

## ENVIRONMENTAL STUDIES

## Natural climate solutions for the United States

Joseph E. Fargione<sup>1\*</sup>, Steven Bassett<sup>2</sup>, Timothy Boucher<sup>3</sup>, Scott D. Bridgman<sup>4</sup>, Richard T. Conant<sup>5</sup>, Susan C. Cook-Patton<sup>3,6</sup>, Peter W. Ellis<sup>3</sup>, Alessandra Falcucci<sup>7</sup>, James W. Fourqurean<sup>8</sup>, Trisha Gopalakrishna<sup>3</sup>, Huan Gu<sup>9</sup>, Benjamin Henderson<sup>10</sup>, Matthew D. Hurteau<sup>11</sup>, Kevin D. Kroeger<sup>12</sup>, Timm Kroeger<sup>3</sup>, Tyler J. Lark<sup>13</sup>, Sara M. Leavitt<sup>3</sup>, Guy Lomax<sup>14</sup>, Robert I. McDonald<sup>3</sup>, J. Patrick Megonigal<sup>6</sup>, Daniela A. Miteva<sup>15</sup>, Curtis J. Richardson<sup>16</sup>, Jonathan Sanderman<sup>17</sup>, David Shoch<sup>18</sup>, Seth A. Spawn<sup>13</sup>, Joseph W. Veldman<sup>19</sup>, Christopher A. Williams<sup>9</sup>, Peter B. Woodbury<sup>20</sup>, Chris Zganjar<sup>3</sup>, Marci Baranski<sup>21</sup>, Patricia Elias<sup>3</sup>, Richard A. Houghton<sup>17</sup>, Emily Landis<sup>3</sup>, Emily McGlynn<sup>22</sup>, William H. Schlesinger<sup>23</sup>, Juha V. Siikamäki<sup>24</sup>, Ariana E. Sutton-Grier<sup>25,26</sup>, Bronson W. Griscom<sup>3</sup>

Limiting climate warming to <2°C requires increased mitigation efforts, including land stewardship, whose potential in the United States is poorly understood. We quantified the potential of natural climate solutions (NCS)—21 conservation, restoration, and improved land management interventions on natural and agricultural lands—to increase carbon storage and avoid greenhouse gas emissions in the United States. We found a maximum potential of 1.2 (0.9 to 1.6) Pg CO<sub>2</sub>e year<sup>-1</sup>, the equivalent of 21% of current net annual emissions of the United States. At current carbon market prices (USD 10 per Mg CO<sub>2</sub>e), 299 Tg CO<sub>2</sub>e year<sup>-1</sup> could be achieved. NCS would also provide air and water filtration, flood control, soil health, wildlife habitat, and climate resilience benefits.

## INTRODUCTION

Limiting global warming below the 2°C threshold set by the Paris Climate Agreement is contingent upon both reducing emissions and removing greenhouse gases (GHGs) from the atmosphere (1, 2). Natural climate solutions (NCS), a portfolio of discrete land stewardship options (3), are the most mature approaches available for carbon conservation and uptake compared to nascent carbon capture technologies (4) and could complement increases in zero-carbon energy production and energy efficiency to achieve needed climate change mitigation. Within the United States, the maximum and economically viable mitigation potentials from NCS are unclear.

Here, we quantify the maximum potential for NCS in the United States and the portion of this maximum that could be achieved at

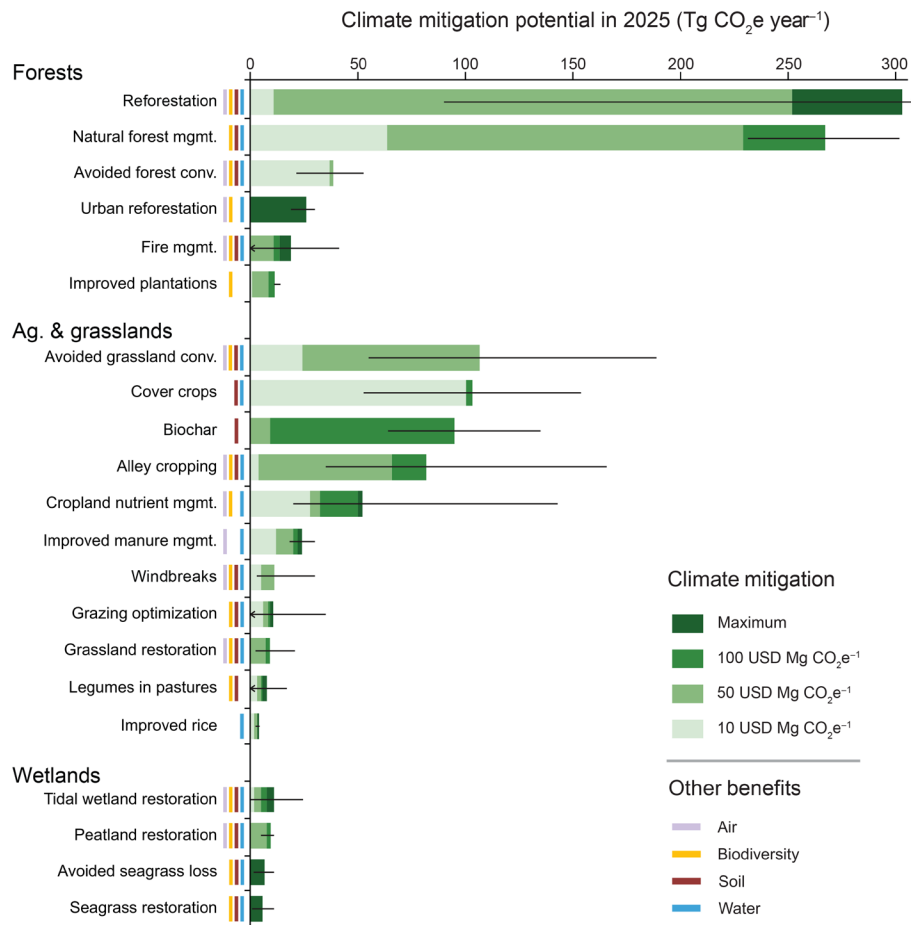
several price points. We consider 21 distinct NCS to provide a consistent and comprehensive exploration of the mitigation potential of conservation, restoration, and improved management in forests, grasslands, agricultural lands, and wetlands (Fig. 1), carefully defined to avoid double counting (details in the Supplementary Materials). We estimate the potential for NCS in the year 2025, which is the target year for the United States' Nationally Determined Contribution (NDC) under the Paris Agreement to reduce GHG emissions by 26 to 28% from 2005 levels. Our work refines a coarser-resolution global analysis (3) and updates and expands the range of options considered in previous analyses for the United States (5–8).

For each NCS opportunity (Fig. 1 and the Supplementary Materials), we estimate the maximum mitigation potential of GHGs measured in CO<sub>2</sub> equivalents (CO<sub>2</sub>e), given the below constraints. We then estimate the reductions obtainable for less than USD 10, 50, and 100 per Mg CO<sub>2</sub>e. Current carbon markets pay around USD 10 (9). The social cost of carbon in 2025 is approximately USD 50, using a 3% discount rate (10). However, a price of at least USD 100 is thought to be needed to keep the 100-year average temperature from warming more than 2.5°C (11), and an even higher price may be needed to meet the Paris Agreement <2°C target. Many NCS also generate co-benefits, which, even without a price on carbon, provide incentives to invest in NCS implementation. We identified co-benefits generated by each NCS in four categories of ecosystem services: air, biodiversity, water, and soil (Fig. 1 and table S2).

To avoid conflicts with other important societal goals for land use, we constrain our maximum estimate to be compatible with human needs for food and fiber (Supplementary Materials). Within these constraints, 5.1 Mha of cropland can be restored to grasslands, forests, and wetlands, equal to the area that has left the Conservation Reserve Program (CRP) since 2007 (8) and less than half the land currently dedicated to corn ethanol. We also estimate that 1.3 Mha of pasture could be reforested without affecting livestock production, assuming recent improvements in efficiency continue (see the Supplementary Materials). We assume that timber production can temporarily decrease by 10%, which maintains timber production

<sup>1</sup>The Nature Conservancy, Minneapolis, MN 55415, USA. <sup>2</sup>The Nature Conservancy, Santa Fe, NM 87501, USA. <sup>3</sup>The Nature Conservancy, Arlington, VA 22203, USA. <sup>4</sup>Institute of Ecology and Evolution, University of Oregon, Eugene, OR 97403, USA. <sup>5</sup>Natural Resources Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, USA. <sup>6</sup>Smithsonian Environmental Research Center, Edgewater, MD 21037, USA. <sup>7</sup>Food and Agriculture Organization, Rome, Italy. <sup>8</sup>Marine Sciences Program, Florida International University, North Miami, FL 33181, USA. <sup>9</sup>Graduate School of Geography, Clark University, Worcester, MA 01610, USA. <sup>10</sup>Trade and Agriculture Directorate, Organization for Economic Cooperation and Development, Paris 75016, France. <sup>11</sup>Department of Biology, University of New Mexico, Albuquerque, NM 87131, USA. <sup>12</sup>Woods Hole Coastal and Marine Science Center, United States Geological Survey, Woods Hole, MA 02543, USA. <sup>13</sup>Center for Sustainability and the Global Environment, University of Wisconsin-Madison, Madison, WI 53726, USA. <sup>14</sup>The Nature Conservancy, Oxford OX1 1HU, UK. <sup>15</sup>Department of Agricultural, Environmental and Development Economics, Ohio State University, Columbus, OH 43210, USA. <sup>16</sup>Duke University Wetland Center, Nicholas School of the Environment, Durham, NC 27708, USA. <sup>17</sup>Woods Hole Research Center, Falmouth, MA 02540, USA. <sup>18</sup>TerraCarbon LLC, Charlottesville, VA 22903, USA. <sup>19</sup>Department of Ecosystem Science and Management, Texas A&M University, College Station, TX 77843, USA. <sup>20</sup>College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14853, USA. <sup>21</sup>U.S. Department of Agriculture, Washington, DC 20250, USA. <sup>22</sup>Department of Agriculture and Resource Economics, University of California, Davis, Davis, CA 95616, USA. <sup>23</sup>Cary Institute of Ecosystem Studies, Millbrook, NY 12545, USA. <sup>24</sup>International Union for Conservation of Nature, Washington, DC 20009, USA. <sup>25</sup>The Nature Conservancy, Bethesda, MD 20814, USA. <sup>26</sup>Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20740, USA.

\*Corresponding author. Email: jfargione@tnc.org



**Fig. 1. Climate mitigation potential of 21 NCS in the United States.** Black lines indicate the 95% CI or reported range (see table S1). Ecosystem service benefits linked with each NCS are indicated by colored bars for air (filtration), biodiversity (habitat protection or restoration), soil (enrichment), and water (filtration and flood control). See the Supplementary Materials for detailed findings and sources.

levels within the historic range of variation and enables managed forests and plantations to transition to longer harvest rotations (see the Supplementary Materials). We assume that extensive natural forests on private lands can all undergo harvest extension, with the temporary loss of timber supply replaced by reforestation and thinning for fire risk reduction (12) or with thinning or select harvest practices that still provide timber but maintain carbon levels (Supplementary Materials) (13, 14). We further constrain our analysis to avoid impacts on biodiversity. This biodiversity constraint precludes both the conversion of natural habitat to energy crops and the afforestation of native grasslands.

## RESULTS

We find a maximum additional NCS mitigation potential of 1.2 Pg CO<sub>2</sub>e year<sup>-1</sup> [95% confidence interval (CI), 0.9 to 1.6 Pg CO<sub>2</sub>e year<sup>-1</sup>] in the year 2025 (Fig. 1 and table S1). This is 21% of the 5794.5 Tg CO<sub>2</sub>e of net emissions in 2016 (15). The majority (63%) of this potential comes from increased carbon sequestration in plant biomass, with 29% coming from increased carbon sequestration in soil and 7% coming from avoided emissions of CH<sub>4</sub> and N<sub>2</sub>O. At the USD 10, 50, and 100 price points, 25, 76, and 91%, respectively, of

the maximum mitigation would be achieved. This means that 1.1 Pg CO<sub>2</sub>e year<sup>-1</sup> are available at USD 100 per Mg CO<sub>2</sub>e, which equals the emission reductions needed to meet the U.S. NDC under the Paris Agreement (see the Supplementary Materials). If NCS were pursued in combination with additional mitigation in the energy sector, then it would therefore enable the United States to exceed its current NDC ambition. This is important because, globally, current NDCs (7 to 9 Pg CO<sub>2</sub>e year<sup>-1</sup>) would need to be dramatically increased (by an additional 10 to 16 Pg CO<sub>2</sub>e year<sup>-1</sup>) to limit warming below 2°C (16).

This estimate of maximum NCS potential is similar to or higher than several previous syntheses of mitigation opportunities in the land sector. For example, the United States Mid-Century Strategy for Deep Decarbonization estimated a potential land sink of 912 Tg CO<sub>2</sub>e year<sup>-1</sup>, 30% lower than our estimate (5). While other efforts have focused on the forest sector (7) or the agricultural sector (6), this analysis presents a comprehensive and up-to-date synthesis of NCS opportunities in the United States. For example, this analysis considers potential additional mitigation from tidal wetlands and seagrass (“blue carbon”), which has been comprehensively analyzed for its current status in the United States (17), but not its potential for additional mitigation.

Reforestation has the single largest maximum mitigation potential (307 Tg CO<sub>2</sub>e year<sup>-1</sup>). The majority of this potential occurs in the northeast (35%) and south central (31%) areas of the United States (fig. S1). This mitigation potential increases to 381 Tg CO<sub>2</sub>e year<sup>-1</sup> if all pastures in historically forested areas are reforested. Previous estimates of reforestation potential range widely from 208 to 1290 Tg CO<sub>2</sub>e year<sup>-1</sup> (7). Higher estimates than ours can be obtained by reforesting or afforesting areas that we excluded (e.g., productive crop and pasture lands and natural grasslands) and/or by using rates of carbon sequestration from plantation systems rather than from natural regenerating forests [e.g., (7)].

Natural forest management of privately held forests has the second largest maximum mitigation potential (267 Tg CO<sub>2</sub>e year<sup>-1</sup>). This maximum mitigation is achieved by extending harvest cycles. Mitigation can also be achieved through forest management practices such as reduced impact logging and improved silvicultural practices that release suppressed forest growth (18–20), although often at lower sequestration rates than extending harvest cycles. These management practices can be implemented at low or no net cost (21, 22) and do not require a change in business-as-usual (BAU) land use or ownership rights.

Another promising opportunity associated with forests is fire management (18 Tg CO<sub>2</sub>e year<sup>-1</sup>; fig. S6). Fire management entails restoring frequent, low-intensity, understory fires in fire-prone forest ecosystems to reduce the potential for high-severity wildfires (23). The primary carbon benefit from fire management is avoiding decreased net ecosystem production from tree-killing wildfire. In the absence of improved fire management, climate change is expected to continue to increase the frequency of high-severity fires and compromise the ability of forests to regenerate following these fires (24). The high uncertainty associated with the climate mitigation benefits of fire management would be reduced by additional research to quantify the carbon storage benefits of prescribed fire across a diversity of forest types, including the length of time that prescribed fire reduces the risk of subsequent high-severity fires.

Avoided conversion protects carbon stored in extant forests and grasslands from ongoing losses. More than two-thirds of the avoided forest conversion potential (38 Tg CO<sub>2</sub>e year<sup>-1</sup>) occurs in the Southern and Pacific Northwest regions (table S14 and fig. S9). Many of the most intensive areas of rapid forest conversion were located near urban zones, with additional hot spots in recent agricultural expansion zones (such as California's Central Valley) and semi-arid regions of the West. Avoided conversion of grassland to cropland prevents emissions from soils and root biomass (107 Tg CO<sub>2</sub>e year<sup>-1</sup>; fig. S12). The emissions from grassland conversion exceed the emissions from forest conversion because both the rate of conversion and the per hectare emissions are higher (table S1). Cropland expansion is a major cause of conversion that affects grasslands much more than forests (25). The higher rate of emissions occurs because the conversion of grasslands to croplands results in a 28% loss of soil carbon from the top meter of soil (26). This generates 125 Mg CO<sub>2</sub>e ha<sup>-1</sup> in emissions, comprising 81% of the emissions from grassland conversion (see the Supplementary Materials). Because research shows conflicting conclusions regarding the impact of forest conversion in the United States on soil carbon, we do not include the soil carbon pool in our estimate of emissions from forest conversion (see the Supplementary Materials).

Carbon sequestration opportunities in croplands include the use of cover crops and improved cropland nutrient management. Cover

crops, grown when fields are normally bare, provide additional carbon inputs to soils. Growing cover crops on the 88 Mha of the five primary crops in United States not already using cover crops presents a substantial opportunity for mitigation (103 Tg CO<sub>2</sub>e year<sup>-1</sup>). Cover crops are increasingly used by U.S. farmers to improve soil health, yields, and yield consistency (27). Improved management of nitrogen fertilizers reduces N<sub>2</sub>O emissions and avoids fossil fuel emissions associated with fertilizer production (52 Tg CO<sub>2</sub>e year<sup>-1</sup>). Fertilizer rates can be reduced while maintaining yields by using precision agriculture to apply only the amount required in each part of the field and by splitting fertilizer applications to match the timing and supply of fertilizer with crop demand (see the Supplementary Materials). Emissions can also be reduced by switching from anhydrous fertilizer to urea, which has lower N<sub>2</sub>O emission (6).

