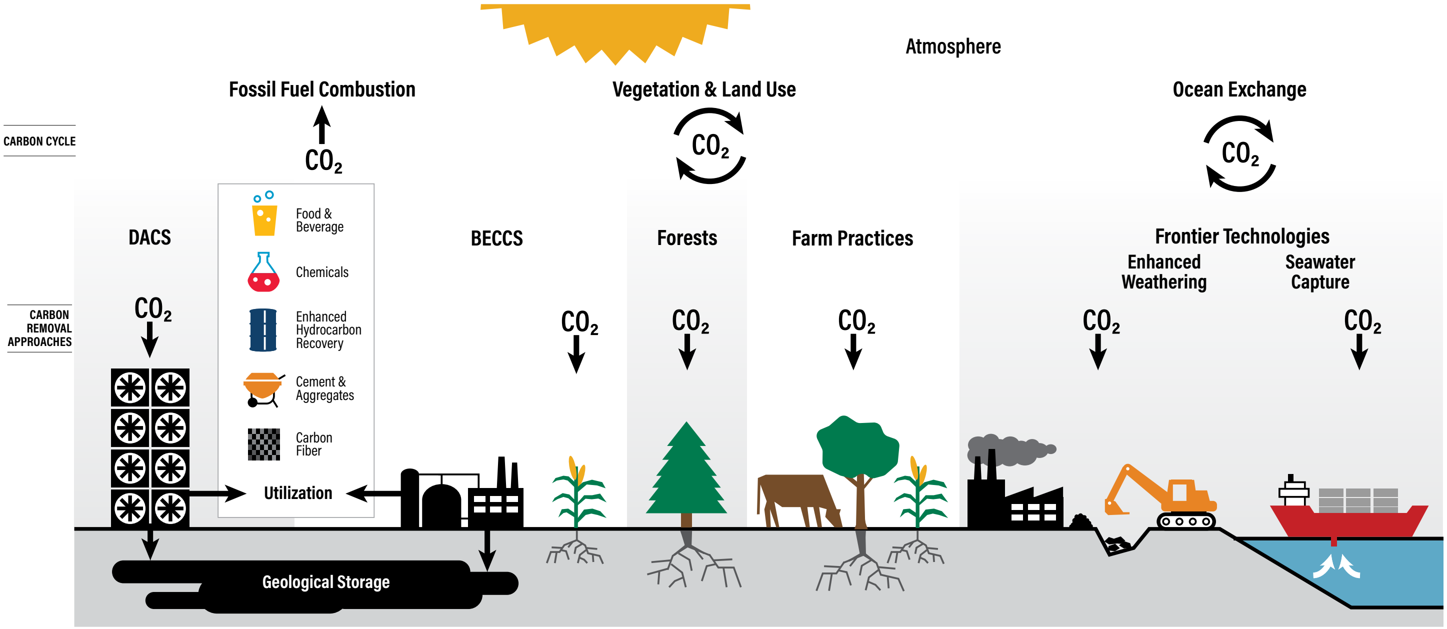
Carbon removal in forests and farms can be achieved through several different practices. These practices interact differently with global land-use trade-offs that affect food and fiber security as well

Figure ES-1.1 | The Carbon Cycle



Source: Adapted from U.S. DOE NETL 2018.

Figure ES-1.2 | Augmenting the Net Transfer of Carbon from the Atmosphere via Carbon Removal Approaches



Source: Adapted from Minx et al. 2018.

as net climate benefits. Some practices, like restoring croplands to grassland or forestland, or extending timber harvest rotation lengths, reduce the supply of food or fiber and may lead to indirect land-use change. While these measures have potential, unlocking that potential would require increasing food and fiber yields on existing agricultural lands and reducing growth in demand for land-intensive agricultural products—for example by reducing food loss and waste. The following other measures do not reduce the supply of food or fiber:

- Reforestation on nonagricultural lands such as post-disturbance forest areas, abandoned mine lands, abandoned farmland,[4] roadsides, parks, and urban areas.
- Forest carbon management practices such as restocking understocked stands, reducing the risk of catastrophic wildfire, reduced impact logging, active replanting post-harvest, and silvicultural practices that improve growth rates.
- Agricultural practices that boost yields and build soil carbon without shifting land uses.
- Integration of trees into agricultural lands while maintaining or increasing farm productivity.

The potential scale of carbon removal in forests and farms in the United States alone appears to be on the order of hundreds of millions of metric tons of CO_2 per year. Estimates of the global need for carbon removal reach into the gigatons (billion metric tons) per year by 2050 in scenarios consistent with both 1.5°C and a likely chance of 2°C temperature rise above pre-industrial levels. The majority of the estimated potential in the U.S. land sector is linked to reforestation on nonagricultural lands. Additional potential may be available from soil carbon management measures that are excluded from estimates of technical potential in the literature due to lack of field data.

This paper proposes that achieving this potential would require addressing needs related to scientific uncertainty, measurement, and monitoring; mechanisms to drive adoption by landowners at large scale; and public funding. Government agencies (federal, state, and local), the private sector, and individual landowners and producers all have a role to play in addressing these needs.

ABBREVIATIONS

BECCS	bioenergy with carbon capture and storage
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CWSRF	Clean Water State Revolving Fund
DACS	direct air capture and storage
FIA	Forest Inventory and Analysis
GHG	greenhouse gas
Gt	gigaton (billion metric tons)
Mt	megaton (million metric tons)
N_2O	nitrous oxide
t	metric ton
USDA	United States Department of Agriculture
WRI	World Resources Institute

INTRODUCTION

Background on Carbon Removal

The Paris Agreement established a goal of limiting average global temperature rise to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C. These targets are intended to avoid the worst impacts of climate change. Global scenario planning models are used to identify the pace and scale of mitigation efforts that will be required to meet a target for temperature rise. The large majority of modeled scenarios indicate that ambitious greenhouse gas (GHG) emissions reductions alone will not be enough to have a likely chance of achieving the Paris Agreement targets (Nemet et al. 2018). These models therefore combine ambitious emissions reductions with the removal of carbon dioxide (CO_2) from the atmosphere (Minx et al. 2018). However, the approaches and technologies for what is often called “carbon removal” are largely unproven at the scale that appears in these models (Fuss et al. 2018). Modeled scenarios for global emissions pathways consistent with 1.5°C temperature rise above pre-industrial levels rely on 5–15 $GtCO_2$ (15th and 85th percentiles) of emissions removed per year by 2050 and 10–17 $GtCO_2$ removed per year by 2100 (Fuss et al. 2018). In scenarios consistent with a likely chance of stabilizing at 2°C, the models rely on 1–7 $GtCO_2$ of emissions removed per year by 2050 and 7–17 $GtCO_2$ removed per year by 2100.

Carbon removal can take a variety of forms. These include land-management approaches in forests and farms; bioenergy with carbon capture and storage (BECCS); direct air capture with storage (DACS); and several "frontier technologies such as biochar, plant breeding and engineering, enhanced weathering, and seawater capture, among others.

Objectives of This Paper

The purpose of this working paper is to explore the potential for carbon removal in forests and farms in the United States in order to identify needs likely to arise on the pathway to large scale deployment and to consider ways to begin addressing those needs.

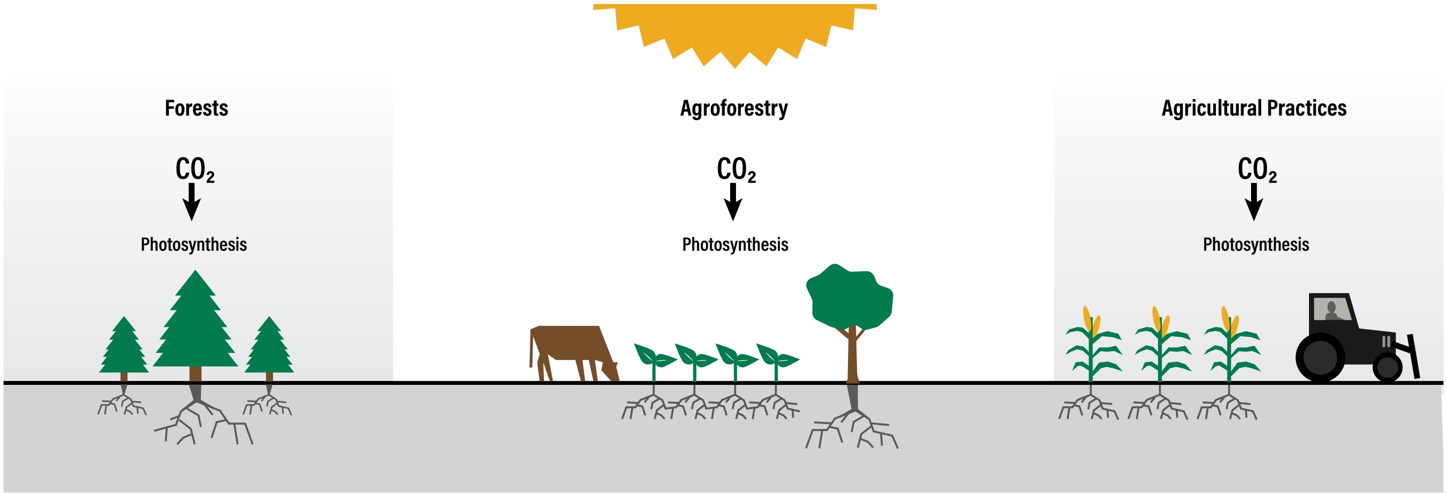
World Resources Institute (WRI), with support from the Linden Trust for Conservation (LTC) and in partnership with Carbon180 and Carbon Wrangler LLC, surveyed the technical potential, economic dynamics, and uncertainties associated with the approaches identified in Box 1; identified the key needs to facilitate large-scale deployment; and explored possible measures for addressing those needs.

This working paper examines candidate options to grow the land carbon sink in the United States. A range of land-sector approaches has been posited in the literature and communities of practice as viable options to grow the carbon sink globally and in the United States (NRC 2015; Minasny et al. 2017; Fuss et al. 2018; Griscom et al. 2017; Paustian et al. 2016). In this paper, these approaches are grouped into two categories: carbon removal in forests and carbon removal in farms.

Although this paper focuses on measures that increase removal of CO_2 from the atmosphere in forests and farms (see Figure 1), growing the carbon sink on a net basis also requires reducing the loss of carbon already stored in the land (see Box 2). In policy and in practice, reducing emissions and increasing removals can be pursued hand-in-hand in the land sector.

Each of the candidate approaches and technologies faces its own set of challenges, potential pitfalls, and limitations (Minx et al. 2018). There are no "silver bullets." And, there appears to be a gap between the need for rapid emissions reductions to stabilize the climate at the temperature targets established in the Paris Agreement and the availability of cost-effective measures that can provide those reductions (UNEP 2017). As major emitters like the United States continue to delay action, that gap will only widen. That necessitates the creation of options—for deeper, faster emissions reductions than envisioned in global scenario planning models, and for removing CO_2 from the atmosphere at large scale.

Figure 1 | **Augmenting the Net Transfer of Carbon from the Atmosphere to Trees and Soils in Forests and Farms**



Source: Adapted from Minx et al. 2018.

Box 1 | WRI Series CarbonShot: Creating Options for Carbon Removal at Scale in the United States

In the publication series CarbonShot: Creating Options for Carbon Removal at Scale in the United States [wri.org/carbonremoval], WRI presents three thematic working papers that outline the findings of an assessment of prospects for carbon removal in the United States:

- Foundational Questions on Carbon Removal in the United States
- Carbon Removal in Forests and Farms in the United States
- Technological Carbon Removal in the United States

These papers cover the key needs facing major carbon removal approaches and technologies, and the policies that could begin to address those needs.

The assessment relied on an integrated process of expert consultations and literature review, review of existing policy mechanisms, and the application of a structured assessment framework to guide information collection and synthesis.

The assessment was limited to terrestrial-based and select marine-based carbon removal approaches potentially applicable in the United States. The five carbon removal approaches within the scope of this assessment were forest carbon; soil carbon on agricultural lands; BECCS; DACS; and frontier technologies (biochar, plant breeding and engineering, enhanced weathering, seawater capture). These were selected as they are the approaches most commonly referenced in the literature. Although all carbon removal technologies are arguably "emerging," the technologies grouped together as "frontier" technologies commonly face uncertainties that the authors determined would prohibit a robust evaluation of potential scale and its specific dependencies.

The assessment excluded ocean fertilization because of potential negative effects on ocean ecosystems, associated transboundary effects, and international law complications. Previous studies largely agree that ocean fertilization at large scale poses risks that outweigh potential benefits (NRC 2015). The assessment further excluded wetlands on the basis of preliminary findings that wetland interventions were more relevant to emissions reduction strategies than carbon removal strategies, although recent literature shows mitigation potential for coastal restoration (Griscom et al. 2017), with potential in the United States (Euliss et al. 2006).

