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The influence of fire history on soil nutrients and vegetation cover in mixed-severity fire regime forests of the eastern Olympic Peninsula, Washington, USA

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ABSTRACT

The rain shadow forests of the Olympic Peninsula exemplify a mixed-severity fire regime class in the midst of a highly productive landscape where spatial heterogeneity of fire severity may have significant implications for below and aboveground post-fire recovery. The purpose of this study was to quantify the impacts of wildfire on forest soil carbon (C) and nitrogen (N) pools and assess the relationship of pyrogenic carbon (PyC) to soil processes in this mixed-severity ecosystem. We established a 112-year fire chronosequence with nine similar forest stands ranging in time since lastfire (TSF) from 3 to 115 years prior to site establishment. At each site, we measured understory vegetation cover, overstory composition, physical and chemical attributes of surface mineral soils to a depth of 10 cm, and forest floor organic matter. Additionally, non-ionic resin lysimeters were buried over the winter and spring (7–8 months) at the interface of organic and mineral soil to collect O-horizon leached DOC that would potentially contact PyC particles on the forest floor. Nitrogen transformations were also monitored in laboratory soil incubations for a subset of sites. The TSF gradient was significantly correlated with PyC mass in the O-horizon ($r = -0.4$), O-horizon C ($r = 0.4$), total phenol content in both O-horizon ($r = 0.4$) and mineral soils ($r = 0.2$), and potentially mineralizable N (PMN) ($r = 0.4$). Recent fire sites contained higher mineral soil total N and inorganic available N, but were not correlated with TSF. Total DOC that accumulated on the non-ionic resins averaged 1.14 (SE ± 0.54) g DOC m^{-2} $year^{-1}$ and increased with TSF ($r = 0.52$; $p < 0.0001$). Over time, soils appeared to shift toward a more phenolic-rich organic and surface mineral soil, a higher PMN index, denser moss cover, and higher cover of *Mahonia nervosa* and *Rosa gymnocarpa*. Multivariate, non-parametric analysis of soil and vegetation factors showed a significant relationship with the TSF gradient between sites ($p < 0.001$), but not within sites. Soil characteristics were found to be less sensitive to wildfire disturbances than aboveground vegetation composition.

1. Introduction

Wildfire is a major disturbance in the east side, rain shadow forests of the Olympic Peninsula, yet little is known regarding the effect of wildfire on soil biogeochemistry, nutrient pools, and nutrient cycles that are essential to ecosystem function. The *Tsuga heterophylla/Pseudotsuga menziesii* forests of the eastern Olympic Peninsula are characterized by low- to moderate-intensity fires with 20–70% overstory mortality (Agee, 1993) occurring between infrequent high-intensity, stand-replacing fires (Fonda and Binney, 2011; Henderson et al., 1989). Fire return intervals in this region range from 120 to 300 years (Fonda and Bliss, 1969; Henderson et al., 1989; Wendel and Zabowskl, 2010; Wetzel and Fonda, 2000) making wildfire a dominant disturbance and driver of change. Prior timber harvest practices in the mid-20th century combined with contemporary fire exclusion in these forests have led to increased forest density and decreased structural diversity, where historically non-stand-replacing wildfires maintained more resilient and diverse forest conditions better apt to recover from fire events (Dunn and Bailey, 2016; Perry et al., 2011; Tepley et al., 2013; Weisberg, 2004). Prescribed fire in this region remains a viable approach to the reintroduction of low-severity surface fire as a restoration tool in the old growth *P. menziesii* dominated forests (Fonda and Binney, 2011). To date, however, there has been limited effort to evaluate the influence of fire or potential changes brought by fire

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exclusion on soil biochemical processes in mixed-severity fire regime forests where the reintroduction of low-severity surface fire may be a valuable management tool.

