Forest Soil Carbon and Climate Change

Issues

Preparers

David D'Amore, Pacific Northwest Research Station
Evan Kane, Michigan Technological University

Any consideration of forest carbon storage must include soils. In temperate forest ecosystems, the amount of carbon stored in soils is often greater than the amount stored aboveground in living and dead plant biomass. Although the relative amounts of organic carbon in plant and soil components vary by climate and region belowground carbon is a substantial carbon pool. The total amount of carbon stored in aboveground forest biomass (living and dead) varies far less across diverse forest types, with an average aboveground stock for US forests being 55 Mg carbon ha-1 (1). In contrast, belowground carbon stocks show more variation, even when we limit our consideration to the top meter of soil.

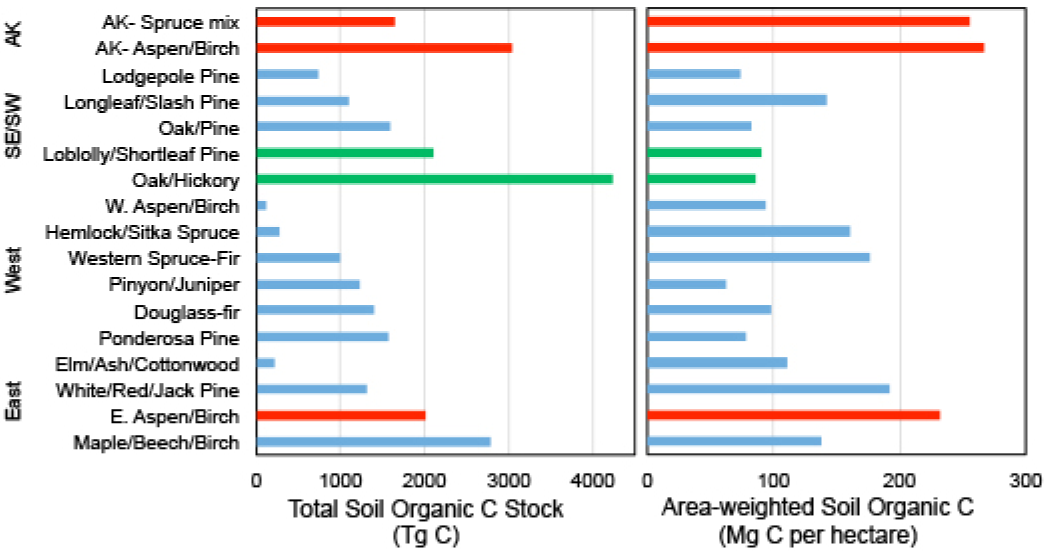


Figure: *The total stock of soil organic carbon varies for forest types in the U.S., with high stocks occurring where a forest type is common, or, in areas where there is a lot of soil carbon per unit area. It may be a challenge to increase soil carbon storage in extensive forest types that have a relatively high carbon density per unit area, especially if carbon is protected by cold temperatures or saturated conditions (for example, red bars depicted above). On the other hand, extensive forest types presently occupied by forest type groups with low carbon density represent opportunities for increasing soil carbon through management activities (e.g., green bars). Data from Johnson and Kern, 2003 (2).*

This variability in belowground carbon is an important consideration for evaluating forest management options that maintain and promote soil organic carbon, rather than allowing it to be lost to the atmosphere. Here, we focus discussion of changes in soil carbon in terms of inputs and outputs. The primary management controls we have available include such input factors as stand type, productivity, and rotation age, and such output terms as controls on decomposition and carbon export; these latter factors are affected by management activities related to changes in stand structure and microclimate, wildfire and changes in site drainage.