To identify key needs for scaling the evaluated approaches and technologies, the team first explored the "core parameters" of each approach and technology:

- Scale of potential
- Economics
- Co-benefits as well as negative effects related to emissions reductions, environmental resources, and human well-being
- Major areas of uncertainty that may affect deployment

Information collected and synthesized was then used to identify key needs that, if addressed, would facilitate deployment at a large scale: technological maturity; enabling infrastructure and markets; the need for additional knowledge to reduce uncertainty; and the need for dedicated funding mechanisms. The team then judged which of the identified needs to prioritize, setting aside needs that were not clearly essential to deploy a carbon removal approach or technology at a large scale and needs that could be more easily addressed if other needs were addressed first. The needs prioritized through this process were classified as "key needs." The team sought to identify actions by government, civil society, and the private sector that could address those needs. Among the types of actions considered for each key need were

- research, development, and demonstration;
- government incentives and regulations;
- government procurement and land management; and
- voluntary action by the private sector.

The papers highlight a preliminary list of actions that could address some of these needs. The actions should not be taken as recommendations; they should be fully evaluated before adoption.

Initial findings related to the carbon removal potential, costs, uncertainties, key needs, and actions for scaling these approaches and technologies were then subjected to external feedback—first in expert interviews, then in an informal review process.

In all, 34 subject-matter experts from academia, government, and civil society were consulted. These experts were affiliated with the following institutions: Advanced Research Projects Agency-Energy, American Association for the Advancement of Science, Applied Geospatial Solutions, Carbon180, Clean Air Task Force, Colorado State University, Columbia University, Delta Institute, Duke University, Energy Futures Initiative, Global CO_2 Initiative, Lawrence Livermore National Lab, Massachusetts Institute of Technology, Ohio State University, Oxford University, Pinchot Institute for Conservation, Princeton University, Stanford University, U.S. Department of Agriculture, Office of Fossil Energy of the U.S. Department of Energy, U.S. Environmental Protection Agency, University of California–Davis, Woods Hole Research Center, and World Resources Institute. Experts were identified on the basis of past publication of relevant literature, past or ongoing assessment work related to one or more carbon removal approach or technology, or deep subject matter expertise in a specific area where the assessment team required insight. Expert consultations were unstructured and tailored to the expertise of each individual. In some cases, the team interacted with a single expert on multiple occasions.

Then, two in-person gatherings with experts and practitioners in the climate community were hosted in San Francisco, California, and Washington, D.C. Participants included a subset of the experts that were consulted previously, as well as a number of practitioners from the broader climate change mitigation community of practice. These practitioners included analysts and decision-makers in the nonprofit and philanthropic sectors. Through facilitated discussions at these events, the assessment team affirmed its prioritization of needs, identified additional policy ideas, and gleaned insights about perceptions of carbon removal in the climate community.

Background on the Land Sector

The land sector is both a source of emissions and a sink. On average, between 2000 and 2009, the global land sink sequestered more than 9 $GtCO_2$ per year. However, emissions from agriculture, forestry, and land use in that same period were more than 10 $GtCO_2e$ per year. Of those emissions, over 5 $GtCO_2e$ per year resulted from agricultural operations, and nearly 4 $GtCO_2e$ per year came from the conversion of forests to cropland and pasture (Tubiello et al. 2015).

Globally, land-use emissions since 1750 total about 660 $GtCO_2e$, give or take 290 $GtCO_2e$ (NRC 2015). The National Academy of Sciences has suggested this total for historical land-use emissions acts as a theoretical upper limit on the physical potential for land-management-based carbon removal approaches. The academy further argues that in practice the upper limit will be considerably lower because the ongoing and increasing need to produce food and fiber prevents the full restoration of lands to the carbon-dense states that existed prior to large-scale human intervention. If 660 $GtCO_2$ is indeed an upper limit to carbon removal from land management, on their own these potentially significant approaches will be insufficient to fulfill the estimated need for carbon removal to meet the temperature targets in the Paris Agreement. Global climate models indicate that carbon removal of roughly 700 $GtCO_2$—and up to 1,000 $GtCO_2$—may be necessary in the 2011–2100 period to stabilize temperatures at either 1.5°C or 2°C above pre-industrial levels (Minx et al. 2018).

Any large-scale intervention in the land sector must also be considered in the broader context of global land use and management. Perhaps the most salient trend that affects the land sector is the increasing need to feed a growing population. There is considerable uncertainty as to the trajectory of future demand for food, given population growth, shifting diets, and several other factors, and how that trajectory will influence land use globally, given advances in agricultural productivity, trends in other demands for land, and relevant land-use policies (Popp et al. 2017). One way to measure the needed increase in agricultural output is to focus on calories. WRI estimates that calorie availability between 2018 and 2050 will need to increase by 40 percent (Searchinger et al. Forthcoming). Pathways to closing that gap without converting more land to agriculture—by boosting crop yields or limiting crop demand—pose steep challenges of their own (Hanson and Searchinger 2015).

Thus, while carbon removal in the land sector seeks to grow the carbon sink, these efforts will row against the tide of rising demand for food. This brings into focus two types of interventions that may be critical for liberating land to be used for other purposes, including carbon removal, over the coming decades: **increasing food and fiber yields on existing agricultural lands** and **reducing growth in demand for land-intensive agricultural products**, including by

- boosting yields on existing managed forests and farms (including by reducing the conversion of the most productive farmland to development);
- shifting diets away from meat (Ranganathan et al. 2016);
- reducing food loss and waste (Lipinski et al. 2013);
- avoiding competition for land between bioenergy and food crops (Searchinger and Heimlich 2015);
- non-coercively reducing fertility rates—for example, by improving education (Searchinger et al. 2013); and
- improving the productivity of aquaculture (Waite et al. 2014).

The structure of agricultural systems in the United States implies significant potential for these types of measures. Just 27 percent of the calories produced by American farms is food for people. The lion's share (67 percent) is feed for livestock, and 6 percent is used for biofuels (Cassidy et al. 2013)—including roughly 20 million acres in corn production (Mumm et al. 2014). Furthermore, food loss and waste claims almost one-third of the cropland used for food in North America (Kummu et al. 2012). Nonetheless, redistributing the cropland base in the United States to more efficiently feed a growing population is a challenging proposition. Without effective interventions of the types described above, the potential scale of opportunity to increase carbon removal in the land sector is more limited, as discussed later.

Importantly, however, food, fiber, and carbon are only three dimensions of global and local land-use and land-management decision-making, which should also balance other ecosystem services and landowner profitability. For example, reforestation and restoration of croplands to grassland can yield benefits for water resources, air quality, disaster risk, biodiversity, and quality of life (Intergovernmental Panel on Climate Change 2014; Mangalassery et al. 2014; Kane 2015; Jose 2009).

Background on U.S. Land Sector Carbon Policy

Land-sector carbon removal in the United States has gained prominence in policy discussions in recent years. The Mid-Century Strategy for Deep Decarbonization, published by the White House in 2016, posited that the percentage of U.S. GHG emissions that could be offset by carbon sequestration in the land sector could grow from 11 percent to 30–50 percent by 2050. This goal was supported by a combination of carbon removal strategies like reforestation and adoption of cover crops and emissions reduction strategies like avoided forest conversion and use of wood products in place of fossil-fuel-intensive construction materials. The Mid-Century Strategy called for an expansion of forested area in the United States of 40 to 50 million acres (about 10 percent over current levels of forest cover), accompanied by a contraction of grasslands and pasture and stable land bases for crops and other natural areas.

Also in 2016, the U.S. Department of Agriculture released its Building Blocks for Climate Smart Agriculture and Forestry, which set a goal of reducing land-sector GHG emissions by roughly 60 to 75 $MtCO_2e$ (0.06–0.075 $GtCO_2e$) per year by 2025. Again, these goals were supported by a combination of planned carbon removal and emissions reduction actions. If achieved, the Building Blocks goal would turn U.S. agriculture from a source of GHG emissions into a sink (White House 2016; U.S. Department of Agriculture 2016a).

Despite these ambitious national goals, the current policy landscape for carbon removal in the land sector remains limited. At the federal level, carbon removal is primarily incentivized through certain conservation programs administered by the U.S. Department of Agriculture that count carbon sequestration among their multiple objectives. For example, the Conservation Reserve Program and the Environmental Quality Incentives Program both rank project applications for funding according to a set of criteria that includes enhancement of carbon sequestration. The Conservation Stewardship Program does not explicitly consider carbon sequestration in project selection but covers several soil health conservation enhancements that can also serve to increase carbon sequestration.

Additionally, state-run carbon markets provide incentives for certain activities that promote land-sector carbon removal through the issuance of carbon offsets. The California Air Resources Board has published a carbon offset protocol for U.S. forestry projects that increase carbon removal through reforestation or improved forest management or that reduce emissions through avoided forest conversion. As of July 2018, 86 $MtCO_2e$ has been certified under this forestry protocol. The Regional Greenhouse Gas Initiative in the northeastern United States has also published a U.S. forestry offset protocol, but because of low prices in that market no projects have yet been developed under it.

The policy landscape for carbon removal at the state level also includes state actions that are driven by land-use and land-management issues unrelated to carbon. For example, Maryland has achieved significant penetration rates of cover cropping thanks in part to a financial assistance program intended to reduce nutrient runoff into the Chesapeake Bay. Several states have current use tax programs, which reduce the cost of keeping forest as forest relative to other land uses (by assessing its value at its current use, rather than its highest and best use). These programs are not motivated by an interest in removing carbon from the atmosphere but may nevertheless have a carbon benefit by incentivizing forested use of land.

This paper first describes commonly cited approaches for enhancing land carbon sequestration and exploring their costs, interactions with global land uses, and potential for carbon removal in the United States. It then identifies three key needs for advancing land-management approaches to carbon removal and the kinds of actions that could begin to address those needs.

CARBON REMOVAL IN FORESTS

What Is Carbon Removal in Forests?

Carbon removal in forests refers to the intentional efforts to increase the transfer of carbon from the atmosphere into plant biomass and forest soils via photosynthesis. The following suite of land-use and land-management approaches can increase carbon removal in forests:

- Reforestation/afforestation. These approaches increase carbon removal by expanding forest cover. *Reforestation* commonly refers to converting deforested land back to forest. In contrast, *afforestation* refers to converting to forest land that has not been forested for at least 50 years or longer (NRC 2015). Forests can be established through planting, seeding, and/or promotion of natural seed sources.
- Forest carbon management. This approach, often referred to in the literature as improved forest management, includes a range of individual practices—such as extending timber rotations, optimizing tree stocking levels, breeding selectively

Box 2 | **Offense and Defense**

In the universe of land-use and land-management options that provide climate benefits, some reduce anthropogenic emissions from the land sector, while others increase removals in the land sector. For example, converting non-forest land uses to forest increases removals. Avoiding the conversion of forests to other land uses is considered an emissions reduction measure. Increasing carbon removals and reducing emissions are, respectively, the offense and defense of growing the land carbon sink. Both sides are critically important for mitigating climate change. While this paper focuses on offense, policy can be designed to address both offense and defense strategies in tandem.

In the United States, land use, land use change, and forestry is a net sink—offsetting roughly 11 percent of total annual GHG emissions—largely due to continued growth of standing forests. However, forest loss in the United States associated with population growth is projected to exceed 50 million acres by 2050 as urban land area grows by an estimated 79 percent (Alig et al. 2010). Accelerating urbanization could increase the CO_2 emissions from land conversion to urban areas, which already reduces the magnitude of the U.S. land carbon sink by 8 percentage points each year (U.S. Environmental Protection Agency 2018). Meanwhile, the area of land burned by wildfires has been on an upward trend over the past three decades—millions of acres of forest burn annually—and the Forest Service expects this trend will continue (U.S. Department of Agriculture 2016b). Forest fire emissions of methane and nitrous oxide—both exceptionally powerful GHGs—have nearly doubled in the past decade and now reduce the net carbon sink by an additional 4 percentage points each year. Agricultural operations also emit large quantities of methane and nitrous oxide; the combination of agricultural soil management, enteric fermentation from cattle, and manure management is responsible for more than 8 percent of total GHG emissions in the United States, and emissions from the sector have trended upward in recent years (U.S. Environmental Protection Agency 2018). Addressing these sources of land-sector emissions is an essential component of any land-based climate mitigation strategy.

for faster-growing tree stocks, enhancing growth through fertilization or irrigation, controlling for pests and disease, and active replanting after harvest—that increase carbon removals in existing forests (McKinley et al. 2011). Special attention has been given in the literature to restocking understocked forests (Huang et al. 2004; Hoover and Heath 2011) and extending timber rotations for both natural and plantation forests (Sohngen and Brown 2008; Fargione et al. In Press), due to the magnitude of their potential for increased carbon removal and wide applicability to forested regions of the United States. Some practices, such as controlled burning and thinning for fire risk management, changes in logging practices, and extended timber rotations reduce emissions in addition to enhancing the carbon removal function of forests (Williams et al. 2016; McKinley et al. 2011).

Avoiding the loss of existing forests may be equally important for growing the carbon sink but is not commonly thought of as a carbon removal measure because it maintains the carbon sink already in place.

Is Carbon Removal in Forests Cost-Effective?

