Reforestation can sequester two petagrams of carbon in US topsoils in a century

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Soils are Earth's largest terrestrial carbon (C) pool, and their responsiveness to land use and management make them appealing targets for strategies to enhance C sequestration. Numerous studies have identified practices that increase soil C, but their inferences are often based on limited data extrapolated over large areas. Here, we combine 15,000 observations from two national-level databases with remote sensing information to address the impacts of reforestation on the sequestration of C in topsoils (uppermost mineral soil horizons). We quantify C stocks in cultivated, reforesting, and natural forest topsoils; rates of C accumulation in reforesting topsoils; and their contribution to the US forest C sink. Our results indicate that reforestation increases topsoil C storage, and that reforesting lands, currently occupying >500,000 km² in the United States, will sequester a cumulative 1.3–2.1 Pg C within a century (13–21 Tg C·y⁻¹). Annually, these C gains constitute 10% of the US forest sector C sink and offset 1% of all US greenhouse gas emissions.

land use | greenhouse gas | mitigation | soil carbon | management

In the midst of growing urgency to enhance terrestrial C sequestration, mitigate climate change, and sustain soil-based ecosystem services, there is widespread agreement on the need to understand how land use practices impact soil C. Indeed, for years, scientists have estimated the C cycle impacts of land use and soil management strategies, often calling for new or improved practices to be implemented on increased land areas. These forward-looking studies have defined targets (1, 2), developed networks and methodologies (3, 4), and advanced soil and C cycle science along the way. However, they have rarely used large observational datasets to directly address how land use affects soil C (5). Far more often, these big-picture studies employ expert judgment, literature review, or sophisticated model-data fusion methods (6–9). Against this range of approaches, there is a recognized need for empirical analyses of large datasets to develop observational constraints on modeled and/or extrapolated results (10–13). Without a doubt, observational approaches have their own limitations, and large databases incorporate natural variation and associated uncertainty. Nonetheless, the magnitude of the problem and the nature of science in the collaboration age—which applies complementary methods to pressing questions—establish a strong role for observations in addressing large-scale questions of soil C sequestration. Here, we demonstrate an approach that synthesizes multiple data types and sources to address a problem at the nexus of soils, land use, and the C cycle.

Soils to 1 m depth hold 74% of all terrestrial C (14–16), with North America and the conterminous US (CONUS) representing 35% and 4% of all soil C, respectively (17, 18). Because adding even a few percent to this large C stock translates into a globally relevant increase, it is essential to quantify the increases achievable through changes in land use and management. Reforestation of marginal croplands and active reforestation (replanting) on understocked forestlands are two promising strategies for increasing terrestrial C sequestration (19–21). Reviews of site-level studies (22, 23) suggest reforestation and other land use and management changes increase

soil C by 0.1–0.4 Mg of C·ha⁻¹·y⁻¹, with potential increases of 50–100 Tg·y⁻¹ estimated for US and European agricultural lands (1, 24). However, it may be more important to develop a framework for constraining these estimates with observations than to precisely quantify the soil C increases associated with specific land use or management changes. To that end, we offer an approach for synthesis—and a set of empirical data resources for collective use—while also directly quantifying C sequestration in the topsoils (uppermost mineral soil horizons) of lands that are currently undergoing reforestation in the United States.

Data Synthesis

We used several large data sources as starting points in a series of filtering, gap-filling, validation, and analysis steps, described in *Methods* and detailed in *Supporting Information*. Because these independent data sources have different applications and align with different questions, we must first summarize them briefly. The first source was the International Soil Carbon Network (ISCN) Gen3 Database (25), containing data for >433,000 individual soil layers worldwide. Individual layers make up soil profiles; profiles are one to many per site, and sites are georeferenced. The ISCN Database contains data contributed by individuals, networks, and government agencies. Geospatial data are the second data type we used for this analysis; we extracted point attributes from two geospatial datasets to overlay these upon the geographical coordinates of ISCN sites. These secondary geospatial (overlay) data include the following: (i) land cover attributes from all four versions of the National Land Cover Dataset (NLCD; refs. 26–29), a LANDSAT-derived, 30-m

Significance

Forestland in the United States is a carbon (C) sink, offsetting ~10% of annual greenhouse gas emissions and mitigating climate change. Most of the C in forests is held in soils, and the capacity of forest soils to sequester C makes them a major component of the US forest C sink. Where reforestation is presently occurring, either through deliberate replanting after forestland is disturbed (e.g., burned), or where previously nonforested lands (e.g., cultivated) are converting to forestland, topsoils are accumulating C. However, these C accumulation rates are poorly constrained; quantifying them with empirical data are critical to accurately represent the role of reforestation in the US C budget and forecast the longevity of the US forest C sink.