The agronomic practices of biochar incorporation (95 Tg CO<sub>2</sub>e year<sup>-1</sup>) and alley cropping (planting widely spaced trees interspersed with a row crop; 82 Tg CO<sub>2</sub>e year<sup>-1</sup>) also have high maximum potential. However, current adoption is negligible due to a variety of cultural, technological, and cost barriers that would need to be overcome if these practices were to achieve their mitigation potential (28, 29).

Tidal wetland restoration is the largest wetland NCS (12 Tg CO<sub>2</sub>e year<sup>-1</sup>). Roughly 27% of U.S. salt marshes are disconnected from the ocean and subject to freshwater inundation. This results in a large increase in CH<sub>4</sub> emissions from these “freshened” salt marshes. Reconnecting salt marshes with the ocean, such as via culverts under roads or other barriers, can avoid these CH<sub>4</sub> emissions (30).

The 10 opportunities described above account for 90% (1082 Tg CO<sub>2</sub>e year<sup>-1</sup>) of the maximum NCS mitigation potential across all 21 opportunities. An additional 11 opportunities, which sum to 122 Tg CO<sub>2</sub>e year<sup>-1</sup>, account for just 10% of the maximum potential. However, these NCS may offer optimal ecological and economic opportunities at local scales (Fig. 1 and Supplementary Materials). For example, peatland restoration offers a high per hectare mitigation benefit, especially in regions of the United States with warm temperate climates (8.2 Mg CO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>).

Lower-cost opportunities represent particularly promising areas for increased near-term investment. We identified 299 Tg CO<sub>2</sub>e year<sup>-1</sup> of NCS opportunities that could be realized for USD 10 Mg CO<sub>2</sub>e<sup>-1</sup> or less (table S1), a price that is in line with many current carbon markets (9). The two largest lower-cost opportunities are improved management practices: cover crops (100 Tg CO<sub>2</sub>e year<sup>-1</sup>) and improved natural forest management (64 Tg CO<sub>2</sub>e year<sup>-1</sup>). Both of these practices, along with planting windbreaks (5 Tg CO<sub>2</sub>e year<sup>-1</sup>) and legumes in pastures (3 Tg CO<sub>2</sub>e year<sup>-1</sup>), have the potential to increase yields (21, 22, 27) and therefore to generate additional revenue for landowners. Improved manure management can also provide low-cost mitigation (12 Tg CO<sub>2</sub>e year<sup>-1</sup>) (8). In addition, lower-cost NCS include increased efficiencies (cropland nutrient management, 28 Tg CO<sub>2</sub>e year<sup>-1</sup>; grazing optimization, 6 Tg CO<sub>2</sub>e year<sup>-1</sup>) and avoided conversion (avoided forest conversion, 37 Tg CO<sub>2</sub>e year<sup>-1</sup>; avoided grassland conversion, 24 Tg CO<sub>2</sub>e year<sup>-1</sup>).

By itself, the marginal abatement cost gives an incomplete picture of the potential for implementation of NCS, in part because NCS provide a variety of co-benefits (Fig. 1 and table S2). The values of these co-benefits are not captured in our marginal abatement costs yet may drive NCS implementation. For example, investments in fire management are needed to avoid impacts on air quality and drinking water provision; urban forestry provides human health, aesthetic, and direct temperature reduction benefits; nutrient management is

needed to improve water quality and avoid toxic algal blooms (table S2). Further, NCS can help provide resilience to climate change impacts on nature and people. For example, building soil carbon increases the resilience of cropland (31); protecting coastal wetlands can provide coastal defense against storms (32); and fire management can help avoid damaging wildfires (23).

We have restricted our analysis to those opportunities where the literature conclusively demonstrates the potential for mitigation. This suggests that new research may reveal additional opportunities for NCS, which would increase the potential identified here. At the same time, substantial uncertainties exist in some NCS opportunities (Fig. 1 and table S1), highlighting the need for implementation to be coupled with monitoring and assessment of NCS.

## DISCUSSION

The United States is the largest cumulative emitter of carbon dioxide from fossil fuels (33). Despite the immense size of U.S. GHG emissions from fossil fuel use, we find that NCS have the potential to generate mitigation equivalent to 21% of net annual emissions. This reveals the important contribution to climate mitigation that the land sector can make, even in developed countries such as the United States.

Globally, current NCS efforts receive only 0.8% of public and private climate financing (34), despite offering roughly 37% of potential mitigation needed through 2030 (3). One concern that may have limited the adoption of NCS to date includes competition with other land uses such as food and bioenergy production. A growing body of literature suggests that future global food demand can be met via investments in yield increases, closing yield gaps, diet shifts, aquaculture, and biofuel policy, without the need to further expand cropland into natural areas (35, 36). In the United States, marginal cropland, much of which is unprofitable (37), could be restored to grassland or forests with net societal benefits (38). Similarly, NCS may compete with bioenergy production. However, this conflict can be reduced or avoided depending on the form of bioenergy production or NCS. Some forms of biomass production, such as residues and wastes, or high-yielding methods, such as algae, do not require productive land (39). Our grassland restoration pathway could produce a limited amount of additional biomass while maintaining carbon sequestration in soils if low-productivity croplands are converted to perennial energy grasses (40). Further, NCS based on improved management of existing land uses do not create land use conflict and can even increase productivity within that land use (e.g., fire management or cover crops). However, aggressive expansion of dedicated bioenergy crops, given the large land requirement of both first- and second-generation bioenergy crops (41), would be likely to reduce the mitigation potential available through NCS, notably via reforestation, avoided grassland conversion, and natural forest management.

A second concern is that ecosystems have a limited ability to store additional carbon. For each pathway, we quantified the duration of time for which mitigation is expected to occur at the rates we estimate, before saturation effects decrease this rate (table S1). We note that carbon can continue to accumulate in forests for hundreds of years and in soils for centuries or millennia (table S1 and the Supplementary Materials). Further, four of our NCS opportunities (cropland nutrient management, tidal wetland restoration, manure management, and improved rice management) are based on avoided emissions of CH<sub>4</sub> and N<sub>2</sub>O, which are benefits that do not saturate. The mitigation potential of avoided conversion of habitat is limited

by the total carbon contained in the habitat. Our analysis assumes that rates of conversion persist at current levels in a BAU scenario, which would represent a continuing source of emissions for at least 67 years for each habitat considered here before reaching “saturation” when the total area has been lost. However, the long-term benefit of avoided conversion depends on assumed future BAU conversion rates.

The permanence of the ~2270 Pg C currently stored globally in biomass (42) and soils to 1 m (26) is a significant concern, because unmitigated climate change is likely to cause feedbacks that may increase disturbances such as fire or pest outbreaks (43) or limit net ecosystem productivity or forest regeneration (24). While NCS would marginally increase this large carbon pool, putting some additional carbon at risk, rapid and widespread implementation of NCS would reduce the overall risk of impermanence to the terrestrial biosphere that unmitigated climate change is likely to cause.

Another challenge is that avoiding conversion in one area can cause conversion to shift to other areas, often referred to as “leakage.” Large-scale sectoral and landscape approaches to land use planning and policies will be needed to realize the NCS opportunities identified here. These approaches can and should be designed to buffer risks of leakage associated with individual projects (44).

Reducing carbon-intensive energy consumption is necessary but insufficient to meet the ambitious goals of the Paris Agreement. Comprehensive mitigation efforts that include fossil fuel emission reductions coupled with NCS hold promise for keeping warming below 2°C. Beyond providing meaningful climate mitigation, NCS investment can increase other important ecosystem services. The conservation, restoration, and improved management of lands in the United States represent a necessary and urgent component of efforts to stabilize the climate.

## MATERIALS AND METHODS

Below, we provide a brief overview of methods for each of the 21 NCS that we quantified. Full methodological details are provided in the Supplementary Materials.

**Reforestation:** Additional carbon sequestration in above- and belowground biomass and soils gained by converting nonforest (<25% tree cover) to forest [>25% tree cover (45)] in areas of the conterminous United States where forests are the native cover type. We excluded areas with intensive human development, including all major roads (46), impervious surfaces (47), and urban areas (48). To eliminate double counting with the peatland restoration pathway, we removed Histosol soils (49). To safeguard food production, we removed most cropland and pasture. We discounted the carbon sequestration mitigation benefit in conifer-dominated forests to account for albedo effects.

**Natural forest management:** Additional carbon sequestration in above- and belowground biomass gained through improved management in forests on private lands under nonintensive timber management. The maximum mitigation potential was quantified on the basis of a “harvest hiatus” scenario starting in 2025, in which natural forests are shifted to longer harvest rotations. This could be accomplished with less than 10% reduction in timber supply with new timber supply from thinning treatments for fuel risk reduction until new timber from reforestation is available in 2030.

**Fire management:** Use of prescribed fire to reduce the risk of high-intensity wildfire. We considered fire-prone forests in the western United States. We assume that treatment eliminates the risk of

subsequent wildfire for 20 years, but only on the land that was directly treated. We assume that 5% of lands are treated each year, and we calculated the benefits that accrue over 20 years, finding that the initial increase in emissions associated with prescribed fire treatment is more than offset over time by the avoided impacts of wildfires. We report the average annual benefit across these 20 years. The impact of wildfires includes both direct emissions from combustion and suppression of net ecosystem productivity following wildfires.

**Avoided forest conversion:** Emissions of CO<sub>2</sub> avoided by avoiding anthropogenic forest conversion. Most forest clearing is followed by forest regeneration rather than conversion to another land use. To estimate the rate of persistent conversion (i.e., to another land use), we first calculated forest clearing in the conterminous United States from 2000 to 2010 and then used the proportion of forest clearing that historically was converted to another land use to estimate conversion rates in 2000 to 2010. We used estimates of avoided carbon emissions from above- and belowground biomass that are specific to each region and forest type. We did not count forest loss due to fire to avoid double counting with the improved fire management opportunity. We did not count forest loss due to pests because it is unclear whether this loss can be avoided. We reduced the benefit of avoided conversion in conifer-dominated forests to account for their albedo effects.

**Urban reforestation:** Additional carbon sequestration in above- and belowground biomass gained by increasing urban tree cover. We considered the potential to increase urban tree cover in 3535 cities in the conterminous United States. We considered the potential for additional street trees, and for those cities not in deserts, we also considered the potential for park and yard tree plantings. The potential percent increase in tree cover was estimated on the basis of high-resolution analysis of 27 cities, which excluded sports fields, golf courses, and lawns (50).

**Improved plantations:** Additional carbon sequestration gained in above- and belowground tree biomass by extending rotation lengths for a limited time in even-aged, intensively managed wood production forests. Rotation lengths were extended from current economic optimal rotation length to a biological optimal rotation length in which harvest occurs when stands reach their maximum annual growth.

**Cover crops:** Additional soil carbon sequestration gained by growing a cover crop in the fallow season between main crops. We quantified the benefit of using cover crops on all of the five major crops in the United States (corn, soy, wheat, rice, and cotton) that are not already growing cover crops (27), using the mean sequestration rate quantified in a recent meta-analysis (51).

**Avoided conversion of grassland:** Emissions of CO<sub>2</sub> avoided by avoiding conversion of grassland and shrubland to cropland. We quantified avoided emissions from soil and roots (for shrubs, we also considered aboveground biomass) based on the spatial pattern of conversion from 2008 to 2012. We used spatial information on location of recent conversion and variation in soil carbon and root biomass to estimate mean annual emission rate from historic conversion. We estimated a 28% loss of soil carbon down to 1 m (26). We modeled spatial variation in root biomass based on mean annual temperature and mean annual precipitation using data from (52).

**Biochar:** Increased soil carbon sequestration by amending agricultural soils with biochar, which converts nonrecalcitrant carbon (crop residue biomass) to recalcitrant carbon (charcoal) through pyrolysis. We limited the source of biochar production to crop residue that can be sustainably harvested. We assumed that 79.6% of

biochar carbon persists on a time scale of >100 years (53, 54) and that there are no effects of biochar on emissions of N<sub>2</sub>O or CH<sub>4</sub> (55, 56).

**Alley cropping:** Additional carbon sequestration gained by planting wide rows of trees with a companion crop grown in the alleyways between the rows. We estimated a maximum potential of alley cropping on 10% of U.S. cropland (15.4 Mha) (57).

**Cropland nutrient management:** Avoided N<sub>2</sub>O emissions due to more efficient use of nitrogen fertilizers and avoided upstream emissions from fertilizer manufacture. We considered four improved management practices: (i) reduced whole-field application rate, (ii) switching from anhydrous ammonia to urea, (iii) improved timing of fertilizer application, and (iv) variable application rate within field. We projected a 4.6% BAU growth in fertilizer use in the United States by 2025. On the basis of these four practices, we found a maximum potential of 22% reduction in nitrogen use, which leads to a 33% reduction in field emissions and a 29% reduction including upstream emissions.

**Improved manure management:** Avoided CH<sub>4</sub> emissions from dairy and hog manure. We estimated the potential for emission reductions from improved manure management on dairy farms with over 300 cows and hog farms with over 825 hogs. Our calculations are based on improved management practices described by Pape *et al.* (8).

**Windbreaks:** Additional sequestration in above- and belowground biomass and soils from planting windbreaks adjacent to croplands that would benefit from reduced wind erosion. We estimated that windbreaks could be planted on 0.88 Mha, based on an estimated 17.6 Mha that would benefit from windbreaks, and that windbreaks would be planted on ~5% of that cropland (8).

**Grazing optimization:** Additional soil carbon sequestration due to grazing optimization on rangeland and planted pastures, derived directly from a recent study by Henderson *et al.* (58). Grazing optimization prescribes a decrease in stocking rates in areas that are overgrazed and an increase in stocking rates in areas that are undergrazed, but with the net result of increased forage offtake and livestock production.

**Grassland restoration:** Additional carbon sequestration in soils and root biomass gained by restoring 2.1 Mha of cropland to grassland, equivalent to returning to the 2007 peak in CRP enrollment. Grassland restoration does not include restoration of shrubland.

**Legumes in pastures:** Additional soil carbon sequestration due to sowing legumes in planted pastures, derived directly from a recent global study by Henderson *et al.* (58). Restricted to planted pastures and to where sowing legumes would result in net sequestration after taking into account potential increases in N<sub>2</sub>O emissions from the planted legumes.

**Improved rice management:** Avoided emissions of CH<sub>4</sub> and N<sub>2</sub>O through improved practices in flooded rice cultivation. Practices including mid-season drainage, alternate wetting and drying, and residue removal can reduce these emissions. We used a U.S. Environmental Protection Agency (EPA) analysis that projects the potential for improvement across U.S. rice fields, in comparison with current agricultural practices (59).

**Tidal wetland restoration:** In the United States, 27% of tidal wetlands (salt marshes and mangroves) have limited tidal connection with the sea, causing their salinity to decline to the point where CH<sub>4</sub> emissions increase (30). We estimated the potential for reconnecting these tidal wetlands to the ocean to increase salinity and reduce CH<sub>4</sub> emissions.

**Peatland restoration:** Avoided carbon emissions from rewetting and restoring drained peatlands. To estimate the extent of restorable peatlands, we quantified the difference between historic peatland extent [based on the extent of Histosols in soil maps (60)] and current peatland extent. Our estimate of mitigation potential accounted for changes in soil carbon, biomass, and CH<sub>4</sub> emissions, considering regional differences, the type of land use of the converted peatland, and whether the peatland was originally forested.

**Avoided seagrass loss:** Avoided CO<sub>2</sub> emissions from avoiding seagrass loss. An estimated 1.5% of seagrass extent is lost every year (61). We assumed that half of the carbon contained in biomass and sediment from disappearing seagrass beds is lost to the atmosphere (62).

**Seagrass restoration:** Increased sequestration from restoring the estimated 29 to 52% of historic seagrass extent that has been lost and could be restored (61). We estimated the average carbon sequestration rate in the sediment of seagrass restorations based on data from six seagrass restoration sites in the United States (63).

## SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/4/11/eaat1869/DC1>

Supplementary Materials and Methods

Fig. S1. Mapped reforestation opportunity areas in the lower 48 states.

Fig. S2. Conceptual framework for improved forest management carbon accounting.

Fig. S3. MAC for carbon sequestration through forest management and aging, after Golub *et al.* (99).

Fig. S4. MAC for natural forest management after Latta *et al.* (98) and best-fit functions.

Fig. S5. MAC curves for improved plantations.

Fig. S6. Fire management analysis area.

Fig. S7. Regions used for reporting avoided forest conversion results.

Fig. S8. Forest conversion from 1986 to 2000.

Fig. S9. Potential carbon emissions from areas at high risk of forest conversion.

Fig. S10. Cities included in the urban reforestation analysis.

Fig. S11. Calibration of remote sensing data for forest cover estimation in urban areas.

Fig. S12. Avoided grassland conversion map.