Several studies have estimated the marginal cost of carbon removal in forests to be generally less than $50/$tCO_2e$ (Fargione et al. In Press; Murray et al. 2005; Richards and Stokes 2004; Lubowski et al. 2006). Some additional potential becomes available at higher costs in areas where forests grow less quickly or where the measure imposes a significant opportunity cost.

Opportunity cost arises where a landowner must forgo economic value, such as timber harvest or crop production, to maintain or increase carbon storage. The opportunity cost of carbon removal approaches that require dedicated land use tend to increase over time and scale as demand grows for land for alternative uses like food production. Land-sector modeling in the United States has shown this effect. An Environmental Protection Agency study found that a $50/$tCO_2$ carbon price would result in the near-immediate reforestation of nearly 100 million acres in the United States. However, after a few decades, the study found that increasing demand for food and energy crops increased the opportunity costs of holding land in forest to the point where almost all of the reforested land reverted to agricultural production, despite the carbon price (Murray et al. 2005).

Other economic dynamics, such as additionality, leakage, and permanence can increase the effective cost of implementation:

- **Additionality** refers to whether the apparent effect of an intervention would have occurred in the absence of the intervention. For example, carbon removal in forests due to incentive programs is only additional if it would not have occurred in the absence of the incentive.
- **Leakage** occurs when an incentive for a land-use measure results in an offsetting land-use activity that occurs in another area—for example, reforesting one acre results in deforestation of another acre, providing a net-zero increase in carbon removal (e.g., see Wear and Murray 2004; Murray et al. 2005; NRC 2015). Similar to additionality effects, leakage can increase the total effective cost of carbon removal in forests, as well as put the success of climate change mitigation policies at risk.

- **Permanence** refers to whether the effects of an intervention are permanent. Forest carbon permanence depends on disturbance (e.g., disease, wildfire), land-use change, and the use of any harvested biomass (e.g., conversion to long-lived products versus combustion for energy versus decomposition). Requiring assurance of permanence as part of a contract with a landowner could make the contract more expensive.

Managing for these dynamics in a way that avoids imposing significant transaction costs on landowners is important to ensure that carbon removal approaches are cost-effective.

How Does Carbon Removal in Forests Interact with Global Land-Use Challenges?

Some approaches for carbon removal in forests reduce the supply of food or fiber. These include reforestation or afforestation on agricultural lands and some forest carbon management practices like extending rotation lengths. Reforestation is especially land-intensive given that it requires shifting land uses.[5] These approaches might provide significant localized carbon gains if deployed at large scale, but those gains may be offset by indirect land-use changes elsewhere.

As the supply of food or fiber is reduced, all else being equal, the prices of those commodities will increase, and at least some portion of the lost supply will be replaced from elsewhere. In the case of fiber, that may involve forest harvest in other areas that could reverse the carbon gains. In the case of food, that may involve clearing of forest or tilling grasslands that could have a similar offsetting effect (Smith et al. 2010; Wise et al. 2009). If production is not replaced from elsewhere, prices will remain higher. This could negatively affect food security for vulnerable populations.

Alternatively, lost supply could be matched with a reduction in demand or replaced by an intensification of production on existing productive land. These alternative scenarios are conditions under which the net carbon gains from approaches that reduce supply of food or fiber are likely to be most robust and are most likely to persist.

Additionally, several available approaches for carbon removal in forests do not reduce the supply of food or fiber:

- Reforestation of non-agricultural lands, such as post-disturbance forest areas, abandoned mine lands, abandoned farmland, roadsides, parks, and urban areas.
- Forest carbon management practices that do not reduce the provision of forest products, such as restocking understocked stands, reducing the risk of stand-replacing wildfire, reduced impact logging, active replanting post-harvest, and silvicultural practices that improve growth rates.

Because they do not reduce the supply of food or fiber, these strategies are not likely to cause leakage of forest harvesting or conversion in other areas. Instead, by increasing the supply of fiber on forested and agricultural land in the United States, these strategies could help to alleviate market pressure caused by other carbon removal strategies that do reduce fiber supply. However, note that abandoned farmland is sometimes treated in the literature as a free land reserve for various conflicting purposes. For example, literature that examines the potential to increase food production often relies on abandoned farmland as fully available for that purpose. Literature that examines the potential to increase forest cover or bioenergy production sometimes does the same.

How Much Carbon Removal Can Forests Provide in the United States?

In the United States specifically, Fargione et al. (In Press) provide the most recent and comprehensive estimate of the potential scale of land-sector carbon removal. Estimates of potential carbon removal in forests in the United States generally do not account for land-use change effects outside of the United States due to leakage that could offset carbon gains (e.g., Murray et al. 2005). Fargione et al. sought to address this modeling challenge by constraining measures that involve land-use change and offsetting measures that reduce the supply of fiber (extended rotation lengths) with other measures that increase the supply of fiber (thinning for fire management).

In all, the study found 580 $MtCO_2$ per year of potential carbon removal in forests in the United States at marginal costs of less than $100/$tCO_2$—with most potential available at significantly lower costs.[6] Significant emissions reduction potential was also found for land-sector measures like avoided forest conversion. This estimate is of the same order of magnitude as past estimates of carbon removal potential in forests in the United States (Murray et al. 2005; Jackson and Baker 2010) despite considerable differences in approach. Importantly, estimates of total potential for carbon removal in forests rarely account for permanence risks, which would reduce total net carbon removal over the long-term relative to estimates (NRC 2015).

Of the 580 $MtCO_2$ per year potential estimated by Fargione et al.,

- 252 $MtCO_2$ per year comes from reforestation—despite excluding most cropland and pasture, except riparian areas and some pasture land assumed to be liberated by continued increases in livestock productivity;
- 279 $MtCO_2$ per year is linked to measures that would temporarily reduce the supply of fiber through the extension of harvest rotations; and
- 49 $MtCO_2$ per year is related to fire management, which is assumed to produce replacement fiber to offset extensions of harvest rotations.

An additional 23 $MtCO_2$ per year of potential was estimated for urban reforestation, but at marginal costs that exceed \$100/tCO_2 per year if other benefits of urban forests are not accounted for.

Spatial analysis underlying the study identified nearly 150 million acres of historically forested non-agricultural land with less than 25 percent tree cover. This area serves as the basis for the estimate of reforestation potential, although its composition is not quite clear. A portion appears to be historically forested wetlands, post-disturbance forest areas, abandoned mine lands, abandoned farms, and roadsides. Zumkehr and Campbell (2013) estimated there are 45 million acres of abandoned farmland, almost entirely in the eastern United States, that have not been converted to either forest or urban areas. These lands could be available for reforestation, at least in the near-term. Other portions of the land identified as reforestable would be more difficult or undesirable to reforest—for example, golf courses and transmission rights of way. Further work is needed to isolate viable reforestation opportunity in these "spaces in between," given conflicting demands for land now and into the future.

While the literature consistently points to an important role for forest carbon management, studies vary widely in their specific estimates of carbon removal potential from that approach (Van Winkle et al. 2017). At a carbon price at or near \$50/tCO_2, carbon removal estimates in the United States range from less than 50 $MtCO_2$ per year to more than 500 $MtCO_2$ per year (Sohngen and Brown 2008; Nabuurs et al. 2007). Contributing to this wide variation in estimates of potential are challenges inherent in estimating the effect of forest carbon management across a large geographic area—including differences in management costs and available practices across time and location, as well as scarce public information on baseline management practices on private forest lands (Van Winkle et al. 2017).

Another cause of the variation in estimates of carbon removal potential are differences in the specific management practices modeled (Van Winkle et al. 2017). No study has examined the potential effects of all possible forest carbon management interventions on aggregate carbon removal in forests. Some studies approximate forest carbon management potential solely by estimating the effect of extending rotations on timber plantations and/or in natural forests (Sohngen and Brown 2008; Fargione et al. In Press). Others focus only on restocking understocked forests (Huang et al. 2004; Hoover and Heath 2011). Murray et al. (2005) estimate the potential from forest carbon management by modeling the effect of a change from natural unmanaged forests to plantation-style forest management.

Given divergent methods and assumptions across studies, it is difficult to converge on a firm estimate of the potential scale of carbon removal from forest carbon management in the United States. In any event, given differences in forest type, condition, and market factors across regions, it will be important to develop finer-grained estimations of specific forest carbon management practices in specific regions, while accounting for the prospect of leakage to other regions.

CARBON REMOVAL IN FARMS

What Is Carbon Removal in Farms?

Carbon removal in farms refers to efforts to increase carbon removal and storage in agricultural lands through management of soils or integrating trees into farming systems. A suite of land-use and land-management approaches aims to increase carbon removal in farms. Even small increases in soil organic carbon can disproportionately benefit soil functioning and quality (Poulton et al. 2018). Because agricultural land uses are so expansive—915 million acres in farmland in the United States in 2012 (U.S. Department of Agriculture National Agricultural Statistics Service 2014)—even small increases in carbon storage per acre on just a portion of those acres could yield large climate benefits.

Farmers have used different combinations of practices suited to their particular climate, soils, and farming systems in order to build soil organic carbon and capture other benefits. The following practices are commonly cited:

- Planting cover crops when fields are not being used to grow market crops

- Reducing the frequency with which croplands are left bare (that is, fallow) during a regular growing season
- Rotating crops
- Planting higher-residue crops (that is, crops with more biomass compared to other options)
- Growing crops without disturbing the soil (reduced tillage and no-till)
- Shifting grazing patterns to increase vegetative productivity and reduce soil disturbance on pastures
- Increasing use of perennials
- Restoring cropland to grassland
- Adding manure, compost, or biochar [7] to soils
- Planting legumes in grazing land

Photosynthesis is the engine of carbon accrual in soils. Crops and grasses convert atmospheric CO_2 and water into carbohydrate molecules, some of which are deposited into soils through root systems and plant residues that form a litter layer on the ground. Generally, carbon-beneficial soil carbon removal practices seek to enhance the photosynthetic productivity of agricultural land by increasing plant growth or extending the amount of time that plants are growing. Other practices seek to increase the amount of biomass left behind on the field or in the soil, or to reduce the loss of soil carbon to the atmosphere (Paustian et al. 2016).

The carbon benefits of some practices like conservation tillage have come under scrutiny as new research that examined total carbon accumulation in deeper soil profiles failed to find statistically significant differences with conventionally tilled land (Powlson et al. 2014). Others have attributed these findings to natural variability and attendant challenges in drawing statistically significant conclusions in tillage field studies (Kravchenko and Robertson 2011; Paustian et al. 2016).

Practices that involve soil additives—manure, compost, and biochar—in part increase soil carbon content simply by moving carbon to the soil from another location. This does not directly remove CO_2 from the atmosphere but could have climate benefits if the decomposition of the added carbon is slowed by the addition to the soil compared to its likely alternate fate (Powlson et al. 2012; Paustian et al. 2016). For example, in the United States, food waste and other compostable material is typically routed to landfills, which are designed to accelerate decomposition. Diverting that material to soil instead could delay the return of the carbon to the atmosphere. Soil additives can also increase carbon removal by increasing the productivity of plants in the soil. Lifecycle assessments are needed to fully capture the net climate effects of these practices.

Note that several soil carbon management practices can interact with other processes that influence GHG emissions from soils. For example, cover crops may reduce nitrous oxide (N_2O) emissions by taking up excess soil nitrogen and preventing leaching (Poeplau and Don 2015). Adoption of no-till may increase N_2O emissions, especially in poorly aerated soils (Rochette 2008). These dynamics are often overlooked but need to be accounted for.

In addition to managing soil carbon, farmers can adopt various forms of agroforestry—all of which involve adding trees in an agricultural landscape. For example, forested riparian buffers around streams help to shade and partially protect streams from the impact of adjacent land uses. Silvopasture combines trees with livestock production, providing tree-based sources of revenue to the landowner and shade and shelter for livestock. Alley cropping combines agricultural crops with tree crops, usually to provide annual income while the tree crop matures. Windbreaks protect wind-sensitive crops and reduce soil erosion. These practices have the benefit of increasing the number of trees on the landscape without changing land uses. Agroforestry has been shown to improve soil health in grazed pastureland, potentially improving the long-term capacity of the land to support livestock production (Paudel et al. 2011). By reducing soil erosion, windbreaks and alley cropping can also increase the long-term viability of row crop operations (USDA National Agroforestry Center 2012).

In addition to soil carbon management practices and agroforestry, selective plant breeding and engineering is beginning to focus on enhancing photosynthesis and promoting longer root structures. These enhanced functions could increase carbon storage in soils and biomass. For example, the Rhizosphere Observations Optimizing Terrestrial Sequestration program at the Department of Energy's Advanced Research Projects Agency-Energy is seeking to develop advanced technologies and crop cultivars that enable a 50 percent increase in soil carbon accumulation, a 50 percent reduction in N_2O emissions, and a 25 percent increase in water productivity. These approaches remain in the early stages of development. They are discussed in more detail in the companion working paper in this series: "Technological Carbon Removal in the United States".

Is Carbon Removal in Farms Cost-Effective?

