

## INTRODUCTION

Fire is a key ecological driver in determining vegetation composition, biomass, and ecosystem dynamics in coniferous forests of the Laurentian Mixed Forest in the Great Lakes region (Cleland and others 2004, Frelich 1995). Regional projections of future climate conditions indicate warmer temperatures, more variable precipitation patterns, and greater moisture stress (Handler and others 2014). These conditions are likely to increase the occurrence of drought that in turn influences fire risk and severity (Clark 1989, Neary and others 2008). For example, a recent modeling investigation of relationships between future climate and wildland fire risk in the Great Lakes region showed that the expected changes in precipitation and temperature are associated with increased duration of conditions of high fire risk and earlier timing of the peak wildland fire season (Kerr and others 2016). Further, the 2011 Forest Health Monitoring Program's national report identified a pattern of persistent and/or severe to extreme drought in recent previous years across the Laurentian Mixed Forest of the western Great Lakes region (Potter and Conkling 2013), and the 2011 Pagami Creek wildfire in northern Minnesota resulted from a lightning strike during these conditions.

Fire has direct impact to forest carbon (C) stocks by releasing C via combustion, including partial to complete consumption of the organic horizon of forest soil (Jain and others 2012; Kolka and others 2014, 2017). However, indirect effects on forest C may also occur via changes to the rate of C sequestration by the regenerating forest, as well as by affecting the composition and quality of the soil organic matter, which stores and provides nutrients to the soil ecosystem (Miesel and others 2015). For example, pyrogenic C (PyC) may be a component of soil organic matter and is produced via thermal decomposition (pyrolysis) of biomass, which occurs under oxygen-limited conditions during wildfires (Bird and others 2015, Santín and others 2015). Pyrogenic C is characterized by a polyaromatic chemical structure, which contributes to resistance to decomposition and a long residence time in soil (Bird and others 2015). An earlier study in this region reported PyC concentrations of up to 70 percent of total C in the soil organic horizon and up to 30 percent in the upper 10 cm of mineral soil, and PyC was present even in areas unburned since 1864 (Miesel and others 2015). Pyrogenic C has been positively correlated with soil pH, total C and nitrogen (N), phosphorus (P) availability, and conifer seedling regeneration (MacKenzie and others 2008, Makoto and

## CHAPTER 10. Wildfire and Fire Severity Effects on Post-Fire Carbon and Nitrogen Cycling in Forest Soil (Project NC-EM-F-14-1)

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others 2011), suggesting that PyC may play an ecologically important role in post-fire forest recovery. Efforts to evaluate ecosystem response to gradients of burn severity are relatively recent, and widely available estimates of aboveground burn severity derived from remote sensing approaches may not accurately reflect soil burn severity (e.g., Kolka and others 2014, 2017). Information about how fire and burn severity affect soil and soil ecosystem processes in the Great Lakes region is particularly limited but important to understand, given the potential for future drought to influence fire risk and severity (e.g., Handler and others 2014, Kerr and others 2016). The direct and indirect effects of fire therefore have potential for long-term impacts to forest health via effects on soil properties and nutrient cycling.

The overarching goal of our study was to investigate the impacts of fire on post-fire carbon and nutrient cycling in forest soil and to determine whether the magnitude of effect differs across a gradient of burn severity level. This information is important for understanding the potential ecological impacts that may result from increasingly extreme wildfire disturbance events, as anticipated in future climate scenarios. The specific objectives of this project were to evaluate wildfire effects on soil C and N pools and cycling along a gradient of fire severity within the 2011 Pagami Creek wildfire site, and to determine the relationships between wildfire-produced black C on P availability and N mineralization rates.

## METHODS

The 2011 Pagami Creek wildfire was a late summer lightning-ignited fire that burned through diverse vegetation and resulted in areas of varying fire severity across a range of forest types in the Boundary Waters Canoe Area Wilderness (BWCAW) in northern Minnesota. Heinselman (1996) reported a fire frequency of 4.3 years in the BWCAW for the 1727–1868 presettlement time period and 6.1 years for the 1911–1972 time period following the initiation of U.S. fire suppression policy. Therefore, the 2011 Pagami Creek fire occurred after a historically unprecedented fire-free interval, and although the Lake States region (Michigan, Minnesota, and Wisconsin) has experienced an average of 3,787 wildfire ignitions annually over the past decade ([https://www.nifc.gov/fireInfo/fireInfo\\_statistics.html](https://www.nifc.gov/fireInfo/fireInfo_statistics.html)), the 38 000 ha Pagami Creek fire was among the largest in the past century. A previous study at this site used advanced remote sensing technology and intensive field measurements to characterize pre-fire forest attributes as well as post-fire severity, aboveground forest structure and composition, and total soil C and N (Kolka and others 2014) across forest composition types previously investigated by Wolter and Townsend (2011). We used these existing data on forest structure and composition and burn severity level to select a subset of the study plots established by Kolka and others (2014) for our July 2014 field sampling. These sites included areas dominated by jack pine (*Pinus banksiana*)