Fig. S13. MAC curve for avoided grassland conversion.

Fig. S14. Nitrogen fertilizer use in the United States.

Fig. S15. Marginal abatement cost curve for reducing N fertilizer rate.

Fig. S16. Marginal abatement cost curve for applying variable rate technology fertilizer application.

Fig. S17. Grazing optimization map.

Fig. S18. Legumes in pastures map.

Fig. S19. Grassland restoration map.

Fig. S20. MAC curve for grassland restoration.

Fig. S21. Break-even prices for GHG abatement from rice production.

Fig. S22. MAC curve for salt marsh restoration.

Fig. S23. MAC of avoided GHG emissions from seagrass.

Table S1. Mitigation potential of NCS in 2025.

Table S2. Co-benefits of NCS.

Table S3. Literature MAC estimates for reforestation of agricultural lands.

Table S4. Literature estimates of reforestation costs used to estimate MAC of reforesting natural ecosystems.

Table S5. Estimated marginal abatement cost of fire management by major forest region.

Table S6. Forest disturbance rates by source.

Table S7. Mean annual forest hectares cleared per year from 1986 to 2000.

Table S8. Mean annual forest hectares cleared per year from 2001 to 2010.

Table S9. Mean annual forest hectares converted per year from 1986 to 2000.

Table S10. Proportion of areas cleared from 1986 to 2000 that had not regenerated to forest by 2010.

Table S11. Mean predisturbance dry biomass (kg m<sup>-2</sup>) in forest areas converted from 1986 to 2000.

Table S12. Mean predisturbance dry biomass (kg m<sup>-2</sup>) in forest areas converted from 2001 to 2010.

Table S13. Carbon emissions (Mg C year<sup>-1</sup>) from estimated forest conversion from 2001 to 2010.

Table S14. Albedo-adjusted carbon emissions equivalent (Mg C<sub>e</sub> year<sup>-1</sup>) from estimated forest conversion from 2001 to 2010.

Table S15. Urban reforestation maximum potential annual net C sequestration in 2025.

Table S16. Uncertainty in urban reforestation average annual abatement (Tg CO<sub>2</sub>) by 2025 at a cost of USD 100 per Mg CO<sub>2</sub>.

Table S17. Profitability impacts of cover crops for selected crops.

Table S18. Marginal abatement costs of cover crops in the five primary crops.

Table S19. Maximum feasible N<sub>2</sub>O reduction for multiple nitrogen fertilizer practices.

Table S20. Results from the literature of the potential for reducing N fertilizer rate using within-field management.

Table S21. Current and projected GHG emissions from nitrogen fertilizer manufacturing in the United States.

Table S22. Mitigation potential for grazing optimization and legumes in pasture NCS at different marginal abatement costs.

Table S23. Areas and carbon fluxes for Histosols in the conterminous United States.

Table S24. Peatland restoration mitigation calculations for climate zones within the United States.

Table S25. 95% CIs for Histosol calculations.

References (64–398)

## REFERENCES AND NOTES

- United Nations, *United Nations Framework Convention on Climate Change: Adoption of the Paris Agreement* (United Nations, 2015).
- P. Smith, S. J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R. B. Jackson, A. Cowie, E. Kriegler, D. P. van Vuuren, J. Rogelj, P. Ciais, J. Milne, J. G. Canadell, D. McCollum, G. Peters, R. Andrew, V. Krey, G. Shrestha, P. Friedlingstein, T. Gasser, A. Grübler, W. K. Heidug, M. Jonas, C. D. Jones, F. Kraxner, E. Littleton, J. Lowe, J. Roberto Moreira, N. Nakicenovic, M. Obersteiner, A. Patwardhan, M. Rogner, E. Rubin, A. Sharifi, A. Torvanger, Y. Yamagata, J. Edmonds, C. Yongsung, Biophysical and economic limits to negative CO<sub>2</sub> emissions. *Nat. Clim. Change* **6**, 42–50 (2016).
- B. W. Griscom, J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H. Schlesinger, D. Shoch, J. V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R. T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M. R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S. M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F. E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, J. Fargione, Natural climate solutions. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 11645–11650 (2017).
- C. B. Field, K. J. Mach, Rightsizing carbon dioxide removal. *Science* **356**, 706–707 (2017).
- The White House, *United States Mid-Century Strategy for Deep Decarbonization* (The White House, 2016).
- A. J. Eagle, L. R. Henry, L. P. Olander, K. Haugen-Kozyra, N. Millar, G. P. Robertson, *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature* (Nicholas Institute, Duke University, 2012).
- C. Van Winkle, J. S. Baker, D. Lapidus, S. Ohrel, J. Steller, G. Latta, D. Birur, *US Forest Sector Greenhouse Mitigation Potential and Implications for Nationally Determined Contributions* (RTI Press, 2017).
- D. Pape, J. Lewandrowski, R. Steele, D. Man, M. Riley-Gilbert, K. Moffroid, S. Kolansky, *Managing Agricultural Land for Greenhouse Gas Mitigation Within the United States* (U.S. Department of Agriculture, 2016); [www.usda.gov/oce/climate\\_change/mitigation.htm](http://www.usda.gov/oce/climate_change/mitigation.htm).
- World Bank; Ecofys; Vivid Economics, *State and Trends of Carbon Pricing 2017* (World Bank, 2017).
- National Academies of Science Engineering and Medicine, *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide* (The National Academies Press, 2017).
- W. D. Nordhaus, Evolution of modeling of the economics of global warming: Changes in the DICE model, 1992–2017. *Clim. Change* **148**, 623–640 (2018).
- K. E. Skog, P. J. Ince, H. Spelter, A. Kramp, R. J. Barbour, in *Woody Biomass Utilization: Challenges and Opportunities* (Forest Products Society, 2008), pp. 3–14.
- S. C. Davis, A. E. Hessl, C. J. Scott, M. B. Adams, R. B. Thomas, Forest carbon sequestration changes in response to timber harvest. *For. Ecol. Manage.* **258**, 2101–2109 (2009).
- C. Hoover, S. Stout, The carbon consequences of thinning techniques: Stand structure makes a difference. *J. For.* **105**, 266–270 (2007).
- U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2016* (U.S. Environmental Protection Agency, 2018); [www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016](http://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016).
- J. Rogelj, M. den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, M. Meinshausen, Paris Agreement climate proposals need boost to keep warming well below 2°C. *Nat. Clim. Change* **534**, 631–639 (2016).
- Commission for Environmental Cooperation, *North America's Blue Carbon: Assessing Seagrass, Salt Marsh and Mangrove Distribution and Carbon Sinks* (Commission for Environmental Cooperation, 2016).

18. T. D. Lee, S. E. Eisenhaure, I. P. Gaudreau, Pre-logging treatment of invasive glossy buckthorn (*Frangula alnus* Mill.) promotes regeneration of eastern white pine (*Pinus strobus* L.). *Forests* **8**, 16 (2017).
19. T. M. Schuler, M. Thomas-Van Gundy, J. P. Brown, J. K. Wiedenbeck, Managing Appalachian hardwood stands using four management practices: 60-year results. *For. Ecol. Manage.* **387**, 3–11 (2017).
20. S. A. Moss, E. Heitzman, The economic impact of timber harvesting practices on NIPF properties in West Virginia, in *Proceedings of the 18th Central Hardwood Forest Conference*, G. W. Miller, T. M. Schuler, K. W. Gottschalk, J. R. Brooks, S. T. Grushecky, B. D. Spong, J. S. Rentch, Eds. (U.S. Department of Agriculture, Forest Service, 2013), pp. 129–141.
21. Ruslandi, C. Romero, F. E. Putz, Financial viability and carbon payment potential of large-scale silvicultural intensification in logged dipterocarp forests in Indonesia. *For. Policy Econ.* **85**, 95–102 (2017).
22. V. P. Medjibe, F. E. Putz, Cost comparisons of reduced-impact and conventional logging in the tropics. *J. For. Econ.* **18**, 242–256 (2012).
23. J. Williams, Exploring the onset of high-impact mega-fires through a forest land management prism. *For. Ecol. Manage.* **294**, 4–10 (2013).
24. C. S. Stevens-Rumann, K. B. Kemp, P. E. Higuera, B. J. Harvey, M. T. Rother, D. C. Donato, P. Morgan, T. T. Veblen, Evidence for declining forest resilience to wildfires under climate change. *Ecol. Lett.* **21**, 243–252 (2018).
25. T. J. Lark, J. Meghan Salmon, H. K. Gibbs, Cropland expansion outpaces agricultural and biofuel policies in the United States. *Environ. Res. Lett.* **10**, 044003 (2015).
26. J. Sanderman, T. Hengl, G. J. Fiske, Soil carbon debt of 12,000 years of human land use. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 9575–9580 (2017).
27. Conservation Technology Information Center, Sustainable Agriculture Research and Education, American Seed Trade Association, *Annual Report 2016-2017 Cover Crop Survey* (Conservation Technology Information Center, Sustainable Agriculture Research and Education, American Seed Trade Association, 2017).
28. D. Knowler, B. Bradshaw, Farmers' adoption of conservation agriculture: A review and synthesis of recent research. *Food Policy* **32**, 25–48 (2007).
29. S. Shackley, G. Ruyschaert, K. Zwart, B. Glaser, *Biochar in European Soils and Agriculture: Science and Practice* (Routledge, 2016).
30. K. D. Kroeger, S. Crooks, S. Moseman-valtierra, J. Tang, Restoring tides to avoid methane emissions in impounded wetlands: A new and potent Blue Carbon climate change intervention. *Sci. Rep.* **7**, 1621 (2017).
31. S. Banwart, S. Banwart, H. Black, Z. Cai, P. Gicheru, H. Joosten, R. Victoria, E. Milne, E. Noellemeyer, U. Pascual, G. Nziguheba, R. Vargas, A. Bationo, D. Buschiazzo, D. de-Brogniez, J. Melillo, D. Richter, M. Termansen, M. van Noordwijk, T. Goverse, C. Ballabio, T. Bhattacharyya, M. Goldhaber, N. Nikolaidis, Y. Zhao, R. Funk, C. Duffy, G. Pan, N. la Scala, P. Gottschalk, N. Batjes, J. Six, B. van Wesemael, M. Stocking, F. Bampa, M. Bernoux, C. Feller, P. Lemanceau, L. Montanarella, Benefits of soil carbon: Report on the outcomes of an international scientific committee on problems of the environment rapid assessment workshop. *Carbon Manage.* **5**, 185–192 (2014).
32. S. Narayan, M. W. Beck, P. Wilson, C. J. Thomas, A. Guerrero, C. C. Shepard, B. G. Reguero, G. Franco, J. Carter Ingram, D. Trespalacios, The value of coastal wetlands for flood damage reduction in the northeastern USA. *Sci. Rep.* **7**, 9463 (2017).
33. T. A. Boden, R. J. Andres, G. Marland, *Global, Regional, and National Fossil-Fuel CO<sub>2</sub> Emissions (1751-2014)* (V. 2017) (U.S. Department of Energy, 2017).
34. B. K. Buchner, C. Trabacchi, F. Mazza, D. Abramskieh, D. Wang, *Global Landscape of Climate Finance 2015* (Climate Policy Initiative, 2015); www.climatepolicyinitiative.org.
35. K.-H. Erb, C. Lauk, T. Kastner, A. Mayer, M. C. Theurl, H. Haberl, Exploring the biophysical option space for feeding the world without deforestation. *Nat. Commun.* **7**, 11382 (2016).
36. P. Smith, H. Haberl, A. Popp, K. H. Erb, C. Lauk, R. Harper, F. N. Tubiello, A. de Siqueira Pinto, M. Jafari, S. Sohi, O. Maser, H. Böttcher, G. Berndes, M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. A. Elsidig, C. Mbow, N. H. Ravindranath, C. W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, M. Herrero, J. I. House, S. Rose, How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob. Chang. Biol.* **19**, 2285–2302 (2013).
37. E. Brandes, G. S. McNunn, L. A. Schulte, I. J. Bonner, D. J. Muth, B. A. Babcock, B. Sharma, E. A. Heaton, Subfield profitability analysis reveals an economic case for cropland diversification. *Environ. Res. Lett.* **11**, 014009 (2016).
38. K. A. Johnson, B. J. Dalzell, M. Donahue, J. Gourevitch, D. L. Johnson, G. S. Karlovits, B. Keeler, J. T. Smith, Conservation Reserve Program (CRP) lands provide ecosystem service benefits that exceed land rental payment costs. *Ecosyst. Serv.* **18**, 175–185 (2016).
39. D. Tilman, R. Socolow, J. A. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Searchinger, C. Somerville, R. Williams, Beneficial biofuels—The food, energy, and environment trilemma. *Science* **325**, 270–271 (2009).
40. D. Tilman, J. Hill, C. Lehman, Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* **314**, 1598–1600 (2006).
41. J. E. Fargione, R. J. Plevin, J. D. Hill, The ecological impact of biofuels. *Annu. Rev. Ecol. Evol. Syst.* **41**, 351–377 (2010).
42. K. H. Erb, T. Kastner, C. Plutzer, A. L. S. Bais, N. Carvalhais, T. Fetzl, S. Gingrich, H. Haberl, C. Lauk, M. Niedertscheider, J. Pongratz, M. Thurner, S. Luysaert, Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* **553**, 73–76 (2018).
43. J. T. Abatzoglou, A. P. Williams, Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 11770–11775 (2016).
44. J. Sayer, T. Sunderland, J. Ghazoul, J.-L. Pfund, D. Sheil, E. Meijaard, M. Venter, A. Klinton Boedihartono, M. Day, C. Garcia, C. van Oosten, L. E. Buck, Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 8349–8356 (2013).
45. M. C. Hansen, P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, J. R. G. Townshend, High-resolution global maps of 21st-century forest cover change. *Science* **342**, 850–853 (2013).
46. Open Street Map, Osm2Shp (2016); http://osm2shp.ru/.
47. G. Xian, C. G. Homer, J. Dewitz, J. Fry, N. Hossain, J. Wickham, The change of impervious surface area between 2001 and 2006 in the conterminous United States. *Photogramm. Eng. Remote Sens.* **77**, 758–762 (2011).
48. U.S. Census Bureau, *Cartographic Boundary File, Urban Area for United States* (U.S. Census Bureau, 2015); www.census.gov/geo/maps-data/data/cbf/cbf\_ua.html.
49. Soil Survey Staff, *U.S. General Soil Map (STATSGO2)* (U.S. Department of Agriculture, 2017); https://sdmdataaccess.sc.gov.usda.gov.
50. T. Kroeger, R. I. McDonald, T. Boucher, P. Zhang, L. Wang, Where the people are: Current trends and future potential targeted investments in urban trees for PM<sub>10</sub> and temperature mitigation in 27 U.S. cities. *Landsch. Urban Plan.* **177**, 277–240 (2018).
51. C. Poeplau, A. Don, Carbon sequestration in agricultural soils via cultivation of cover crops—A meta-analysis. *Agric. Ecosyst. Environ.* **200**, 33–41 (2015).
52. K. Mokany, R. J. Raison, A. S. Prokushkin, Critical analysis of root: Shoot ratios in terrestrial biomes. *Glob. Chang. Biol.* **12**, 84–96 (2006).
53. R. S. Dharmakeerthi, K. Hanley, T. Whitman, D. Woolf, J. Lehmann, Organic carbon dynamics in soils with pyrogenic organic matter that received plant residue additions over seven years. *Soil Biol. Biochem.* **88**, 268–274 (2015).
54. B. Liang, J. Lehmann, D. Solomon, S. Sohi, J. E. Thies, J. O. Skjemstad, F. J. Luizão, M. H. Engelhard, E. G. Neves, S. Wirick, Stability of biomass-derived black carbon in soils. *Geochim. Cosmochim. Acta* **72**, 6069–6078 (2008).
55. X. Song, G. Pan, C. Zhang, L. Zhang, H. Wang, Effects of biochar application on fluxes of three biogenic greenhouse gases: A meta-analysis. *Ecosyst. Health Sustain.* **2**, e01202 (2016).
56. J. Wang, Z. Xiong, Y. Kuzyakov, Biochar stability in soil: Meta-analysis of decomposition and priming effects. *Glob. Change Biol. Bioenergy* **8**, 512–523 (2016).
57. R. P. Udawatta, S. Jose, Carbon sequestration potential of agroforestry practices in temperate North America, in *Carbon Sequestration Potential of Agroforestry Systems*, vol. 8 of *Advances in Agroforestry*, B. M. Kumar, P. K. R. Nair, Eds. (Springer Netherlands, 2011), pp. 17–42.
58. B. B. Henderson, P. J. Gerber, T. E. Hilinski, A. Faluccci, D. S. Ojima, M. Salvatore, R. T. Conant, Greenhouse gas mitigation potential of the world's grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. *Agric. Ecosyst. Environ.* **207**, 91–100 (2015).
59. U.S. Environmental Protection Agency, *Global Mitigation of Non-CO<sub>2</sub> Greenhouse Gases: 2010-2030* (U.S. Environmental Protection Agency, 2013).
60. Soil Survey Staff, *Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States* (U.S. Department of Agriculture, 2016); https://gdg.sc.egov.usda.gov/.
61. M. Waycott, C. M. Duarte, T. J. Carruthers, R. J. Orth, W. C. Dennison, S. Olyarnik, A. Calladine, J. W. Fourqurean, K. L. Heck Jr., A. R. Hughes, G. A. Kendrick, W. J. Kenworthy, F. T. Short, S. L. Williams, Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 12377–12381 (2009).
62. L. Pendleton, D. C. Donato, B. C. Murray, S. Crooks, W. A. Jenkins, S. Sifleet, C. Craft, J. W. Fourqurean, J. B. Kauffman, N. Marbà, P. Megonigal, E. Pidgeon, D. Herr, D. Gordon, A. Baldera, Estimating global “blue carbon” emissions from conversion and degradation of vegetated coastal ecosystems. *PLOS ONE* **7**, e43542 (2012).
63. A. Thorhaug, H. M. Poulos, J. López-Portillo, T. C. W. Ku, G. P. Berlyn, Seagrass blue carbon dynamics in the Gulf of Mexico: Stocks, losses from anthropogenic disturbance, and gains through seagrass restoration. *Sci. Total Environ.* **605–606**, 626–636 (2017).
64. J. W. Veldman, G. E. Overbeck, D. Negreiros, G. Mahy, S. Le Stradic, G. W. Fernandes, G. Durigan, E. Buisson, F. E. Putz, W. J. Bond, Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *Bioscience* **65**, 1011–1018 (2015).
65. S. Luysaert, E. D. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B. E. Law, P. Ciais, J. Grace, Old-growth forests as global carbon sinks. *Nature* **455**, 213–215 (2008).
66. B. E. Law, O. J. Sun, J. Campbell, S. Van Tuyl, P. E. Thornton, Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. *Glob. Change Biol.* **4**, 510–524 (2003).
67. D. J. Nowak, J. C. Stevens, S. M. Sisinni, C. J. Luley, Effects of urban tree management and species selection on atmospheric carbon dioxide. *J. Arboric.* **28**, 113–122 (2002).