Several studies have estimated the marginal cost of measures that build carbon in soils to be generally less than \$30/tCO_2 and in some cases provides a net financial gain for farmers (Smith 2016; Fargione et al. In Press; Murray et al. 2005; Minasny et al. 2017; Paustian et al. 2016). Some measures require specialized farm equipment that pose up-front costs.[8] Similar to carbon removal in forests, additionality, leakage, and permanence issues can increase the effective cost of implementation. Leakage is less of a concern for carbon removal in farms, except where cropland is shifted into grassland or where crop production is reduced by the adoption of agroforestry systems. However, permanence may be a major challenge for cost-effective implementation of measures that build carbon in soils. Gains in soil carbon are highly susceptible to reversion, especially in no-till systems where reintroduction of conventional tillage can reverse years of gains (NRC 2015; Choi and Sohngen 2010). Warming soils under climate change could also accelerate loss of soil carbon (Melillo et al. 2017).

How Does Carbon Removal in Farms Interact with Global Land Use Challenges?

The prospect of carbon removal in farms through changes in management practices on existing land uses, rather than changes in land uses, minimizes the conflict between carbon removal in farms and other land-use trade-offs. In many cases, practices for carbon removal can actually boost crop yields. The exception is restoration of croplands to grasslands, which builds carbon in soils but would displace crop production and could result in leakage. However, restoration of cropland to other uses may be more feasible on land that is ill-suited to crop production. Recent research indicates that even during years with favorable conditions for crop production, some areas of farmland operate at a loss (Brandes et al. 2016). Precision agriculture specialists believe that within most corn and soybean fields in the United States, 3 to 15 percent of cultivated land is unprofitable (Betts 2017). Although shifting these areas from crops to perennial grasses or trees would reduce food production, it would also increase the profitability and financial security of farm operations (Brandes et al. 2016).

How Much Carbon Removal Can Farms Provide in the United States?

Fargione et al. (In Press) found carbon removal potential of 315 MtCO_2 per year in existing farmland in the United States. This includes

- 103 MtCO_2 per year from cover crops;
- 95 MtCO_2 per year from biochar;
- 82 MtCO_2 per year from alley cropping;
- 11 MtCO_2 per year from windbreaks;
- 6 MtCO_2 per year from legumes in pastures;
- 9 MtCO_2 per year from grazing optimization; and
- 9 MtCO_2 per year from grassland restoration.

Tillage practices were excluded. Previous estimates for soil carbon removal potential, which generally include tillage practices but exclude agroforestry, are in the range of 200 MtCO_2 per year (Minasny et al. 2017).

Generally, estimates of potential carbon removal in soils are derived by scaling “per acre soil carbon accrual rates”—based on meta-analyses of field studies of specific best management practices—to the available land area (Minasny et al. 2017). These studies do not account for spatial heterogeneity in practice efficacy. They also tend to exclude practices for which those per-acre accrual rates cannot be reliably identified. Some practices still have relatively sparse field data (Paustian et al. 2016) and so are excluded, potentially reducing the perceived and documented technical potential for carbon removal in farms.

Estimates of potential also generally do not account for practical constraints that may pose barriers to widespread adoption at the scale envisioned. The large area requirements of measures that build carbon in soils imply implementation challenges related to working with landowners to adopt carbon-beneficial practices. Every 100 MtCO_2 per year of carbon removals in agricultural soils would require changes in land management practices over at least 100 million–200 million acres—about 20–40 percent of total U.S. farmland or, on the low end, about the size of Iowa and Missouri combined—assuming a sequestration rate of 0.5–1 tCO_2 per acre (Poeplau and Don 2015). Agroforestry, on the other hand, provides a more concentrated benefit per acre.

Soil carbon removal approaches in particular are often assumed in the literature to be low-cost or even net cost savers for farmers (Minasny et al. 2017). Yet, the fact that farmers have not yet adopted many of these practices at large scale is a clear indication that the literature is not accounting for some real economic or noneconomic barriers to adoption. Practical constraints may also relate to permanence. Even if carbon is successfully accumulated in a given field, soil management practices are highly susceptible to reversion. Changing ownership or farming systems may cause the subsequent release of accumulated carbon back to the atmosphere.

The practices that are modeled are subject to persistent scientific uncertainty, as well. The carbon effects of soil carbon management practices over time and across crops, soil types, and regions can be highly variable and have not been mapped. Minasny et al. (2017) found significant variation in the carbon benefit of soil carbon management practices across studies, and although most estimates were positive, a few studies failed to find statistically significant benefits or even found a loss of carbon.

KEY NEEDS FOR GROWING THE LAND CARBON SINK

Bringing a carbon removal approach or technology to scale requires that several needs first be addressed. First, the technology must exist and be sufficiently mature to be deployed at large scale at acceptable costs. Second, sufficient knowledge about the technology's requirements and effects must be generated to understand how it could be deployed to meet a given set of objectives—including how to manage any risks or negative effects. Third, in many cases a technology will require extensive enabling infrastructure of various types—everything from information to systems and physical assets—to be operationalized at large scale. For example, this might include new mills and other infrastructure to process fiber produced from fire management treatments. Fourth, if the costs of the technology exceed its private benefits, public funding will be needed for deployment.

Stock was taken of the outstanding needs to bring carbon removal in forests and farms to scale in the United States. The technologies (land-management approaches to carbon removal) are already mature, and direct implementation costs are relatively modest. However, this paper proposes that improved scientific understanding of the benefits of many of the carbon removal approaches detailed here and of the means to motivate adoption among farmers and forest landowners are outstanding needs to enable effective implementation at scale. Additional enabling infrastructure is also likely needed—especially data and tools to enable cost-effective monitoring of carbon fluxes in the land sector and mechanisms to drive landowner adoption.

Finally, in some cases, deploying carbon-beneficial measures will require private landowners to incur net costs—including opportunity costs and transaction costs—to generate a public good (carbon removal). In these cases, landowners will need to be compensated accordingly. Even where the measures are economically beneficial to the landowner, landowners may need financial assistance to overcome up-front financial hurdles. Similarly, where the economic benefits to the landowner are relatively small, not well-understood, or accrue over an extended period of time, as is often the case with both tree planting and soil health measures, landowners may need additional financial inducement in the near term.

We synthesize these needs into three areas for action:

- Actionable science, measurement, and monitoring
- Mechanisms to drive landowner adoption at a large scale
- Public funding

Actionable Science, Measurement, and Monitoring

Why Is It Needed?

Natural systems are inherently complex and variable. Changes in carbon stocks due to practice implementation can be difficult to accurately predict without continued advances in science, data, and technology. This is particularly true for below-ground carbon stocks. Scientific uncertainty frustrates efforts to plan, prioritize, and monitor investments in carbon removal in the land sector—even where the science is clear on the directional impact and even the general magnitude of impact of the carbon removal approaches. Scientific uncertainty can also affect efforts to build broad-based trust and support for public policies that would make those investments.

Monitoring is especially important for allocating resources efficiently to meet objectives over time—whether those objectives relate to carbon, water, farm profitability, or other outcomes. Monitoring is not about checking up on the activities of individual landowners. Monitoring is about ensuring that public investments in land management are working as intended across the broader landscape—and if not, making the necessary adjustments. Because the quantitative link between practices and carbon outcomes can be uncertain and spatially variable,[9] some form of measurement system is needed to estimate and monitor the effects of practice implementation. Past studies have found that offering uniform payments for carbon management practices would be several times as expensive as performance-based payments simply due to spatial variability in the effectiveness of practices across acres (Antle et al. 2003; Murray et al. 2005b). Operationalizing a payment system that can size payments in proportion to the performance of different practices on different acres would require advances in measurement and monitoring.

Furthermore, land-management approaches to carbon removal would need to be deployed over many millions of acres in the United States to be climatically meaningful. The scale and distributed nature of the undertaking increases the challenges and potential cost of measuring and monitoring the effectiveness of public policy interventions. It remains unclear whether traditional tools for land carbon monitoring—typically field surveys at the farm- or forest-stand level—can effectively support implementation of land carbon policies at scale without imposing prohibitive transaction costs, especially on small landowners.[10] Alternative approaches to generating data and monitoring changes in carbon accumulation over time may be needed.

What Would It Look Like?

Carbon offset markets generally require measurement, reporting, and verification at the site level to validate individual transactions. However, this level of effort and the site-level granularity it produces are not necessary to provide a basis for planning, implementing, and adapting public investments in land-management approaches to carbon removal over time. Instead, national networks of sample plots can be combined with models that impute carbon flux at a landscape scale using satellite data. Such a system need only provide accuracy in the aggregate, rather than at the site level.

Some of the ingredients for such a system exist—satellite data, artificial intelligence technology to process those data, and models that link observations in those data to carbon fluxes—but have not been stitched together into a coherent monitoring system. However, the backbone of such a system would be an extensive network of long-term sample plots in farms and forests. This network would provide field data essential for calibrating models that estimate carbon fluxes.

In the forest sector, such a network already exists. USDA Forest Service Research and Development operates the Forest Inventory and Analysis (FIA) program in cooperation with state and private forestry and national forest systems. The inventory has been improved from a periodic survey to an annual survey. (Individual plots are resampled on several-year rotations.)

The current forest inventory design and sample intensity can detect large disturbance events (>3 percent stock change) but may not be able to statistically detect smaller changes in forest woody carbon stocks (Westfall et al. 2013). The inventory also does not include sampling in interior Alaska, which contains over a third of all the carbon stored in U.S. forests (Woodall et al. 2015). Additional resources for increasing sample intensity would yield additional data and statistical power, improving the precision of monitoring and other efforts that draw on FIA data—including the U.S. GHG Inventory. Expenditure of public resources on this kind of data collection should be balanced with the value it provides for decision-making.

Box 3 | Spotlight on Potential Policy Measures to Advance Science, Measurement, and Monitoring

- Explore ways to enhance land-sector GHG monitoring capabilities at the landscape scale, including by leveraging satellite data.
- Improve on-the-ground measurement of land-sector GHGs through the FIA network and by establishing a similar network for agricultural lands.
- Enhance data sharing, especially from existing USDA datasets, while protecting landowner privacy.

In the agricultural sector, although there is a long history of soil carbon measurement field experiments, there is no ongoing farm carbon measurement network in the United States that can provide regular information feedback on trees in farms or soil carbon accumulation over time across the variables like soil types, climate conditions, land use, land-use history, land-management practices, and others. The data collected by such a network could help to resolve persistent scientific uncertainties and inform policymaking. Advances in field measurement technology for soil carbon—like reflectance spectroscopy, which uses spectral radiation to quickly detect soil organic carbon—could reduce the cost of collecting frequent soil carbon measurements over a large network while enhancing researchers' ability to quantify specific ecosystem processes like decomposition and accretion of soil carbon (Knox et al. 2015).

USDA also collects producer data that are enormously valuable for research purposes. Data on practice adoption across parcels could help to improve the accuracy of models that link practice adoption to carbon outcomes. Much of these data are collected by USDA (e.g., in the Agricultural Census, National Resources Inventory, and Conservation Effects Assessment Project) but are not shared with academic researchers. Other agencies like the Census Bureau have managed privacy concerns by developing confidential business information protocols to protect privacy while enabling collaborative agreements with academic researchers.

The federal government is in a unique position to lead in measurement and monitoring given existing funding for agricultural research and for cooperative research, extension, and education programs. USDA also administers the census of agriculture every five years and collects a substantial amount of data through the federal crop insurance program, such as producer practices and geographic coordinates. States also have the ability to establish their own measurement networks in collaboration with state universities. Such state efforts could provide a model for a federal soil carbon measurement network.

Mechanisms to Drive Landowner Adoption at a Large Scale

Why Are They Needed?

From perennially oversubscribed federal conservation cost-share programs to California's state-run carbon market with a long backlog of forest offset projects, existing incentive programs have a positive track record in encouraging landowners to adopt carbon-beneficial land management practices. These programs provide value in terms of carbon removal (Food and Agricultural Policy Research Institute 2007; Pape et al. 2016), and expanding them could deliver further gains in landowner adoption. However, an array of pervasive challenges in scaling landowner adoption programs, as described below, suggests that a more comprehensive suite of landowner incentives and support mechanisms will be needed to achieve sustained adoption at a large scale.

ADMINISTRATIVE BURDEN AT SCALE

Cost-share programs and carbon markets both present administrative barriers to entry for small landowners. Several studies have indicated that small-scale forest landowners may struggle to satisfy rigorous requirements for accounting, monitoring, and permanence in carbon markets (Kelly and Schmitz 2016; Charnley et al. 2010). These challenges would likely also affect agricultural lands, where accounting, monitoring, and permanence issues are at least as challenging as in forests. Cost-share programs also impose administrative burdens for landowners. In a survey of 800 property owners in the interior Northwest, over half of respondents indicated that the paperwork required by conservation programs is complex, and nearly half suggested that participating in these programs was "not worth the hassle" (Bennett et al. 2014).