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Fig. 2. Cultivated soils are clay-rich, forests persist on sandy and stony soils, and reforestation tends to happen on marginal soils of intermediate textures. Graphs show the percentage clay, sand, and stone contents of topsoil horizons from cultivated, reforesting, and natural forest ISCN-NLCD sites ($n = 12,617$). Boxes are medians and 25th and 75th percentiles; whiskers are 10th and 90th percentiles; dots are fifth and 95th percentiles. Medians are significantly different ($P < 0.05$) for all three land use groups except in the case of sand content (no significant difference between cultivated and reforesting).

on continuous forestland will contribute an additional 0.5 Pg C. Collectively, this total C gain (1.3–2.1 Pg C) is on lands that are already reforesting, i.e., it is not a theoretical projection based on increased replanting efforts or large-scale crop-to-forest land use changes, as is often suggested in arguments for enhancing soil C sequestration. However, realizing these topsoil C gains over the course of a century requires previously cultivated lands now undergoing reforestation to remain in forest land use, as recultivation could cause larger soil C losses than the C gains achievable by substituting reforestation on a similar area of cultivated land. However, in light of relatively low areal percentages for both types of reforestation, modest increases in area would have a multiplicative impact on nationwide C sequestration. For example, replanting could be implemented on more than 7% of current forestland (Table 1), or additional marginal lands could be transferred from cultivation to forest, increasing the contribution of reforesting cultivated lands to the national forest land base. In either case, a small increase in reforestation area as a percentage of the total forest land area, over a long time period, would create significant C cycle impacts that are readily quantifiable using the empirical models we present here.

Our estimates of the realized and potential topsoil C gains on cultivated lands that are undergoing reforestation help to constrain C sequestration under this type of land use change at multiple levels. Most importantly, at the CONUS level, the C gains that have been realized thus far for this type of reforestation are only about 10% of their potential, highlighting the substantial C sink capacity of this land use transition if these lands are allowed to continue returning

toward a natural forest condition. However, because our results are not based upon a longitudinally sampled set of sites undergoing land use change, but rather on a space-for-time substitution, it is important to recognize that individual sites may show no change in topsoil C, or changes over time that differ from the estimates we calculate based on statistical differences (i.e., between medians or means). In this regard, our broader inferences are based on statistical differences and are only as robust as the assumptions that underlie them. Regardless of whether all prerequisites of space-for-time substitution are met, the metrics that we have termed realized and potential topsoil C gains (Table 1) can be used to prioritizing ecoregions for C management, because they indicate significant statistical differences in soil C between land uses. For example, some ecoregions have less potential overall (dry domain or Mediterranean division), while some have much remaining potential (humid temperate domain or hot continental division). Our empirical models can be used similarly; ecoregions with particularly low (subtropical) or high (warm continental) topsoil C stocks are indicated by corresponding differences in their y intercepts, while differing C accumulation rates are suggested by differences in model slopes. Overall, our modeled rates of topsoil C accumulation range from 0.11 to 0.34 Mg of C·ha⁻¹·y⁻¹, confirming the rates reported in expert reviews and cross-site studies while providing a more detailed view that can help move C management in an increasingly regionalized direction.

To estimate how long C accumulation will continue during reforestation on cultivated lands, we need some way to constrain the age of the forests that are currently growing at ISCN-NLCD

Fig. 3. Topsoil C stocks are least under cultivation, greatest in natural forest, and intermediate on reforesting soils (Left); soil C stocks to 30 cm only differ significantly between cultivated and natural forest land uses (Right). Data are from ISCN-NLCD sites ($n = 12,617$). See Fig. 2 for box, whisker, and dot information. Within each depth, superscripts denote significant differences ($P < 0.05$) in median C stocks between land uses. The dotted lines in each figure are intended to aid in visual reference and show thresholds that are 5%, 50%, or 100% greater than cultivated baseline levels.

