Carbon Dynamics In Relation To Prescribed Fire In The Lake States

Lodi Marsh Wildlife Area / Photo Credit: Wisconsin DNR

April 2022

Jed Meunier & Colleen M. Sutheimer

Wisconsin Department of Natural Resources
Division of Forestry – Forest Economics and Ecology Section

SUMMARY

With carbon management emerging as an additional consideration for land managers due to growing concerns about climate change effects and prescribed burning representing a potentially avoidable source of carbon emissions, the carbon dynamics of prescribed fire need evaluation.

On the surface, fire as a carbon emission is simple. However, the reality is much more complicated, given the interactions between fire and vegetation across time and space and the potential for climate change to influence both (Hurteau and Brooks 2011).

Fire consumes biomass and releases carbon compounds such as carbon dioxide, carbon monoxide, methane, and particulate matter immediately during combustion, and longer-term carbon emissions from fire occur as vegetation killed during burning decomposes (Schlesinger and Bernhardt 2020). Total emissions from fire vary because of many factors, including:

- Region
- Ecosystem
- Weather conditions before, during and after burning

Total emissions from fire are also influenced by short-term and long-term carbon dynamics (Schlesinger and Bernhardt 2020).

A portion of carbon emitted during burning is also returned to soils as pyrogenic carbon, a thermally altered form of organic carbon produced during fires. It can contribute to long-term carbon sequestration in soils due to its stability and residence in soils over long (e.g., millennial) timescales (Santos et al. 2012, Singh et al. 2012, Fang et al. 2014).

In ecosystems like grasslands, where most carbon is stored belowground as soil organic carbon, burning has minimal impacts on overall carbon stocks because aboveground carbon pools and net primary production are smaller (Schlesinger and Bernhardt 2020). Even when these systems are burned repeatedly, carbon is quickly recovered after fire as new plant growth uptakes atmospheric carbon emitted during burning (Janowiak et al. 2017).

In other ecosystems, like forests, burning can have greater impacts on carbon dynamics, especially where aboveground carbon pools are large. In forests, carbon is released during burning as understories are consumed in surface fires, and overstories are consumed in stand-replacing fires. After a fire, dead vegetation and litter on the forest floor continue to release carbon dioxide via decomposition (Schlesinger and Bernhardt 2020, Janowiak et al. 2017). Carbon emissions from the decomposition of fire-killed trees from stand-replacing fires can account for more carbon released than during combustion itself (Campbell et al. 2016). Forested systems have high annual net primary productivity, and as trees re-establish after a fire or continue growing if not killed during fire, they sequester carbon emitted during burning and decomposition. These carbon dynamics after a fire in forests operate at scales of tens to hundreds of years, and forests remain carbon sinks when natural fire regimes are maintained (Janowiak et al. 2017).

When fire frequency and severity are within the historical range of variability that ecosystems have adapted to, fire maintains aboveground and belowground carbon pools through time (McLauchlan et al. 2014). The effects of prescribed fire on mainly understory plant and leaf litter carbon are short-lived, and carbon pools are replenished quickly (Mitchell et al. 1999, Starr et al. 2015, Kirkman et al. 2016, Flanagan et al. 2019).

Management that maintains the amount and longevity of sequestered carbon leads to increased carbon storage and regulates long-term carbon balances. For example, mixed-conifer forests maintained by frequent surface fires historically had fewer trees but overall stored more carbon in larger and longer-lived trees. Recent fire exclusion has resulted in more smaller trees but less carbon storage over time due to increased mortality rates from increased stand density, shorter-lived species and increased carbon dioxide emissions from decomposition (Fellows and Goulden 2008, North et al. 2009).

The successful application of prescribed fire should consider the historical role of fire in ecosystems, the short-term and long-term impacts of fire on carbon dynamics, and the role of fire in maintaining stable carbon pools aboveground and belowground in ecosystems over relevant time scales.

General conclusions of fire effects on carbon stocks and cycling are below, with more in-depth discussion by system and related literature in the following chapters.