Understanding Forest Soil Carbon

The amount of carbon stored in soils depends on a variety of factors, including carbon inputs rom vegetation, carbon losses from decomposition and biodegredation, soil physiochemical characteristics, and climate variables like temperature and precipitation. Forest contributions to the soil organic carbon pool include leaf litter, coarse woody debris, roots, root exudates, and dissolved organics leached from the litter layer. Whether these inputs are stabilized in the mineral soil matrix (sequestered) or biodegraded and returned to the atmosphere as carbon dioxide depend on complex, fine-scale interactions involving soil minerals, plants and soil organisms, and organic components (where most of the nutrients are stored), and these interactions are all influenced by larger-scale factors like climate and stand management.

Perhaps counter-intuitively, large aboveground carbon stocks do not necessarily result in large belowground carbon stocks. This is because high levels of forest productivity require pools of nutrients that become available through the decomposition of organic matter, and decomposition also releases carbon to the atmosphere. On the other hand, conditions which impede decomposition are often related to the accumulation of soil carbon, such as a lack of oxygen (high water table) and cold temperatures. While aboveground plant productivity is largely governed by nutrient availability and drainage conditions, belowground carbon stocks are heavily influenced by soil mineralogical and chemical characteristics. Soils with higher clay content are generally associated with larger soil carbon stocks because they offer a greater amount of surface area for carbon to “stick” to. In addition, the stickiness of the mineral matrix is related to the type of clay that forms from the parent material and soil conditions. For example, the carbon-rich forest soils (Andisols) of the Northwest are formed from volcanic parent material which yields soils with very high surface area. These mixed conifer-hardwood systems have some of the largest soil carbon stocks in the country. In contrast, the mixed hardwood soils of the Northeast and northern Midwest are formed on sandy substrates which have low surface area and consequently smaller soil carbon stocks which are very sensitive to disturbance.

Conditions that limit biodegradation also increase carbon stored in soils. Inundation, freezing temperatures, and highly acidic soils are all associated with accumulation of organic matter, either in the litter layer or the mineral soil through association with clay minerals like iron and aluminum. In general, increasing forest productivity means increasing inputs to soil carbon stocks, however increasing plant inputs can also stimulate biodegradation of soil carbon in some systems. Therefore, management decisions must consider both the vegetation and soil characteristics.

Forest harvest and wildfire can accelerate rates of carbon loss from soils. Harvest removes the amount of vegetation that can be added to soils while wildfire removes organic carbon from both vegetation and soil. Both disturbances can accelerate erosion or leaching losses from soils and lead to a loss of carbon from the terrestrial realm and a transfer to “downstream” ecosystems. Harvest practices that do not appropriately consider equipment suitability for a given site (e.g., slope, soil texture, or seasons of operability) can cause significant losses of soil organic matter (3,4). Moreover, harvesting can have indirect effects on carbon storage by changing microclimate conditions, such as changes in soil temperature and moisture. At the same time, it is worth mentioning that analyses of harvesting and fire on soil carbon stores show that the effects of these events are typically small when considered in the broader context of landscape-scale sources in variation, such as with changes in soil carbon across different vegetative communities, soil types, and physiographic provinces (5,6).

Likely Changes

There are a few ways in which soil carbon may change in response to climate change. Changes may occur through changes in the relationship between biomass production and decomposition, or alternatively, in response to shifts in vegetation communities that are driven by climate change.

Both vegetation growth and decomposition processes will respond to changes in temperature. Decomposition, which releases mineral nutrients through weathering and produces carbon dioxide as organic matter breaks down, will rise along with temperature increases as long as factors like oxygen, moisture, and vegetation inputs are not limiting. Since both primary production and decomposition may increase with temperature, changes in soil carbon will likely depend on how individual forests respond to factors other than temperature in different soil types. For example, changes in precipitation patterns are predicted to create exaggerated periods of both drought and extreme precipitation (7), leading to either increased erosion of stabilized mineral soil carbon, or decreased decomposition linked to low oxygen availability in wet soils.