mean net removal of 651-Tg CO₂ equivalents (176 Tg of C) annually during the past 5 y (47). Based on estimates from our empirical models, annual topsoil C gains on reforesting lands (1.3–2.1 Pg of C over 100 y = 13–21 Tg of C·y⁻¹) represent 7–12% of the entire forest sector greenhouse sink, effectively offsetting 0.8–1.3% of all US greenhouse gas emissions. Given that our results suggest this C sink will persist for decades, C sequestration in reforesting topsoils can be a significant long-range solution to the problem of the declining sink strength of the US forest sector. For over 20 y, strategic planning analyses and reports have warned that the C sink strength of US forests is declining, and is expected to become neutral beyond the mid-21st century (48–51). An additional 100–200 Tg of C·y⁻¹ has been identified as an achievable target that would stabilize the long-range trajectory of the forest C sink (52). In light of these far-reaching assessments, our analysis is significant for two reasons. First, there are no published empirical estimates for the role of reforesting topsoils in US forest C sequestration; researchers overwhelmingly focus on more readily quantified (but admittedly complex) aboveground components. Second, even at their current extent, topsoils that are now undergoing reforestation represent a >10% contribution toward the additional C sequestration needed to stabilize the C sink trajectory beyond the mid-21st century. Given that the majority of their potential C gains are yet to be realized, and even slight increases in reforestation area will have a multiplicative impact on long-term CONUS-level C sequestration, topsoils in reforesting lands are indeed a natural climate solution (1).

Conclusion

Through a synthesis that integrates 15,000 soil observations with remote sensing and geospatial information, we estimate topsoil C gains on lands undergoing two types of reforestation in CONUS. By quantifying the impact of replanting on topsoil C accumulation in continuous forestland, revealing differences in the underlying soil properties of cultivated, reforesting, and natural forest lands nationwide, and placing our results in an ecoregional framework, we reveal the physical basis for patterns of land use change on marginal soils, and provide regionalized insight into rates of topsoil C accumulation and long-term C sequestration potentials. Even if continued topsoil C accumulation rates are slower than we estimate, or whole-profile C stocks follow a different trajectory, we demonstrate the use of complementary empirical data sources suggesting that topsoil C stocks have already increased in CONUS due to ongoing reforestation. Currently, reforesting topsoils are accumulating 13–21 Tg of C·y⁻¹, with the potential to accumulate hundreds more Tg of C within a century. Collectively, the cumulative potential for topsoil C sequestration on these lands may exceed 2 Pg of C—double the global land use change emission (53)—highlighting the significance of continued forest recovery on these lands, as well as the magnitude of additional C accumulation that could be achieved with modest area increases in reforestation.

Methods

ISCN Dataset. We used the ISCN map-based data tool to download a dataset of 319,316 soil layers from 52,178 profiles in CONUS. The dataset included geographic coordinates, descriptive, physical, chemical, and metadata for all sites, profiles, and layers contained in the download, which contained data from multiple sources (25, 54–58). Next, we proceeded through a series of filtering, gap-filling, and validation steps, described in greater detail in *ISCN Dataset Preparation*. The present analysis focuses on results for 12,617 topsoil layers (A horizons) across the CONUS, representing those layers that met all criteria and were appropriate to address the questions of interest.

Overlay Data: Land Cover and Canopy Age. We extracted land cover and canopy age for each ISCN site, assigning each location to its closest (in time) NLCD product. We assumed that land cover attributes for soils sampled between January 1, 1989, and December 31, 1996, were reasonably represented by the NLCD1992 product; soils from 1997 to 2001 were represented by NLCD2001; soils from 2002 to 2006 by NLCD2006; soils from 2007 to most recent (2014) by NLCD2011. After matching each ISCN site to the appropriate

NLCD classification, we performed a series of land cover aggregation and validation steps described in *ISCN Overlay Data: Aggregating and Validating Land Cover Classifications*.

For our second overlay dataset, we extracted canopy ages (year 2006) from a 250-m resolution North American forest canopy age map produced by combining plot-level and multiple remote sensing data sources. We performed this extraction only for a subset of the ISCN-NLCD sites; specifically, those matched to NLCD2001 and NLCD2006, to obtain forest canopy ages only for ISCN-NLCD sites that were closely temporally aligned with the input data and estimated canopy age attributes of the data product. To overlay an age value on each site, we extracted the age for the pixel containing the ISCN-NLCD geographic coordinates using ArcGIS (ESRI), which was also our approach for obtaining other overlay data.