- Forests sequester higher amounts of carbon than grasslands, including in large aboveground carbon pools, but are more vulnerable to perturbations (pests, pathogens, climate variability, disturbance, etc.).
- Prairies store most ecosystem carbon belowground and pull more carbon from the atmosphere than they release during and after fires – even when burned repeatedly.
- Cumulative carbon emissions in forests through decomposition of fire-killed trees usually exceed pyrogenic emissions, with emissions during burning dependent on fire severity.
- Most systems in the Lake States (MN, WI, MI) sequester carbon within the same time scale of their fire frequency – systems in the Lakes States continue to be carbon sinks due to large carbon sequestration in the soils of grasslands and wetlands and carbon sequestration in forests both in trees and soils.
- Both carbon stocks and dynamics must be considered when estimating the impacts of fire – fire initially decreases net ecosystem productivity (NEP) and aboveground biomass, but in most ecosystems of the Lake States, both net ecosystem productivity and biomass recover quickly.

- Carbon dynamics are complex and driven by many factors such as soil temperature, site productivity, plant phenology, burn timing, burn frequency and species composition. Generally, total carbon stocks in natural communities remain stable under prescribed fire management.

Lodi Marsh Wildlife Area / Photo Credit: Wisconsin DNR

GRASSLANDS

Western Prairie Habitat Restoration Area / Photo Credit: Wisconsin DNR

Grasslands store 80 to 90% of ecosystem carbon in belowground pools as soil organic matter (Adams et al. 1990, Neary and Leonard 2020). Temperate grasslands have 150% more carbon in belowground pools than temperate forest belowground pools, with evidence that carbon storage capacity in grasslands will increase with global warming (IPCC 2000).

Prescribed fires and wildfires in grasslands constitute a large portion of total annual acres burned in North America (Morton et al. 2013) but do not contribute significantly to overall carbon dioxide emissions (Wiedinmyer and Neff 2007). Fires in grasslands move rapidly with narrow flame fronts and do not significantly impact belowground pools where most carbon is stored (Janowiak et al. 2017, Neary and Leonard 2020).

While burning grasslands emits carbon, fires stimulate plant growth by removing competition, increasing light availability and stimulating soil bacteria that make nitrogen available for new growth (Janowiak et al. 2017). Carbon released during prescribed fires is not the same as fossil carbon released by burning gas. Atmospheric carbon that is released during prescribed burning is subsequently reabsorbed over short periods of time both by new vegetation and through sequestration in belowground carbon pools (Wilhelm 2000).

In temperate latitudes, aboveground plant biomass in grasslands senesces and decomposes, releasing carbon annually but over a longer period than burning. Restoring degraded grasslands globally could increase carbon sequestration by more than three gigatons of carbon per year (Lal 2009). Restored grasslands have been shown to increase carbon capture and sequestration even under climate change scenarios (Janowiak et al. 2017, Yang et al. 2019). Fire exclusion may lead to increased encroachment of woody shrubs, resulting in species composition changes that reduce soil carbon pools and native plant productivity (Briggs and Knapp 1995, Knapp et al. 2009, Jackson et al. 2002).

Key Takeaways

- Prescribed fire consumes aboveground biomass releasing carbon dioxide but rarely impacts belowground stocks where most carbon is stored in grasslands (Fischer et al. 2012, Neary and Leonard 2020).
- Prescribed fire impacts depend on fuel loads, species composition, fire frequency, burn season, and climatic conditions before and after burning in grasslands (Anderson 2006, MacNeil et al. 2008, Connell et al. 2020).
- Prescribed fire enhances productivity and carbon sequestration in grasslands when precipitation and soil moisture are sufficient (Gale et al. 1990, Heisler et al. 2004, Dai et al. 2006, Bremer and Ham 2010).
- Periodic prescribed fires (e.g., 2-3 burns every five years) can maintain and increase total ecosystem carbon in grasslands (Ansley et al. 2006, Anderson 2006, Bremer and Ham 2010).

WETLANDS

Horicon Marsh Wildlife Area / Photo Credit: Wisconsin DNR

Wetlands in the Lake States are important carbon sinks, storing 42% of all carbon while covering only 27% of the region. They are projected to continue sequestering more carbon per unit area than all other ecosystems under climate change (Liu et al. 2014).

Approximately 60% of carbon in Lake States wetlands is stored in soil organic matter, with the remainder in aboveground biomass (Liu et al. 2014). Practitioners have used prescribed fire in wetlands since the early 1900s to promote the growth of desirable wetland vegetation, reduce dead litter, create mixtures of wildlife habitats that include both open water and vegetated cover and reduce risks of unpredictable wildfires (Stoddard 1931, Lynch 1941, Flores et al. 2011). Historical evidence in the Lake States has shown that relatively frequent fires were important to wetland development and maintenance (Sutheimer et al. 2021).