68. K. K. McLaughlan, S. E. Hobbie, W. M. Post, Conversion from agriculture to grassland builds soil organic matter on decadal timescales. *Ecol. Appl.* **16**, 143–153 (2006).
69. E. Mclod, G. L. Chmura, S. Bouillon, R. Salm, M. Björk, C. M. Duarte, C. E. Lovelock, W. H. Schlesinger, B. R. Silliman, A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO<sub>2</sub>. *Front. Ecol. Environ.* **9**, 552–560 (2011).
70. J. W. Fourqurean, C. M. Duarte, H. Kennedy, N. Marbà, M. Holmer, M. Angel Mateo, E. T. Apostolaki, G. A. Kendrick, D. Krause-Jensen, K. J. McGlathery, O. Serrano, Seagrass ecosystems as a globally significant carbon stock. *Nat. Geosci.* **5**, 505–509 (2012).
71. J. Loisel, J. Loisel, Z. Yu, D. W. Beilman, P. Camill, J. Alm, M. J. Amesbury, D. Anderson, S. Andersson, C. Bochicchio, K. Barber, L. R. Belyea, J. Bunbury, F. M. Chambers, D. J. Charman, F. De Vleeschouwer, B. Fialkiewicz-Kozielec, S. A. Finkelstein, M. Galka, M. Garneau, D. Hammarlund, W. Hinchcliffe, J. Holmquist, P. Hughes, M. C. Jones, E. S. Klein, U. Kokfelt, A. Korhola, P. Kuhry, A. Lamarre, M. Lamentowicz, D. Large, M. Lavoie, G. MacDonald, G. Magnan, M. Mäkilä, G. Mallon, P. Mathijssen, D. Mauquoy, J. McCarroll, T. R. Moore, J. Nichols, B. O'Reilly, P. Oksanen, M. Packalen, D. Peteet, P. J. H. Richard, S. Robinson, T. Ronkainen, M. Rundgren, A. B. K. Sannel, C. Tarnocai, T. Thom, E.-S. Tuittila, M. Turetsky, M. Väliranta, M. van der Linden, B. van Geel, S. van Bellen, D. Vitt, Y. Zhao, W. Zhou, A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *Holocene* **24**, 1028–1042 (2014).
72. C. Frey, J. Penman, L. Hanle, S. Monni, S. Ogle, Chapter 3: Uncertainties, in *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Intergovernmental Panel on Climate Change, 2006), p. 3.1–3.66; [www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1\\_Volume1/V1\\_3\\_Ch3\\_Uncertainties.pdf](http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_3_Ch3_Uncertainties.pdf).
73. Climate Policy Initiative, California Carbon Dashboard (2017); <http://calcarbondash.org/>.
74. K. Hamrick, M. Gallant, *Unlocking Potential State of the Voluntary Carbon Markets 2017* (Ecosystem Marketplace, 2017).
75. U.S. Bureau of Labor Statistics, Consumer Price Index Inflation Calculator (2017); [www.bls.gov/data/inflation\\_calculator.htm](http://www.bls.gov/data/inflation_calculator.htm).
76. United Nations, *Convention on Biological Diversity* (United Nations, 1992); [www.cbd.int/doc/legal/cbd-en.pdf](http://www.cbd.int/doc/legal/cbd-en.pdf).
77. Millennium Ecosystem Assessment, *Ecosystems and Human Well-being: Synthesis* (Island Press, 2005); [www.millenniumassessment.org/en/Synthesis.html](http://www.millenniumassessment.org/en/Synthesis.html).
78. U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015* (U.S. Environmental Protection Agency, 2017).
79. E. G. Brockerhoff, H. Jactel, J. A. Parrotta, C. P. Quine, J. Sayer, Plantation forests and biodiversity: Oxymoron or opportunity? *Biodivers. Conserv.* **17**, 925–951 (2008).
80. L. L. Bremer, K. A. Farley, Does plantation forestry restore biodiversity or create green deserts? A synthesis of the effects of land-use transitions on plant species richness. *Biodivers. Conserv.* **19**, 3893–3915 (2010).
81. LANDFIRE, Biophysical Settings (2014); [www.landfire.gov/NationalProductDescriptions20.php](http://www.landfire.gov/NationalProductDescriptions20.php).
82. S. N. Goward, C. Huang, F. Zhao, K. Schleeuwis, K. Rishmawi, M. Lindsey, J. L. Dungan, A. Michaelis, *NACP NAFD Project: Forest Disturbance History from Landsat, 1986–2010* (Oak Ridge National Laboratory Distributed Active Archive Center, 2015); <http://dx.doi.org/10.3334/ORNLDAAC/1290>.
83. U.S. Department of Agriculture National Agricultural Statistics Service, *2015 Cultivated Layer* (U.S. Department of Agriculture, 2015); [www.nass.usda.gov/Research\\_and\\_Science/Cropland/Release/](http://www.nass.usda.gov/Research_and_Science/Cropland/Release/).
84. S. Jin, L. Yang, P. Danielson, C. Homer, J. Fry, G. Xian, A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sens. Environ.* **132**, 159–175 (2013).
85. U.S. Department of Agriculture National Agricultural Statistics Service, *Quick Stats* (U.S. Department of Agriculture, 2017); <https://quickstats.nass.usda.gov>.
86. J. Smith, L. Heath, K. Skog, R. Birdsey, *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States* (U.S. Department of Agriculture Forest Service, 2006); [www.actrees.org/files/Research/ne\\_gtr343.pdf](http://www.actrees.org/files/Research/ne_gtr343.pdf).
87. T. O. West, G. Marland, A. W. King, W. M. Post, A. K. Jain, K. Andrasko, Carbon management response curves: Estimates of temporal soil carbon dynamics. *Environ. Manage.* **33**, 507–518 (2004).
88. B. Ruefenacht, M. V. Finco, M. D. Nelson, R. Czaplewski, E. H. Helmer, J. A. Blackard, G. R. Holden, A. J. Lister, D. Salajano, D. Weyerhann, K. Winterberger, Coterminous U.S. and Alaska forest type mapping using forest inventory and analysis data. *Photogramm. Eng. Remote Sens.* **11**, 1379–1388 (2008).
89. K. Naudts, Y. Chen, M. J. McGrath, J. Ryder, A. Valade, J. Otto, S. Luysaert, Europe's forest management did not mitigate climate warming. *Science* **351**, 597–600 (2016).
90. L. S. Heath, P. E. Kauppi, P. Burschel, H.-D. Gregor, R. Guderian, G. H. Kohlmaier, S. Lorenz, D. Overdieck, F. Scholz, H. Thomasius, M. Weber, Contribution of temperate forests to the world's carbon budget. *Water Air Soil Pollut.* **70**, 55–69 (1993).
91. J. Creyts, A. Derkach, S. Nyquist, K. Ostrowski, J. Stephenson, *Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?* (McKinsey & Company, 2007).
92. R. W. Gorte, "U.S. tree planting for carbon sequestration" (Technical Report R40562, Congressional Research Service, 2009).
93. P. Potapov, L. Laestadius, S. Minnemeyer, *Global Map of Potential Forest Cover* (World Resources Institute, 2011); [www.wri.org/resources/maps/atlas-forest-and-landscape-restoration-opportunities/data-info](http://www.wri.org/resources/maps/atlas-forest-and-landscape-restoration-opportunities/data-info).
94. V. A. Sample, Potential for Additional carbon sequestration through regeneration of nonstocked forest land in the United States. *J. For.* **115**, 309–318 (2016).
95. U.S. Environmental Protection Agency, *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture* (U.S. Environmental Protection Agency, 2005).
96. R. Alig, G. Latta, D. Adams, B. McCarl, Mitigating greenhouse gases: The importance of land base interactions between forests, agriculture, and residential development in the face of changes in bioenergy and carbon prices. *For. Policy Econ.* **12**, 67–75 (2010).
97. D. Haim, E. M. White, R. J. Alig, Agriculture afforestation for carbon sequestration under carbon markets in the United States: Leakage behavior from regional allowance programs. *Appl. Econ. Perspect. Policy* **38**, 132–151 (2015).
98. G. Latta, D. M. Adams, R. J. Alig, E. White, Simulated effects of mandatory versus voluntary participation in private forest carbon offset markets in the United States. *J. For. Econ.* **17**, 127–141 (2011).
99. A. Golub, T. Hertel, H.-L. Lee, S. Rose, B. Sohngen, The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. *Resour. Energy Econ.* **31**, 299–319 (2009).
100. M. M. Atkinson, S. A. Fitzgerald, *Successful Reforestation: An Overview* (Oregon State University, 2002); <https://archive.extension.oregonstate.edu/sorec/sites/default/files/successful.pdf>.
101. T. Kroeger, F. J. Escobedo, J. L. Hernandez, S. Varela, S. Delphin, J. R. B. Fisher, J. Waldron, Reforestation as a novel abatement and compliance measure for ground-level ozone. *Proc. Natl. Acad. Sci. U.S.A.* **111**, E4204–E4213 (2014).
102. J. Sessions, P. Bettinger, R. Buckman, M. Newton, J. Hamann, Hastening the return of complex forests following fire: The consequences of delay. *J. For.* **102**, 38–45 (2004).
103. J. A. Stanturf, S. H. Schoenholz, C. J. Schweitzer, J. P. Shepard, Achieving restoration success: Myths in bottomland hardwood forests. *Restor. Ecol.* **9**, 189–200 (2001).
104. H. E. Garrett, W. D. Walter, L. D. Godsey, Alley Cropping: A relic from the past or a bridge to the future? *Inside Agrofor.* **19**, 1–12 (2011).
105. Board of Governors of the Federal Reserve System, *10-Year Treasury Constant Maturity Rate (DG510)* (Federal Reserve System, 2017); <https://fred.stlouisfed.org/series/DG510>.
106. S. N. Oswald, W. B. Smith, P. D. Miles, S. A. Pugh, "Forest Resources of the United States, 2012: A technical document supporting the Forest Service 2015 update of the RPA Assessment" (General Technical Report WO-91, U.S. Department of Agriculture, Forest Service, 2014).
107. B. Zeide, Thinning and growth: A full turnaround. *J. For.* **99**, 20–25 (2001).
108. M. J. Schelhaas, K. Kramer, H. Peltola, D. C. van der Werf, S. M. J. Wijdeven, Introducing tree interactions in wind damage simulation. *Ecol. Modell.* **207**, 197–209 (2007).
109. R. Goodnow, J. Sullivan, G. S. Amacher, Ice damage and forest stand management. *J. For. Econ.* **14**, 268–288 (2008).
110. C. Kuehne, A. R. Weiskittel, S. Fraver, K. J. Puettmann, Effects of thinning-induced changes in structural heterogeneity on growth, ingrowth, and mortality in secondary coastal Douglas-fir forests. *Can. J. For. Res.* **45**, 1448–1461 (2015).
111. S. M. Hood, S. Baker, A. Sala, Fortifying the forest: Thinning and burning increase resistance to a bark beetle outbreak and promote forest resilience. *Ecol. Appl.* **26**, 1984–2000 (2016).
112. M. G. Ryan, D. Binkley, J. H. Fownes, Age-related decline in forest productivity: Pattern and Process. *Adv. Ecol. Res.* **27**, 213–262 (1997).
113. U.S. Environmental Protection Agency, *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2006* (U.S. Environmental Protection Agency, 2008).
114. U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013* (U.S. Environmental Protection Agency, 2015).
115. L. S. Heath, J. E. Smith, K. E. Skog, D. J. Nowak, C. W. Woodall, Managed forest carbon estimates for the US greenhouse gas inventory, 1990–2008. *J. For.* **109**, 167–173 (2011).
116. P. B. Woodbury, J. E. Smith, L. S. Heath, Carbon sequestration in the U.S. forest sector from 1990 to 2010. *For. Ecol. Manage.* **241**, 14–27 (2007).
117. R. A. Birdsey, G. M. Lewis, "Carbon in U.S. forests and wood products, 1987–1997: State-by-state estimates" (General Technical Report NE-310, U.S. Department of Agriculture Forest Service, 2003).
118. Y. Pan, R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A. Shvidenko, S. L. Lewis, J. G. Canadell, P. Ciais, R. B. Jackson, S. W. Pacala, A. D. McGuire, S. Piao, A. Rautiainen, S. Sitch, D. Hayes, A large and persistent carbon sink in the world's forests. *Science* **333**, 988–993 (2011).
119. C. D. Oliver, B. C. Larson, *Forest Stand Dynamics: Updated Edition* (CAB Direct, 1996); [www.cabdirect.org/cabdirect/abstract/19980604521](http://www.cabdirect.org/cabdirect/abstract/19980604521).