Studies conducted in temperate and boreal forests suggest that fire occurrence in historically fire-prone forests contributes to the resilience of ecosystem processes (e.g. nutrient cycling) mediated by aboveground and belowground interactions (DeLuca et al., 2006; DeLuca and Sala, 2006; MacKenzie et al., 2004; MacKenzie and DeLuca, 2006a). For example, in low elevation *Pinus ponderosa* forests, frequent fires were found to stimulate net nitrogen (N) mineralization notwithstanding a reduction in total N and litter quality (C:N) over a fire chronosequence (DeLuca et al., 2006; DeLuca and Sala, 2006; MacKenzie et al., 2004). Nitrification potential was likewise stimulated by pyrogenic carbon (PyC) additions to late secondary succession mineral soil (DeLuca et al., 2006; DeLuca and Sala, 2006; MacKenzie et al., 2004). Similarly, in Swedish boreal forest stands ranging in ages 3–352 years following fire disturbance, fire was the dominant driver of successional trajectories where forests were N-limited in late successional stages. Net N mineralization and nitrification were highest in early succession sites and decreased linearly and logarithmically, respectively, while feathermosses (mainly *Pleurozium schreberi*) and ericaceous shrubs (e.g. *Empetrum hermaphroditum*) increased logarithmically with time since fire (TSF) (DeLuca et al., 2002). Furthermore, the addition of activated carbon (C), a proxy for fresh PyC, to the O-horizon of late succession soils increased net nitrification rates, which was shown to be independent of net mineralization of an added labile organic N substrate (DeLuca et al., 2002). This response was likely driven by adsorption of compounds that otherwise inhibited net nitrification or resulted in N immobilization (Berglund et al., 2004; DeLuca et al., 2006; Gundale and DeLuca, 2006). A more recent investigation of a 79-year interior Alaskan boreal chronosequence similarly observed an overall increase in O-horizon depth, feathermoss cover, and ericaceous shrubs, but in this case the intermediate sites (40 yrs TSF) measured the highest N mineralization rates and extractable N (Lavoie and Mack, 2012). Fire is a dominant driver of soil and vegetation characteristics in these dry temperate and boreal forest ecosystems, yet we have limited information on patterns in mixed-severity fire regime forests in relation to fire history.

Post-fire secondary succession patterns in the *T. heterophylla/P. menziesii* forests in this region can be inferred from long-term studies in similar forests where sites were monitored after a typical clearcut and slash burn operation. Immediate to three-year post-fire understory vegetation is commonly diverse but dominated by herbaceous species such as *Senecio sylvaticus*, *Epilobium angustifolium*, and *Rubus* species, then shifting to shrub dominance including *Ceanothus* (Franklin and Dyrness, 1988; Halpern and Lutz, 2013). Late seral and climax communities are often dominated by *Gaultheria shallon* and *Polystichum munitum*, depending on the site quality (Franklin and Dyrness, 1988). An application of prescribed fire in eastern Olympic Peninsula *P. menziesii*-dominated forests resulted in a 40% reduction in total cover of dominant understory vegetation and an increase in forest floor organic matter due to needlefall. Dominant understory species were able to persist through slow moving ($< 1\,m\,min^{-1}$) and low-intensity ($< 2\,m$ flame length) fires (Fonda and Binney, 2011).