While low-severity surface fire during times of high soil moisture is beneficial to wetlands, globally, climate change is contributing to increasing threats to wetlands due to destructive ground fires that enter hydrologically altered wetlands soils and smolder for years, consuming and releasing massive amounts of carbon (Dahl 2011, Angel et al. 2018).

Key Takeaways

- Historically, surface fires were frequent in certain wetland types across North America, including the Lake States (Heinselman et al. 1973, Neary et al. 2005, and Sutheimer et al. 2021).
- Periodic low-intensity fire supports long-term carbon storage and minimizes carbon emissions in wetlands when soils are wet enough to inhibit vertical movement of fire and

vegetation is sufficiently dry to carry surface fire across the wetland (Neary et al. 2005, Flanagan et al. 2020).

- Pyrogenic carbon produced during low-severity fires in wetlands can be stored for thousands of years belowground. Once incorporated into deep peat soils, it is resistant to decomposition and release during subsequent fires (Flanagan et al. 2020).
- Wildfires that move vertically into the soil can result in significant atmospheric carbon emissions, e.g., smoldering ground fires can burn underground for months, reigniting as surface fires long after initial ignition (Neary et al. 2005, Scholten et al. 2021).

BARRENS AND SAVANNAS

Crex Meadows Wildlife Area / Photo Credit: Wisconsin DNR

Barrens and savannas are fire-dependent natural communities with a partial tree canopy of primarily pine and oak with open areas dominated by herbaceous vegetation with a structure resembling a transition between grasslands and forests (Chapter 7, WI DNR 2015). Barrens and savannas are an especially important system for understanding carbon dynamics relative to prescribed fire because prescribed fire is one of the primary management tools in these systems.

Carbon dynamics in barrens and savannas are similar to grasslands, particularly where trees' levels of mortality with burning are low. Fire exclusion has contributed to barrens and savannas converting to closed canopy hardwood forests throughout the Lake States. Prescribed fire is an increasingly important tool for restoring ecosystem structure and function, including carbon sequestration in above and belowground carbon pools (Quigley et al. 2020). Efficacy of prescribed fire in barrens and savannas is dependent on fire frequency, current vegetative structure and species composition, degree of land-use changes, and soil fertility (Quigley et al. 2020, La Puma et al. 2013).

The soil characteristics of glacial outwash sands across the Lake States make the use of prescribed fire effective for restoring barrens and savanna habitats (Quigley et al. 2020). Barrens and savannas are dependent on pyrogenic carbon (a general term for organic materials that have been subject to partial combustion) produced during burning with much of this pyrogenic carbon stored in belowground carbon pools for hundreds to thousands of years, contributing to net ecosystem carbon sequestration, even when burned frequently (Pingree and DeLuca 2017).

Key Takeaways

- Barrens and savannas are resilient to fire, and carbon will continue to accumulate under active fire management due to the adaptive capacity of dominant vegetation (Scheller et al. 2011).
- Long-term carbon dynamics in barrens and savannas dominated by fire-adapted species are minimally impacted under prescribed fire management at the landscape level, given prescribed burn rotations allow sufficient time for carbon accumulation between fires (Clark et al. 2015).
- Prescribed fire initially decreases carbon stocks in barrens and savannas through the consumption of surface fuels resulting in high concentrations of leachable nutrients in ash – this ultimately helps maintain and restore these systems by limiting tree and shrub growth (Quigley et al. 2019).
- A comparison of carbon emissions from forest floor fuel consumption during prescribed burning of barrens and savannas to wildfire carbon emissions showed a single wildfire can emit two to three times more carbon than average annual emissions from prescribed burning (Clark et al. 2010).

NORTHERN AND SOUTHERN FORESTS

Kettle Moraine State Forest / Photo Credit: Wisconsin DNR

Roughly half of all terrestrial carbon in the Lake States is stored in forests, and of that carbon, approximately 50% is stored belowground, approximately 37% in live trees and understory vegetation, and approximately 13% is stored in dead wood and leaf litter on the forest floor (USDA 2004, Liu et al. 2014).