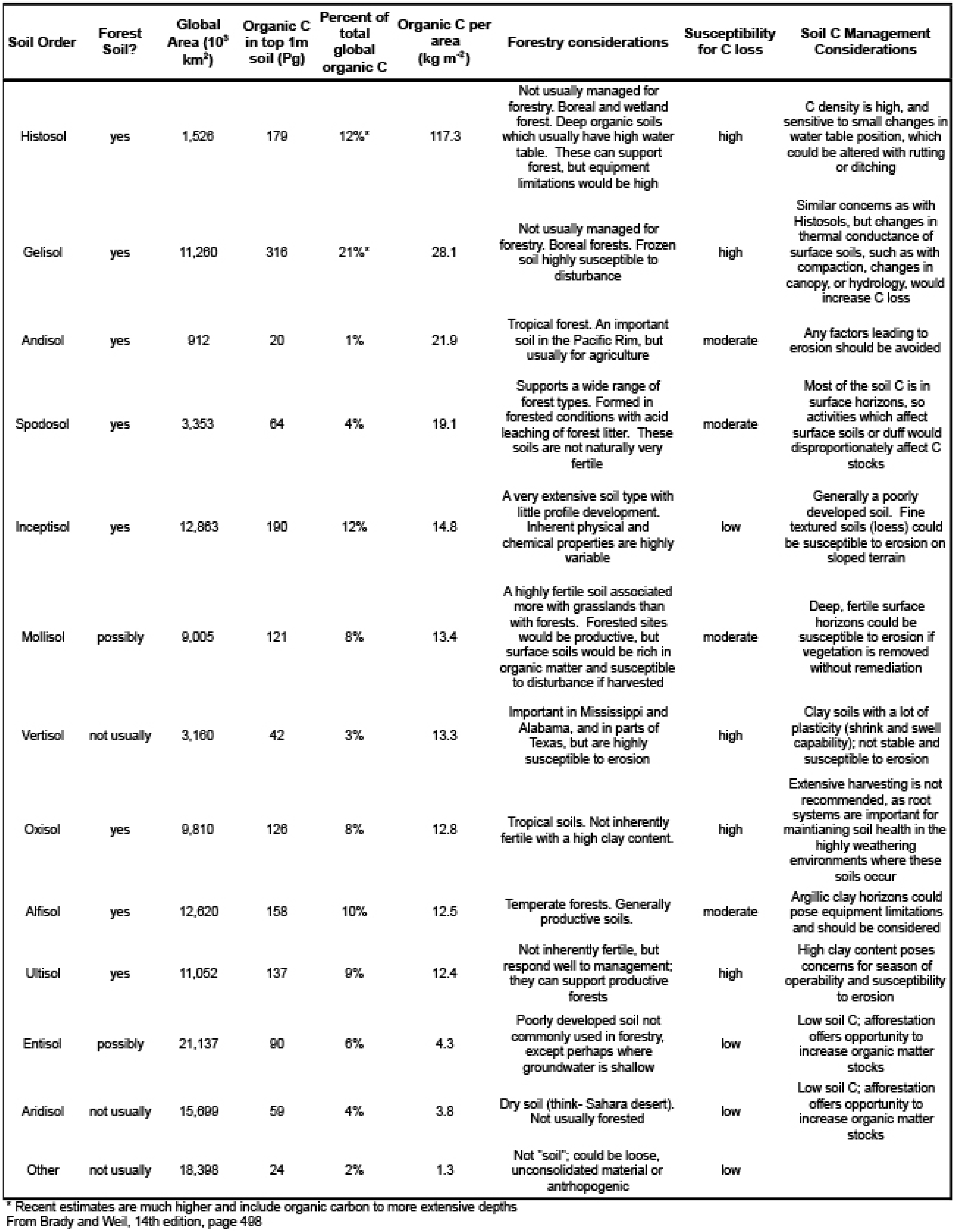
Table: *Forest management considerations for soil organic carbon, by soil order (broad taxonomic unit of soil). Data from Eswaran et al., 2000 (8).*

Climate changes are likely to favor different forest communities across the landscape (9), which has consequences for the quantity and intrinsic properties of carbon inputs to the soil. Although it is not possible to predict the future species composition of forests, current observational studies can lend some insight into the changing nature of stand carbon inputs with climate. Shifts in forest types, growth rates, and soil decomposition have been observed across varying landscape positions and within climate gradients, and some studies have observed specific climate conditions which optimize biomass and soil carbon sequestration within a forest type (10,11).