120. J. S. Nunery, W. S. Keeton, Forest carbon storage in the northeastern United States: Net effects of harvesting frequency, post-harvest retention, and wood products. *For. Ecol. Manage.* **259**, 1363–1375 (2010).
121. A. W. D'Amato, J. B. Bradford, S. Fraver, B. J. Palik, Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. *For. Ecol. Manage.* **262**, 803–816 (2011).
122. S. Pugh, "RPA Data Wiz users guide, version 1.0" (General Technical Report NC-242, U.S. Department of Agriculture Forest Service, 2012); [www.nrs.fs.fed.us/pubs/1950](http://www.nrs.fs.fed.us/pubs/1950).
123. T. G. Johnson, J. W. Bentley, M. Howell, T. G. Johnson, J. W. Bentley, *The South's Timber Industry—An Assessment of Timber Product Output and Use, 2009* (U.S. Department of Agriculture Forest Service, 2011); [www.srs.fs.usda.gov/pubs/39409](http://www.srs.fs.usda.gov/pubs/39409).
124. M. E. Harmon, B. Marks, Effects of silvicultural practices on carbon stores in Douglas-fir western hemlock forests in the Pacific Northwest, U.S.A.: Results from a simulation model. *Can. J. For. Res.* **32**, 863–877 (2002).
125. B. Griscom, P. Ellis, F. E. Putz, Carbon emissions performance of commercial logging in East Kalimantan, Indonesia. *Glob. Chang. Biol.* **20**, 923–937 (2014).
126. D. Lussetti, E. P. Axelsson, U. Ilstedt, J. Falck, A. Karlsson, Supervised logging and climber cutting improves stand development: 18 years of post-logging data in a tropical rain forest in Borneo. *For. Ecol. Manage.* **381**, 335–346 (2016).
127. C. D. Oliver, N. T. Nassar, B. R. Lippke, J. B. McCarter, Carbon, fossil fuel, and biodiversity mitigation with wood and forests. *J. Sustain. For.* **33**, 248–275 (2014).
128. U.S. Department of Agriculture Forest Service, *Increasing the Pace of Restoration and Job Creation on Our National Forests* (U.S. Department of Agriculture Forest Service, 2012); [www.fs.fed.us/publications/restoration/restoration.pdf](http://www.fs.fed.us/publications/restoration/restoration.pdf).
129. M. A. Cairns, S. Brown, E. H. Helmer, G. A. Baumgardner, Root biomass allocation in the world's upland forests. *Oecologia* **111**, 1–11 (1997).
130. J. C. Jenkins, D. C. Chojnacky, L. S. Heath, R. A. Birdsey, "Comprehensive database of diameter-based biomass regressions for North American tree species" (General Technical Report NE-319, U.S. Department of Agriculture Forest Service, 2004).
131. Intergovernmental Panel on Climate Change, *IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 4 Forest Land* (Intergovernmental Panel on Climate Change, 2006).
132. J. Q. Chambers, N. Higuchi, J. P. Schimel, L. V. Ferreira, J. M. Melack, Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon. *Oecologia* **122**, 380–388 (2000).
133. C. A. Williams, H. Gu, R. MacLean, J. G. Masek, G. J. Collatz, Disturbance and the carbon balance of US forests: A quantitative review of impacts from harvests, fires, insects, and droughts. *Glob. Planet. Change* **143**, 66–80 (2016).
134. B. Sohngen, S. Brown, Extending timber rotations: Carbon and cost implications. *Clim. Policy* **8**, 435–451 (2008).
135. U.S. Forest Service, *National Fire Plan Operations and Reporting System* (U.S. Forest Service, 2016); <https://cohesivefire.nemac.org/node/251>.
136. D. C. Lee, A. A. Ager, D. E. Calkin, M. A. Finney, M. P. Thompson, T. M. Quigley, C. W. McHugh, *A National Cohesive Wildland Fire Management Strategy* (U.S. Department of Agriculture Forest Service, 2011), pp. 1–44.
137. M. G. Rollins, LANDFIRE: A nationally consistent vegetation, wildland fire, and fuel assessment. *Int. J. Wildland Fire* **18**, 235–249 (2009).
138. C. Wiedinmyer, M. D. Hurteau, Prescribed fire as a means of reducing forest carbon emissions in the western United States. *Environ. Sci. Technol.* **44**, 1926–1932 (2010).
139. A. L. Westerling, Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **371**, 20150178 (2016).
140. J. Kellndorfer, W. Walker, K. Kirsch, G. Fiske, J. Bishop, L. LaPoint, M. Hoppus, J. Westfall, *NACP Aboveground Biomass and Carbon Baseline Data, V.2. (NBCD 2000), U.S.A., 2000* (Oak Ridge National Laboratory Distributed Active Archive Center, 2013); <http://dx.doi.org/10.3334/ORNLDAAC/1161>.
141. Intergovernmental Panel on Climate Change, *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (Intergovernmental Panel on Climate Change, 2003); [www.ipcc-nggip.iges.or.jp](http://www.ipcc-nggip.iges.or.jp).
142. LANDFIRE, Fuel Loading Models, LANDFIRE 1.1.0 (2008); <http://landfire.cr.usgs.gov/viewer/>.
143. J. E. Smith, L. S. Heath, *A Model of Forest Floor Carbon Mass for United States Forest Types* (U.S. Department of Agriculture Forest Service, 2002); <http://purl.access.gpo.gov/GPO/LPS25756>.
144. G. W. Meijs, D. C. Donato, J. L. Campbell, J. G. Martin, B. E. Law, Forest fire impacts on carbon uptake, storage, and emission: The role of burn severity in the Eastern Cascades, Oregon. *Ecosystems* **12**, 1246–1267 (2009).
145. G. Collatz, C. Williams, B. Ghimire, S. Goward, J. Masek, CMS: Forest Biomass and Productivity, 1-degree and 5-km, Conterminous US, 2005 (Oak Ridge National Laboratory Distributed Active Archive Center, 2014); [http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds\\_id=1221](http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1221).
146. S. Dore, M. Montes-Helu, S. C. Hart, B. A. Hungate, G. W. Koch, J. B. Moon, A. J. Finkral, T. E. Kolb, Recovery of ponderosa pine ecosystem carbon and water fluxes from thinning and stand-replacing fire. *Glob. Chang. Biol.* **18**, 3171–3185 (2012).
147. J. Eidenshink, B. Schwind, K. Brewer, Z.-L. Zhu, B. Quayle, S. M. Howard, A project for monitoring trends in burn severity. *Fire Ecol.* **3**, 3–21 (2007).
148. Monitoring Trends in Burn Severity, Annual Burn Severity Mosaics (2016); [www.mtbs.gov/direct-download](http://www.mtbs.gov/direct-download).
149. O. F. Price, R. A. Bradstock, J. E. Keeley, A. D. Syphard, The impact of antecedent fire area on burned area in southern California coastal ecosystems. *J. Environ. Manage.* **113**, 301–307 (2012).
150. B. R. Hartsough, S. Abrams, R. James Barbour, E. S. Drews, J. D. Mclver, J. J. Moghaddas, D. W. Schwilk, S. L. Stephense, The economics of alternative fuel reduction treatments in western United States dry forests: Financial and policy implications from the National Fire and Fire Surrogate Study. *For. Policy Econ.* **10**, 344–354 (2008).
151. E. D. Reinhardt, R. E. Keane, D. E. Calkin, J. D. Cohen, Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *For. Ecol. Manage.* **256**, 1997–2006 (2008).
152. LANDFIRE, Biophysical Settings, LANDFIRE 1.3.0 (2012); <http://landfire.cr.usgs.gov/viewer/>.
153. U.S. Department of Agriculture Forest Service Automated Lands Program (ALP), Forest Service Regional Boundaries. *S\_USA.AdministrativeRegion* (2016); <http://data.fs.usda.gov/geodata/edw/datasets.php>.
154. J. G. Masek, W. B. Cohen, D. Leckie, M. A. Wulder, R. Vargas, B. de Jong, S. Healey, B. Law, R. Birdsey, R. A. Houghton, D. Mildrexler, S. Goward, W. B. Smith, Recent rates of forest harvest and conversion in North America. *J. Geophys. Res.* **116**, G00K03 (2011).
155. S. M. Nusser, J. J. Goebel, The National Resources Inventory: A long-term multi-resource monitoring programme. *Environ. Ecol. Stat.* **4**, 181–204 (1997).
156. U.S. Department of Agriculture, *Summary Report: 2007 National Resources Inventory* (Natural Resources Conservation Service, 2009).
157. F. Achard, H. D. Eva, P. Mayaux, H.-J. Stibig, A. Belward, Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochem. Cycles* **18**, GB2008 (2004).
158. Y. Li, M. Zhao, S. Motesharrei, Q. Mu, E. Kalnay, S. Li, Local cooling and warming effects of forests based on satellite observations. *Nat. Commun.* **6**, 6603 (2015).
159. C. Milesi, S. W. Running, C. D. Elvidge, J. B. Dietz, B. T. Tuttle, R. R. Nemani, Mapping and modeling the biogeochemical cycling of turf grasses in the United States. *Environ. Manage.* **36**, 426–438 (2005).
160. C. D. Campbell, J. R. Seiler, P. Eric Wiseman, B. D. Strahm, J. F. Munsell, Soil carbon dynamics in residential lawns converted from Appalachian mixed oak stands. *Forests* **5**, 425–438 (2014).
161. U.S. Geological Survey Gap Analysis Program, *Protected Areas Database of the United States (PAD-US), Version 1.4 Combined Feature Class* (U.S. Geological Survey, 2016); <https://gapanalysis.usgs.gov/padus/>.
162. N. L. Harris, S. C. Hagen, S. S. Saatchi, T. R. H. Pearson, C. W. Woodall, G. M. Domke, B. H. Braswell, B. F. Walters, S. Brown, W. A. Salas, A. Fore, Y. Yu, Attribution of net carbon change by disturbance type across forest lands of the conterminous United States. *Carbon Balance Manage.* **11**, 24 (2016).
163. D. Zheng, L. S. Heath, M. J. Ducey, J. E. Smith, Carbon changes in conterminous US forests associated with growth and major disturbances: 1992–2001. *Environ. Res. Lett.* **6**, 019502 (2011).
164. N. E. Thomas, C. Huang, S. N. Goward, S. Powell, K. Rishmawi, K. Schleeweis, A. Hinds, Validation of North American Forest Disturbance dynamics derived from Landsat time series stacks. *Remote Sens. Environ.* **115**, 19–32 (2011).
165. P. Olofsson, G. M. Foody, M. Herold, S. V. Stehman, C. E. Woodcock, M. A. Wulder, Good practices for estimating area and assessing accuracy of land change. *Remote Sens. Environ.* **148**, 42–57 (2014).
166. S. Hagen, N. Harris, S. S. Saatchi, T. Pearson, C. W. Woodall, S. Ganguly, G. M. Domke, B. H. Braswell, B. F. Walters, J. C. Jenkins, S. Brown, W. A. Salas, A. Fore, Y. Yu, R. R. Nemani, C. Ipsan, K. R. Brown, *CMS: Forest Carbon Stocks, Emissions, and Net Flux for the Conterminous US: 2005-2010* (ORNL DAAC, 2016); <http://dx.doi.org/10.3334/ORNLDAAC/1313>.
167. J. A. Blackard, M. V. Finco, E. H. Helmer, G. R. Holden, M. L. Hoppus, D. M. Jacobs, A. J. Lister, G. G. Moisen, M. D. Nelson, R. Riemann, B. Rufenacht, D. Salajanu, D. L. Weyermann, K. C. Winterberger, T. J. Brandeis, R. L. Czaplewski, R. E. McRoberts, P. L. Patterson, R. P. Tymcio, Mapping U.S. forest biomass using nationwide forest inventory data and moderate resolution information. *Remote Sens. Environ.* **112**, 1658–1677 (2008).
168. U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis National Program; [www.fia.fs.fed.us/tools-data](http://www.fia.fs.fed.us/tools-data).
169. B. T. Wilson, C. W. Woodall, D. M. Griffith, Imputing forest carbon stock estimates from inventory plots to a nationally continuous coverage. *Carbon Balance Manage.* **8**, 1 (2013).
170. N. Neeti, R. Kennedy, Comparison of national level biomass maps for conterminous US: Understanding pattern and causes of differences. *Carbon Balance Manage.* **11**, 19 (2016).

171. R. N. Lubowski, A. J. Plantinga, R. N. Stavins, Land-use change and carbon sinks: Econometric estimation of the carbon sequestration supply function. *J. Environ. Econ. Manage.* **51**, 135–152 (2006).
172. J. O. Sexton, J. O. Sexton, X.-P. Song, M. Feng, P. Noojipady, A. Anand, C. Huang, D.-H. Kim, K. M. Collins, S. Channan, C. DiMiceli, J. R. Townshend, Global, 30-m resolution continuous fields of tree cover: Landsat-based rescaling of MODIS vegetation continuous fields with lidar-based estimates of error. *Int. J. Digit. Earth* **6**, 427–448 (2013).
173. E. G. McPherson, J. R. Simpson, P. J. Peper, S. E. Maco, Q. Xiao, Municipal forest benefits and costs in five US cities. *J. For.* **103**, 411–416 (2005).
174. U.S. Department of Agriculture, Farm Service Agency, National Agricultural Inventory Program (2015); [www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/](http://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/).
175. D. J. Nowak, E. J. Greenfield, Tree and impervious cover change in U.S. cities. *Urban For. Urban Green.* **11**, 21–30 (2012).
176. D. M. Olson, E. Dinerstein, E. D. Wikramanayake, N. D. Burgess, G. V. N. Powell, E. C. Underwood, J. A. D'Amico, I. Itoua, H. E. Strand, J. C. Morrison, C. J. Loucks, T. F. Allnutt, T. H. Ricketts, Y. Kura, J. F. Lamoreux, W. W. Wettengel, P. Hedao, K. R. Kassem, Terrestrial ecoregions of the world: A new map of life on Earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *Bioscience* **51**, 933–938 (2001).
177. N. Bassuk, D. Curtis, B. Murrain, B. Neal, *Recommended Urban Trees: Site Assessment and Tree Selection for Stress Tolerance* (Cornell University, 2009); [www.hort.cornell.edu/uhil/outreach/recurbtrees/pdfs/~recurbtrees.pdf](http://www.hort.cornell.edu/uhil/outreach/recurbtrees/pdfs/~recurbtrees.pdf).
178. L. Bounoua, J. Nigro, P. Zhang, K. Thome, Mapping impact of urbanization in the continental U.S. from 2001–2020, in 2016 *IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (IEEE, 2016), pp. 6750–6753.
179. E. G. McPherson, J. R. Simpson, P. J. Peper, K. I. Scott, Q. Xiao, *Tree Guidelines for Coastal Southern California Communities* (Local Government Commission, 2000); [www.lgc.org/wordpress/docs/freepub/energy/guides/social\\_tree\\_guidelines.pdf](http://www.lgc.org/wordpress/docs/freepub/energy/guides/social_tree_guidelines.pdf).
180. E. G. McPherson, S. E. Maco, J. R. Simpson, P. J. Peper, Q. Xiao, A. Van Der Zanden, N. Bell, *Western Washington and Oregon Community Tree Guide: Benefits, Costs and Strategic Planting* (U.S. Department of Agriculture Forest Service, 2002); [www.treesearch.fs.fed.us/pubs/45962](http://www.treesearch.fs.fed.us/pubs/45962).
181. E. G. McPherson, J. R. Simpson, P. J. Peper, Q. Xiao, S. E. Maco, P. J. Hoefer, *Northern Mountain and Prairie Community Tree Guide: Benefits, Costs and Strategic Planting* (U.S. Department of Agriculture Forest Service, 2003); [www.fs.fed.us/psw/topics/urban\\_forestry/products/cufr\\_258.pdf](http://www.fs.fed.us/psw/topics/urban_forestry/products/cufr_258.pdf).
182. H. Pretzsch, P. Biber, E. Uhl, J. Dahlhausen, T. Rötzer, J. Caldentey, T. Koike, T. van Con, A. Chavanne, T. Seifert, B. du Toit, C. Farnen, S. Pauleit, Crown size and growing space requirement of common tree species in urban centres, parks, and forests. *Urban For. Urban Green.* **14**, 466–479 (2015).
183. D. J. Nowak, E. J. Greenfield, R. E. Hoehn, E. Lapoint, Carbon storage and sequestration by trees in urban and community areas of the United States. *Environ. Pollut.* **178**, 229–236 (2013).
184. S. N. Oswalt, W. B. Smith, *U.S. Forest Resource Facts and Historical Trends* (U.S. Department of Agriculture, 2014).
185. R. Harper, G. Hernandez, J. Arseneault, M. Bryntesen, S. Enebak, R. Overton, Forest nursery seedling production in the United States—Fiscal year 2012. *Tree Plant. Notes* **56**, 72–75 (2013).
186. J. Bond, *The Inclusion of Large-Scale Tree Planting in a State Implementation Plan: A Feasibility Study* (Davey Research Group, 2006); [www.urbanforestanalytics.com/sites/default/files/pdf/TreesInSIP.pdf](http://www.urbanforestanalytics.com/sites/default/files/pdf/TreesInSIP.pdf).
187. U.S. Census Bureau, Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2010 to July 1, 2015 (NST-EST2015-01); <https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk>.
188. M. W. Strohbach, E. Arnold, D. Haase, The carbon footprint of urban green space—A life cycle approach. *Landsc. Urban Plan.* **104**, 220–229 (2012).
189. G. H. Donovan, D. T. Butry, The value of shade: Estimating the effect of urban trees on summertime electricity use. *Energy Build.* **41**, 662–668 (2009).
190. H. Akbari, Shade trees reduce building energy use and CO<sub>2</sub> emissions from power plants. *Environ. Pollut.* **116**, S119–S126 (2002).
191. M. R. McHale, E. G. McPherson, I. C. Burke, The potential of urban tree plantings to be cost effective in carbon credit markets. *Urban For. Urban Green.* **6**, 49–60 (2007).
192. L. A. Roman, J. J. Battles, J. R. McBride, *Urban Tree Mortality: A Primer on Demographic Approaches* (U.S. Department of Agriculture Forest Service, 2016); [www.treesearch.fs.fed.us/pubs/50688](http://www.treesearch.fs.fed.us/pubs/50688).
193. J. B. Bradford, D. N. Kastendick, Age-related patterns of forest complexity and carbon storage in pine and aspen–birch ecosystems of northern Minnesota, USA. *Can. J. For. Res.* **40**, 401–409 (2010).
194. WM Financial Strategies, Rates Over Time - Interest Rate Trends; [www.munibondadvisor.com/market.htm](http://www.munibondadvisor.com/market.htm).
195. T. Hengl, J. M. de Jesus, G. B. M. Heuvelink, M. R. Gonzalez, M. Kilbarda, A. Blagotić, W. Shangguan, M. N. Wright, X. Geng, B. Bauer-Marschallinger, M. A. Guevara, R. Vargas, R. A. MacMillan, N. H. Batjes, J. G. B. Leenaars, E. Ribeiro, I. Wheeler, S. Mantel, B. Kempen, SoilGrids250m: Global gridded soil information based on machine learning. *PLOS ONE* **12**, e0169748 (2017).
196. European Space Agency, *Land Cover CCI Product User Guide Version 2.0* (European Space Agency, 2017), pp. 1–105.
197. P. L. Sims, J. S. Singh, The structure and function of ten Western North American grasslands: II. Intra-seasonal dynamics in primary producer compartments. *J. Ecol.* **66**, 547–572 (1978).
198. P. L. Sims, J. S. Singh, W. K. Lauenroth, The structure and function of ten Western North American Grasslands: I. Abiotic and vegetational characteristics. *J. Ecol.* **66**, 251–285 (1978).
199. M. B. Cleary, E. Pendall, B. E. Ewers, Aboveground and belowground carbon pools after fire in mountain big sagebrush steppe. *Rangel. Ecol. Manag.* **63**, 187–196 (2010).
200. B. A. Bradley, R. A. Houghton, J. F. Mustard, S. P. Hamburg, Invasive grass reduces aboveground carbon stocks in shrublands of the Western US. *Glob. Chang. Biol.* **12**, 1815–1822 (2006).
201. Conservation Reserve Program Average Payments by County (2017); <https://catalog.data.gov/dataset/conservation-reserve-program-average-payments-by-county>.
202. U.S. Department of Agriculture National Agricultural Statistics Service, *Crop Production 2016 Summary* (U.S. Department of Agriculture National Agricultural Statistics Service, 2017); [www.nass.usda.gov/](http://www.nass.usda.gov/).
203. U.S. Department of Agriculture National Agricultural Statistics Service, *2012 Census of Agriculture* (U.S. Department of Agriculture National Agricultural Statistics Service, 2014); [www.nass.usda.gov/Publications/AgCensus/2012/](http://www.nass.usda.gov/Publications/AgCensus/2012/).
204. K. D. Belfry, L. L. Van Eerd, Establishment and impact of cover crops intersown into corn. *Crop. Sci.* **56**, 1245–1256 (2016).
205. P. Smith, D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider, S. Towprayoon, M. Wattenbach, J. Smith, Greenhouse gas mitigation in agriculture. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **363**, 789–813 (2008).
206. J. M. Baker, T. E. Ochsner, R. T. Venterea, T. J. Griffith, Tillage and soil carbon sequestration—What do we really know? *Agric. Ecosyst. Environ.* **118**, 1–5 (2007).
207. Z. Luo, E. Wang, O. J. Sun, Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. *Agric. Ecosyst. Environ.* **139**, 224–231 (2010).
208. C. Palm, H. Blanco-Canqui, F. DeClerck, L. Gátere, P. Grace, Conservation agriculture and ecosystem services: An overview. *Agric. Ecosyst. Environ.* **187**, 87–105 (2014).
209. D. S. Powlson, C. M. Stirling, M. L. Jat, B. G. Gerard, C. A. Palm, P. A. Sanchez, K. G. Cassman, Limited potential of no-till agriculture for climate change mitigation. *Nat. Clim. Change* **4**, 678–683 (2014).
210. A. J. VandenBygaart, The myth that no-till can mitigate global climate change. *Agric. Ecosyst. Environ.* **216**, 98–99 (2016).
211. J. Six, S. M. Ogle, F. J. Breidt, R. T. Conant, A. R. Mosier, K. Paustian, The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. *Glob. Chang. Biol.* **10**, 155–160 (2004).
212. B. A. Linquist, M. A. Adviento-Borbe, C. M. Pittelkow, C. van Kessel, K. J. van Groenigen, Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Res.* **135**, 10–21 (2012).
213. P. R. Hill, Use of continuous no-till and rotational tillage systems in the central and northern Corn Belt. *J. Soil Water Conserv.* **56**, 286–290 (2001).
214. S. S. Snapp, S. M. Swinton, R. Labarta, D. Mutch, J. R. Black, R. Leep, J. Nyiraneza, K. O'Neil, Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agron. J.* **97**, 322–332 (2005).
215. M. Liebig, A. J. Franzluebbers, R. F. Follett, *Managing Agricultural Greenhouse Gases: Coordinated Agricultural Research Through GRACEnet to Address Our Changing Climate* (Elsevier, 2012).
216. ICF International, *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production Within the United States* (U.S. Department of Agriculture, 2013).
217. A. Clark, *Managing Cover Crops Profitably* (Sustainable Agriculture Network, ed. 3, 2007), vol. 9.
218. R. L. Cochran, R. K. Roberts, J. A. Larson, D. D. Tyler, Cotton profitability with alternative lime application rates, cover crops, nitrogen rates, and tillage methods. *Agron. J.* **99**, 1085–1092 (2007).
219. P. Smith, M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. A. Elsidig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N. H. Ravindranath, C. W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, F. Tubiello, *Agriculture, Forestry and Other Land Use (AFOLU)* (Cambridge Univ. Press, 2014).
220. C. L. Keene, W. S. Curran, Optimizing high-residue cultivation timing and frequency in reduced-tillage soybean and corn. *Agron. J.* **108**, 1897–1906 (2016).