Across the U.S., increasing carbon dioxide concentrations over the last 50 years have maintained eastern forests as carbon sinks (Birdsey et al. 2019), while in the western U.S., increasingly frequent and severe wildfires are turning forests into carbon sources (North and Hurteau 2011, Birdsey et al. 2019).

Studies of large wildfires in the U.S. found that the use of prescribed fire could reduce carbon dioxide emissions during wildfires by more than 50% and increase the effectiveness of suppression efforts (Wiedinmyer and Hurteau 2010, Harris et al. 2021). Research and simulations in the mid-Atlantic region suggest that prescribed burning does not significantly alter short- or long-term carbon sequestration at either stand or landscape scales and, in concert with fire suppression activities, may reduce carbon losses associated with wildfires (Clark et al. 2014).

Outside of reducing carbon emissions from unplanned wildfires, the role of prescribed burning in carbon dynamics is less clear. It requires an understanding of the dynamics of combustible biomass pools over time, which are lacking in this region. Research suggests that across the U.S., as much carbon is released from insect- and pathogen-killed trees as is released from forest fires (Kautz et al. 2017). Prescribed fire has been shown to increase resistance to drought, pests and pathogens in conifers (fir and pine species) and reduce the general mortality of trees (van Mantgem et al. 2021).

Prescribed burning may also reduce competition, increase target species' growth rates, and improve aboveground and belowground ecosystem structures and functions. Prescribed fire has been found to maintain and promote carbon stability and mitigate long-term carbon emissions in forests (Martin et al. 2015, Flanagan et al. 2019, Pellegrini et al. 2021) while creating resilient and resistant forests by restoring forest structure (Earles et al. 2014, Martin et al. 2015). For example, in southeastern pine forests, prescribed fire management resulted in greater aboveground storage and less net carbon emissions than fire exclusion over 100-year intervals (Flanagan et al. 2019).

Generally, mature stands with fewer and larger diameter trees, within stands maintained by frequent low-severity fire, take in more carbon over time than they release as trees accumulate more carbon with increasing size (Xu et al. 2014, Stephenson et al. 2014). Small-tree carbon is unstable and prone to shifting a stand's major carbon stocks (Hurteau et al. 2019). During fire, a portion of the burning vegetation and soil organic matter is also converted into charcoal, a relatively stable form of pyrogenic carbon (Wiechmann et al. 2015).

Key Takeaways

- Net carbon emissions from disturbances (harvest, pests, pathogens, severe weather events, fire, etc.) are variable among forest types and forest carbon pools (Birdsey et al 2019, USDA 2013).
- Prescribed fire reduces forest floor carbon stocks, minimally impacts forest overstories and does not impact mineral soil in forest types that evolved with fire (Chiang et al. 2008, Nave et al 2011, Miesel et al. 2012, Kolka et al. 2014).
- Effective prescribed fire use in forests includes consideration of impacts of burning on long-term and short-term carbon cycles (Nave et al. 2011, Martin et al. 2015, James et al. 2018).
- Prescribed fires emit less carbon dioxide than wildfires in forests (Flanagan et al. 2019).
- Prescribed fire can reduce wildfire hazards and stabilize forests' carbon stocks when used appropriately (Mickler et al. 2007, North et al. 2009, Clark et al. 2014, and Hurteau et al. 2019).

REFERENCES

Adams, J.M., H. Faure, L. Faure-Denard, J.M. McGlade, F.I. Woodward. 1990. Increase in terrestrial carbon storage from the last glacial maximum to the present. *Nature* 348: 711–714.

Association for Fire Ecology. 2013. The merits of prescribed fire outweigh potential carbon emissions effects. A white paper developed by Association for Fire Ecology, International Association of Wildland Fire, Tall Timbers Research Station, and The Nature Conservancy.

Anderson, R.C. 2006. Evolution and origin of the Central Grassland of North America: climate, fire, and mammalian grazers. *The Journal of the Torrey Botanical Society* 133:626–647.

Angel, J.R., C. Swanson, B.M. Boustead, K. Conlon, K.R. Hall, J.L. Jorns, K.E. Kunkel, M.C. Lemos, B.M. Lofgren, T. Ontl, J. Posey, K. Stone, E. Takle, and D. Todey. 2018. Chapter 21: Midwest. Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program.

