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Replacement of wildfire by whole-tree harvesting increases nitrification and nitrate movement in jack pine forest soils

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ABSTRACT

Forest types that were once naturally maintained by stand-replacing wildfires are typically managed with clearcut harvesting; however, we know relatively little about how well clearcutting mimics the effects of stand-replacing wildfire on the availability and cycling of nitrogen (N) in forest soils. We compared net N mineralization, nitrification and NO_3^- movement in soils from young (2–9 y) jack pine (*Pinus banksiana*) stands that had been regenerated by either stand-replacing wildfire or clearcut harvesting. We located four pairs of burned and harvested stands that were otherwise similar in age, soil type and geographic location. Net N mineralization, measured both in situ and in the laboratory, was nearly 2 times higher in young stands of clearcut origin compared to stands of wildfire origin. Differences between disturbance types were much more pronounced for net nitrification, which was more than 20 times greater, on average, in clearcut-origin sites. Burned sites rarely exhibited any net nitrification in field incubations, and at nearly 2/3 of the sampling times burned sites exhibited net immobilization of NO_3^-. This lack of nitrification occurred despite the fact that we always observed net N mineralization across all of our in-situ incubations in wildfire-origin stands. Finally, we observed nearly four times greater NO_3^- movement through the soil profile in clearcut stands, as evidenced by capture on ion-exchange resins at a depth of 25 cm. Together, these results clearly indicate that replacement of wildfire disturbance by clearcut harvesting promotes nitrification and NO_3^- movement in jack pine ecosystems of northern Lower Michigan. The exact mechanism underlying this response in our sites remains uncertain; however, it appears that some factor that restricts net nitrification in young stands of wildfire origin is not present in clearcut-origin stands. Our finding of increased nitrification and NO_3^- movement in the years following clearcutting could lead to increased losses of N and base cations, and could also favor plant species with greater preference for NO_3^- as a N source.

1. Introduction

Current thinking in forest management emphasizes emulating the intensity, timing and effects of natural disturbance regimes as a framework for sustaining biodiversity and ecosystem services (Hunter, 1993; Lindenmayer et al., 2006; North and Keeton, 2008). Therefore, an understanding of the effects of natural disturbance on ecosystem structure, composition and function can provide a useful baseline against which to compare the effects of forest management actions (e.g. harvests) (Lindenmayer et al., 2006). Forest types that were once naturally maintained by stand-replacing wildfires are typically managed with clearcut harvesting (McRae et al., 2001; Bergeron, 2004), which can be used to mimic even-aged structure associated with this natural disturbance regime. However, we know relatively little about how well clearcutting mimics the effects of stand-replacing wildfire on the availability and cycling of nitrogen (N) in forest soils (but see Giardina and Rhoades, 2001; Simard et al., 2001). If clearcut harvesting changes the availability or predominant form of N compared to wildfire, this, in turn, could have impacts on forest productivity and community composition Kronzucker et al., 1997; Boudsocq et al., 2012; Britto and Kronzucker, 2013) or hydrologic losses of N and other nutrient elements (Van Miegroet and Cole, 1984; Harrison et al., 1996; Jussy et al., 2000; Lundin and Nilsson, 2014).

Stand replacing disturbances have long been known to have profound impacts on the availability, cycling and loss of N from forest ecosystems (e.g. Borman and Likens, 1979; Vitousek et al., 1979). In general, some combination of decreased plant uptake and improved temperature and moisture conditions for decomposition typically results in increased N availability following disturbance. Perhaps of greater importance than overall N availability is the predominant form of N cycled, NH_4^+ vs NO_3^-, following disturbance. This is because production of NO_3^- in soil (i.e. nitrification) represents a key

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biogeochemical process with several important ecosystem- and community-level consequences. The nitrification process itself generates acidity and also can produce gaseous emissions of NO and N_2O (Firestone and Davidson, 1989; Zhang et al., 2015). Once NO_3^- is generated in soil it can form the substrate for denitrifying bacteria resulting in emissions of N_2O (a potent greenhouse gas) and N_2 to the atmosphere, even in upland forest soils (Morse et al., 2015). Alternatively, due to its high mobility in soil, NO_3^- is easily leached, potentially contributing to eutrophication of adjacent aquatic systems and accelerated leaching of base cations (Van Miegroet and Cole, 1984; Harrison et al., 1996; Jussy et al., 2000; Lundin and Nilsson, 2014). Finally, different plant species often demonstrate strong preferences for NH_4^+ vs NO_3^-, such that differences in N-form availability following disturbance could have important influences on plant performance and community dynamics (Kronzucker et al., 1997; Boudsocq et al., 2012; Britto and Kronzucker, 2013).