221. K. A. O'Reilly, J. D. Lauzon, R. J. Vyn, L. L. Van Eerd, Nitrogen cycling, profit margins and sweet corn yield under fall cover crop systems. *Can. J. Soil Sci.* **92**, 353–365 (2012).
222. R. K. Roberts, J. A. Larson, D. D. Tyler, B. N. Duck, K. D. Dillivan, Economic analysis of the effects of winter cover crops on no-tillage corn yield response to applied nitrogen. *J. Soil Water Conserv.* **53**, 280–284 (1998).
223. CTIC, SARE, ASTA, *Annual Report 2015-2016: Cover Crop Survey* (CTIC, SARE, ASTA, 2016).
224. S. Jeffery, F. G. A. Verheijen, M. van der Velde, A. C. Bastos, A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agric. Ecosyst. Environ.* **144**, 175–187 (2011).
225. U.S. Department of Energy, *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks* (Oak Ridge National Laboratory, 2016).
226. K. A. Spokas, Review of the stability of biochar in soils: Predictability of O:C molar ratios. *Carbon Manage.* **1**, 289–303 (2010).
227. D. Woolf, J. E. Amonette, F. A. Street-Perrott, J. Lehmann, S. Joseph, Sustainable biochar to mitigate global climate change. *Nat. Commun.* **1**, 56 (2010).
228. P. Gallagher, M. Dikeman, J. Fritz, E. Wailes, W. Gauthier, H. Shapouri, "Biomass from crop residues: Cost and supply estimates" (Agricultural Economic Report No. 819, U.S. Department of Agriculture, 2003).
229. A. Milbrandt, "A geographic perspective on the current biomass resource availability in the United States" (Technical Report NREL/TP-560-39181, National Renewable Energy Laboratory, 2005).
230. S. Kumarappan, S. Joshi, H. L. MacLean, Biomass supply for biofuel production: Estimates for the United States and Canada. *BioResources* **4**, 1070–1087 (2009).
231. J. S. Gregg, S. J. Smith, Global and regional potential for bioenergy from agricultural and forestry residue biomass. *Mitigation Adapt. Strategies Glob. Change* **15**, 241–262 (2010).
232. A. Chatterjee, Annual crop residue production and nutrient replacement costs for Bioenergy feedstock production in United States. *Agron. J.* **105**, 685–692 (2013).
233. A. Demirbas, Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues. *J. Anal. Appl. Pyrolysis* **72**, 243–248 (2004).
234. H. Sun, W. C. Hockaday, C. A. Masiello, K. Zygourakis, Multiple controls on the chemical and physical structure of biochars. *Ind. Eng. Chem. Res.* **51**, 3587–3597 (2012).
235. Y. Sun, B. Gao, Y. Yao, J. Fang, M. Zhang, Y. Zhou, H. Chen, L. Yang, Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties. *Chem. Eng. J.* **240**, 574–578 (2014).
236. Y. Lee, J. Park, C. Ryu, K. S. Gang, W. Yang, Y.-K. Park, J. Jung, S. Hyun, Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500°C. *Bioresour. Technol.* **148**, 196–201 (2013).
237. L. Zhao, X. Cao, O. Mašek, A. Zimmerman, Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. *J. Hazard. Mater.* **256–257**, 1–9 (2013).
238. R. P. Udawatta, S. Jose, Agroforestry strategies to sequester carbon in temperate North America. *Agroforest. Syst.* **86**, 225–242 (2012).
239. P. K. R. Nair, B. M. Kumar, V. D. Nair, Agroforestry as a strategy for carbon sequestration. *J. Plant Nutr. Soil Sci.* **172**, 10–23 (2009).
240. A. D. Bambrick, J. K. Whalen, R. L. Bradley, A. Cogliastro, A. M. Gordon, A. Olivier, N. V. Thevathasan, Spatial heterogeneity of soil organic carbon in tree-based intercropping systems in Quebec and Ontario, Canada. *Agroforest. Syst.* **79**, 343–353 (2010).
241. R. Cardinael, T. Chevallier, B. G. Barthès, N. P. A. Saby, T. Parent, C. Dupraz, M. Bernoux, C. Chenu, Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon—A case study in a Mediterranean context. *Geoderma* **259–260**, 288–299 (2015).
242. P. Tsonkova, C. Böhm, A. Quinkenstein, D. Freese, Ecological benefits provided by alley cropping systems for production of woody biomass in the temperate region: A review. *Agroforest. Syst.* **85**, 133–152 (2012).
243. M. Oelbermann, R. P. Voroney, N. V. Thevathasan, A. M. Gordon, D. C. L. Kass, A. M. Schlönvoigt, Soil carbon dynamics and residue stabilization in a Costa Rican and southern Canadian alley cropping system. *Agroforest. Syst.* **68**, 27–36 (2006).
244. M. Peichl, N. V. Thevathasan, A. M. Gordon, J. Huss, R. A. Abohassan, Carbon sequestration potentials in temperate tree-based intercropping systems, Southern Ontario, Canada. *Agroforest. Syst.* **66**, 243–257 (2006).
245. S. Lu, P. Meng, J. Zhang, C. Yin, S. Sun, Changes in soil organic carbon and total nitrogen in croplands converted to walnut-based agroforestry systems and orchards in southeastern Loess Plateau of China. *Environ. Monit. Assess.* **187**, 688 (2015).
246. F. Montagnini, P. K. R. Nair, Carbon sequestration: An underexploited environmental benefit of agroforestry systems. *Agroforest. Syst.* **61–62**, 281–295 (2004).
247. J. R. Thiessen Martens, M. H. Entz, M. D. Wonneck, Review: Redesigning Canadian prairie cropping systems for profitability, sustainability, and resilience. *Can. J. Plant Sci.* **95**, 1049–1072 (2015).
248. G. M. M. A. Senaviratne, R. P. Udawatta, K. A. Nelson, K. Shannon, S. Jose, Temporal and spatial influence of perennial upland buffers on corn and soybean yields. *Agron. J.* **104**, 1356–1362 (2012).
249. M. A. Cary, G. E. Frey, D. E. Mercer, The value of versatile alley cropping in the Southeast US: A Monte Carlo simulation, in *Proceedings of the Inaugural Symposium of the International Society of Forest Resource Economics 2014* (U.S. Department of Agriculture Forest Service, 2014), pp. 1–6; www.srs.fs.usda.gov/pubs/ja/2014/ja\_2014\_frey\_001.pdf.
250. G. Garrett, W. Walter, L. D. Godsey, Alley cropping: Farming between the trees. *Green Horizons.* **19**, 1 (2015).
251. L. Harper, W. Kurtz, Economics of Eastern black walnut agroforestry systems, in *Nut Production Handbook for Eastern Black Walnut* (Southwest Missouri Resources, Conservation & Development, 1998), pp. 32–36.
252. W. T. Stamps, R. L. McGraw, L. Godsey, T. L. Woods, The ecology and economics of insect pest management in nut tree alley cropping systems in the Midwestern United States. *Agric. Ecosyst. Environ.* **131**, 4–8 (2009).
253. U.S. Department of Agriculture National Agroforestry Center, Alley cropping. A relic from the past or a bridge to the future? *Inside Agroforest.* **19**, 1–12 (2009).
254. G. E. Frey, D. E. Mercer, F. W. Cabbage, R. C. Abt, Economic potential of agroforestry and forestry in the lower Mississippi alluvial valley with incentive programs and carbon payments. *South. J. Appl. For.* **34**, 176–185 (2011).
255. D. E. Mercer, G. E. Cabbage, F. W. Frey, Economics of agroforestry, in *Handbook of Forest Resource Economics*, S. Kant, J. R. R. Alavalapati, Eds. (Earthscan from Routledge, 2014), pp. 188–209.
256. U.S. Department of Agriculture, *Summary Report: 2012 National Resources Inventory* (U.S. Department of Agriculture, 2015); www.nrcs.usda.gov/technical/nri/12summary.
257. A. Wotherspoon, N. V. Thevathasan, A. M. Gordon, R. P. Voroney, Carbon sequestration potential of five tree species in a 25-year-old temperate tree-based intercropping system in southern Ontario, Canada. *Agroforest. Syst.* **88**, 631–643 (2014).
258. E. A. Davidson, The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nat. Geosci.* **2**, 659–662 (2009).
259. C. S. Snyder, T. W. Brulsema, T. L. Jensen, P. E. Fixen, Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. Environ.* **133**, 247–266 (2009).
260. J. Hill, S. Polasky, E. Nelson, D. Tilman, H. Huo, L. Ludwig, J. Neumann, H. Zheng, D. Bonta, Climate change and health costs of air emissions from biofuels and gasoline. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 2077–2082 (2009).
261. J. Lelieveld, J. S. Evans, M. Fnais, D. Giannadaki, A. Pozzer, The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* **525**, 367–371 (2015).
262. G. Myhre, D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, H. Zhang, Anthropogenic and Natural Radiative Forcing, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M. Midgley, Eds. (Cambridge Univ. Press, 2013), vol. 423, pp. 659–740.
263. S. Sela, H. M. van Es, B. N. Moebius-Clune, R. Marjerison, J. Melkonian, D. Moebius-Clune, R. Schindelbeck, S. Gomes, Adapt-N outperforms grower-selected nitrogen rates in northeast and midwestern united states strip trials. *Agron. J.* **108**, 1726–1734 (2016).
264. Food and Agriculture Organization of the United Nations, *FAOSTAT Online Statistical Service* (Food and Agriculture Organization of the United Nations, 2014); www.fao.org/faostat/en/#data.
265. E. Stehfest, L. Bouwman, N<sub>2</sub>O and NO emission from agricultural fields and soils under natural vegetation: Summarizing available measurement data and modeling of global annual emissions. *Nutr. Cycling Agroecosyst.* **74**, 207–228 (2006).
266. D. L. Burton, X. Li, C. A. Grant, Influence of fertilizer nitrogen source and management practice on N<sub>2</sub>O emissions from two Black Chernozemic soils. *Can. J. Soil Sci.* **88**, 219–227 (2008).
267. R. T. Venterea, M. S. Dolan, T. E. Ochsner, Urea decreases nitrous oxide emissions compared with anhydrous ammonia in a Minnesota corn cropping system. *Soil Sci. Soc. Am. J.* **74**, 407–418 (2010).
268. M. J. Bell, J. M. Cloy, C. F. E. Topp, B. C. Ball, A. Bagnall, R. M. Rees, D. R. Chadwick, Quantifying N<sub>2</sub>O emissions from intensive grassland production: The role of synthetic fertilizer type, application rate, timing and nitrification inhibitors. *J. Agric. Sci.* **154**, 812–827 (2016).
269. X. Hao, C. Chang, J. M. Carefoot, H. H. Janzen, B. H. Ellert, Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. *Nutr. Cycling Agroecosyst.* **60**, 1–8 (2001).
270. C. F. Drury, W. D. Reynolds, X. M. Yang, N. B. McLaughlin, T. W. Welacky, W. Calder, C. A. Grant, Nitrogen source, application time, and tillage effects on soil nitrous oxide emissions and corn grain yields. *Soil Sci. Soc. Am. J.* **76**, 1268–1279 (2011).