Options for Management

Forest management for increased carbon storage is not a new concept: there is a well-developed science on optimizing tree biomass and approximately half of biomass is carbon. However, managing forests to optimize biomass accumulation and carbon sequestration is difficult because there is still a great deal of uncertainty about how to increase soil organic carbon storage in managed stands.

In practice, there are two aspects of managing forests for soil carbon storage, including reducing carbon losses and increasing inputs from net primary production. The main source of uncertainty regarding management options for soil carbon stem from the difficulty in quantifying the large variability in soil carbon stocks in a spatially extensive way. Moreover, there are few studies where soil carbon stocks have been measured over time, both prior to harvesting and repeatedly after several rotations (13). Studies to date do suggest that managed forests are effective at maintaining carbon stocks and show little long-term effects on soil carbon stocks with harvesting (5,14,15). In fact, some studies have suggested that site preparation can effectively mix surface litter into the mineral soil and marginally increase soil carbon near the surface (16); however, this is not the normal condition after harvesting in most forest types (5) and integrating mixing of surface organics with mineral soil could also enhance decomposition. It is important to note that existing studies focus mainly on soils which have lower carbon storage potential (Spodosols, Alfisols, Inceptisols, and Ultisols).



Soil Order	Forest Soil?	Global Area (10^3 km^2)	Organic C in top 1m soil (Pg)	Percent of total global organic C	Organic C per area (kg m^{-2})	Forestry considerations	Susceptibility for C loss	Soil C Management Considerations
Histosol	yes	1,526	179	12%*	117.3	Not usually managed for forestry. Boreal and wetland forest. Deep organic soils which usually have high water table. These can support forest, but equipment limitations would be high	high	C density is high, and sensitive to small changes in water table position, which could be altered with rutting or ditching
Gelisol	yes	11,260	316	21%*	28.1	Not usually managed for forestry. Boreal forests. Frozen soil highly susceptible to disturbance	high	Similar concerns as with Histosols, but changes in thermal conductance of surface soils, such as with compaction, changes in canopy, or hydrology, would increase C loss
Andisol	yes	912	20	1%	21.9	Tropical forest. An important soil in the Pacific Rim, but usually for agriculture	moderate	Any factors leading to erosion should be avoided
Spodosol	yes	3,353	64	4%	19.1	Supports a wide range of forest types. Formed in forested conditions with acid leaching of forest litter. These soils are not naturally very fertile	moderate	Most of the soil C is in surface horizons, so activities which affect surface soils or duff would disproportionately affect C stocks
Inceptisol	yes	12,863	190	12%	14.8	A very extensive soil type with little profile development. Inherent physical and chemical properties are highly variable	low	Generally a poorly developed soil. Fine textured soils (loess) could be susceptible to erosion on sloped terrain
Mollisol	possibly	9,005	121	8%	13.4	A highly fertile soil associated more with grasslands than with forests. Forested sites would be productive, but surface soils would be rich in organic matter and susceptible to disturbance if harvested	moderate	Deep, fertile surface horizons could be susceptible to erosion if vegetation is removed without remediation
Vertisol	not usually	3,160	42	3%	13.3	Important in Mississippi and Alabama, and in parts of Texas, but are highly susceptible to erosion	high	Clay soils with a lot of plasticity (shrink and swell capability); not stable and susceptible to erosion
Oxisol	yes	9,810	126	8%	12.8	Tropical soils. Not inherently fertile with a high clay content.	high	Extensive harvesting is not recommended, as root systems are important for maintianing soil health in the highly weathering environments where these soils occur
Alfisol	yes	12,620	158	10%	12.5	Temperate forests. Generally productive soils.	moderate	Argillic clay horizons could pose equipment limitations and should be considered
Ultisol	yes	11,052	137	9%	12.4	Not inherently fertile, but respond well to management; they can support productive forests	high	High clay content poses concerns for season of operability and susceptibility to erosion
Entisol	possibly	21,137	90	6%	4.3	Poorly developed soil not commonly used in forestry, except perhaps where groundwater is shallow	low	Low soil C; afforestation offers opportunity to increase organic matter stocks
Aridisol	not usually	15,699	59	4%	3.8	Dry soil (think- Sahara desert). Not usually forested	low	Low soil C; afforestation offers opportunity to increase organic matter stocks
Other	not usually	18,398	24	2%	1.3	Not "soil"; could be loose, unconsolidated material or antrhopogenic	low	