Pioneering work from the 1980s documented marked differences in the response of nitrification to disturbance across different types of forest ecosystems (Robertson, 1982, Vitousek et al., 1982). In a previous study from our lab group (Leduc and Rothstein, 2007) we found that different types of stand-replacing disturbance resulted in very different rates of nitrification by soil samples from a single ecosystem type. In that study, we found that laboratory rates of net nitrification in soils from young jack pine (*Pinus banksiana*) stands of clearcut origin were nearly double those from stands of wildfire origin (149 vs 84 µg NO_3^--N g^{-1}). Although this finding was intriguing, we do not know if these results from laboratory incubations reflect differences in in-situ rates of nitrification between harvesting and wildfire. We are aware of only two other studies which have directly compared the effects of harvesting vs fire on nitrification, and neither observed a similar pattern of greater nitrification following harvesting. Giardina and Rhoades (2001) found more extractable N in recently clear-cut lodgepole pine (*P. contorta*) stands compared to burned stands, but no significant difference in rates of nitrification. Similarly, Simard et al. (2001) found greater rates of net N mineralization in harvested sites compared to burned sites in boreal forests of Quebec, Canada, but negligible rates of nitrification after either disturbance type. Many studies over the years have focused solely on the effects of fire on soil N dynamics, and these overwhelmingly demonstrate increases in soil NO_3^- pools in recently burned sites compared to undisturbed controls (see Wan et al., 2001 for a review and meta-analysis). Several studies have focused specifically on the role of charcoal produced by wildfire and found strong evidence that it can stimulate rates of nitrification in both Scandinavian boreal forests (Zackrisson et al., 1996) and montane conifer forests of western North America (DeLuca et al., 2006; Ball et al., 2010). On the other hand, a recent meta-analysis of ^{15}N pool-dilution studies concluded that wildfires tend to reduce gross production of NO_3^- within 6 months following burning, with variable effects over longer time scales (Wang et al., 2014).

We undertook this study to evaluate if the harvest-induced increases in nitrification rates observed in the laboratory by Leduc and Rothstein (2007) are actually occurring in situ, and if they result in greater NO_3^- movement through soils following harvesting compared to following wildfire. We hypothesized that in-situ net nitrification would be greater in young stands of clearcut origin compared to young stands of wildfire origin. We further hypothesized that NO_3^- movement through the soil profile would be greater in clearcut-origin stands compared to wildfire-origin stands.

2. Materials and methods

We worked in the same Highplains region of northern Lower Michigan as Leduc and Rothstein (2007), on public-ownership jack pine forests occurring on high-energy outwash landforms with sandy, poorly developed soils (Albert et al., 1995). Jack pine is currently the dominant tree species in this environment as it was prior to European settlement of the region (Comer et al., 1995). Droughty soils combined with highly flammable vegetation resulted in a pre-settlement return interval for stand-replacing fires of ca. 60 y (Cleland et al., 2004). Large wildfires still occur occasionally, but the dominant disturbance regime is now clear-cut harvesting followed by planting of jack pine on a 50-y rotation (MDNR, 2014).

In order to set up our comparative study, we first identified sites where crown fires had burned through large (> 200 ha) areas of jack pine on USDA Forest Service (USDAFS) or Michigan Department of Natural Resources (MDNR) land. These four sites were the Hughes' Lake (HU) fire which burned ca. 2500 hectares in 2006; the Meridian Boundary (ME) fire which burned ca. 3500 hectares in 2010; the Howe's Lake (HO) fire which burned 330 hectares in 2011; and the Little Mack Lake (ML) fire which burned over 600 hectares in 2012. Because the USDAFS and MDNR together harvest and plant over 1500 ha of jack pine each year to provide breeding habitat for the endangered Kirtland's warbler (*Setophaga kirtandii*), we were able to readily locate nearby sites that had been clearcut within 1 year of each of these wildfires. We used stand inventory data, soil maps and field scouting to identify sampling areas within each disturbance that were as similar as possible in terms of preceding stand conditions, soil properties and topography (Table 1). Paired wildfire and clearcut sites were 1.6 (Hughes' Lake), 3.6 (Meridian Boundary), 1.9 (Howe's Lake) and 2.8 (Little Mack Lake) km apart.

On May 6, 2015 (HU, ME, ML) and May 19, 2015 (HO) we located three random sampling points ca. 30 meters apart along a transect through the middle of each study area, at least 50 meters from any stand boundary. We visited these points again on June 25, August 26 and October 25, 2015. This sampling scheme allowed us to measure in-situ N mineralization, nitrification and NO_3^- movement over three periods during the 2015 growing season: spring and early summer (May-June), late summer (July-August), and autumn (September-

Table 1
Treatment, stand age, location and soil information for all study sites.

Fire name and treatment	Age in 2015	Lat. (N)	Long. (W)	Soil series	Soil classification
Hughes' Lake (HU)					
Wildfire	9	44°32′15″	84°15′04″	Grayling Sand	Typic Udipsamment
Clearcut	9	44°33′05″	84°15′17″	Grayling Sand	Typic Udipsamment
Meridian (ME)					
Wildfire	5	44°32′19″	84°26′11″	Grayling Sand	Typic Udipsamment
Clearcut	4	44°32′43″	84°23′30″	Grayling Sand	Typic Udipsamment
Howe's Lake (HO)					
Wildfire	4	44°41′37″	84°49′16″	Croswell Sand	Oxyaquic Haplorthod
Clearcut	4	44°41′03″	84°50′22″	Croswell Sand	Oxyaquic Haplorthod
Little Mack Lake (ML)					
Wildfire	3	44°35′22″	84°05′34″	Graycalm Sand	Lamellic Udipsamment
Clearcut	2	44°35′37″	84°03′32″	Grayling Sand	Typic Udipsamment