271. J. P. Burzaco, D. R. Smith, T. J. Vyn, Nitrous oxide emissions in Midwest US maize production vary widely with band-injected N fertilizer rates, timing and nitrapyrin presence. *Environ. Res. Lett.* **8**, 035031 (2013).
272. R. T. Venterea, J. A. Coulter, M. S. Dolan, Evaluation of intensive "4R" strategies for decreasing nitrous oxide emissions and nitrogen surplus in rainfed corn. *J. Environ. Qual.* **45**, 1186–1195 (2016).
273. R. H. Beach, B. J. DeAngelo, S. Rose, C. Li, W. Salas, S. J. DelGrosso, Mitigation potential and costs for global agricultural greenhouse gas emissions. *Agric. Econ.* **38**, 109–115 (2008).
274. D. S. Reay, E. A. Davidson, K. A. Smith, P. Smith, J. M. Melillo, F. Dentener, P. J. Crutzen, Global agriculture and nitrous oxide emissions. *Nat. Clim. Change* **2**, 410–416 (2012).
275. O. Oenema, X. Ju, C. Klein, M. Alfaro, A. Prado, J. P. Lesschen, X. Zheng, G. Velthof, L. Ma, B. Gao, C. Kroeze, M. Sutton, Reducing nitrous oxide emissions from the global food system. *Curr. Opin. Environ. Sustain.* **9–10**, 55–64 (2014).
276. P. C. West, J. S. Gerber, P. M. Engstrom, N. D. Mueller, K. A. Brauman, K. M. Carlson, E. S. Cassidy, M. Johnston, Graham K. MacDonald, D. K. Ray, S. Siebert, Leverage points for improving global food security and the environment. *Science* **345**, 325–328 (2014).
277. M. Ribaud, J. Delgado, L. Hansen, M. Livingston, R. Mosheim, J. Williamson, "Nitrogen in agricultural systems: Implications for conservation policy" (Economic Research Report No. ERR-127, U.S. Department of Agriculture Economic Research Service, 2011).
278. N. Millar, G. P. Robertson, P. R. Grace, R. J. Gehl, J. P. Hoben, Nitrogen fertilizer management for nitrous oxide (N<sub>2</sub>O) mitigation in intensive corn (Maize) production: An emissions reduction protocol for US Midwest agriculture. *Mitigation Adapt. Strategies Glob. Change* **15**, 185–204 (2010).
279. U. Sehy, R. Ruser, J. C. Munch, Nitrous oxide fluxes from maize fields: Relationship to yield, site-specific fertilization, and soil conditions. *Agric. Ecosyst. Environ.* **99**, 97–111 (2003).
280. P. C. Scharf, D. K. Shannon, H. L. Palm, K. A. Sudduth, S. T. Drummond, N. R. Kitchen, L. J. Mueller, V. C. Hubbard, L. F. Oliveira, Sensor-based nitrogen applications out-performed producer-chosen rates for corn in on-farm demonstrations. *Agron. J.* **103**, 1683–1691 (2011).
281. D. Schimmpfenning, *Farm Profits and Adoption of Precision Agriculture* (United States Department of Agriculture Economic Research Service, 2016); [www.ers.usda.gov/webdocs/publications/80326/err-217.pdf?v=4266](http://www.ers.usda.gov/webdocs/publications/80326/err-217.pdf?v=4266).
282. U.S. Department of Agriculture National Agricultural Statistics Service, *Agricultural Prices* (U.S. Department of Agriculture National Agricultural Statistics Service, 2017); <http://usda.mannlib.cornell.edu/usda/nass/AgriPric//2010s/2017/AgriPric-12-28-2017.pdf>.
283. D. B. Mengel, *Types and Uses of Nitrogen Fertilizers for Crop Production* (Purdue University, 1986).
284. B. G. Bareja, General information and practices in using urea fertilizer (2013); [www.cropsreview.com](http://www.cropsreview.com).
285. G. A. Helmers, J. Brandle, Optimum windbreak spacing in great plains agriculture. *Great Plains Res.* **15**, 179–198 (2005).
286. Y. G. Chendev, L. L. Novykh, T. J. Sauer, C. L. Petin, A. N. Zazdravnykh, E. A. Burras, in *Soil Carbon Progress in Soil Science*, A. E. Hartemink, K. McSweeney, Eds. (Springer International Publishing, 2014), pp. 475–482.
287. F. Wang, X. Xu, B. Zou, Z. Guo, Z. Li, W. Zhu, Biomass accumulation and carbon sequestration in four different aged *Casuarina equisetifolia* coastal shelterbelt plantations in South China. *PLOS ONE* **8**, e77449 (2013).
288. T. J. Sauer, C. A. Cambardella, J. R. Brandle, Soil carbon and tree litter dynamics in a red cedar–scotch pine shelterbelt. *Agroforest. Syst.* **71**, 163–174 (2007).
289. J. Kort, R. Turnock, Carbon reservoir and biomass in Canadian prairie shelterbelts. *Agroforest. Syst.* **44**, 175–186.
290. M. M. Schoeneberger, Agroforestry: Working trees for sequestering carbon on agricultural lands. *Agroforest. Syst.* **75**, 27–37 (2008).
291. U.S. Department of Agriculture Farm Service Agency, *Conservation Reserve Program: Annual Summary and Enrollment Statistics-FY2010* (U.S. Department of Agriculture Farm Service Agency, 2010).
292. B. Henderson, A. Faluccci, A. Mottet, L. Early, B. Werner, H. Steinfeld, P. Gerber, Marginal costs of abating greenhouse gases in the global ruminant livestock sector. *Mitigation Adapt. Strategies Glob. Change* **22**, 199–224 (2017).
293. L. M. Porensky, E. A. Leger, J. Davison, W. W. Miller, E. M. Goergen, E. K. Espeland, E. M. Carroll-Moore, Arid old-field restoration: Native perennial grasses suppress weeds and erosion, but also suppress native shrubs. *Agric. Ecosyst. Environ.* **184**, 135–144 (2014).
294. I. Kämpf, N. Hölzel, M. Störrle, G. Broll, K. Kiehl, Potential of temperate agricultural soils for carbon sequestration: A meta-analysis of land-use effects. *Sci. Total Environ.* **566–567**, 428–435 (2016).
295. D. L. Gebhart, H. B. Johnson, H. S. Mayeux, H. W. Polley, The CRP increases soil organic carbon. *J. Soil Water Conserv.* **49**, 488–492 (1994).
296. J. Fargione, J. Hill, D. Tilman, S. Polasky, P. Hawthorne, Land clearing and the biofuel carbon debt. *Science* **319**, 1235–1238 (2008).
297. B. O. Sander, R. Wassmann, D. L. C. Siopongco, *Mitigating Greenhouse Gas Emissions from Rice Production Through Water-Saving Techniques: Potential, Adoption and Empirical Evidence* (International Rice Research Institute, 2015).
298. X. Yan, H. Akiyama, K. Yagi, H. Akimoto, Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change guidelines. *Global Biogeochem. Cycles* **23**, GB2002 (2009).
299. U.S. Department of Agriculture Foreign Agricultural Service, "World agricultural production" (Circular Series WAP 05-17, U.S. Department of Agriculture Foreign Agricultural Service, 2017).
300. P. Fazli, H. C. Man, Comparison of methane emission from conventional and modified paddy cultivation in Malaysia. *Agric. Agric. Sci. Proc.* **2**, 272–279 (2014).
301. M. Peyron, C. Bertora, S. Pelissetti, D. Said-Pullicino, L. Celi, E. Miniotti, M. Romani, D. Sacco, Greenhouse gas emissions as affected by different water management practices in temperate rice paddies. *Agric. Ecosyst. Environ.* **232**, 17–28 (2016).
302. C. M. Pittelkow, Y. Assa, M. Burger, R. G. Mutters, C. A. Greer, L. A. Espino, J. E. Hill, W. R. Horwath, C. van Kessel, B. A. Linquist, Nitrogen management and methane emissions in direct-seeded rice systems. *Agron. J.* **106**, 968–980 (2014).
303. A. L. Hinson, R. A. Feagin, M. Eriksson, R. G. Najjar, M. Herrmann, T. S. Bianchi, M. Kemp, J. A. Hutchings, S. Crooks, T. Boutton, The spatial distribution of soil organic carbon in tidal wetland soils of the continental United States. *Glob. Chang. Biol.* **23**, 5468–5480 (2017).
304. H. J. Poffenbarger, B. A. Needelman, J. P. Megonigal, Salinity influence on methane emissions from tidal marshes. *Wetlands* **31**, 831–842 (2011).
305. Intergovernmental Panel on Climate Change, *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (Intergovernmental Panel on Climate Change, 2013).
306. S. C. Neubauer, J. P. Megonigal, Moving beyond global warming potentials to quantify the climatic role of ecosystems. *Ecosystems* **18**, 1000–1013 (2015).
307. F. E. Anderson, B. Bergamaschi, C. Sturtevant, S. Knox, L. Hastings, L. Windham-Myers, M. Detto, E. L. Hestir, J. Drexler, R. L. Miller, J. H. Matthes, J. Verfaillie, D. Baldocchi, R. L. Snyder, R. Fujii, Variation of energy and carbon fluxes from a restored temperate freshwater wetland and implications for carbon market verification protocols. *J. Geophys. Res. Biogeosci.* **121**, 777–795 (2016).
308. S. D. Bridgman, J. P. Megonigal, J. K. Keller, N. B. Bliss, C. Trettin, The carbon balance of North American wetlands. *Wetlands* **26**, 889–916 (2006).
309. U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014* (Environmental Protection Agency, 2016).
310. C. Richardson, R. Evans, D. Carr, in *Pocosin Wetlands: An Integrated Analysis of Coastal Plain Freshwater Bogs in North Carolina* (Hutchinson Ross Publishing Company, 1981), pp. 3–19.
311. S. D. Bridgman, C. J. Richardson, Mechanisms controlling soil respiration (CO<sub>2</sub> and CH<sub>4</sub>) in southern peatlands. *Soil Biol. Biochem.* **24**, 1089–1099 (1992).
312. J. P. Megonigal, W. H. Schlesinger, Enhanced CH<sub>4</sub> emission from a wetland soil exposed to elevated CO<sub>2</sub>. *Biogeochemistry* **37**, 77–88 (1997).
313. H. Wang, C. J. Richardson, M. Ho, Dual controls on carbon loss during drought in peatlands. *Nat. Clim. Change* **5**, 584–587 (2015).
314. U.S. Department of Agriculture Natural Resources Conservation Service, *Web Soil Survey (SSURGO)* (U.S. Department of Agriculture Natural Resources Conservation Service, 2016); <http://websoilsurvey.nrcs.usda.gov/app/>.
315. S. D. Bridgman, C. L. Ping, J. L. Richardson, K. Updegraff, in *Wetland Soils: Genesis, Hydrology, Landscapes, and Classification*, J. L. Richardson, M. J. Vepraskas, Eds. (CRC Press, 2001), pp. 343–370.
316. U.S. Fish & Wildlife Service, *National Wetlands Inventory* (U.S. Fish & Wildlife Service, 2017); [www.fws.gov/wetlands/Data/Data-Download.html](http://www.fws.gov/wetlands/Data/Data-Download.html).
317. C. Homer, J. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. Herold, J. Wickham, K. Megown, Completion of the 2011 national land cover database for the conterminous United States – representing a decade of land cover change information. *Photogramm. Eng. Remote Sens.* **81**, 345–354 (2015).
318. C. J. Richardson, N. Flanagan, H. Wang, M. Ho, "Impacts of peatland ditching and draining on water quality and carbon sequestration benefits of peatland restoration" (Duke University for the Eastern North Carolina/Southeastern Virginia Strategic Habitat Conservation Team, U.S. Fish and Wildlife Service, Region 4 and The Nature Conservancy North Carolina Chapter, Final Project, 2014).
319. L. Hansen, D. M. Hellerstein, M. O. Ribaud, J. Williamson, D. Nulph, C. Loesch, W. Crompton, *Targeting Investments to Cost Effectively Restore and Protect Wetland Ecosystems: Some Economic Insights* (United States Department of Agriculture Economic Research Service, 2015); <https://ageconsearch.umn.edu/bitstream/199283/2/ERR183.pdf>.
320. J. Howard, A. Sutton-Grier, D. Herr, J. Kleypas, E. Landis, E. Mcleod, E. Pidgeon, S. Simpson, Clarifying the role of coastal and marine systems in climate mitigation. *Front. Ecol. Environ.* **15**, 42–50 (2017).