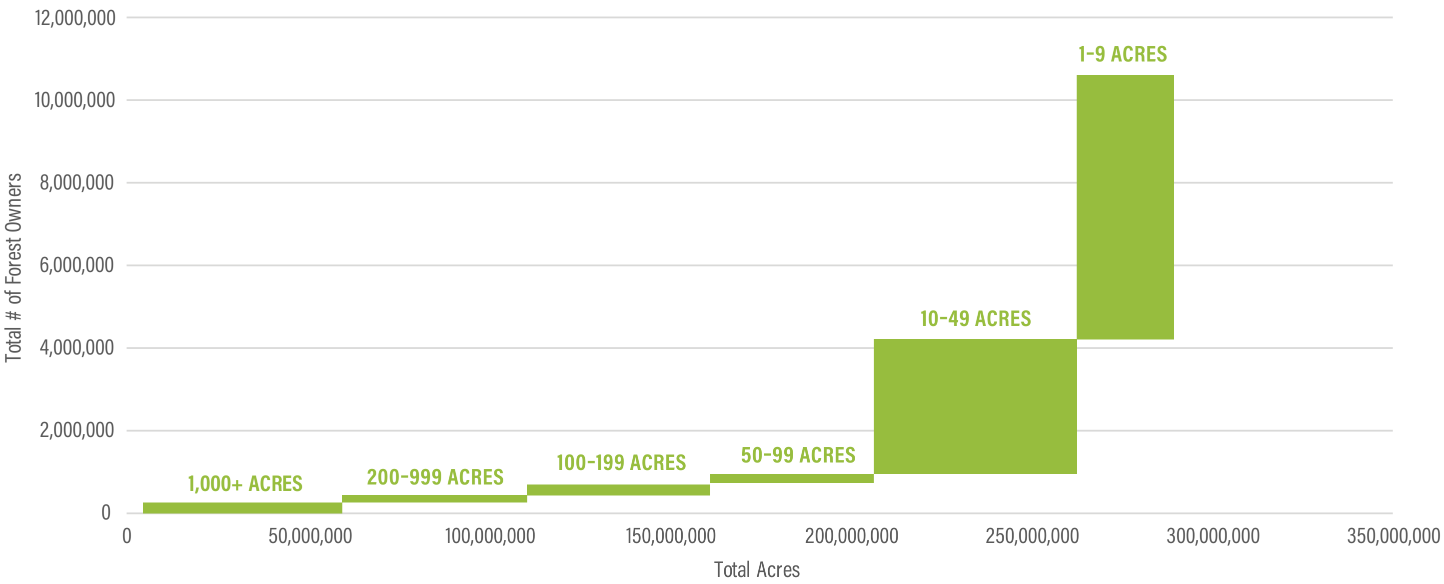
Small landowners will be an increasingly important part of any effort to achieve carbon removal at a large scale in the land sector. Of the 441 million acres of forestland in the United States, more than half (286 million acres) is privately owned; and 95 percent of these 10.7 million forest ownerships are families and individuals (U.S. Forest Service 2015). The average family forest ownership size is just 67 acres (Butler et al. 2016). There is a similar story across the more than 2 million farms and 915 million acres of farmland in the United States. Ninety-seven percent are family-owned and 91 percent are smaller than 1,000 acres (U.S. Department of Agriculture National Agricultural Statistics Service 2014).

Figures 2 and 3 illustrate the challenge at hand. Given annual per-acre carbon accrual rates for carbon removal measures on forests and farms, pushing carbon removal to scale will require working with an increasing portion of the land area in U.S. forests and farms and, necessarily, increasingly small landownerships. For instance, assuming accrual rates of 0.25 tCO_2 per acre per year (Griscom et al. 2017),[11] a forest carbon management initiative that included only large forest owners—those with more than 1,000 acres of forestland–could achieve less than 13 $MtCO_2$ per year. By contrast, an initiative that included even half of all private forest acreage would remove over 82 $MtCO_2$, exceeding USDA's 2025 target for the entire land sector—but this would require buy-in from (all) landowners with as few as 100 acres of forest.

NEED FOR TECHNICAL ASSISTANCE

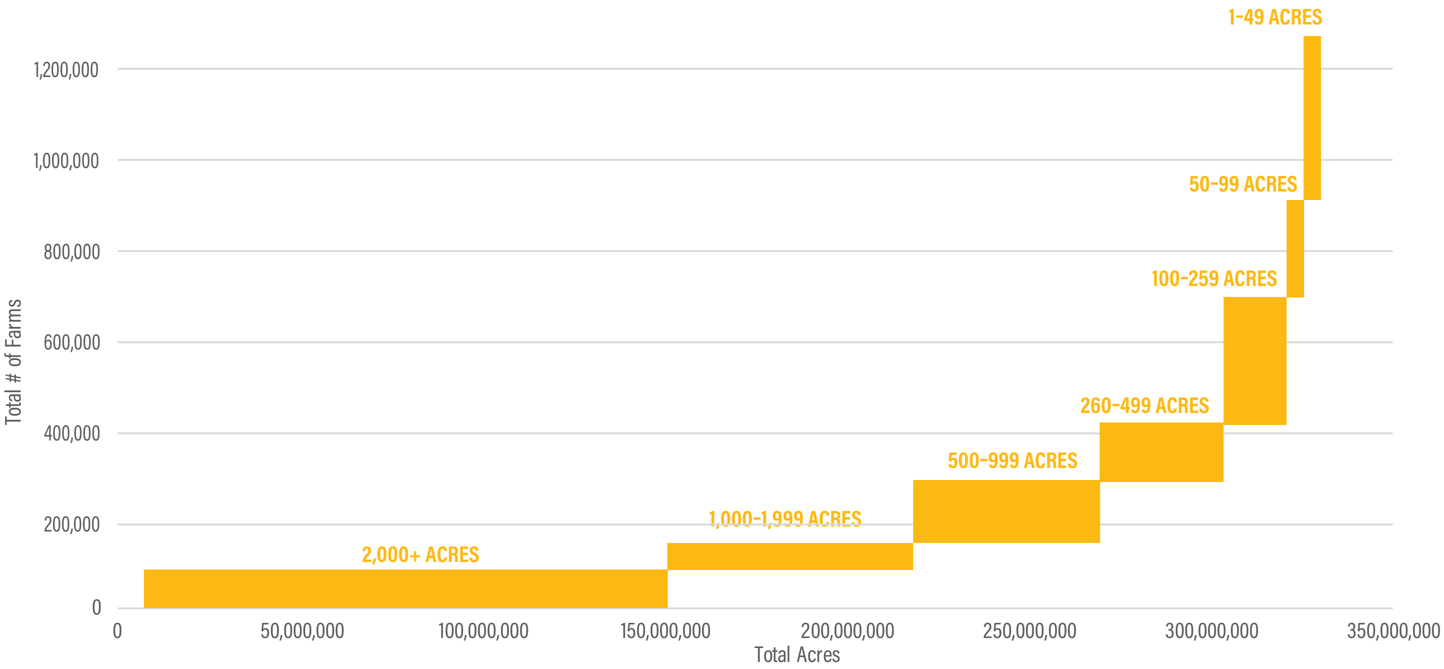
For many family forest owners, technical assistance is more important than financial incentives in promoting conservation-oriented stewardship (Kilgore et al. 2007). Currently, many family forest owners lack the management tools to meet their ownership objectives. Just one-quarter of family-owned forest land is covered by a written forest management plan (U.S. Forest Service 2015)—a document typically written by a professional forester that can include conservation and carbon-related management practices to advance the forest owner's management goals. The need for technical assistance is just as clear

Figure 2 | Distribution of United States Forest Land by Forest Size



Note: Just 18 percent of forests are contained in parcels larger than 1,000 acres, while 44 percent of forests are contained in small parcels under 100 acres.
Source: Butler et al. 2016.

Figure 3 | Distribution of United States Harvested Cropland by Farm Size



Note: Sixty-four percent of cropland acreage is contained in farms larger than 1,000 acres, while less than 4 percent is contained in small farms under 100 acres.
Source: U.S. Department of Agriculture National Agricultural Statistics Service 2014.

among farmers: Studies in Pennsylvania and Missouri, for example, have identified access to information as the single most important prerequisite for adoption of agroforestry techniques (Strong and Jacobson 2005; Valdivia and Poulos 2009). Small landowners may also require access to information on the effectiveness of carbon-beneficial practices in terms of yield improvements and conservation outcomes (Tosakana et al. 2010)—especially beginning farmers,[12] who operate 25 percent of U.S. farms (Jablonski et al. 2017), and family forest owners, who hold 40 percent of all forested acres in the United States (Butler et al. 2016).

FINANCIAL CONSIDERATIONS

Simple costs and benefits are just one part of the equation for landowners. Risk aversion, desire for flexibility to respond to market dynamics, preference for short-term returns over long-term returns, and landlord-tenant relations can also affect adoption of new practices (Lesch and Wachenheim 2014). These factors may increase the required financial inducement from cost-share programs or carbon markets if not otherwise addressed:

- Landowners who supply food and fiber under short-term contracts with little price certainty may choose to avoid investments that reduce their flexibility to respond to price fluctuations, even if they might provide a return over the long term.
- Nearly 40 percent of U.S. farmland is rented (U.S. Department of Agriculture National Agricultural Statistics Service 2014). Past studies have found indication of lack of incentive among renter farmers to make investments that would improve the land but not provide a short-term return—although the evidence on this is mixed (Fraser 2004; Soule et al. 2000; Tosakana et al. 2010).
- Broader considerations related to landowner financial security may also be important. A USDA Forest Service survey found that family forest owners had harvested 40 million acres of forestland over the prior five years because the landowners “needed the money” (Butler 2006). Unexpected financial emergencies may influence small landowners’ management of the land. For example, interviews conducted by the Pinchot Institute for Conservation suggested that medical care costs can be a major driver of forestland conversion and unsustainable management (Pinchot Institute 2011).

NONFINANCIAL INTERESTS

Landowners respond to more than financial interests. Several nonfinancial factors—including group norms, perception of self, and environmental consciousness, among others—have been found to influence landowners’ management decisions to some degree (Lesch and Wachenheim 2014). These factors may be most important for smaller landowners, who are less likely to manage a farm or forest primarily for financial gain. Among family forest owners, for instance, non-economic motivations like scenery, wildlife habitat, and nature protection were all ranked as more popular reasons for owning forest land than timber production (U.S. Forest Service 2015). Addressing nonfinancial interests in some way may therefore be useful or even necessary for achieving large-scale landowner adoption of carbon removal approaches.

NEED FOR PERSISTENCE

To contribute meaningfully to climate change mitigation, carbon-beneficial changes in land use and land management must be enduring. Cost-share programs offer fixed-term contracts with landowners (generally 5–10 years), with the hope that landowners continue to implement conservation practices after expiration of the cost-share contract. These programs could, in fact, affect landowner decisions well beyond the life of a contract by shifting landowner perceptions, demonstrating value, forming habits, or even shifting social norms (Dayer et al. 2018). However, the effectiveness of temporary incentives in achieving persistent changes in landowner practices remains an important area for further empirical research (Reimer 2015).

What Would They Look Like?

The form of landowner incentive and support mechanisms likely has important implications for scalability given the range of factors that affect landowner adoption. However, the need for and effectiveness of different combinations of interventions has not been systematically studied. Public and private-sector experimentation, combined with better data and monitoring, would be critical to build the evidence base for these interventions and to enable effective prioritization and targeting at the landscape-scale.

This paper proposes that new mechanisms to drive landowner adoption of carbon removal approaches should seek to reduce administrative burdens and related transaction costs, account for landowner preferences along with both

Box 4 | Spotlight on Potential Policy Measures for Landowner Adoption

- Design landowner adoption mechanisms in ways that work for landowners big and small, including by managing administrative barriers to participation and providing technical assistance.
- Explore market- and policy-based mechanisms to empower landowners to make long-term investments in the land, including by enhancing landowners' overall financial security.
- Experiment with ways to create conditions for enduring shifts in land management, even beyond the life of a financial incentive. Further investigate the long-term effects of temporary financial incentives on landowner decision-making.

financial and nonfinancial needs, and manage the value of the financial incentive such that limited public funding can be used as effectively as possible. Additional research is needed to identify effective mechanisms that advance these objectives. Following are some key questions:

- **Can existing administrative programs that interface with landowners—for example, crop insurance, grazing leases, or property taxes—be used to deliver additional landowner incentives and support for adoption of carbon-beneficial practices?** Policy experimentation could test whether embedding incentives for carbon-beneficial practices into existing programs offers advantages in terms of reducing administrative costs associated with landowner outreach and aggregation, and/or increasing receptiveness among landowners.

  The State of Iowa is embedding incentives for cover cropping in the federal crop insurance program. Farmers who agree to plant cover crops receive a per-acre discount on crop insurance premiums, rather than a separate payment (Iowa Department of Agriculture and Land Stewardship 2017). A similar piggybacking approach could be tested through rural credit unions, farm suppliers, and county property tax assessments.

  Several states also have current-use tax programs, which provide beneficial tax treatment for forest landowners. Some states require that participating landowners follow an approved forest management plan, and at least one state is considering tailoring these requirements to promote management practices for forest carbon retention and removal.

