The relationship between prescribed fire management and carbon storage in the Missouri Ozarks

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A common concern among forest managers today is how best to manage forests using prescribed fires while simultaneously minimizing carbon emissions. In light of increased public awareness concerning climate change, the need to reduce carbon emissions into the atmosphere is a top priority around the world. Therefore, research into the most optimal forest management practices that reduce carbon emissions have been conducted in various regions and contiguous forested tracts. Further, models of carbon emissions produced by various forest management practices have been developed to shed light on those that are the most suitable for sustainable management of a forest ecosystem while minimizing the release of carbon.

In a forest ecosystem, carbon is stored in live and dead biomass as well as in the root system and soil components. These components can be either a source or a sink of carbon due to annual exchanges between these components (Li 2006). Fire is a necessary requirement for promoting carbon sequestration in our forests and the magnitude of impact that fire events have on carbon storage is related to fire characteristics such as fire behavior (e.g., intensity), frequency, seasonality, topography, and combustion efficiency (e.g., how much was burned and how well did it burn) (Houghton 1996, Pyne et al. 1996). The objective of this paper was to review current literature addressing carbon levels in the various forest components and the impact of fire on carbon storage in each of these components.

LIVE TREE AND ABOVE-GROUND BIOMASS

Carbon content

Documentation of historical land use and biomass burning in the Ozarks has not been well documented; therefore, a definitive baseline from which to measure carbon storage and fluxes in the system is nonexistent. The amount of carbon stored in live tree biomass was estimated by Li et al. (2007) among three different forest management treatments as part of the Missouri Forest Ecosystems Project (MOFEP). In control plots they recorded the stored carbon to be 80.2 Mg C·ha^{-1} compared to uneven-aged (i.e., single-tree selection) and even-aged (i.e., clearcut) management which contained 55.1 Mg C·ha^{-1} and 5.4 Mg C·ha^{-1}, respectively (Li et al. 2007). The precipitous decline of carbon storage on even-aged plots is explained by the number of mature, large diameter trees that are removed. Among the three treatments, the majority of carbon was found to be allocated to live trees in the control and uneven-aged management stands. However, only 4% of carbon appeared to be stored in live trees in the even-aged management stands (Li 2006). In even-aged stands, the majority of carbon was found in coarse woody debris and soils because the treatment intensity caused carbon to transfer between different forest components (Li 2006, Concilio 2006).

Other estimates for mixed-oak forests in the southeastern Missouri Ozarks yielded 8.7 million metric tons of above-ground biomass with an average of 126 Mg C·ha^{-1} (Li 2006). Estimates of above-ground overstory biomass in a temperate deciduous forest was estimated at 8.0 ± 1.4 kg/m^2 which translates into approximately 3.6 ± 0.6 kg/m^2 of carbon (Botkin 1993). Individual oak-hickory plot values for mean tree biomass ranged from 48.06 to 348.1 tons per acre (Rochow 1974). The disparity in means among plots is due to considerable variation in forest floor vegetation, canopy condition, slope position, and light intensities on the forest floor (Rochow 1974). However, these amounts of biomass convert to approximately 21.5 Mg ha^{-1} to 155.4 Mg ha^{-1} of carbon that would be lost through combustion of the tree biomass.

Fire effects

In fire-prone forests, large releases of carbon can result if trees are killed or partially destroyed by high intensity fires (Breshears and Allen 2002). Tree mortality, whether immediate from scarring of trees or delayed from the creation of cavities that eventually lead to tree decay, results in both carbon loss and increased growth of adjacent surviving vegetation. Studies from the Ozarks have shown that scarlet and southern red oaks suffer the greatest fire-induced mortality (Burns 1955, Paulsell 1957) while hickory, black, and post oak suffer the least (Berry and Beaton 1972). But, the relative contribution that each species makes toward sequestering carbon is largely unknown. This fire-induced thinning of trees reduces competition and increases the amount of available resources. Forests that are managed with a combination of thinning and prescribed burning had lower carbon emissions than stands with only thinning (Hurteau and North 2009) and that thinning and/or burning treatments had no long-term impact on aboveground carbon uptake in oak forests (Chiang et al. 2008). Thinning has several positive outcomes including thinned biomass being available for wood products (Pacala et al. 2001), reduction in resource competition (Sheriff 1996), and carbon storage in fewer, larger trees per hectare (Wirth et al. 2002).