FS Data: Plots, Land Areas, and Ecoregions. Data contained in the FIA Database are taken as part of the NFI, an equal-probability sample of forestland across CONUS. There is one NFI plot on approximately every 2,400 ha across the United States, placed randomly within a hexagonal grid. We queried the FIA Database for plots with topsoil C measurements (Mg of C·ha⁻¹ to 10 cm), and filtered query returns to use topsoil C stocks only for single-condition plots, i.e., those not subdivided into different forest conditions (e.g., stand ages). We made this exclusion to ensure straightforward data interpretation and avoid potential edge effects. As additional constraints, we utilized only the most recent observation of each plot (NFI plots are periodically remeasured), and only plots observed since 2000, to ensure NFI data were concurrent with the observations from the ISCN-NLCD dataset. Altogether, our NFI soil C dataset held 2,383 observations. To test relationships between soil and biomass C, we also assembled a dataset of plot-level aboveground biomass C stocks for the same plots that provided soils information. We obtained forestland areas for ecoregions of CONUS (described in *Ecoregional Framework*) using standard FIA estimation procedures (59).

Data Analysis. We used nonparametric and parametric tests, in a phased approach, to address our questions of interest. We used nonparametric analyses in the first phase with the goal of showing data distributions, describing patterns, and testing for significant differences in what is essentially a national soil census. Nonparametric tests are suited for this portion of our analysis because skewed distributions that challenge parametric criteria are common in large datasets, and reflect the reality of the populations of interest (e.g., a small number of topsoils have very large C stocks). We used nonparametric tests rather than eliminate outliers from our populations of interest, retain them and incur skewness, or attempt to normalize the distributions with transformations.

In our nonparametric analyses, we used Kruskal–Wallis tests with Dunn’s multiple comparisons to indicate whether topsoil textures, thicknesses, and C stocks differed significantly between land uses. Observations included in these tests were ISCN-NLCD sites with cultivated, reforesting, or natural forest land uses; we assigned sites into these land use groups using a combination of remote sensing (NLCD) and soil profile information (ISCN). We review our approach for assigning land use (Fig. 1) here because it contextualizes our results. Because cultivation is reliably indicated by a distinctive land cover, ISCN-NLCD sites with cultivated land cover represent cultivation as a land use. However, ISCN-NLCD sites attributed as forest are separable into two land uses: natural forests (soils never cultivated) and forests that have become established on previously cultivated lands, with an Ap horizon serving as the distinguishing feature. An Ap horizon (i.e., plow layer) is readily recognized in a soil pit by its consistent (often deep) thickness and clear abrupt boundary over underlying horizons, and may persist for centuries following agricultural abandonment (60, 61). In contrast, A horizons in forest soils are usually thinner and have wavy, irregular, or otherwise variable thicknesses and boundaries.

For the second phase of our data analysis, we used parametric statistics to estimate mean values, SEs, and significant differences for topsoils from various land use by ecoregion groups. In these tests, we did not include topsoils with C stocks separated from the grand mean by >2σ (3% of the 12,617 total observations). Also, we diagnosed transformations of the right-skewed distribution of topsoil C stocks, selecting the square-root transformation which provided the greatest mitigation of nonnormality. Subsequently, we ran ANOVA with Fisher’s Least Significant Difference multiple comparisons to indicate whether land uses had significantly different topsoil C stocks across the entire CONUS, as well as within individual ecoregions. We back-transformed the means of ecoregion by land use for scaling exercises described in *Scaling: Projection and Prediction of Topsoil C Stocks*.

In all statistical tests comprising our data analysis, conducted using Sigmaplot (SYSTAT), we set $P < 0.05$ as the threshold for accepting test results as significant.