Ansley, R.J., T.W. Boutton, and J.O. Skjemstad. 2006. Soil organic carbon and black carbon storage and dynamics under different fire regimes in temperate mixed-grass savanna: Soil Organic Carbon and Black Carbon Responses to Fire Regime. *Global Biogeochemical Cycles* 20: n/a-n/a.

Birdsey, R.A., A.J. Dugan, S.P. Healey, K. Dante-Wood, F. Zhang, G. Mo, J.M. Chen, A.J. Hernandez, C.L. Raymond, and J. McCarter. 2019. Assessment of the influence of disturbance, management activities, and environmental factors on carbon stocks of U.S. national forests. Page RMRS-GTR-402. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.

Bremer, D.J., and J.M. Ham. 2010. Net Carbon Fluxes Over Burned and Unburned Native Tallgrass Prairie. *Rangeland Ecology & Management* 63: 72–81.

Briggs, J.M., and A.K. Knapp. 1995. Interannual Variability in Primary Production in Tallgrass Prairie: Climate, Soil Moisture, Topographic Position, and Fire as Determinants of Aboveground Biomass. *American Journal of Botany* 82: 1024–1030.

Campbell, J.L., J.B. Fontaine, and D.C. Donato. 2016. Carbon emissions from decomposition of fire-killed trees following a large wildfire in Oregon, United States. *Journal of Geophysical Research*, 10.1002/2015JG003165.

Chiang, J.M., R.W. McEwan, D.A. Yaussy, and K.J. Brown. 2008. The effects of prescribed fire and silvicultural thinning on the aboveground carbon stocks and net primary production of overstory trees in an oak-hickory ecosystem in southern Ohio. *Forest Ecology and Management* 255: 1584–1594.

Clark, K.L. 2010. Fuel consumption and particulate emissions during fires in the New Jersey Pinelands: 19.

Clark, K.L., N. Skowronski, H. Renninger, and R. Scheller. 2014. Climate change and fire management in the mid-Atlantic region. *Forest Ecology and Management* 327: 306–315.

Clark, K.L., N. Skowronski, and M. Gallagher. 2015. Fire Management and Carbon Sequestration in Pine Barren Forests. *Journal of Sustainable Forestry* 34: 125–146.

Connell, R.K., J B. Nippert, and J.M. Blair. 2020. Three Decades of Divergent Land Use and Plant Community Change Alters Soil C and N Content in Tallgrass Prairie. *Journal of Geophysical Research: Biogeosciences* 125.

Dahl, T.E. 2011. Status and Trends of Wetlands in the Conterminous United States 2004 to 2009. Page 112.

Dai, X., T.W. Boutton, M. Hailemichael, R.J. Ansley, and K.E. Jessup. 2006. Soil Carbon and Nitrogen Storage in Response to Fire in a Temperate Mixed-Grass Savanna.

Earles, J.M., M.P. North, and M.D. Hurteau. 2014. Wildfire and drought dynamics destabilize carbon stores of fire-suppressed forests. *Ecological Applications* 24: 732–740.

US Environmental Protection Agency (EPA). 2021. Comparative assessment of the impacts of prescribed versus wildfire: a case study in the Western U.S. Office of Research and Development Center for Public Health & Environmental Assessment, Research Triangle Park, NC, USA.

Wisconsin Department of Natural Resources. 2015. Chapter 7: Natural communities, aquatic features, and selected habitats of Wisconsin. In: The ecological landscapes of Wisconsin: an assessment of ecological resources and a guide to planning sustainable management. Wisconsin Department of Natural Resources, PUB-SS-1131, Madison, WI.

Fang, Y., B. Singh, B.P. Singh, E. Krull. 2014. Biochar carbon stability in four contrasting soils. *Soil Science* 65: 60–71.

Fellows, A.W., M.L. Goulden. 2008. Has fire suppression increased the amount of carbon stored in western U.S. forests? *Geophysical Research Letters* 35: L12404.

Fischer, M.L., M.S. Torn, D.P. Billesbach, G. Doyle, B. Northup, and S.C. Biraud. 2012. Carbon, water, and heat flux responses to experimental burning and drought in a tallgrass prairie. *Agricultural and Forest Meteorology* 166–167: 169–174.

Flanagan, S.A., S. Bhotika, C. Hawley, G. Starr, S. Wiesner, J.K. Hiers, J.J. O'Brien, S. Goodrick, M.A. Callaham, R.M. Scheller et al. 2019. Quantifying carbon and species dynamics under different fire regimes in a southeastern U.S. pineland. *Ecosphere* 10: doi.org/10.1002/ecs2.2772.