Support for fuel-reduction treatments has increased as research shows that such treatments can reduce the risk of stand-replacing fire (i.e., large carbon releases), thereby reducing the amount of carbon released from live tree biomass (Hurteau et al. 2008). In the Missouri Ozarks, fuel loading was reported to be reduced by 50% when burning alone was used compared to a 25% reduction when burning was applied to thinned stands (Kolaks et al. 2004).

How much carbon is released could be determined on a stand-by-stand basis depending on where the majority of carbon was stored before a fire event and what percentage of each carbon enriched fuel (i.e., litter vs. live trees) was removed, but as a general rule of thumb, carbon storage is assumed to be 45% of the total biomass (Whittaker 1975).

The recovery of carbon lost through combustion varies based on stand composition such that sparse stands have a decrease in vegetative biomass that is able to act as a carbon sink source (Kashian et al. 2006). A conceptual model by Kashian et al. (2006) found that fire frequency and tree density following a fire are important factors affecting landscape carbon storage. They report that frequent fires promote re-vegetation and young forests with high productivity, although, younger forests have less biomass and store less carbon. Although in fire-prone forests managing forests in a way that reduces the threat of wildfire while increasing carbon sequestration seems appropriate, Clark (2007) warns that “Although high density soft-wood monocultures may quickly sequester large amounts of carbon, those gains are often short-lived.”

COARSE WOODY DEBRIS AND LITTER

Carbon content

Litter accumulation and decomposition per hectare is dependent upon many uncontrollable factors including but not limited to species composition, location and the age of the stand, weather, and climate (Paulsell 1957). Upland oak forests in Tennessee have a leaf fall average of 1.3 tons per acre (Blow 1955) whereas a hardwood forest in the southern Appalachians averaged 3.2 to 3.5 tons per acre of litter on an undisturbed site (Helvey 1964). Across thirtyfive sites in the Ozark Highlands, a mean maximum accumulation over a 20 year period for litter resulted in 4.57 tons per acre (Stambaugh et al. 2006). Similarly, mean leaf litter values from a period of three years in an oak-hickory forest were 349.1 g m^{-2} yr^{-1} and were 107.6 g yr^{-1} m^{-2} for coarse woody debris fall which was reported to be close to the world mean for cool temperate forests (Rochow 1974). Preburn estimates of leaf litter accumulation in an oak-hickory and oak-pine forest were 3.5 tons per acre on south facing slopes and 3.3 tons per acre on north facing slopes (Hartman and Heumann 2003); while postburn estimates were 2.0 tons per acre leaving approximately 1.5 tons of carbon per acre that could be released by fire events. Further, on a control plot in south-central Missouri, coarse woody debris was estimated at 0.59 tons per acre and leafy and herbaceous material at 6.10 tons per acre (Paulsell 1957).

Fire effects

The herbaceous layer of a forest often remains unaffected by burning and more so benefits indirectly from fire by removal of leaf litter and opening of the canopy (Blow 1955, Hutchinson 2006). Plants in the herbaceous layer vary in their response to fire by immediate die-back (Glitzenstein et al. 2003) but rigorous growth and increased density and cover (Paulsell 1957, Phillips et al. 2007, Hartman and Heumann 2003) or delayed response (Phillips et al. 2007). The variability associated with ground flora vegetation response to fire makes it difficult to quantify initial carbon release and future sequestration. Studies in the eastern United States and in similar oak-hickory forest stands like the Ozarks have reported no consistent changes in the ground flora cover following prescribed fires (Paulsell 1957, Sasseen 2003). The increase in species richness and plant cover could increase the amount of carbon sequestered by the herbaceous layer (Hutchinson 2006) although the amount of litter that accumulates can influence fire intensity and combustion efficiency (Pyne et al. 1996). Therefore, fire events and the amount of litter can have implications for carbon cycling by release of carbon from forest floor litter and the subsequent uptake by above-ground biomass including shrubs, saplings, and trees (Stambaugh et al. 2006).