* Recent estimates are much higher and include organic carbon to more extensive depths
From Brady and Weil, 14th edition, page 498

Forest management affects many soil processes. For example, compaction from harvesting equipment can reduce total pore space, which may be beneficial for plant production in poorly-structured soils (17). Soils with reactive mineralogy, such as with clay or argillic horizons, may be more able to stabilize carbon inputs where management increases primary production, but these soils would also be more susceptible to increased compaction during harvest. Carbon losses can be reduced by avoiding harvest practices that lead to erosion or exposure of the forest floor. It is likely that the forest types and their associated soils which have high carbon densities as a result of climate protection mechanisms (e.g., cold temperature or water saturation) are much more likely to lose carbon if disturbed, which may occur as a result of predicted changes in climate. By considering mechanisms of soil carbon stabilization, distribution and density of soil organic carbon, and increased harvest rotations in management, forest managers can help to manage soil carbon.

Mechanism of Soil Carbon Stabilization

The vulnerability of soil carbon to changes in climate or a change in management activities is dependent on the mechanisms responsible for maintaining a positive carbon balance in a forest soil. Climate factors that decrease soil decomposition, such as cool temperatures or saturated conditions, are nearly impossible to control in managed forests. As such, managing for increased soil carbon in forests where carbon is currently protected by cool temperatures or frozen soil may be a losing battle; cool moist forests are at a greater risk of losing soil carbon in a warmer world with more variable precipitation or under conditions where harvesting is intensified. Increased growth rates will increase the fresh litter pool, but litter is likely to also be turned over faster as conditions improve for growth. There may be a net gain in the aboveground stock of carbon in live biomass, but it may come at the expense of the soil. On the other hand, carbon in more reactive soils such as Ultisols or Andisols is stabilized by physico-chemical mechanisms as opposed to cool temperatures. These soils may be more responsive to management activities which increase carbon inputs to the soil, such as fertilization or afforestation. We note here that there is huge variability within soil Order, so a more specific inquiry as to a soil's "reactivity" would be available at the Family level of classification, which includes a soil's particle size category and a descriptor of mineralogy (these details are available through the USDA Soil Survey [direct link].

Distribution and Density of Soil Carbon by Forest Type

Soil carbon stocks may be more vulnerable to loss from harvesting or disturbance in forest types where more carbon is held in the surface organic matter ("O" horizons, or "duff") when compared to forests where carbon is harbored deeper in the soil profile or stabilized with mineral complexes. Forest types with higher levels of soil carbon near the surface also generally have higher carbon densities and usually accumulate carbon because of cool and/or wet conditions, which would be likely to change when disturbed. Even small changes in climate or soil carbon stabilization in forests with high carbon densities can result in relatively large declines in carbon storage. For example, Alaskan forests and eastern aspen-birch forests have large soil carbon stores because they have high carbon densities in surface organic horizons, which are vulnerable to increased mineralization through disturbances such as altered drainage or wildfire. On the other hand, oak-hickory forests contain large stocks of soil carbon where the distribution of soil carbon is not concentrated in the surface horizons, which probably makes it less vulnerable to climate change. Because oak-hickory forests are widely distributed, this forest type may represent an opportunity for increased carbon storage through management activities, which promote plant growth.