Flanagan, N.E., H. Wang, S. Winton, and C.J. Richardson. 2020. Low-severity fire as a mechanism of organic matter protection in global peatlands: Thermal alteration slows decomposition. *Global Change Biology* 26: 3930–3946.

Flanagan, S.A., S. Bhotika, C. Hawley, G. Starr, S. Wiesner, J K. Hiers, J.J. O'Brien, S. Goodrick, M.A. Callaham, R.M. Scheller, K.D. Klepzig, R.S. Taylor, and E.L. Loudermilk. 2019. Quantifying carbon and species dynamics under different fire regimes in a southeastern U.S. pineland. *Ecosphere* 10.

Flores, C., D.L. Bounds, and D.E. Ruby. 2011. Does Prescribed Fire Benefit Wetland Vegetation? *Wetlands* 31: 35–44.

Gale, W.J., M.B. Kirkham, E.T. Kanemasu, and C.E. Owensby. 1990. Net carbon dioxide exchange in canopies of burned and unburned tallgrass prairie. *Theoretical and Applied Climatology* 42: 237–244.

Harris, L.B., S.A. Drury, C.A. Farris, and A.H. Taylor. 2021. Prescribed fire and fire suppression operations influence wildfire severity under severe weather in Lassen Volcanic National Park, California, USA. *International Journal of Wildland Fire* 30: 536.

Heinselman, M.L. 1973. Fire in the Virgin Forests of the Boundary Waters Canoe Area, Minnesota. *Quaternary Research* 3: 329–382.

Heisler, J.L., J.M. Briggs, A.K. Knapp, J.M. Blair, and A. Seery. 2004. Direct and indirect effects of fire on shrub density and aboveground productivity in a mesic grassland. *Ecology* 85: 2245–2257.

Hurteau, M.D., and M.L. Brooks. 2011. Short- and Long-term Effects of Fire on Carbon in US Dry Temperate Forest Systems. *BioScience* 61: 139–146.

Hurteau, M.D., M.P. North, G.W. Koch, and B.A. Hungate. 2019. Opinion: Managing for disturbance stabilizes forest carbon. *Proceedings of the National Academy of Sciences* 116: 10193–10195.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Land use, land-use change, and forestry*. Report. Cambridge University Press, UK. Pp 875.

Jackson, R., J. Banner, E. Jobbágy, W. Pockman, and D. Wall. 2002. Ecosystem Carbon Loss with Woody Plant Invasion of Grasslands. *Nature* 418: 623–6.

James, J.A., C.C. Kern, and J.R. Miesel. 2018. Legacy effects of prescribed fire season and frequency on soil properties in a Pinus resinosa forest in northern Minnesota. *Forest Ecology and Management* 415–416: 47–57.

Janowiak, M., W.J. Connelly, K. Dante-Wood, G.M. Domke, C. Giardina, Z. Kayler, K. Marcinkowski, T. Ontl, C. Rodriguez-Franco, C. Swanston, C.W. Woodall, and M. Buford. 2017. Considering Forest and Grassland Carbon in Land Management. Page WO-GTR-95. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC.

Kautz, M., P. Anthoni, A.J.H. Meddens, T.A.M. Pugh, and A. Arneth. Simulting the recent impacts of multiple biotic disturbances on forest carbon cycling across the United States. *Global Change Biology* 24: doi.org/10.1111/gcb.13974.

Kirkman, L.K., L.M. Giencke, R.S. Taylor, L.R. Boring, C.L. Staudhammer, and R.J. Mitchell. 2016. Productivity and species richness in longleaf pine woodlands: resource-disturbance influences across an edaphic gradient. *Ecology* 97: 2259–2271.

Knapp, E.E., B.L. Estes, and C.N. Skinner. 2009. Ecological effects of prescribed fire season: a literature review and synthesis for managers. Page PSW-GTR-224. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

Kolka, R., B. Sturtevant, P. Townsend, J. Miesel, P. Wolter, S. Fraver, and T. DeSutter. 2014. Post-Fire Comparisons of Forest Floor and Soil Carbon, Nitrogen, and Mercury Pools with Fire Severity Indices. *Soil Science Society of America Journal* 78: S58–S65.