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- Griscom BW, et al. (2017) Natural climate solutions. *Proc Natl Acad Sci USA* 114: 11645–11650.
- Minasny B, et al. (2017) Soil carbon 4 per mille. *Geoderma* 292:59–86.
- Follett RF (2012) Beyond mitigation: Adaptation of agricultural strategies to overcome projected climate change. *Managing Agricultural Greenhouse Gases: Coordinated Agricultural Research through GRACEnet to Address Our Changing Climate*, eds Liebig MA, Franzluebbers AJ, Follett RF (Elsevier, New York), pp 693–718.
- Poelau C, Don A (2015) Carbon sequestration in agricultural soils via cultivation of cover crops—A meta-analysis. *Agric Ecosyst Environ* 200:33–41.
- Jobbagy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol Appl* 10:423–436.
- Jandl R, et al. (2007) How strongly can forest management influence soil carbon sequestration? *Geoderma* 137:253–268.
- Paul KI, et al. (2000) Change in soil carbon following afforestation. *For Ecol Manage* 168:241–257.
- Sanderman J, Berhe AA (2017) The soil carbon erosion paradox. *Nat Clim Chang* 7: 317–319.
- Sanderman J, Hengl T, Fiske GJ (2017) Soil carbon debt of 12,000 years of human land use. *Proc Natl Acad Sci USA* 114:9575–9580.
- Harden JW, et al. (2017) Networking our science to characterize the state, vulnerabilities, and management opportunities of soil organic matter. *Glob Change Biol* 24: e705–e718.
- Jackson RB, et al. (2017) The ecology of soil carbon: Pools, vulnerabilities, and biotic and abiotic controls. *Annu Rev Ecol Syst* 48:419–445.
- Paustian K, et al. (2016) Climate-smart soils. *Nature* 532:49–57.
- Smith P, et al. (2012) Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: Current capability and future vision. *Glob Change Biol* 18:2089–2101.
- Bajtes NH (2016) Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks. *Geoderma* 269:61–68.
- Scharlemann JPW, Tanner EVJ, Hiederer R, Kapos V (2014) Global soil carbon: Understanding and managing the largest terrestrial carbon pool. *Carbon Manage* 5: 81–91.
- Kochy M, Hiederer R, Freibauer A (2015) Global distribution of soil organic carbon – Part 1: Masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world. *Soil* 1:351–365.
- Liu S, et al. (2013) The Unified North American Soil Map and its implication on the soil organic carbon stock in North America. *Biogeosciences* 10:2915–2930.
- Bliss NB, et al. (2014) Distribution of soil organic carbon in the conterminous United States. *Soil Carbon, Progress in Soil Science*, eds Hartemink A, McSweeney K (Springer, Cham, Switzerland).
- Lal R (2005) Forest soils and carbon sequestration. *For Ecol Manage* 220:242–258.
- Booker K, et al. (2013) What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States? *Glob Environ Change* 23:240–251.
- Sample VA (2017) Potential for additional carbon sequestration through regeneration of nonstocked forest land in the United States. *J For* 115:309–318.
- Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: Processes and potential. *Glob Change Biol* 6:317–327.
- Silver WL, Ostertag R, Lugo AE (2000) The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. *Restor Ecol* 8: 394–407.
- Smith P, et al. (2000) Meeting Europe's climate change commitments: Quantitative estimates of the potential for carbon mitigation by agriculture. *Glob Change Biol* 6: 525–539.
- Nave L, et al. (2017) Data from "International Soil Carbon Network (ISCN) Database V3-1." *ISCN*, 10.17040/ISCN/1305039.
- Homer C, et al. (2004) Development of a 2001 National Landcover Database for the United States. *Photogramm Eng Remote Sens* 70:829–840.
- Fry J, et al. (2011) Completion of the 2006 National Land Cover Database for the conterminous United States. *Photogramm Eng Remote Sens* 77:858–864.
- Vogelmann JE, et al. (2001) Completion of the 1990s National Land Cover Dataset for the conterminous United States. *Photogramm Eng Remote Sens* 67:650–662.
- Homer CG, et al. (2015) 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.
- Pan Y, et al. (2015) Forest stand age map of Canada (2011) and the United States (2006 & 2011) (US Department of Agriculture, Forest Service Research Data Archive, Fort Collins, CO).
- USDA-Forest Service (2017) The Forest Inventory and Analysis Database: Database Description and User Guide for Phase 3, Version 6.0.1. Available at <https://apps.fs.usda.gov/fia/datamart/>. Accessed April 4, 2017.
- USDA-Forest Service (2017) FSGeodata Clearinghouse. Available at <https://data.fs.usda.gov/geodata/>. Accessed April 3, 2017.
- Woodall CW, et al. (2016) A tale of two forest carbon assessments in the eastern United States: Forest use versus cover as a metric of change. *Ecosystems* 19:1401–1417.
- Nave LE, Swanston CW, Mishra U, Nadelhoffer KJ (2013) Afforestation effects on soil carbon storage in the United States: A synthesis. *Soil Sci Soc Am J* 77:1035–1047.