- **What forms of technical assistance are most effective? Under what circumstances is it most needed?** USDA currently provides technical assistance to farmers and forest owners on a variety of issues relevant to carbon removal. For instance, the Forest Service advises forest owners on protecting forest health against disturbances like insect infestations and pathogens, while the USDA National Agroforestry Center conducts demonstrations and trainings on agroforestry practices. USDA conservation programs like the Environmental Quality Incentives Program and extension services also provide some measure of technical assistance.

  Further research comparing the effectiveness of alternative technical assistance strategies could help USDA as well as other governmental and nongovernmental actors hone their landowner outreach programs for maximum impact. Areas for investigation could include the added benefits of hands-on personal consultation over more generalized dissemination of information; whether to emphasize technical assistance efforts earlier in the landowner adoption process, when landowners need more information on the costs and benefits of management practices, or later when landowners are preparing for practice implementation; and how targeting technical assistance toward certain high-priority groups of landowners could enhance overall results.

  Determining the best messenger to provide landowners with technical assistance is another area ripe for further investigation. Messengers of technical assistance could include any of several agencies within USDA; state agency officials; local or regional officials; representatives from corporations with expertise in the field, such as Monsanto for crop production or Weyerhaeuser for forest management; representatives from nongovernmental organizations, research institutions, and academia; or other farmers though farmer-to-farmer networks.

- **What are the conditions under which the adoption of carbon-beneficial practices could persist even without continued financial incentives?** This question requires further study to inform policy. Key factors may include the availability of infrastructure (e.g., regional sawmills or food processing facilities) to accommodate new land-management practices like crop rotation or agroforestry, the availability of technology like precision agriculture, landowners' broader financial security, and the role nonfinancial factors like social norms.

For example, expansion of woodlots and forested riparian buffers in regions like the Corn Belt may require new sawmill infrastructure to process the fiber. Similarly, shifts from monoculture to regenerative polyculture rely on new processing infrastructure for new crops and livestock.

- **How can companies work with suppliers to increase adoption of carbon-beneficial practices as a way of meeting targets for GHG flux in company supply chains?** Some companies are adopting long-term contracts and price management systems that provide greater assurance of profit margins for landowners. These initiatives are intended in part to create the enabling conditions for investments by landowners in practices that build yields (and carbon) over the long term. Further exploration is needed to understand the relationship between provisions like term lengths in contracts between landowners and buyers of food and fiber, on the one hand, and landowners' ability and willingness to invest in practices with up-front costs but long-term benefits, on the other hand.

  Some companies are sending a market demand signal to landowners for food and fiber produced with carbon-beneficial practices; for example, through the development of regenerative certification standards for commodities produced in ways that build soil health. If successful in motivating landowner adoption of carbon-beneficial practices, these kinds of standards could be more widely adopted, including in federal, state, and local procurement standards.

Continued experimentation with new approaches to incentivizing and supporting landowners can clarify the pathway to scaled adoption over the long term.

Public Funding

Why Is It Needed?

Growing the land carbon sink will likely require large and sustained sources of public funding (or private funding mobilized by public policy) to support several dimensions of a scaling strategy. In part, public funding is needed to provide financial incentives to landowners where the costs of implementation exceed the private benefits that accrue to the landowner, or where up-front costs present a mismatch with the long-term nature of benefits for landowners. However, public funding is also needed in the near to midterm to support technical assistance and other nonfinancial mechanisms for landowner adoption, along with investments in scientific advancements and monitoring systems to support the entire effort to increase carbon removal in the land sector.

Public funding is appropriate in this context for the provision of a public good—carbon removal. Stewards of public resources must ensure a strong return on investment for the public. The social cost of carbon is a good basis for assessing public benefits related to climate change mitigation.[13] The pursuit of carbon removal in forests and farms can also generate other public goods—from improved air quality to biodiversity protection and several others.

The need for public funding may diminish over time. For example, public investments in monitoring networks may decline once those networks are developed and established. Similarly, public investments in research, infrastructure, and technology may decline once those needs are addressed. Public funding for financial incentives may also decline over time, especially for practices that involve large up-front costs but modest maintenance costs.

The Farm Bill already funds several land and resource conservation programs that can be used to advance land management approaches to carbon removal:

- Environmental Quality Incentives Program ($1.4 billion in funding in fiscal year 2017)
- Conservation Stewardship Program ($1.3 billion in fiscal year 2017)
- Conservation Reserve Program ($2 billion in fiscal year 2017)
- Forest Legacy Program ($50 million in fiscal year 2017)

However, these programs are significantly oversubscribed (Stubbs 2017), implying a need for greater funding. They are also intended to address multiple conservation objectives—including soil health, water conservation, and biodiversity protection. As a result, only a portion of available funding is available for land management intended to increase carbon removal (or retention).

Carbon markets, another potential mechanism for funding land-management approaches to carbon removal, remain saddled with low prices. In voluntary carbon markets in

North America, average offset prices hover around \$3/tCO_2 (Hamrick and Gallant 2017). In the Regional Greenhouse Gas Initiative in the Northeast, no land-use offset projects have been developed in part because carbon allowance prices are too low—between \$3 and \$4/tCO_2 (Potomac Economics 2018)—to cover project implementation costs. In the California market, offset prices are higher—about \$10–11/tCO_2 (Hamrick and Gallant 2017)—but still too low to activate much of the potential across the landscape. Two-thirds of the carbon removal potential found in Fargione et al. (In Press) have marginal costs in the range of \$10–50/tCO_2 per year.

What Would It Look Like?

To some degree, existing sources of public funding could be better leveraged to advance objectives related to carbon. Federal policymakers should seek to ensure that cost-share and other conservation programs effectively allocate resources across their multiple objectives, including carbon retention and removal. In some cases, this may involve elevating the carbon removal (and retention) potential among project selection criteria or establishing initiatives within these programs that specifically target carbon removal projects. However, given their multiple objectives, these programs are unlikely on their own to satisfy the need for carbon removal in the land sector.

States can leverage Clean Water State Revolving Funds (CWSRFs) to finance joint water-carbon removal projects as well. CWSRFs are capitalized by federal appropriations, which totaled nearly \$1.7 billion for fiscal year 2018, but are managed by states. States have significant flexibility to provide low-interest loans for projects that address water quality needs, including those related to nonpoint sources of pollution. States have authority to use these funds to finance tree planting, fencing for rotational grazing, and other land-management investments that generate water benefits. Some of those interventions, such as planting riparian buffers along streams, can achieve carbon removal goals in tandem with benefits for water quality and quantity. However, CWSRF funds must be repaid, which limits the relevance of the CWSRFs to only those projects that generate a revenue stream.

Box 5 | Spotlight on Potential Policy Measures for Funding Carbon Removal in Forests and Farms

- Leverage already available sources of funding to the extent practicable, balancing carbon storage with other objectives.
- Explore market-based mechanisms to leverage private funding for carbon-beneficial land management.
- Increase public funding for carbon-beneficial land management, especially for programs and investments that could create the conditions for shifts in land management that endure without continued public funding.

Given the limitations of existing public funding sources, perhaps the most important measure states and the federal government can take is to provide new funding for investments in research, practice adoption, and monitoring related to carbon removal and retention in forests and farms. Regulatory measures can also be used to adopt or increase carbon prices and to enable the land sector to participate in those programs in a way that ensures a good public return on investment relative to other potential investments (e.g., energy efficiency or clean energy).

The total value of needed funding will depend on the form of landowner incentive and support mechanisms and the level of ambition. The direct implementation costs associated with the estimated carbon removal potential in forests and farms can serve as a high-level benchmark for the order of magnitude of investment required to fully fund land-management approaches for carbon removal in the United States. Assuming 200 $MtCO_2$ per year from carbon removal in farms at \$10–20/tCO_2 and 300–500 $MtCO_2$ per year from carbon removal in forests at \$20–50/tCO_2 (based on Fargione et al. [In Press][14]), achieving carbon removal at full scale in forest and farms in the United States would require funding in the range of \$8–31 billion per year—depending in large part on the potential scale and cost of forest measures. This is a ballpark estimate. Additional funding would likely be needed for defensive measures that reduce emissions from the land sector.

In practice, this funding could come from a combination of public and private sources. For example, if food and fiber markets would sustain a price premium for commodities produced with carbon-beneficial practices, a portion of the funding need could be met by consumers. An exit ramp for public funding sources may be possible if initial investments can create the conditions for continued carbon-beneficial land use and land management with reduced support from public funding.

NEXT STEPS

The door is open for federal, state, and private-sector action to help landowners manage land in ways that increase carbon removal and to develop the data, evidence, tools, and approaches to sharpen deployment-support policies and achieve large-scale implementation. Near-term action at all levels will be required to set the United States on a path to achieve carbon removal through land management:

- **States** can experiment. States can forge new measurement networks and monitoring systems, incentive and landowner support mechanisms, and public-private partnerships that fit state-specific needs and opportunities. State programs can also serve as models for uptake in federal policy or as implementation vehicles for state or federal sources of funding. By establishing the administrative and governance infrastructure to channel federal funding, states could facilitate future federal policy.
- **Congress** can provide funding to support state innovation and leadership and to advance federal measurement and monitoring activities. Longer term, Congress will play an essential role in providing public funding for landowner incentive and support mechanisms.
- **Companies** can set targets for carbon removal in their supply chains, work with landowners to achieve those targets, and test the value proposition for carbon-beneficial products in their marketplaces.
- **Civil society** can seek to promote innovation in the land sector, provide the tools and understanding needed to direct investments effectively, and support government and private-sector action.

As part of these efforts, strategies that increase the food and fiber productivity of existing agricultural lands and existing managed forests and that reduce demand for land-intensive food production may be essential components of any effort to grow the land carbon sink globally. These are no-regrets strategies in that they provide for food and fiber security while reducing pressure on land that could otherwise be used to store more carbon.

ENDNOTES

1. Net zero emissions are achieved when there is a balance between anthropogenic GHG emissions and removals of GHG emissions from the atmosphere by enhanced action to sequester it in carbon sinks (e.g., increase afforestation to sequester more carbon dioxide in vegetation).

2. For simplicity, this paper uses "carbon removal" to mean removal of carbon dioxide.

3. These approaches have been classified as technological because they are biotechnological manipulations.

4. Although abandoned farmland by definition is not currently producing food, it may be required for the production of food in the future depending on the future trajectory of agricultural productivity and food demand.

5. Assuming a sequestration rate of 3.5 tCO_2 per acre (Griscom et al. 2017), reaching 100 $MtCO_2$ per year of removals by reforestation would require shifting nearly 29 million acres into forestland, an area about the size of Pennsylvania. The 3.5 tCO_2 per acre per year figure is derived by combining estimated carbon sequestration rates from Griscom et al. (2017) for reforestation from natural and plantation forests into a weighted average, using current data on the ratio of natural and plantation forests in the United States (Oswalt et al. 2014). Griscom et al. (2017) derive an average carbon sequestration rate for reforestation of natural and plantation forests in temperate regions by modeling the conversion of non-forest (<25% tree cover) land to forest (>25% tree cover) land in all ecologically appropriate areas. Forest carbon management approaches do not require changing land uses but would require practice adoption across a larger area to generate the same carbon benefit since the per-acre sequestration rates are smaller.

6. Includes fire management, which reduces emissions and retains the carbon removal function of forests.

7. Biochar is charred biomass that can be applied to soils of agricultural and forested lands to stabilize carbon in the soil (NRC 2015).

8. For example, seeding cover crops prior to harvesting the cash crop requires high-clearance planters to avoid damaging the cash crop.

9. This challenge is salient in farms. Available models struggle to accurately predict soil carbon accumulation on any given acre, even for practices with the most robust scientific support like cover cropping, and often omit effects on non-CO_2 GHGs (Poeplau and Don 2015).

10. Measuring soil organic carbon, for example, is estimated to cost on the order of $80 per sample. Personnel time associated with preparing soil samples for laboratory analysis account for the majority of the cost (Mäkipää et al. 2008). At this rate, the cost of measurement could easily exceed the value of the carbon accumulation if every field must be individually measured (multiple samples are required to arrive at an estimate for a given site).

11. This assumption for this illustrative calculation is not intended to represent the full potential of forest carbon management per acre. Carbon sequestration rates for natural forest management and improved plantations from Griscom et al. (2017) are combined here into a weighted average sequestration rate, using current data on the ratio of natural and plantation forests in the United States (Oswalt et al. 2014).

12. USDA defines "beginning farmer or rancher" as an individual or entity who has not operated a farm or ranch or who has operated a farm or ranch for not more than 10 consecutive years, but who will materially and substantially participate in the operation of a farm or ranch.

13. A body of literature has developed around the social cost of carbon—a measure of the economic benefits of reducing (or removing) CO_2 emissions. Estimates of the social cost of carbon vary widely from \$11/tCO_2 to \$212/tCO_2 depending on the magnitude of future impacts and the rate at which the economic costs those future impacts are discounted to the present. Estimates of the social cost of carbon increase over time as the expected impacts of climate change intensify.