321. CEC, *North American Blue Carbon Scoping Study* (Commission for Environmental Cooperation, 2013).
322. B. C. Murray, L. Pendleton, W. A. Jenkins, S. Sifleet, "Green payments for blue carbon: Economic incentives for protecting threatened coastal habitats" (NI R 11-04, Nicholas Institute, Duke University, 2011).
323. G. Morrison, H. Greening, in *Integrating Science and Resource Management in Tampa Bay, Florida: U.S. Geological Survey Circular 1348*, K. K. Yates, H. Greening, G. Morrison, Eds. (U.S. Geological Survey Circular 1348, 2011) pp. 105–156.
324. Tampa Bay Regional Planning Council, *Integrating Nitrogen Management with Planning* (2013), Final Technical Report #07-13 of the Tampa Bay Estuary Program (available at [https://tbeptech.org/34mkf/6bb2b\\_ngbz/vxoi13.doi](https://tbeptech.org/34mkf/6bb2b_ngbz/vxoi13.doi)).
325. H. Greening, A. Janicki, Toward reversal of eutrophic conditions in a subtropical estuary: Water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA. *Environ. Manage.* **38**, 163–178 (2006).
326. Janicki Environmental Inc., *Estimates of Total Nitrogen, Total Phosphorus, Total Suspended Solids, and Biochemical Oxygen Demand Loadings To Tampa Bay, Florida: 2007-2011* (Tampa Bay Estuary Program, 2013); [www.tbeptech.org/TBEP\\_TECH\\_PUBS/2013/TBEP\\_03\\_13\\_FINAL\\_TBEP\\_Loads\\_2007-2011\\_19Mar2013.pdf](http://www.tbeptech.org/TBEP_TECH_PUBS/2013/TBEP_03_13_FINAL_TBEP_Loads_2007-2011_19Mar2013.pdf).
327. S. B. Bricker, Nutrient pollution in US Estuaries: NOAA's National Estuarine Eutrophication Assessment informs nutrient management; [https://water.usgs.gov/nawqa/headlines/nut\\_pest/NOAA-Estuaries-Bricker.pdf](https://water.usgs.gov/nawqa/headlines/nut_pest/NOAA-Estuaries-Bricker.pdf).
328. S. Cooper, "Integrating nitrogen management with planning" (Technical Report 07-13, Tampa Bay Estuary Program, 2012).
329. E. T. Sherwood, *2016 Tampa Bay Water Quality Assessment* (Tampa Bay Estuary Program, 2017); [www.tbeptech.org/TBEP\\_TECH\\_PUBS/2017/TBEP\\_01\\_17\\_2016\\_Decision\\_Matrix\\_Results\\_Update.pdf](http://www.tbeptech.org/TBEP_TECH_PUBS/2017/TBEP_01_17_2016_Decision_Matrix_Results_Update.pdf).
330. S. S. Rabotyagov, T. D. Campbell, M. White, J. G. Arnold, J. Atwood, M. L. Norfleet, C. L. Kling, P. W. Gassman, A. Valcu, J. Richardson, R. E. Turner, N. N. Rabalais, Cost-effective targeting of conservation investments to reduce the northern Gulf of Mexico hypoxic zone. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 18530–18535 (2014).
331. S. S. Rabotyagov, C. L. Kling, P. W. Gassman, N. N. Rabalais, R. E. Turner, The economics of dead zones: Causes, impacts, policy challenges, and a model of the gulf of Mexico Hypoxic Zone. *Rev. Environ. Econ. Policy* **8**, 58–79 (2014).
332. C. M. Duarte, N. Marbà, D. Krause-Jensen, M. Sánchez-Camacho, Testing the predictive power of seagrass depth limit models. *Estuaries Coast.* **30**, 652–656 (2007).
333. C. M. Duarte, Seagrass depth limits. *Aquat. Bot.* **40**, 363–377 (1991).
334. J. T. Greiner, K. J. McGlathery, J. Gunnell, B. A. McKee, Seagrass restoration enhances "blue carbon" sequestration in coastal waters. *PLOS ONE* **8**, e72469 (2013).
335. E. Bayraktarov, M. I. Saunders, A. Abdullah, M. Mills, J. Behr, H. P. Possingham, P. J. Mumby, C. E. Lovelock, The cost and feasibility of marine coastal restoration. *Ecol. Appl.* **26**, 1055–1074 (2016).
336. U.S. Environmental Protection Agency, *Guidelines for Preparing Economic Analyses* (U.S. Environmental Protection Agency, 2010); [www.epa.gov/environmental-economics/guidelines-preparing-economic-analyses](http://www.epa.gov/environmental-economics/guidelines-preparing-economic-analyses).
337. World Bank, *Lending Interest Rate (%)* (World Bank, 2017); <https://data.worldbank.org/indicator/FR.INR.LEND?locations=US>.
338. U.S. Department of Agriculture Economic Research Service, *Fertilizer Use and Price* (U.S. Department of Agriculture Economic Research Service, 2013); [www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx](http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx).
339. D. J. Nowak, S. Hirabayashi, A. Bodine, E. Greenfield, Tree and forest effects on air quality and human health in the United States. *Environ. Pollut.* **193**, 119–129 (2014).
340. R. Harrison, G. Wardell-Johnson, C. McAlpine, Rainforest reforestation and biodiversity benefits: A case study from the Australian wet tropics. *Ann. Trop. Res.* **25**, 65–76 (2003).
341. K. Niijima, A. Yamane, Effects of reforestation on soil fauna in the Philippines. *Philipp. J. Sci.* **120**, 1–20 (1991).
342. P. J. Ferraro, K. Lawlor, K. L. Mullan, S. K. Pattanayak, Forest figures: Ecosystem services valuation and policy evaluation in developing countries. *Rev. Environ. Econ. Policy* **6**, 20–44 (2012).
343. Z. Burivalova, Ç. H. Şekericioğlu, L. P. Koh, Thresholds of logging intensity to maintain tropical forest biodiversity. *Curr. Biol.* **24**, 1893–1898 (2014).
344. M. F. Jurgensen, A. E. Harvey, R. T. Graham, D. S. Page-Dumroese, J. R. Tonn, M. J. Larsen, T. B. Jain, Impacts of Timber harvesting on soil organic matter, nitrogen, productivity, and health of inland northwest forests. *For. Sci.* **43**, 234–251 (1997).
345. T. A. Burton, Effects of basin-scale Timber harvest on water yield and peak streamflow. *J. Am. Water Resour. Assoc.* **33**, 1187–1196 (1997).
346. S. Vedal, S. J. Dutton, Wildfire air pollution and daily mortality in a large urban area. *Environ. Res.* **102**, 29–35 (2006).
347. J. Bengtsson, S. G. Nilsson, A. Franc, P. Menozzi, Biodiversity, disturbances, ecosystem function and management of European forests. *For. Ecol. Manage.* **132**, 39–50 (2000).
348. K. T. Takano, M. Nakagawa, T. Itoika, K. Kishimoto-Yamada, S. Yamashita, H. O. Tanaka, D. Fukuda, H. Nagamasu, M. Ichikawa, Y. Kato, K. Momose, T. Nakashizuka, S. Sakai, *Social-Ecological Systems in Transition* (Global Environmental Studies, 2014); [http://link.springer.com/chapter/10.1007/978-4-431-54910-9\\_2/fulltext.html](http://link.springer.com/chapter/10.1007/978-4-431-54910-9_2/fulltext.html).
349. E. Gómez-Baggethun, D. N. Barton, Classifying and valuing ecosystem services for urban planning. *Ecol. Econ.* **86**, 235–245 (2013).
350. L. Chaparro, J. Terradas, Ecological services of urban forest in Barcelona. *Shengtai Xuebao/Acta Ecol. Sin.* **29**, 103 (2009).
351. U. G. Sandström, P. Angelstam, G. Mikusiński, Ecological diversity of birds in relation to the structure of urban green space. *Landsc. Urban Plan.* **77**, 39–53 (2006).
352. Y. Depietri, F. G. Renaud, G. Kallis, Heat waves and floods in urban areas: A policy-oriented review of ecosystem services. *Sustain. Sci.* **7**, 95–107 (2012).
353. M. J. Hartley, Rationale and methods for conserving biodiversity in plantation forests. *For. Ecol. Manage.* **155**, 81–95 (2002).
354. M. Ausden, W. J. Sutherland, R. James, The effects of flooding lowland wet grassland on soil macroinvertebrate prey of breeding wading birds. *J. Appl. Ecol.* **38**, 320–338 (2001).
355. G. W. Randall, D. R. Huggins, M. P. Russelle, D. J. Fuchs, W. W. Nelson, J. L. Anderson, Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems. *J. Environ. Qual.* **26**, 1240–1247 (1997).
356. M. J. Helmers, X. Zhou, H. Asbjornsen, R. Kolka, M. D. Tomer, R. M. Cruse, Sediment removal by prairie filter strips in row-cropped ephemeral watersheds. *J. Environ. Qual.* **41**, 1531–1539 (2012).
357. H. Jankowska-Huflejt, The function of permanent grasslands in water resources protection. *J. Water Land Dev.* **10**, 55–65 (2006).
358. P. Smith, M. R. Ashmore, H. I. J. Black, P. J. Burgess, C. D. Evans, T. A. Quine, A. M. Thomson, K. Hicks, H. G. Orr, The role of ecosystems and their management in regulating climate, and soil, water and air quality. *J. Appl. Ecol.* **50**, 812–829 (2013).
359. R. Derpsch, T. Friedrich, A. Kassam, H. Li, Current status of adoption of no-till farming in the world and some of its main benefits. *Int. J. Agric. Biol. Eng.* **3**, 1–25 (2010).
360. M. J. Bell, F. Worrall, Charcoal addition to soils in NE England: A carbon sink with environmental co-benefits? *Sci. Total Environ.* **409**, 1704–1714 (2011).
361. S. Jose, Agroforestry for ecosystem services and environmental benefits: An overview. *Agrofor. Syst.* **76**, 1–10 (2009).
362. S. Pattanayak, D. E. Mercer, Valuing soil conservation benefits of agroforestry: Contour hedgerows in the Eastern Visayas, Philippines. *Agric. Econ.* **18**, 31–46 (1998).
363. D. W. Bussink, Relationships between ammonia volatilization and nitrogen fertilizer application rate, intake and excretion of herbage nitrogen by cattle on grazed swards. *Fertil. Res.* **38**, 111–121 (1994).
364. M. D. Einheuser, A. P. Nejadhashemi, S. P. Sowa, L. Wang, Y. A. Hamaamin, S. A. Woznicki, Modeling the effects of conservation practices on stream health. *Sci. Total Environ.* **435–436**, 380–391 (2012).
365. G. Woodward, M. O. Gessner, P. S. Giller, V. Gulis, S. Hladysz, A. Lecker, B. Malmqvist, B. G. McKie, S. D. Tiegs, H. Cariss, M. Dobson, A. Eloegi, V. Ferreira, M. A. S. Graça, T. Fleituch, J. O. Lacoursière, M. Nistorescu, J. Pozo, G. Risnoveanu, M. Schindler, A. Vadineanu, L. B.-M. Vought, E. Chauvet, Continental-scale effects of nutrient pollution on stream ecosystem functioning. *Science* **336**, 1438–1440 (2012).
366. M. Quemada, M. Baranski, M. N. J. Nobel-de Lange, A. Vallejo, J. M. Cooper, Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. *Agric. Ecosyst. Environ.* **174**, 1–10 (2013).
367. S. R. Carpenter, N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, V. H. Smith, Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Appl.* **8**, 559–568 (1998).
368. M. Bustamante, C. Robledo-Abad, R. Harper, C. Mbow, N. H. Ravindranat, F. Sperling, H. Haberl, A. de Siqueira Pinto, P. Smith, Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. *Glob. Chang. Biol.* **20**, 3270–3290 (2014).
369. D. Malakoff, Death by suffocation in the Gulf of Mexico. *Science* **281**, 190–192 (1998).
370. P. S. Hooda, A. C. Edwards, H. A. Anderson, A. Miller, A review of water quality concerns in livestock farming areas. *Sci. Total Environ.* **250**, 143–167 (2000).
371. A. Kruess, T. Tschamtkte, grazing intensity and the diversity of grasshoppers, butterflies, and trap-nesting bees and wasps. *Conserv. Biol.* **16**, 1570–1580 (2002).
372. C. A. Rotz, S. Asem-Hiablie, J. Dillon, H. Bonifacio, Cradle-to-farm gate environmental footprints of beef cattle production in Kansas, Oklahoma, and Texas. *J. Anim. Sci.* **93**, 2509–2519 (2015).
373. N. M. Haddad, G. M. Crutsinger, K. Gross, J. Haarstad, J. M. H. Knops, D. Tilman, Plant species loss decreases arthropod diversity and shifts trophic structure. *Ecol. Lett.* **12**, 1029–1039 (2009).
374. E. S. Jensen, H. Hauggaard-Nielsen, How can increased use of biological N<sub>2</sub> fixation in agriculture benefit the environment? *Plant Soil* **252**, 177–186 (2003).
375. S. Toze, Reuse of effluent water—Benefits and risks. *Agric. Water Manage.* **80**, 147–159 (2006).
376. B. W. Heumann, Satellite remote sensing of mangrove forests: Recent advances and future opportunities. *Prog. Phys. Geogr.* **35**, 87–108 (2011).
377. B. A. Polidoro, K. E. Carpenter, L. Collins, N. C. Duke, A. M. Ellison, J. C. Ellison, E. J. Farnsworth, E. S. Fernando, K. Kathiresan, N. E. Koedam, S. R. Livingstone, T. Miyagi,

- G. E. Moore, V. N. Nam, J. E. Ong, J. H. Primavera, S. G. Salmo III, J. C. Sanciangco, S. Sukardjo, Y. Wang, J. W. H. Yong, The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLOS ONE* **5**, e10095 (2010).
378. J. B. Zedler, Wetlands at your service: Reducing impacts of agriculture at the watershed scale. *Front. Ecol. Environ.* **1**, 65–72 (2003).
379. M. D. Correll, W. A. Wiest, T. P. Hodgman, W. G. Shriver, C. S. Elphick, B. J. McGill, K. M. O'Brien, B. J. Olsen, Predictors of specialist avifaunal decline in coastal marshes. *Conserv. Biol.* **31**, 172–182 (2017).
380. E. B. Barbier, S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, B. R. Silliman, The value of estuarine and coastal ecosystem services. *Ecol. Monogr.* **81**, 169–193 (2011).
381. A. G. Rappold, S. L. Stone, W. E. Cascio, L. M. Neas, V. J. Kilaru, M. S. Carraway, J. J. Szykman, A. Ising, W. E. Cleve, J. T. Meredith, H. Vaughan-Batten, L. Deyneka, R. B. Devli, Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. *Environ. Health Perspect.* **119**, 1415–1420 (2011).
382. S. Page, A. Hoscilo, H. Wösten, J. Jauhiainen, M. Silvius, J. Rieley, H. Ritzema, K. Tansey, L. Graham, H. Vasander, S. Limin, Restoration ecology of lowland tropical peatlands in Southeast Asia: Current knowledge and future research directions. *Ecosystems* **12**, 888–905 (2009).
383. S. Chapman, A. Buttler, A.-J. Francez, F. Laggoun-Défarge, H. Vasander, M. Schloter, J. Combe, P. Grosvernier, H. Harms, D. Epron, D. Gilbert, E. Mitchell, Exploitation of northern peatlands and biodiversity maintenance: A conflict between economy and ecology. *Front. Ecol. Environ.* **1**, 525–532 (2003).
384. J. P. Curry, J. A. Good, *Soil Restoration* (Springer New York, 1992); [http://link.springer.com/chapter/10.1007/978-1-4612-2820-2\\_7](http://link.springer.com/chapter/10.1007/978-1-4612-2820-2_7).
385. D. P. L. Rousseau, E. Lesage, A. Story, P. A. Vanrolleghem, N. De Pauw, Constructed wetlands for water reclamation. *Desalination* **218**, 181–189 (2008).
386. R. Unsworth, L. C. Cullen-Unsworth, in *Coastal Conservation* (Cambridge Univ. Press, 2014), pp. 95–130.
387. U.S. Department of Agriculture Forest Service, *Fiscal Year 2009 President's Budget: Budget Justification* (U.S. Department of Agriculture Forest Service, 2008), pp. 1–426.
388. E. Lichtenberg, J. C. Hanson, A. M. Decker, A. J. Clark, Profitability of legume cover crops in the mid-Atlantic region. *J. Soil Water Conserv.* **49**, 562–565 (1994).
389. M. R. Pratt, W. E. Tyner, D. J. Muth, E. J. Klavivko, Synergies between cover crops and corn stover removal. *Agric. Syst.* **130**, 67–76 (2014).
390. U.S. Department of Agriculture Natural Resources Conservation Service, *Adding Cover Crops for Seed Production to a Corn/Soybean Rotation* (U.S. Department of Agriculture Natural Resources Conservation Service, 2015); [https://efotg.sc.egov.usda.gov/references/public/MO/Seed\\_Production\\_CaseStudy3.pdf](https://efotg.sc.egov.usda.gov/references/public/MO/Seed_Production_CaseStudy3.pdf).
391. A. R. Smith, R. S. Tubbs, W. D. Shurley, M. D. Toews, G. D. Collins, G. H. Harris, *Economics of Cover Crop and Supplemental Fertilizer in Strip-Tillage Cotton* (The University of Georgia, College of Agricultural and Environmental Sciences, 2014); [https://secure.caes.uga.edu/extension/publications/files/pdf/AP\\_108-2\\_1.PDF](https://secure.caes.uga.edu/extension/publications/files/pdf/AP_108-2_1.PDF).
392. D. F. Roberts, N. R. Kitchen, K. A. Sudduth, S. T. Drummond, P. C. Scharf, Economic and environmental implications of sensor-based nitrogen management. *Better Crops* **94**, 4–6 (2010).
393. P. C. Scharf, N. R. Kitchen, K. A. Sudduth, J. G. Davis, V. C. Hubbard, J. A. Lory, Field-scale variability in optimal nitrogen fertilizer rate for corn. *Agron. J.* **97**, 452–461 (2005).
394. N. Hong, P. C. Scharf, J. G. Davis, N. R. Kitchen, K. A. Sudduth, Economically optimal nitrogen rate reduces soil residual nitrate. *J. Environ. Qual.* **36**, 354–362 (2007).
395. C. Snyder, E. Davidson, P. Smith, R. Venterea, Agriculture: Sustainable crop and animal production to help mitigate nitrous oxide emissions. *Curr. Opin. Environ. Sustain.* **9–10**, 46–54 (2014).
396. Association of American Plant Food Control Officials, The Fertilizer Institute, *Commercial Fertilizers 2013* (Association of American Plant Food Control Officials, The Fertilizer Institute, Fertilizer/Ag Lime Control Service, University of Missouri, 2014).
397. U.S. Department of Agriculture, *USDA Agriculture and Forestry Greenhouse Gas Inventory: 1990–2008* (U.S. Department of Agriculture, 2011).
398. M. J. Brown, G. M. Smith, J. McCollum, *Wetland Forest Statistics for the South Atlantic States* (U.S. Department of Agriculture Forest Service, 2001); [www.srs.fs.usda.gov/pubs/rb/rb\\_srs062.pdf](http://www.srs.fs.usda.gov/pubs/rb/rb_srs062.pdf).

#### Acknowledgments

**Funding:** This study was made possible by funding from the Doris Duke Charitable Foundation. C.A.W. and H.G. acknowledge financial support from NASA's Carbon Monitoring System program (NNH14ZDA001N-CMS) under award NNX14AR39G. S.D.B. acknowledges support from the DOE's Office of Biological and Environmental Research Program under the award DE-SC0014416. J.W.F. acknowledges financial support from the Florida Coastal Everglades Long-Term Ecological Research program under National Science Foundation grant no. DEB-1237517. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The findings and conclusions in this publication have not been formally disseminated by the U.S. Department of Agriculture and should not be construed to represent any agency determination or policy. We thank L. Hansen (USDA Economic Research Service) for providing a shapefile of county-level wetland restoration cost estimates. **Author contributions:** S.B., T.B., S.D.B., R.T.C., S.C.C.-P., P.W.E., A.F., J.E.F., J.W.F., T.G., B.W.G., H.G., B.H., M.D.H., K.D.K., T.K., T.J.L., S.M.L., G.L., R.I.M., J.P.M., D.A.M., C.J.R., J.S., D.S., S.A.S., J.W.V., C.A.W., P.B.W., and C.Z. developed individual NCS opportunities. J.E.F. drafted the manuscript. All authors discussed the results and edited and commented on the manuscript. **Competing interests:** G.L. has been a consultant for Virgin Management Ltd. advising on land-based carbon sequestration strategies. The authors declare no other competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 1 February 2018

Accepted 12 October 2018

Published 14 November 2018

10.1126/sciadv.aat1869

**Citation:** J. E. Fargione, S. Bassett, T. Boucher, S. D. Bridgman, R. T. Conant, S. C. Cook-Patton, P. W. Ellis, A. Falcucci, J. W. Fourqurean, T. Gopalakrishna, H. Gu, B. Henderson, M. D. Hurteau, K. D. Kroeger, T. Kroeger, T. J. Lark, S. M. Leavitt, G. Lomax, R. I. McDonald, J. P. Megonigal, D. A. Miteva, C. J. Richardson, J. Sanderman, D. Shoch, S. A. Spawn, J. W. Veldman, C. A. Williams, P. B. Woodbury, C. Zganjar, M. Baranski, P. Elias, R. A. Houghton, E. Landis, E. McGlynn, W. H. Schlesinger, J. V. Siikamaki, A. E. Sutton-Grier, B. W. Griscom, Natural climate solutions for the United States. *Sci. Adv.* **4**, eaat1869 (2018).

## Natural climate solutions for the United States

Joseph E. Fargione, Steven Bassett, Timothy Boucher, Scott D. Bridgman, Richard T. Conant, Susan C. Cook-Patton, Peter W. Ellis, Alessandra Falcucci, James W. Fourqurean, Trisha Gopalakrishna, Huan Gu, Benjamin Henderson, Matthew D. Hurteau, Kevin D. Kroeger, Timm Kroeger, Tyler J. Lark, Sara M. Leavitt, Guy Lomax, Robert I. McDonald, J. Patrick Megonigal, Daniela A. Miteva, Curtis J. Richardson, Jonathan Sanderman, David Shoch, Seth A. Spawn, Joseph W. Veldman, Christopher A. Williams, Peter B. Woodbury, Chris Zganjar, Marci Baranski, Patricia Elias, Richard A. Houghton, Emily Landis, Emily McGlynn, William H. Schlesinger, Juha V. Siikamaki, Ariana E. Sutton-Grier and Bronson W. Griscom

*Sci Adv* 4 (11), eaat1869.  
DOI: 10.1126/sciadv.aat1869

### ARTICLE TOOLS

<http://advances.sciencemag.org/content/4/11/eaat1869>

### SUPPLEMENTARY MATERIALS

<http://advances.sciencemag.org/content/suppl/2018/11/09/4.11.eaat1869.DC1>

### REFERENCES

This article cites 268 articles, 21 of which you can access for free  
<http://advances.sciencemag.org/content/4/11/eaat1869#BIBL>

### PERMISSIONS

<http://www.sciencemag.org/help/reprints-and-permissions>

Use of this article is subject to the [Terms of Service](#)