Pyrogenic C, defined here as fire-derived organic matter, is one of the primary soil legacies associated with wildfire and prescribed fire events, yet there is little understanding of how PyC in the O-horizon or surface mineral soil influences soil dissolved organic carbon (DOC) dynamics (Pingree and DeLuca, 2017; Santos et al., 2017). The presence of PyC in terrestrial soils can provide increased surfaces for adsorption of DOC compounds (Keech et al., 2005; Pingree et al., 2016; Zackrisson et al., 1996) and can serve as a source of dissolved black carbon (DBC) in watersheds (Ding et al., 2014; Dittmar et al., 2012; Hockaday et al., 2007; Jaffé et al., 2013). The positive correlations between DOC and DBC concentrations in water samples from 27 rivers and wetlands worldwide suggests mobility of the two dissolved C materials from terrestrial to freshwater systems is coupled (Jaffé et al., 2013). Dissolved organic matter incorporated in forest soils from O-horizon leachate represents a significant fraction of total ecosystem C, N, and phosphorus (P), and also has the potential to alter soil solution chemistry and nutrient cycling (Kalbitz and Kaiser, 2008; Michalzik et al., 2001; Qualls and Haines, 1991). In post-wildfire soils, PyC may account for a significant portion of the organic matter in the forest floor of recent fire sites (DeLuca and Aplet, 2008; Pingree et al., 2012; Santín et al., 2015) and may be an important sorbate for soluble and mobile organic compounds introduced through needle fall or canopy throughfall (Pingree et al., 2016).

The purpose of this study was to evaluate the influence of TSF on soil characteristics and understory vegetation, including PyC content of the forest floor, in mixed-severity fire regime forests on the east side of the Olympic Peninsula where climate change is predicted to increase fire frequency and extent (Halofsky et al., 2011). Specific objectives of the study were to (1) characterize the relationships between aboveground vegetation and belowground soil C and N pools with respect to TSF; (2) assess whether sites recently exposed to fire exhibited increased net nitrification compared to paired unburned sites; (3) determine if PyC accumulated in the O-horizon was negatively related to O-horizon leachate rates and if molecular signatures in PyC were related to TSF. Our results provide a first time look at the influence of fire history on soil biogeochemistry and understory vegetation in this area. Unlike previous studies in dry temperate and boreal ecosystems, high annual rainfall in this region (1500–2900 mm annually) and a relatively rapid accumulation of organic matter is likely to result in a unique relationship between soil and vegetation variables and fire history that is, thus far, not represented in published research. Furthermore, this region is expected to experience future change and our studies in this distinctive landscape can provide insights for fire and forest management as well as a comparison for future conditions in similar mixed-severity fire regime forests.

2. Methods

2.1. Study sites

This study was conducted across nine forest stands in the eastern Olympic Peninsula, Washington, previously described by Pingree et al. (2016) during the summers of 2013, 2014, and 2016 (Fig. 1). All sites were located within one day of travel from the laboratory and accessible from a hiking trail for rapid processing of fresh soil samples. Sites were selected along a chronosequence of years since the last wildfire, referred to as the time since fire (TSF). The TSF gradient, 3–115 years, encompassed the mean fire return interval observed in studies on the eastern Olympic Peninsula (Franklin and Dyrness, 1988; Henderson et al., 1989; Wendel and Zabowskl, 2010). Sites were last exposed to wildfire in $1898_{a,b}$, 1922 (historical fire sites: IC, KT, MC), 1977, $1985_{a,b}$ (intermediate fire sites: RC, BF1, BF2), and 2006, 2009, and 2011 (recent fire sites: BG, CF, BH) where subscript "a" and "b" refer to sites within the same fire perimeter (see Fig. 1 for details). Where available, we used MTBS fire perimeters to ensure sites were within the burned area (BF sites, BG, CF, and BH) and consisted of similar distributions of post-fire severity effects that can be classified by moderate- or mixed-severity (25–75% overstory mortality, sites BF, BG, BH) (Agee, 1993; MTBS, 2013). Sites in the lower Elwha River Valley were located with the guidance of fire maps published by Wendel (2009) and provided locations for historical fire sites and one intermediate fire site (RC, 36 years TSF). Site MC (86 years TSF) was described by fire history evidence as having experienced low-severity fire effects from the lack of cohort establishment and likely due to homesteading activity (clearing burn) but preceded by high-severity fire events in 1890 and 1898 (sites IC, KT, and MC) (Wendel, 2009). Remaining sites were established with the guidance of fire history maps provided by the USDA Forest Service and all burned sites were confirmed in the field.