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Disturbance intensity and dominant cover type influence rate of boreal soil carbon change: A Canadian multi-regional analysis

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ABSTRACT

The circumpolar boreal forest biome contains a significant portion of the global forest carbon (C) stocks, and is generally considered to be a sink for atmospheric C. However, there is a concern that disturbances occurring concurrently with fibre utilization may cause these boreal forest ecosystems to become net C sources resulting from cumulative effects of natural and anthropogenic disturbances, and altered C cycling processes at stand- and landscape scales. In this study, we have synthesized soil C data (forest floor + upper 20 cm of mineral soil) from six long-term, forest management-based manipulative experiments situated in both the Boreal Plain and Boreal Shield ecozones to examine the collective effects of disturbance type and intensity, and dominant tree cover type on soil C pools. The disturbances of clearcut harvest, burn, burn + salvage logging, harvest + forest floor removal resulted in rapid and significant declines in measured soil C following disturbance. In contrast, partial stand removals (i.e., light and heavy thinnings through partial harvest treatments) conducted at the Ecosystem Management Emulating Natural Disturbance (EMEND) trial resulted in slight increases in total measured soil C by year 6, with the exception of conifer dominated stands. The observed declines in total soil C, particularly in the high intensity treatments, were largely a function of declines within the forest floor. In most cases, the rate of change in measured soil C converged over time with baseline levels (clearcut and partial harvests by year 6). In contrast, the data suggests that longer periods of time (>15 years) will be required for the total soil C pool to fully recover to pre-disturbance levels for the higher intensity disturbances. Dominant tree species cover type also influenced the rate of change in total measured soil C. There was a clear difference in the rate of change in the soil C pool between conifer-dominated stands compared to mixed or aspen-dominated stands, going from a positive rate of change (accumulation) under deciduous cover to a negative rate of change under conifers. Our results illustrate that the complex and interactive relationships among species effects, inherent soil and site properties, and management practices should collectively be considered in the development of options related to boreal forest soil C management and climate change mitigation strategies.

1. Introduction

In Canada's boreal region, there are 270 million ha of forested land (Brandt et al., 2013), comprising approximately 24% of the circumpolar boreal forest biome (NRCan, 2016). It is estimated that this biome contains 32% of the global forest carbon (C) stocks (Pan et al., 2011). Boreal C is stored in biomass, litter, dead wood, and soil that collectively contribute to significant annual C exchanges with the atmosphere (Denman et al., 2007; Moroni et al., 2010). Uncertainties in estimating total soil and peatland C pools (Bradshaw and Warkentin, 2015), which account for 60%

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(163 Pg C) of the boreal C stock (Pan et al., 2011), may result in underestimates of the total boreal C pool. Boreal forest C storage and sequestration are recognized as playing a critical role in global C dynamics (Harden et al., 2000; Bradshaw et al., 2009; Seedre et al., 2011). There is general acceptance that on a global scale, forests not impacted by land-use change tend to be C sinks (Denman et al., 2007; Stephens et al., 2007; Piao et al., 2009). There is, however, considerable uncertainty about the magnitude and regional distribution of forest C sinks (Stinson et al., 2011).

Forest management offers opportunities for maintaining and increasing stocks of C in forests (Birdsey et al., 2006; Schwenk et al., 2012; Strukelj et al., 2015). Forest management as a consideration in C mitigation policy (e.g., Mackey et al., 2013), particularly in boreal countries, is increasingly being advocated (Stinson et al., 2011; Moen et al., 2014; Clarke et al., 2015). Although in Canada's managed boreal forests biomass C stocks are overall increasing slightly, regional differences in harvest and other disturbance rates, as well as variation in growth rates, may override the increasing trend (Kurz et al., 2013).

To date, the assessment of forest management options for C mitigation in Canada has focused on above-ground biomass and wood products such as building materials (Lemprière et al., 2013; Smyth et al., 2014). Other ecosystem components, such as soil organic matter that store up to nearly 40% of total ecosystem C stocks (Stinson et al., 2011), have not been adequately considered (Moroni et al., 2010). In part this is because high spatial variability and slow accumulation make soil C changes difficult to measure (Giardina et al., 2005).

Large-scale disturbances influence boreal soil C through outright loss or turnover of soil organic matter, the latter being related to the chemical quality of C-rich compounds (Thiffault et al., 2008; Norris et al., 2009), soil temperature and moisture regimes, and biological activity (Siitonen, 2001; Sippola et al., 2004; Jandl et al., 2007). The extent of soil C loss and recovery is dependent on a combination of factors such as the disturbance regime (e.g., frequency, type, and severity), climate, tree species, and soil properties (Maynard et al., 2014). It is therefore critical to gain a better understanding of how boreal ecosystem C dynamics respond to human induced disturbance relative to natural disturbance, and how all disturbance types will affect future C budgets (e.g. Pennock and van Kessel, 1997; Seedre et al., 2011).