14. For the purposes of this illustrative calculation, 200 $MtCO_2$ per year was used as a conservative approximation for carbon removal potential in farms, given that 95 $MtCO_2$ of the 315 $MtCO_2$ per year estimated in Fargione et al. is from biochar, which presents at much higher marginal costs than other measures in farms. Other studies found the potential closer to 200 $MtCO_2$ per year. Most of the remaining potential in farms from Fargione et al. are estimated to be available at less than \$10/tCO_2. Agroforestry measures can pose slightly higher costs. On the forest side, the range used (300–500 $MtCO_2$ per year) reflects on the high end the full potential estimated in Fargione et al. at \$50/tCO_2, which is almost the full potential, and on the low end only the potential related to reforestation and fire management, given the fiber supply trade-offs and leakage risks associated with extending harvest rotations. A modest portion of the forest potential is available at less than \$10/tCO_2, and communications with the authors indicate that a considerable portion is available at marginal costs between \$10 and \$50/tCO_2. \$20/tCO_2 was used as a lower bound for the average cost.

REFERENCES

Alig, Ralph, Susan Stewart, David Wear, and David Nowak. 2010. "Conversions of Forest Land: Trends, Determinants, Projections, and Policy Considerations." In *Advances in Threat Assessment and Their Application to Forest and Rangeland Management. Gen. Tech. Rep. PNW-GTR-802,* edited by John M.Pye, H. Michael Rauscher, Yasmeen Sands, Danny C. Lee, and Jerome S. Beatty. 1–26 Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest and Southern Research Stations.

Antle, John, Susan Capalbo, Siân Mooney, Edward Elliott, and Keith Paustian. 2003. "Spatial Heterogeneity, Contract Design, and the Efficiency of Carbon Sequestration Policies for Agriculture." *Journal of Environmental Economics and Management* 46 (2): 231–250. doi:10.1016/S0095-0696(02)00038-4.

Betts, Lynn. 2017. "Cull Unprofitable Land." *Corn and Soybean Digest*. http://www.cornandsoybeandigest.com/data/cull-unprofitable-land.

Brandes, E., G.S. McNunn, L.A. Schulte, I.J. Bonner, D.J. Muth, B.A. Babcock, B. Sharma, and E.A. Heaton. 2016. "Subfield Profitability Analysis Reveals an Economic Case for Cropland Diversification." *Environmental Research Letters* 11 (1): 014009. doi:10.1088/1748-9326/11/1/014009.

Butler, Brett. 2006. "Family Forest Owners of the United States, 2006." https://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs27.pdf.

Butler, Brett, Jaketon H. Hewes, Brenton J. Dickinson, Kyle Andrejczyk, Sarah M. Butler, and Marla Markowski-Lindsay. 2016. "Family Forest Ownerships of the United States, 2013: Findings from the USDA Forest Service's National Woodland Owner Survey." *Journal of Forestry* 114 (6): 638–647. doi:10.5849/jof.15-099.

Cassidy, Emily S., Paul C. West, James S. Gerber, and Jonathan A. Foley. 2013. "Redefining Agricultural Yields: From Tonnes to People Nourished per Hectare." *Environmental Research Letters* 8 (3): 034015. doi:10.1088/1748-9326/8/3/034015.

Choi, Suk-Won, and Brent Sohngen. 2010. "The Optimal Choice of Residue Management, Crop Rotations, and Cost of Carbon Sequestration: Empirical Results in the Midwest US." *Climatic Change* 99 (1–2): 279–294. doi:10.1007/s10584-009-9680-5.

Dayer, Ashley A., Seth H. Lutter, Kristin A. Sesser, Catherine M. Hickey, and Thomas Gardali. 2018. "Private Landowner Conservation Behavior Following Participation in Voluntary Incentive Programs: Recommendations to Facilitate Behavioral Persistence: Facilitating Landowner Behavioral Persistence." *Conservation Letters* 11 (2): e12394. doi:10.1111/conl.12394.

Euliss, N.H., R.A. Gleason, A. Olness, R.L. McDougal, H.R. Murkin, R.D. Robarts, R.A. Bourbonniere, and B.G. Warner. 2006. "North American Prairie Wetlands Are Important Nonforested Land-Based Carbon Storage Sites." *Science of The Total Environment* 361 (1):179–88. doi:10.1016/j.scitotenv.2005.06.007.

Fargione, Joseph E., Steven Bassett, Timothy Boucher, Scott Bridgham, Richard T. Conant, Susan C. Cook-Patton, Peter W. Ellis et al. In Press. "Natural Climate Solutions for the United States," *Science Advances.*

Food and Agricultural Policy Research Institute. 2007. "Estimating Water Quality, Air Quality, and Soil Carbon Benefits of the Conservation Reserve Program, 01–07." https://www.fsa.usda.gov/Internet/FSA_File/606586_hr.pdf. Accessed August 24, 2018.

Fraser, Evan D.G. 2004. "Land Tenure and Agricultural Management: Soil Conservation on Rented and Owned Fields in Southwest British Columbia." *Agriculture and Human Values* 21 (1): 73–79. doi:10.1023/B:AHUM.0000014020.96820.a1.

Fuss, Sabine, William F. Lamb, Max W. Callaghan, Jérôme Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer et al. 2018. "Negative Emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters* 13 (6): 063002. doi:10.1088/1748-9326/aabf9f.

Griscom, Bronson W., Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger et al. 2017. "Natural Climate Solutions." *Proceedings of the National Academy of Sciences* 114 (44): 11645–11650. doi:10.1073/pnas.1710465114.

Hamrick, Kelley, and Melissa Gallant. 2017. *Unlocking Potential: State of the Voluntary Carbon Markets 2017.* Washington, DC: Ecosystem Marketplace. https://www.forest-trends.org/wp-content/uploads/2017/09/doc_5591.pdf.

Hanson, C. and T. Searchinger. 2015. "Ensuring Crop Expansion Is Limited to Lands with Low Environmental Opportunity Costs." Working Paper. Installment 10 of *Creating a Sustainable Food Future.* Washington, DC: World Resources Institute. http://www.wri.org/publication/ensuring-crop-expansion-limited-lands-low-environmental-opportunity-costs.

Hoover, Coeli M., and Linda S. Heath. 2011. "Potential Gains in C Storage on Productive Forestlands in the Northeastern United States through Stocking Management." *Ecological Applications* 21 (4): 1154–1161. doi:10.1890/10-0046.1.

Huang, Ching-Hsun, Richard Bates, Gary D. Kronrad, and Shiaolin Cheng. 2004. "Economic Analyses of Sequestering Carbon in Loblolly Pine, Cherrybark Oak, and Northern Red Oak in the United States." *Environmental Management* 33 (1): S187–S199. doi:10.1007/s00267-003-9129-y.

Intergovernmental Panel on Climate Change. 2014. *Climate Change 2014 Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press. doi:10.1017/CBO9781107415416.

Jablonski, Becca B.R., Dawn Thilmany McFadden, Martha Sullins, and Kynda R Curtis. 2017. "Determinants of Effective Beginning Farmer Programming and Implications for Future Programs." (3): 427–438

Jackson, Robert B., and Justin S. Baker. 2010. "Opportunities and Constraints for Forest Climate Mitigation." *BioScience* 60 (9): 698–707. doi:10.1525/bio.2010.60.9.7.

Jose, Shibu. 2009. "Agroforestry for Ecosystem Services and Environmental Benefits: An Overview." *Agroforestry Systems* 76 (1): 1–10. doi:10.1007/s10457-009-9229-7.

Kane, Daniel. 2015. *Carbon Sequestration Potential on Agricultural Lands: A Review of Current Science and Available Practices*. Washington, DC: National Sustainable Agriculture Coalition Breakthrough Strategies and Solutions, LLC. http://sustainableagriculture.net/wp-content/uploads/2015/12/Soil_C_review_Kane_Dec_4-final-v4.pdf.

Knox, N.M., S. Grunwald, M.L. McDowell, G.L. Bruland, D.B. Myers, and W.G. Harris. 2015. "Modelling Soil Carbon Fractions with Visible Near-Infrared (VNIR) and Mid-Infrared (MIR) Spectroscopy." *Geoderma* 239–240 (February): 229–239. doi:10.1016/j.geoderma.2014.10.019.

Kravchenko, A.N., and G.P. Robertson. 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. doi:10.2136/sssaj2010.0076.

Kummu, M., H. de Moel, M. Porkka, S. Siebert, O. Varis, and P.J. Ward. 2012. "Lost Food, Wasted Resources: Global Food Supply Chain Losses and Their Impacts on Freshwater, Cropland, and Fertiliser Use." *Science of the Total Environment* 438 (November): 477–489. doi:10.1016/j.scitotenv.2012.08.092.

Lesch, William C., and Cheryl J. Wachenheim. 2014. "Factors Influencing Conservation Practice Adoption in Agriculture: A Review of the Literature." Agribusiness and Applied Economics Report 164828. Fargo, ND: North Dakota State University, Department of Agribusiness and Applied Economics.

Lipinski, Brian, Craig Hanson, James Lomax, Lisa Kitinoja, Richard Waite, and Tim Searchinger. 2013. "Reducing Food Loss and Waste." Working Paper. Installment 2 of *Creating a Sustainable Food Future*. Washington, DC: World Resources Institute. http://pdf.wri.org/reducing_food_loss_and_waste.pdf.

Lubowski, Ruben N., Andrew J. Plantinga, and Robert N. Stavins. 2006. "Land-Use Change and Carbon Sinks: Econometric Estimation of the Carbon Sequestration Supply Function." *Journal of Environmental Economics and Management* 51 (2): 135–152. doi:10.1016/j.jeem.2005.08.001.

Mäkipää, R., M. Häkkinen, M. Peltoniemi, and P. Muukkonen. 2008. "Monitoring Changes in the Carbon Stock of Forest Soils—Costs of Different Sampling Protocols." *Boreal Environment Research* 13 (suppl. B): 120–130.

Mangalassery, Shamsudheen, Sofie Sjögersten, Debbie L. Sparkes, Craig J. Sturrock, Jim Craigon, and Sacha J. Mooney. 2014. "To What Extent Can Zero Tillage Lead to a Reduction in Greenhouse Gas Emissions from Temperate Soils?" *Scientific Reports* 4 (April): 4586. doi:10.1038/srep04586.

McKinley, Duncan C., Michael G. Ryan, Richard A. Birdsey, Christian P. Giardina, Mark E. Harmon, Linda S. Heath, Richard A. Houghton et al. 2011. "A Synthesis of Current Knowledge on Forests and Carbon Storage in the United States." *Ecological Applications* 21 (6): 1902–1924. doi:10.1890/10-0697.1.

Melillo, J.M., S.D. Frey, K.M. DeAngelis, W.J. Werner, M.J. Bernard, F.P. Bowles, G. Pold, M.A. Knorr, and A.S. Grandy. 2017. "Long-Term Pattern and Magnitude of Soil Carbon Feedback to the Climate System in a Warming World." *Science* 358 (6359): 101–105. doi:10.1126/science.aan2874.

Minasny, Budiman, Brendan P. Malone, Alex B. McBratney, Denis A. Angers, Dominique Arrouays, Adam Chambers, Vincent Chaplot et al. 2017. "Soil Carbon 4 per Mille." *Geoderma* 292 (April): 59–86. doi:10.1016/j.geoderma.2017.01.002.

Minx, Jan C., William F. Lamb, Max W. Callaghan, Sabine Fuss, Jérôme Hilaire, Felix Creutzig, Thorben Amann et al. 2018. "Negative Emissions—Part 1: Research Landscape and Synthesis." *Environmental Research Letters* 13 (6): 063001. doi:10.1088/1748-9326/aabf9b.

Mumm, Rita H., Peter D. Goldsmith, Kent D. Rausch, and Hans H. Stein. 2014. "Land Usage Attributed to Corn Ethanol Production in the United States: Sensitivity to Technological Advances in Corn Grain Yield, Ethanol Conversion, and Co-product Utilization." *Biotechnology for Biofuels* 7 (1): 61. doi:10.1186/1754-6834-7-61.

Murray, Brian, Brent Sohngen, Allan Sommer, Brooks Depro, Kelly Jones, Bruce McCarl, Dhazn Gillig, Benjamin DeAngelo, and Kenneth Andrasko. 2005. *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture*. Washington, DC: U.S. Environmental Protection Agency.

Nabuurs, Gert Jan, Omar Masera, Kenneth Andrasko, Pablo Benitez-Ponce, Rizaldi Boer, Michael Dutschke, Elnour Elsiddig et al. 2007. "Forestry." In *Climate Change 2007: Mitigation*, edited by B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York,: Cambridge University Press.

Nemet, Gregory F., Max W. Callaghan, Felix Creutzig, Sabine Fuss, Jens Hartmann, Jérôme Hilaire, William F. Lamb, Jan C. Minx, Sophia Rogers, and Pete Smith. 2018. "Negative Emissions—Part 3: Innovation and Upscaling." *Environmental Research Letters* 13 (6): 063003. doi:10.1088/1748-9326/aabff4.

NRC (National Research Council), ed. 2015. *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington, D.C: National Academies Press. doi:10.17226/18805.