Conclusions

Management options for increasing soil carbon include changes that increase vegetation inputs to soils from plant production as well as actions to reduce losses of soil carbon from decomposition, erosion, or other disturbance. Management options for increasing aboveground forest production are fairly well understood, and mean aboveground biomass values are relatively uniform across forest types in managed systems relative to soil carbon stocks. The accrual of soil carbon is based on the relationship between inputs (from vegetation) and outputs (from decomposition or disturbance). There are some opportunities for increasing soil carbon sequestration in extensive forest types with relatively small soil carbon stocks per unit area. Carbon losses can be reduced by avoiding harvest practices that lead to erosion or exposure of the forest floor. The use of longer stand rotations or less intensive harvests could also increase soil carbon inputs and create favorable microclimates to decrease soil losses from decomposition and erosion. It is important to note here that most forests are reasonably adept at holding onto their carbon. Management practices that maintain forest cover, create forests where they did not exist previously (afforestation) and avoid drainage of systems with deep organic soils (which contain substantial carbon stores), are likely to have the best results for keeping carbon in forest soils.

How to cite

D'Amore, D.; Kane, E. 2016. Climate Change and Forest Soil Carbon. (August, 2016). U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. www.fs.usda.gov/ccrc/topics/forest-soil-carbon

Recommended Reading

The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect. Edited by: Kimble, JM; Heath, LS; Birdsey, RA; Lal, R. 2003. CRC Press, Boca Raton, Fl.

What's in a name? The importance of soil taxonomy for ecology and biogeochemistry. Frontiers in Ecology. Schimmel, J; Chadwick, O. 2013. doi:10.1890/13.WB.016.

Related Links

How will forest types likely change in the future?

http://www.nrs.fs.fed.us/atlas/tree/

How can I tell what soil types are present, given a Township, Section, and Range, or a GPS coordinate?

http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

A short course for land managers interested in soil carbon:

http://www.fsl.orst.edu/fs-pnw/pep/carbon/nave/

A collection of short courses on Carbon and Wildland Management:

http://www.fs.usda.gov/ccrc/videos/collections/short-courses-and-workshops/forest-and-grassland-carbon-north-america-short-cou-1