Within the high variability of C storage in soils (Jobbagy and Jackson, 2000), local variation is partly due to the diverse influences of dominant tree species on litter production and decomposition, and a suite of processes stabilizing soil C in forest systems (Binkley and Fisher, 2013; Laurent et al., 2014; Gahagan et al., 2015). Vesterdal et al.'s (2013) review found in all boreal cases that conifers (*Picea*/*Pinus*) had higher forest floor C stocks compared to broadleaves (*Populus*/*Betula*). Their review also showed that conifers tended to store more soil organic carbon (SOC) in the forest floor, whereas broadleaves generally tended to store more SOC in mineral soil, where depths to 30 cm were considered (Vesterdal et al., 2013). Individual species-level effects on C storage in soils are largely seen in the forest floor (Alriksson and Eriksson, 1998; Hobbie et al., 2006; Laganière et al., 2013), but rarely in the mineral soil (Finzi et al., 1998; Giardina et al., 2001; Vesterdal et al., 2008). Although Laganière et al. (2013) reported that SOC stocks of the entire soil profile did not differ significantly among stand types (conifer vs. aspen vs. mixed), they differed with soil layer and depth.

Not surprisingly, disturbance affects forest floor C stocks to a greater degree than mineral soil C. Nave et al. (2010) reported average temperate post-harvest forest floor C declines of about 30%. Their meta-analysis illustrated that dominant tree species was also an important factor influencing soil C losses following harvesting, with significantly smaller forest floor C losses in conifer-dominated and mixed stands compared to hardwood-dominated stands. Post-disturbance forest floor C declines may be somewhat countered with increases in mineral soil C (Olsson et al., 1996; Kishchuk et al., 2014). Clarke et al. (2015) reported an 8% increase in C in the upper 45 cm of the mineral soil layer for aspen/white spruce mixtures 1–5 years after harvesting. These increases are likely the result of both downward movement of fine particulate and dissolved organic C from the forest floor/logging debris complex (Strukelj et al., 2015) and the decomposition of roots (Clarke et al., 2015). There may also be a priming effect (Salomé et al., 2010; Dungait et al., 2012), where labile organic C-rich compounds leached from the forest floor can increase decomposition of deeper, more recalcitrant soil organic matter through destabilization processes (Fontaine et al., 2007; Diochon and Kellman, 2009). However, the results of Puhlick et al. (2016) support limited long-term changes in mineral soil C following harvesting.

Under fire, forest floor consumption ranged between 15% and 100% for surveyed wildfires in Alaska (Neff et al., 2005). However, in contrast to harvesting, there tends to be little (slight declines) to no change in mineral soil C immediately after fire (Johnson and Curtis, 2001; Neff et al., 2005). Changes are generally restricted to the upper 5 cm of the mineral soil (Johnson and Curtis, 2001; Certini, 2005). Both forest floor and surface mineral soil C pools decreased following wildfire in boreal mixedwood stands (Kishchuk et al., 2015). In that study, forest floor C pools had not recovered 10 years post-fire, while mineral soil C pools had returned to undisturbed levels.

While site and stand level studies provide invaluable information on responses under local conditions, a greater understanding of responses pertaining to Canada's managed boreal forest as a whole can be obtained through combined analyses of multiple empirical studies. Ideally, experimental scenarios designed specifically to obtain empirical data on both disturbance and cover type effects on soil C pools would control for climate, soil and site properties, provide a graduated range of disturbances on the same site, be repeated under different local cover types, and include repeated measurements, including predisturbance baselines over time. To date, temporal patterns of soil C recovery following disturbance have largely been deduced from chronosequences (i.e., replacing time with space) (e.g., Norris et al., 2009; Moroni et al., 2010; Seedre et al., 2011, 2014) or meta-analyses that include collections of site-specific, published results measured at different times since disturbance (e.g., Johnson and Curtis, 2001; Nave et al., 2010). In practice, given the scale and biophysical variation of Canada's managed boreal forest, and the unpredictability of disturbances such as wildfire, most studies of disturbance on soil properties have compared a limited set of disturbances for any given location. Past studies have rarely compared more than two disturbances on the same site, with comparisons of wildfire and clearcut harvesting most frequently used as examples of natural and anthropogenic disturbances. Other disturbance types could include variable retention harvesting, post-fire salvage logging, and biomass and forest floor removal that would, collectively, contribute to a broader continuum of disturbance effects in boreal forest ecosystems.

Our study is based on a unique dataset from six replicated, long-term boreal disturbance trials. One trial contains multiple sites, such that results from ten separate locations are analyzed. In all studies, soil C pools were sampled using similar methodology beginning with baseline status, and resampled at initial, early, and medium to long term points in time (up to 15 years since disturbance) at the same treatment plots. In this analysis we focus on the effect of disturbance (type and intensity) and dominant forest cover type on the rate of change in the soil C pool from the surface of the forest floor to 20 cm depth of mineral soil (% yr^{-1}). The dis-