Oswalt, Sonja N., W. Brad Smith, Patrick D. Miles, and Scott A. Pugh. 2014. *Forest Resources of the United States, 2012: A Technical Document Supporting the Forest Service 2010 Update of the RPA Assessment*. WO-GTR-91. Washington, DC: U.S. Department of Agriculture, Forest Service. doi:10.2737/WO-GTR-91.

Pape, Diana, Jan Lewandrowski, Rachel Steele, Derina Man, Marybeth Riley-Gilbert, Katrin Moffroid, and Sarah Kolansky. 2016. Managing Agricultural Land for Greenhouse Gas Mitigation within the United States. Washington, DC: ICF International for the U.S. Department of Agriculture. https://www.usda.gov/oce/climate_change/mitigation_technologies/ICFMitgationReportWEB.pdf.

Paustian, Keith, Johannes Lehmann, Stephen Ogle, David Reay, G. Philip Robertson, and Pete Smith. 2016. "Climate-Smart Soils." *Nature* 532 (7597): 49–57. doi:10.1038/nature17174.

Pinchot Institute. 2011. *Forest Health Human Health Survey Results*. http://www.pinchot.org/uploads/download?fileId=1124.

Poeplau, Christopher, and Axel Don. 2015. "Carbon Sequestration in Agricultural Soils via Cultivation of Cover Crops—A Meta-Analysis." *Agriculture, Ecosystems & Environment* 200 (February): 33–41. doi:10.1016/j.agee.2014.10.024.

Popp, Alexander, Katherine Calvin, Shinichiro Fujimori, Petr Havlik, Florian Humpenöder, Elke Stehfest, Benjamin Leon Bodirsky. et al. 2017. "Land-Use Futures in the Shared Socio-Economic Pathways." *Global Environmental Change* 42 (January): 331–345. doi:10.1016/j.gloenvcha.2016.10.002.

Potomac Economics. 2018. Annual Report on the Market for RGGI CO_2 Allowances: 2017. RGGI, Inc. https://www.rggi.org/sites/default/files/Uploads/Market-Monitor/Annual-Reports/MM_2017_Annual_Report.pdf.

Poulton, Paul, Johnny Johnston, Andy Macdonald, Rodger White, and David Powlson. 2018. "Major Limitations to Achieving '4 per 1000' Increases in Soil Organic Carbon Stock in Temperate Regions: Evidence from Long-Term Experiments at Rothamsted Research, United Kingdom." *Global Change Biology* 24 (6): 2563–2584. doi:10.1111/gcb.14066.

Powlson, David S., Clare M. Stirling, M.L. Jat, Bruno G. Gerard, Cheryl A. Palm, Pedro A. Sanchez, and Kenneth G. Cassman. 2014. "Limited Potential of No-till Agriculture for Climate Change Mitigation." *Nature Climate Change* 4 (July): 678.

Powlson, D.S., A. Bhogal, B.J. Chambers, K. Coleman, A.J. Macdonald, K.W.T. Goulding, and A.P. Whitmore. 2012. "The Potential to Increase Soil Carbon Stocks through Reduced Tillage or Organic Material Additions in England and Wales: A Case Study." *Agriculture, Ecosystems & Environment* 146 (1): 23–33. doi:10.1016/j.agee.2011.10.004.

Ranganathan, J., D. Vennard, R. Waite, P. Dumas, B. Lipinski, and T. Searchinger. 2016. "Shifting Diets for a Sustainable Food Future," Working Paper. Installment 11 of *Creating a Sustainable Food Future*. Washington, DC: World Resources Institute. https://www.wri.org/sites/default/files/Shifting_Diets_for_a_Sustainable_Food_Future_0.pdf.

Reimer, Adam. 2015. "Ecological Modernization in U.S. Agri-environmental Programs: Trends in the 2014 Farm Bill." *Land Use Policy* 47 (September): 209–217. doi:10.1016/j.landusepol.2015.04.013.

Richards, Kenneth R., and Carrie Stokes. 2004. "A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research." *Climatic Change* 63 (1–2): 1–48. doi:10.1023/B:CLIM.0000018503.10080.89.

Rochette, P. 2008. "No-till Only Increases N_2O Emissions in Poorly-Aerated Soils." *Soil and Tillage Research* 101 (1–2): 97–100. doi:10.1016/j.still.2008.07.011.

Searchinger, T., C. Hanson, R. Waite, S. Harper, G. Leeson, and B. Lipinski. 2013. "Achieving Replacement Level Fertility." Working Paper, Installment 3 of *Creating a Sustainable Food Future*. Washington, DC: World Resources Institute. http://www.worldresourcesreport.org.

Searchinger, Tim, and Ralph Heimlich. 2015. "Avoiding Bioenergy Competition for Food Crops and Land." Working Paper. Installment 9 of *Creating a Sustainable Food Future*. Washington, DC: World Resources Institute. http://www.worldresourcesreport.org.

Searchinger, Tim, Richard Waite, Craig Hanson, Janet Ranganathan, Brian Lipinski, and Patrice Dumas. Forthcoming. *Creating a Sustainable Food Future: A Menu of Solutions to Sustainable Feed 10 Billion People by 2050. Final Synthesis.* World Resources Report. Washington, DC: World Resources Institute.

Smith, P., J. Gregory, D. van Vuuren, M. Obersteiner, P. Havlik, M. Rounsevell, J. Woods, E. Stehfest, and J. Bellarby. 2010. "Competition for Land." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365 (1554): 2941–2957. doi:10.1098/rstb.2010.0127.

Smith, Pete. 2016. "Soil Carbon Sequestration and Biochar as Negative Emission Technologies." *Global Change Biology* 22 (3): 1315–1324. doi:10.1111/gcb.13178.

Sohngen, Brent, and Sandra Brown. 2008. "Extending Timber Rotations: Carbon and Cost Implications." *Climate Policy* 8 (5): 435–451. doi:10.3763/cpol.2007.0396.

Soule, Meredith J., Abebayehu Tegene, and Keith D. Wiebe. 2000. "Land Tenure and the Adoption of Conservation Practices." *American Journal of Agricultural Economics* 82 (4): 993–1005. doi:10.1111/0002-9092.00097.

Strong, Nicole A., and Michael G. Jacobson. 2005. "Assessing Agroforestry Adoption Potential Utilising Market Segmentation: A Case Study in Pennsylvania." *Small-Scale Forest Economics, Management and Policy* 4 (2): 215–228. doi:10.1007/s11842-005-0014-9.

Stubbs, Megan. 2017. *Agricultural Conservation: A Guide to Programs*. R40763. Washington, DC: Congressional Research Service.

Tosakana, N.S.P., L.W. Van Tassell, J.D. Wulfhorst, J. Boll, R. Mahler, E.-S. Brooks, and S. Kane. 2010. "Determinants of the Adoption of Conservation Practices by Farmers in the Northwest Wheat and Range Region." *Journal of Soil and Water Conservation* 65 (6): 404–412. doi:10.2489/jswc.65.6.404.

Tubiello, Francesco N., Mirella Salvatore, Alessandro F. Ferrara, Jo House, Sandro Federici, Simone Rossi, Riccardo Biancalani et al. 2015. "The Contribution of Agriculture, Forestry and Other Land Use Activities to Global Warming, 1990-2012." *Global Change Biology* 21 (7): 2655–2660. doi:10.1111/gcb.12865.

UNEP (United Nations Environment Programme). 2017. *The Emissions Gap Report 2017: A UN Environment Synthesis Report.* Nairobi: United NationsEnvironment Programme. http://edepot.wur.nl/426310.

U.S. Department of Agriculture. 2016a. *USDA Building Blocks for Climate Smart Agriculture and Forestry.* Washington, DC: U.S. Department of Agriculture. https://www.usda.gov/sites/default/files/documents/building-blocks-implementation-plan-progress-report.pdf.

U.S. Department of Agriculture. 2016b. "Fire Outlook." https://www.usda.gov/topics/disaster/fire-outlook.

U.S. Department of Agriculture National Agricultural Statistics Service. 2014. "Land in Farms, Harvested Cropland, and Irrigated Land, by Size of Farm: 2012 and 2007." https://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/st99_1_009_010.pdf.

U.S. DOE (Department of Energy) NETL (National Energy Technology Laboratory). 2018. "What Is the Carbon Cycle?" FAQ. What Is the Carbon Cycle? https://www.netl.doe.gov/research/coal/carbon-storage-1/faqs/what-is-the-carbon-cycle. Accessed July 27, 2018.

U.S. Environmental Protection Agency. 2018. "Inventory of U.S. Greenhouse Gas Emissions and Sinks (1990–2016)." EPA 430-R-19-003. https://www.epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf.

U.S. Forest Service. 2015. *Who Owns America's Trees, Woods, and Forests?* NRS-INF-31-15.

Valdivia, Corinne, and Christine Poulos. 2009. "Factors Affecting Farm Operators' Interest in Incorporating Riparian Buffers and Forest Farming Practices in Northeast and Southeast Missouri." *Agroforestry Systems* 75 (1): 61–71. doi:10.1007/s10457-008-9129-2.

Van Winkle, Christina, Justin Baker, Daniel Lapidus, Sara Bushey Ohrel, John Steller, Gregory Latta, and Dileep Birur. 2017. "U.S. Forest Sector Greenhouse Mitigation Potential and Implications for Nationally Determined Contributions:" Research Triangle Park, NC: RTI Press. doi:10.3768/rtipress.2017.op.0033.1705.

Waite, Richard, Malcolm Beveridge, Randall Brummett, Sarah Castine, Nuttapon Chaiyawannakarn, Sadasivam Kaushik, Rattanawan Mungkung, Supawat Nawapakpilai, and Michael Phillips. 2014. "Improving Productivity and Environmental Performance of Aquaculture." Working Paper. Installment 5 of *Creating a Sustainable Food Future*. Washington, DC: World Resources Institute. https://www.wri.org/sites/default/files/wrr_installment_5_improving_productivity_environmental_performance_aquaculture.pdf.

Wear, David N., and Brian C. Murray. 2004. "Federal Timber Restrictions, Interregional Spillovers, and the Impact on U.S. Softwood Markets." *Journal of Environmental Economics and Management* 47 (2): 307–330. doi:10.1016/S0095-0696(03)00081-0.

White House. 2016. "United States Mid-century Strategy for Deep Decarbonization." https://unfccc.int/files/focus/long-term_strategies/application/pdf/us_mid_century_strategy.pdf.

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds. 2009. "Implications of Limiting CO_2 Concentrations for Land Use and Energy." *Science* 324 (5931): 1183–1186. doi:10.1126/science.1168475.

Woodall, Christopher W., John W. Coulston, Grant M. Domke, Brian F. Walters, David N. Wear, James E. Smith, Hans-Erik Andersen et al. 2015. "The U.S. Forest Carbon Accounting Framework: Stocks and Stock Change, 1990–2016." *Gen. Tech. Rep.* NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 P. 154: 1–49. doi:10.2737/NRS-GTR-154.

Zumkehr, A., and J.E. Campbell. 2013. "Historical U.S. Cropland Areas and the Potential for Bioenergy Production on Abandoned Croplands." *Environmental Science & Technology* 47 (8): 3840–3847. doi:10.1021/es3033132.

ACKNOWLEDGMENTS

The authors would like to thank Craig Hanson for the guidance and leadership he provided for this work.

Julio Friedmann of Carbon Wrangler LLC and the Carbon180 team—Giana Amador, Noah Deich, Jason Funk, Rory Jacobson, Matt Lucas, and Jane Zelikova—served as an invaluable resource in the development of the assessment underlying this paper.

Thank you also to our peer reviewers and others who provided valuable inputs or feedback: Nicholas Bianco, Christina DeConcini, Noah Deich, Jimmy Daukas, Joseph Fargione, Jason Funk, Sabine Fuss, Todd Gartner, David Gibbs, Nancy Harris, Eugene Kelly, Dan Lashof, Laura Malaguzzi Valeri, Michelle Manion, David Powlson, Sabin Ray, Tim Searchinger, and Pete Smith. We also wish to thank Emily Matthews, Julie Moretti, Lauri Scherer, Caroline Taylor, and Romain Warnault for editing and design, Rhys Gerholdt for communications support, and WRI's science and research team, especially Laura Malaguzzi Valeri and Maria Hart.

This publication was made possible due to financial support from the Linden Trust for Conservation.

We are pleased to acknowledge our institutional strategic partners, who provide core funding to WRI: Netherlands Ministry of Foreign Affairs, Royal Danish Ministry of Foreign Affairs, and Swedish International Development Cooperation Agency. ww

ABOUT THE AUTHORS

James Mulligan is an Associate in WRI's Food, Forests, and Water Program.

Contact: james.mulligan@wri.org

Gretchen Ellison is a Research Analyst in WRI's Food, Forests, and Water Program.

Contact: gretchen.ellison@wri.org

Rebecca Gasper is a Research Associate with WRI's Climate and Energy Program.

Contact: rebecca.gasper@wri.org

Alexander Rudee is an Intern with WRI's Food, Forests, and Water Program.

ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.