References

1. Birdsey, RA. 1992. Carbon Storage and Accumulation in United States Forest Ecosystems. United States Department of Agriculture, Forest Service General Technical Report WO-59.
2. Johnson, MG; Kern, JS. 2003. Quantifying the organic carbon held in forested soils of the United States and Puerto Rico. In: The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect; edited by: Kimble, JM; Heath, LS; Birdsey, RA; Lal, R. CRC Press, LLC. pp. 47-72.
3. Page-Dumroese, D; Jurgensen, M; Elliot, W, et al. 2000. Soil quality standards and guidelines for forest sustainability in northwestern North America. Forest Ecology and Management. 138: 445–462.
4. Page-Dumroese, DS; Abbott, AM; Rice, TM. 2009. Forest Soil Disturbance Monitoring Protocol Volume II: Supplementary Methods, Statistics, and Data Collection. United States Department of Agriculture, Forest Service General Technical Report, WO-82b.
5. Nave, LE; Vance, ED; Swanston, CW; Curtis, PS. 2010. Harvest impacts on soil carbon storage in temperate forests. Forest Ecology and Management 259:857–866.
6. Nave, LE; Vance, ED; Swanston, CW; Curtis, PS. 2011. Fire effects on temperate forest soil C and N storage. Ecological Applications 21(4):1189–1201.
7. Wuebbles, D; Meehl, G; Hayhoe, K; et al. 2014. CMIP5 Climate Model Analyses: Climate Extremes in the United States. Bulletin of the American Meteorological Society 95(4):571-583.
8. Eswaran, H; Reich, PF; Kimble, J; Beinroth, FH; Padmanabhan, E; Moncharoen, P. 2000. Global Carbon Stocks. In: Global Climate Change and Pedogenic Carbonates, edited by: Lal, R. Boca Raton, Fl: Lewis Publishers. pp. 15-26.
9. Vose, J.M.; Peterson, D.L.; Patel-Weynand, T. 2012. Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 265 p.
10. Griffiths, RP; Madritch, MD; Swanson, AK. 2009. The effects of topography on forest soil characteristics in the Oregon Cascade Mountains (USA): Implications for the effects of climate change on soil properties. Forest Ecology and Management 257:1-7.
11. Johnson, K; Scatena, FN; Johnson, AH; Pan, Y. 2009. Controls on soil organic matter content within a northern hardwood forest. Geoderma 148:346-356.
12. Iverson, LR; Prasad, AM; Matthews, SN; Peters, MP. 2011. Lessons learned while integrating habitat, dispersal, disturbance, and life history traits into species habitat

models under climate change. Ecosystems 14:1005-1020.

13. Hoover, CM. 2003. Soil carbon sequestration and forest management: challenges and opportunities. In: The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect; edited by: Kimble, JM; Heath, LS; Birdsey, RA; Lal, R. CRC Press, LLC. pp. 211-238.
14. Johnson, DW; Curtis, PS. 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management 140:227-238.
15. Powers, M; Kolka, R; Palik, B; McDonald, R; Jurgensen, M. 2011. Long-term management impacts on carbon storage in Lake States forests. Forest Ecology and Management 262:424-431.
16. McLaughlin, JW; Liu, G; Jurgensen, MF; Gale, MR. 1996. Organic Carbon Characteristics in a Spruce Swamp Five Years after Harvesting. Soil Science Society of America Journal 60(4): 1228-1236.
17. Powers, RF; Scott, DA; Sanchez, FG; Voldseth, RA; Page-Dumroese, D; Elioff, JD; Stone, DM. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. Forest Ecology and Management 220:31-50.
18. D’Amato, AW; Bradford, JB; Fraver, S; Palik, BJ. 2011. Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. Forest Ecology and Management 262:803-816.
19. Harmon, ME, Marks, B. 2002. Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, USA: results from a simulation model. Canadian Journal of Forest Research 32:863–877.
20. Pregitzer, KS; Euskirchen, ES. 2004. Carbon cycling and storage in world forests: biome patterns related to forest age. Global Change Biology 10:2052–207
21. Rhemtulla,, JM; Mladenoff, DJ; Clayton, MK. 2009. Historical forest baselines reveal potential for continued carbon sequestration. Proceedings of the National Academy of Sciences 106:6082–6087.

Search CCRC

Related Topics

Forest Management for Carbon Benefits

Carbon Considerations in Land Management

Management of Forest Carbon Stocks

Carbon Benefits of Wood-Based Products and Energy

Grassland Carbon Management

Carbon and Land Management, an introduction

Importance of Forest Cover

Global Carbon

Carbon as One of Many Management Objectives

About the Climate Change Resource Center

The Climate Change Resource Center welcomes your comments and suggestions:
ccrc@fs.fed.us, USDA FS Climate Change Resource Center

USDA.Gov | Site Map | Policies & Links | Our Performance | Report Fraud On USDA Contracts | Visit OIG | Plain Writing | Get Adobe Reader
FOIA | Accessibility Statement | Privacy Policy | Non-Discrimination Statement | Information Quality | USDA Recovery | USA.Gov | Whitehouse.Gov