- Schrumpf M, Schulze ED, Kaiser K, Schumacher J (2011) How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? *Biogeosciences* 8: 1193–1212.
- Homann PS, Bormann BT, Boyle JR (2001) Detecting treatment differences in soil carbon and nitrogen resulting from forest manipulations. *Soil Sci Soc Am J* 65:463–469.
- Nave LE, Vance ED, Swanston CW, Curtis PS (2010) Harvest impacts on soil carbon storage in temperate forests. *For Ecol Manage* 259:857–866.
- Nave LE, Vance ED, Swanston CW, Curtis PS (2011) Fire effects on temperate forest soil C and N storage. *Ecol Appl* 21:1189–1201.
- Powlson DS, Jenkinson DS (1981) A comparison of the organic-matter, biomass, ATP and mineralizable nitrogen contents of ploughed and direct-drilled soils. *J Agric Sci* 97:713–721.
- McCarty GW, Lyssenko NN, Starr JL (1998) Short-term changes in soil carbon and nitrogen pools during tillage management transition. *Soil Sci Soc Am J* 62:1564–1571.
- Mishra U, Riley WJ (2015) Scaling impacts on environmental controls and spatial heterogeneity of soil organic carbon stocks. *Biogeosciences* 12:3993–4004.
- Laganiere J, Angers DA, Pare D (2010) Carbon accumulation in agricultural soils after afforestation: A meta-analysis. *Glob Change Biol* 16:439–453.
- Guo LB, Gifford RM (2002) Soil carbon stocks and land use change: A meta analysis. *Glob Change Biol* 8:345–360.
- Richter DD, Markewitz D, Trumbore SE, Wells CG (1999) Rapid accumulation and turnover of soil carbon in a re-establishing forest. *Nature* 400:56–58.
- Mobley ML, et al. (2015) Surficial gains and subsoil losses of soil carbon and nitrogen during secondary forest development. *Glob Change Biol* 21:986–996.
- Stevens JT, et al. (2016) Average stand age from forest inventory plots does not describe historical fire regimes in ponderosa pine and mixed-conifer forests of Western North America. *PLoS One* 11:e0147688.
- US Environmental Protection Agency (2017) Inventory of US greenhouse gas emissions and sinks: 1990-2015 (US Environmental Protection Agency, Washington, DC), EPA 430-P-17-001.
- Birdsey RA, Plantinga AJ, Heath LS (1993) Past and prospective carbon storage in United-States forests. *For Ecol Manage* 58:33–40.
- Oswalt SN, Smith WB, Miles PD, Pugh SA (2014) Forest resources of the United States, 2012: A technical document supporting the Forest Service 2015 update of the RPA Assessment (US Department of Agriculture, Forest Service, Washington Office, Washington, DC), General Technical Report GTR WO-91.
- USDA Forest Service (2016) Future of America's Forests, Rangelands: Update to the 2010 Resources Planning Act Assessment (US Department of Agriculture, Forest Service, Washington, DC), General Technical Report WO-GTR-94, 250 p.
- Wear DN, Coulston JW (2015) From sink to source: Regional variation in US forest carbon futures. *Sci Rep* 5:16518.
- Birdsey R, Pregitzer K, Lucier A (2006) Forest carbon management in the United States: 1600-2100. *J Environ Qual* 35:1461–1469.
- Le Quéré C, et al. (2015) Global carbon budget 2014. *Earth Syst Sci Data* 7:47–85.
- Soil Survey Staff (2014) National Cooperative Soil Characterization Data (Soil Survey Laboratory, National Soil Survey Center, US Department of Agriculture, Natural Resources Conservation Service, Lincoln, NE). Available at <https://ssldata.nrcs.usda.gov/>. Accessed September 9, 2014.
- Buell GR, Markewich HW (2004) *Data Compilation, Synthesis, and Calculations Used for Organic-Carbon Storage and Inventory Estimates for Mineral Soils of the Mississippi River Basin*, US Geological Survey Professional Paper (US Department of Interior, Geological Survey Reston, VA), Vol 1686-A.
- Cole JA, et al. (2013) Database for landscape-scale carbon monitoring sites (US Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA), General Technical Report GTR-NRS-119.
- Heckman KA, et al. (2013) The influence of fire on the radiocarbon signature and character of soil organic matter in the Siskiyou Forest, Oregon. *Fire Ecol* 9:40–56.
- Heckman KA, et al. (2014) Factors affecting the molecular structure and mean residence time of occluded organics in a lithosequence of soils under ponderosa pine. *Soil Biol Biochem* 77:1–11.
- Bechtold WA, Patterson PJ, eds (2005) The enhanced forest inventory and analysis program—National sampling design and estimation procedures (US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC), General Technical Report SRS-80.
- Compton JE, Boone RD (2000) Long-term impacts of agriculture on soil carbon and nitrogen in New England Forests. *Ecology* 81:2314–2330.
- Flinn KM, Marks PL (2007) Agricultural legacies in forest environments: Tree communities, soil properties, and light availability. *Ecol Appl* 17:452–463.