Fuel reductions reduce the amount of carbon that is released and the severity of wildfires which are predicted to increase because of global warming (Kasischke et al. 1995, Kashian et al. 2006). Kolaks et al. (2004) found that prescribed burning on stands with no management or fire for 30 years consumed mostly all litter with 90% of fuels < ¼” and 75% of fuel < 3” being reduced on un-thinned sites. Fire event characteristics such as flame lengths and burn intensity were cited to differ among treatments thereby impacting how much 1,10, and 100-hour fuels were removed (Kolaks et al. 2004). On a control plot in the Missouri Ozarks, coarse woody debris was estimated at 1.15 tons per acre with an additional 5.45 tons per acre of forest floor litter (Scowcroft 1966). Plots in a similar area but treated with annual burning had 1.02 tons per acre of coarse woody debris and 1.64 tons per acre of litter (Scowcroft 1966) reduced by annual fire events which would have released carbon into the atmosphere.

MINERAL SOIL AND ROOTS

Carbon content

The soil respiration rate response to forest management practices provides managers with information related to soil carbon efflux processes and carbon transfer among forest components. Changes in soil respiration rates can serve as a proxy for determining changes in carbon cycling of soils, the largest carbon pool of all forest components combined (Post et al. 1982). In an old-growth, mixed–conifer forest in the Sierra Nevada mountains, it was shown that closed canopy patches subjected to understory and overstory thinning or a combination of overstory thinning with burning produced an increase in soil respiration rates (Concilio et al. 2006). In the hardwood forests of the Ozarks, selective thinning management elevated soil respiration rates by altering litter depth and the forest microclimate (Concilio et al. 2005). Further, soil respiration rates on MOFEP study sites have been shown to be influenced by soil types, aspect, and vegetative cover through autotrophic and heterotropic respiration (Grabner 2000). Soils averaged a respiration rate of 4.14 µmol m^{-2} s^{-2} in mixed oak forests of the southeastern Missouri Ozarks which account for 35% of mean carbon pools in the study area (Li 2006).

Fire effects

Many studies have investigated the effects of prescribed fire and wildlife on soil organic carbon. A study conducted in Missouri on oak-hickory forested stands found no differences between annual spring burns or 4-year periodic burns in the concentration of soil organic carbon (Eivazi and Bayan 1996). Further, they reported no difference in soil organic carbon concentration between burned and control plots. Burning at a mixed-hardwood site in the southeastern Missouri Ozarks also did not produce different soil respiration rates from controls (Concilio et al. 2005). Other studies conducted in the Southeastern United States (Binkley et al. 1992, Vose et al. 1999), Northwestern United States (Kraemer and Hermann 1979) and British Columbia, Canada (Blackwell et al. 1995) all resulted in no significant differences in soil organic carbon concentrations between burning treatments or had no clear trends to report.

Overall, prescribed burning appears to have a negligible effect on soil carbon concentrations. Many studies reported different patterns of soil carbon losses and gains in surface and subsurface samples between similar forest types at different elevations and geographic locations within a region. However, less attention has been paid to charcoal and its contribution to long-term carbon storage. Charcoal is created during fire events when organic material burns in the absence of oxygen and has been found to be highly resistant to decomposition (DeLuca and Aplet 2008). If charcoal is able to make it into long-term soil storage by becoming mixed with mineral soil (Gavin 2003), a conservative estimate is 1 to 4 Mg of charcoal as carbon per hectare could be formed after a fire event (DeLuca and Aplet 2008).

SUMMARY

Although advances in understanding forest carbon cycling have been made during the last decade, quantification of components of the carbon pools in a forested ecosystem is challenging. The direct (i.e., fuel consumption) and indirect (i.e., modified habitat) impacts of fire events cause fluxes in carbon storage further adding to the difficulty of quantifying amounts of carbon. Fire on the landscape affects the ecological functions of a forest which are, in turn, inter-correlated with carbon pools, microclimate (i.e., moisture), and site variables (i.e., canopy cover). The carbon that is stored in forest carbon pools is dynamic because of on-going sequestration and respiration of the pools.

Future research needs should focus on the fire emissions and how they influence the amount of carbon lost during a fire event in addition to the aforementioned ecological functions of a forested ecosystem and its carbon efflux. Further, carbon storage potential among different tree species could help to further quantify accurate amounts of stored carbon between forested stands in different ecological land types, climate regimes, and management practices.

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