Lal, R. 2002. Carbon dynamics in cropland and rangeland. *Environmental Pollution* 116: 353–362.

Lal, R. 2009. Sequestering carbon in soils of arid ecosystems. *Land Degradation & Development* 20: 441–454.

Liu, S., J. Liu, Y. Wu, C.J. Young, J.M. Werner, D. Dahal, J. Oeding, and G.L. Schmidt. 2014. Baseline and projected future carbon storage, carbon sequestration, and greenhouse-gas fluxes in terrestrial ecosystems of the eastern United States. Chapter 7 *in* Z. Zhu and B. C. Reed, editors.

Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of the eastern United States. U.S. Geological Survey, Reston, Virginia.

Lynch, J.J. 1941. The Place of Burning in Management of the Gulf Coast Wildlife Refuges. *The Journal of Wildlife Management* 5: 454–457.

MacNeil, M.D., M.R. Haferkamp, L.T. Vermeire, and J.M. Muscha. 2008. Prescribed fire and grazing effects on carbon dynamics in a northern mixed-grass prairie. *Agriculture, Ecosystems & Environment* 127: 66–72.

Martin, K.L., M.D. Hurteau, B.A. Hungate, G.W. Koch, and M.P. North. 2015. Carbon Tradeoffs of Restoration and Provision of Endangered Species Habitat in a Fire-Maintained Forest. *Ecosystems* 18: 76–88.

Mickler, R., G. Achtemier, C. Geron, M. Rorig, and D. Brownlie. 2007. Development and demonstration of smoke plume, fire emissions, and pre- and post-prescribed fire fuel models to North Carolina Coastal Plain forest ecosystems. JFSP Research Project Report, Joint Fire Science Program.

Miesel, J., P. Goebel, R. Corace, D. Hix, R. Kolka, B. Palik, and D. Mladenoff. 2012. Fire Effects on Soils in Lake States Forests: A Compilation of Published Research to Facilitate Long-Term Investigations. *Forests* 3: 1034–1070.

Mitchell, R. J., L.K. Kirkman, S.D. Pecot, C.A. Wilson, B.J. Palik, and L.R. Boring. 1999. Patterns and controls of ecosystem function in longleaf pine - wiregrass savannas. I. Aboveground net primary productivity. *Canadian Journal of Forest Research* 29: 743–751.

Morton, D.C., G.J. Collatz, D. Wang, J.T. Randerson, L. Giglio, and Y. Chen. 2013. Satellite-based assessment of climate controls on US burned area. *Biogeosciences* 10: 247–260.

Nave, L.E., E.D. Vance, C.W. Swanston, and P.S. Curtis. 2011. Fire effects on temperate forest soil C and N storage. *Ecological Applications* 21: 1189–1201.

Neary, D.G., and J.M. Leonard. 2020. Effects of Fire on Grassland Soils and Water: A Review. Page *in* V. Missiakô Kindomihou, editor. *Grasses and Grassland Aspects*. IntechOpen.

Neary, D.G., K.C. Ryan, and L.F. DeBano. 2005. Wildland fire in ecosystems: effects of fire on soils and water. Page RMRS-GTR-42-V4. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.

North, M., M. Hurteau, and J. Innes. 2009. Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions. *Ecological Applications* 19: 1385–1396.

North, M.P., and M.D. Hurteau. 2011. High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest. *Forest Ecology and Management* 261: 1115–1120.

Pellegrini, A.F. A., A.C. Caprio, K. Georgiou, C. Finnegan, S.E. Hobbie, J.A. Hatten, and R.B. Jackson. 2021. Low-intensity frequent fires in coniferous forests transform soil organic matter in ways that may offset ecosystem carbon losses. *Global Change Biology* 27: 3810–3823.

Pingree, M.R. A., and T.H. DeLuca. 2017. Function of Wildfire-Deposited Pyrogenic Carbon in Terrestrial Ecosystems. *Frontiers in Environmental Science* 5: 53.

Quigley, K.M., R. Kolka, B.R. Sturtevant, M.B. Dickinson, C.C. Kern, D.M. Donner, and J.R. Miesel. 2020. Prescribed burn frequency, vegetation cover, and management legacies influence soil fertility: Implications for restoration of imperiled pine barrens habitat. *Forest Ecology and Management* 470–471: 118163.