or aspen (*Populus tremuloides*) prior to the fire for the full range of soil burn severity levels as determined in the original severity assessment. The original study by Kolka and others (2014) and our study included control plots for each forest cover type in unburned reference areas adjacent to the Pagami Creek fire perimeter. We collected forest floor and 0–10 cm mineral soil samples at locations < 1 m from the original sampling locations, following the protocol described in Kolka and others (2014). We measured *in situ* nitrogen mineralization rates using a 90-day field incubation (Robertson and others 1999), and we performed a 12-month laboratory incubation to measure soil respiration rates. We also measured concentrations of soil total C and N, extractable P, and PyC. Photos of the study area are shown in figure 10.1. Here we present summary information from our study; detailed results will be presented in forthcoming publications in the scientific literature.



Figure 10.1—(A) Lake access to the 2011 Pagami Creek wildfire site in the Boundary Waters Canoe Area Wilderness showing unburned forest on the left adjacent to burned forest on the right. (B) Field personnel collecting 0–10-cm mineral soil sample after removing the organic horizon to return to the laboratory for nutrient analysis and incubation to determine *ex situ* carbon mineralization rates. (C) Field incubation tubes used to determine 90-day *in situ* nitrogen mineralization rates (tubes were loosely capped to allow soil gas exchange during the incubation). Photos by (A) Bethany Laursen, Michigan State University; (B, C) Jessica Miesel, Michigan State University.

## RESULTS AND DISCUSSION

We found that fire caused major decreases in the rates at which C and N are mineralized in forest soil for soil samples collected 3 years after fire. Soil respiration rate (C mineralization) in burned areas decreased between 8 percent and 50 percent in burned coniferous sites and between 8 percent and 20 percent in burned deciduous sites, relative to soils from unburned coniferous or deciduous forest reference areas, respectively. Nitrogen mineralization rates in coniferous areas were between 78 percent and 115 percent slower in low- and high-severity burned areas, respectively, relative to soils from the unburned reference areas. In contrast, N mineralization rates in deciduous areas increased by 171 percent in low-severity areas and decreased by 154 percent in high-severity areas, relative to soils from reference sites.

Extractable P concentrations increased between 56 percent and 63 percent relative to reference area soils in low- to moderate-severity burned areas in coniferous sites, whereas the relative increase in high-severity areas was only 10 percent. Changes in P concentrations in the deciduous sites were both much greater (110 percent increase in low-severity areas and 77 percent increase in high-severity areas) as well as more variable than in the coniferous sites.

In general, PyC concentrations decreased across the severity gradient in coniferous sites, showing 36 percent to 12 percent lower concentrations than unburned coniferous

reference areas. In contrast, PyC concentrations in deciduous forest decreased by 25 percent in low-severity areas and between 15–17 percent in moderate- and high-severity areas. However, the contribution of PyC to soil total C increased in all burned areas. We observed a weak positive relationship between PyC and extractable P concentrations ( $r^2 = 0.10$ ) and a moderately strong relationship between PyC concentration and initial C mineralization rates ( $r^2 = 0.46$ ). Relationships between PyC and net N mineralization rates were not statistically significant.

Nutrient availability and the rates of nutrient cycling provide insight into important ecosystem processes associated with post-fire forest recovery. Fire can alter nutrient concentrations and supply rates by combusting the organic horizon of soil; volatilizing nutrients such as N; and affecting the size, composition, and activity of the soil microbial community (Neary and others 2008). Our study shows that the effects of fire on soil nutrients and C and N mineralization rates persist 3 years after fire. We observed large differences in burned areas compared to unburned reference areas, although differences among severity levels within burned areas were variable and did not consistently increase or decrease across the severity gradient. In general, we observed a different pattern of effect between the two forest cover types, suggesting that the effects of fire on soil nutrients differs among contrasting forest cover types within a single wildfire.

This study extends the original post-fire dataset on soil C and N concentrations and stocks (Kolka and others 2014) to provide an assessment of intermediate-term (3-year) ecosystem response to a wildfire across contrasting soil burn severity levels classified nearly immediately (1 month) after fire in a designated Wilderness Area. This study also provides critically needed information on PyC concentrations in soils from contrasting forest types and as affected by fire and burn severity. Additional results will be presented in forthcoming publications and will include an assessment of fire effects on the soil microbial community. Future studies are needed to quantify how pre-fire forest heterogeneity influences effects observed on soil properties and ecosystem processes and how fire effects interact with other potential future impacts to soil processes likely to result from changes to soil temperature and moisture regimes. For example, a recent study in temperate conifer forest soils showed that soil warming of only 4 °C increases C release from older C pools and increases soil respiration by up to 37 percent (Hicks Pries and others 2017). Information that allows identification of the primary drivers that control the direct and indirect effects of fire on forest soil will be particularly valuable for anticipating potential short- and long-term impacts of fire on forest ecosystems, especially as forests in the Great Lakes and many other regions have experienced disruptions of historical fire regimes.

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