Santos, F., M.S. Torn, and J.A. Bird. 2012. Biological degradation of pyrogenic organic matter in temperate forest soils. *Soil Biol. Biochem.* 51, 115–124. doi: 10.1016/j.soilbio.2012.04.005Scheller, R. M., S. Van Tuyl, K. L. Clark, J. Hom, and I. La Puma. 2011. Carbon Sequestration in the New Jersey Pine Barrens Under Different Scenarios of Fire Management. *Ecosystems* 14: 987–1004.

Schlesinger, W.H., and E.S. Bernhardt. 2020. Biogeochemistry: an analysis of global change. Fourth edition. Elsevier.

Scholten, R.C., R. Jandt, E.A. Miller, B.M. Rogers, and S. Veraverbeke. 2021. Overwintering fires in boreal forests. *Nature* 593: 399–404.

Singh, N., S. Abiven, M.S. Torn, and M.W.I. Schmidt. 2012. Fire-derived organic carbon in soil turns over on a centennial scale. *Biogeosciences* 9: 2847–2857.

Starr, G., C.L. Staudhammer, H.W. Loescher, R. Mitchell, A. Whelan, J.K. Hiers, and J.J. O'Brien. 2015. Time series analysis of forest carbon dynamics: recovery of Pinus palustris physiology following a prescribed fire. *New Forests* 46: 63–90.

Stephenson, N.L., A. J. Das, R. Condit, S.E. Russo, P.J. Baker, N.G. Beckman, D.A. Coomes, E.R. Lines, W.K. Morris, N. Rüger, E. Álvarez, C. Blundo, S. Bunyavejchewin, G. Chuyong, S.J. Davies, Á. Duque, C.N. Ewango, O. Flores, J.F. Franklin, H.R. Grau, Z. Hao, M.E. Harmon, S.P. Hubbell, D. Kenfack, Y. Lin, J.R. Makana, A. Malizia, L.R. Malizia, R.J. Pabst, N. Pongpattananurak, S.H. Su, I.F. Sun, S. Tan, D. Thomas, P.J. van Mantgem, X. Wang, S.K. Wiser, and M.A. Zavala. 2014. Rate of tree carbon accumulation increases continuously with tree size. *Nature* 507: 90–93.

Stoddard, H.L. 1931. The Bobwhite Quail: Its Habits, Preservation and Increase. Scribner.

Sutheimer, C.M., J. Meunier, S.C. Hotchkiss, E. Rebitzke, and V.C. Radeloff. 2021. Historical fire regimes of North American hemiboreal peatlands. *Forest Ecology and Management* 498: 119561.

U.S. Department of Agriculture (USDA). 2004. U.S. Agriculture and Forestry Greenhouse Gas Inventory 1990-2013. Technical Bulletin 1943, U.S. Dept. of Agriculture, Office of the Chief Economist, Global Change Program Office, Washington, D.C.

van Mantgem, P.J., A.C. Caprio, N.L. Stephenson, and A.J. Dias. 2021. Forest resistance to extended drought enhanced by prescribed fire in low elevation forests of the Sierra Nevada. *Forests* 12: 1248. https://doi.org/10.3390/f12091248

Weichmann, M.L., M.D. Hurteau, J.P. Kaye, and J.R. Miesel. Macro-particle charcoal C content following prescribed burning in a mixed-conifer forest, Sierra Nevada, California. *PlosONE* 10: e0135014.

Wiedinmyer, C., and M.D. Hurteau. 2010. Prescribed Fire As a Means of Reducing Forest Carbon Emissions in the Western United States. *Environmental Science & Technology* 44: 1926–1932.

Wiedinmyer, C., and J.C. Neff. 2007. Estimates of CO2 from fires in the United States: implications for carbon management. *Carbon Balance and Management* 2: 10.

Wilhelm, G. 2000. The realities of CO_2: seeing through the smog of rhetoric and politics. Conservation Research Institute, Elmhurst, Illinois.

Xu, B., Y. Yang, P. Li, H. Shen, and J. Fang. 2014. Global patterns of ecosystem carbon flux in forests: A biometric data-based synthesis. *Global Biogeochemical Cycles* 28: 962–973.

Yang, Y., D. Tilman, G. Furey, and C. Lehman. 2019. Soil carbon sequestration accelerated by restoration of grassland biodiversity. *Nature Communications* 10: 718.