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Response of mineral soil carbon storage to harvest residue retention depends on soil texture: A meta-analysis

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ABSTRACT

Harvest residue retention or removal can influence soil carbon (C) sequestration during forest management. Many studies have explored the factors that affect the direction and extent of changes in soil C after different harvest residue management practices. However, the effect of soil properties, especially soil texture, on the difference in mineral soil C storage between harvest residue retention and removal treatment are still not fully understood. Using a meta-analysis approach, we investigated the factors that influence the change in mineral soil C stocks following stem-only harvest (SOH), when compared to whole-tree harvest (WTH). We found that the retention of harvest residues associated with the SOH treatment led to 8.2% greater soil C storage in 0–20 cm mineral soils, compared to the WTH treatment. Soil properties (soil clay content and C concentrations) were the most important factors mediating soil C response to residue retention. Relative to the WTH treatment, the SOH treatment showed smaller mineral soil C pools in some high clay content soils, possibly by increasing the mineralization of existing soil organic matter stocks via a priming mechanism. Climate was a poor predictor of differences in treatment effects, with no significant difference between temperate and tropical forests. There were no significant relationships between the treatment effect on mineral soil C and mean annual temperature or precipitation. Both coniferous and broadleaf forests exhibited a significantly higher mineral soil C storage in the 0–20 cm soil layer with the SOH relative to the WTH treatment. Compared to WTH treatment, the higher soil C contents in upper mineral soils after the SOH treatment appeared to last about one decade after harvesting. The findings of this analysis suggest that soil texture and C concentrations in mineral soils should be considered when assessing the impact of forest harvest residue management on soil C pools.

1. Introduction

Enhancing carbon (C) sequestration by converting non-forested sites to forest plantations has been suggested as an effective measure for mitigating elevated concentrations of atmospheric CO_2 and global warming (IPCC, 2014). In 2010, the Global Forest Resources Assessment showed that the area of forest plantations has reached 264 million hectares, accounting for 7% of the global total forest area, and is still increasing by 2.8 million ha/year (FAO, 2010). Forest soils contain about 45% of terrestrial C, and play a key role in the global C cycle and the future mitigation of climate change (Bonan, 2008; Canadell et al., 2007; Huang et al., 2012). Forest management, especially the harvesting of biomass, can significantly change soil C storage and therefore affect the CO_2 sink strength in forest plantations (Jandl et al., 2007; Nave et al., 2010; Clarke et al., 2015; Webster et al., 2016). For example, in two Swedish Norway spruce stands, total soil C stock (organic + mineral soil) was reduced by 17–22% 15–16 years after harvesting (Olsson et al., 1996). A meta-analysis of harvesting effects in temperate forests by Nave et al. (2010) found that harvesting reduced soil C storage by an average of 13 ± 4%. Jandl et al. (2007) suggested that forest biomass harvesting, which disturbs the soil and changes the microclimate, often causes soil C losses that may exceed C gains in the aboveground biomass following the harvesting and replanting. Using a process-based forest ecosystem model, Wang et al. (2014) found that

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harvest disturbance in northern temperate forests stimulated net C losses of 400–700 $g\,C\,m^{-2}\,yr^{-1}$ for 6–17 years after harvesting. Also, several studies have measured net ecosystem C exchange at harvested sites and found that for at least 14 years after logging, regenerating forests remained net sources of CO_2 owing to increased rates of soil respiration (Schulze et al., 1999; Yanai et al., 2003; Zha et al., 2009).

Globally, the use of forest harvesting residues as renewable energy sources has been considered to be an effective strategy to improve national energy security and to decrease the emission of greenhouse gases (Stupak et al., 2007; Nicholls et al., 2009). However, the true net effect of displacing fossil fuels with forest residues for energy production depends on the carbon balance both aboveground and belowground in the forests from which these residues are removed and other factors, such as the use/residence time of the harvested material (Searchinger et al., 2009). This has led to an increasing focus on the impacts of harvest residue management on the storage of soil C in forest plantations (Johnson and Curtis, 2001; Thiffault et al., 2011; Achat et al., 2015a, 2015b). Previous reviews on forest harvest residue management and the fate of soil C have generally suggested that whole-tree harvesting (WTH), in which the aboveground logging residues are removed, can lead to greater losses of soil C compared to stem-only harvesting (SOH), where only the tree stem is removed while branches and foliage are retained on site (Johnson and Curtis, 2001; Achat et al., 2015a). Achat et al. (2015a) also found that WTH led to significantly lower soil C stocks in the entire soil profile, compared to SOH treatment. In mineral soil, organic C is relatively more persistent and turnover is slower than in organic layers, suggesting that C storage and loss in mineral soils is especially relevant to sequestration and mitigation strategies (Schmidt et al., 2011).

To date, several meta-analyses have examined how forest harvest residue management practices affect mineral soil C storage (Johnson and Curtis, 2001; Thiffault et al., 2011; Achat et al., 2015a). Many factors are responsible for variation in soil C responses to harvest residue management, such as forest type, climatic gradients, time since harvest, mineral soil texture and organic C content. For example, Johnson and Curtis (2001) summarised results from 26 studies in various parts of the world and found that the higher soil C storage with residue retention after SOH treatment was restricted to coniferous species, while residues had little impact on soil C storage under hardwood or mixed forests. A meta-analysis by Achat et al. (2015a) indicated that soil C losses in upper mineral soils due to clear-cutting increased with increasing initial SOC. They also found that soil C losses with residue removal after WTH treatment, when compared to SOH treatment, were lower in cold climates relative to temperate climates. Most of these factors have been studied thoroughly to some extent with the exception of soil texture (e.g. clay content), which is a key determinant of both soil organic matter and forest productivity (Vance, 2000) and a key factor controlling soil C stabilization (Oades, 1988; Scott et al., 1999). Results from field-based studies surveyed for a meta-analysis in boreal and temperate forests have shown that compared to the SOH treatment, the WTH treatment tended to have a less C content in soils that are already poor in organic matter (Thiffault et al., 2011). The lack of a treatment effect on mineral soils with inherently high organic matter content may be due to the fact that these soils can inhibit sorption of new C (Ussiri and Johnson, 2004). Thus it may be that logging residues are a significant source of soil organic matter only in coarse-textured or C-poor soils. In contrast, the results from detrital input and removal experiments have shown that forest residues can be a significant source of organic matter in soils with high clay content and that C in leachate water can be bound easily into soil aggregates (Six et al., 2002; Leff et al., 2012; Six and Paustian, 2014). These varied results reflect the complexity of the effect of harvest residue retention on soil C storage in differently textured soils. These syntheses give background and context to the work presented here, which compiles field trial results to examine the relative changes in soil C storage with harvest residue retention, compared to harvest residue removal, across site and stand gradients and to explore soil texture effects.

The objectives of this analysis are thus to (1) determine the specific impacts of SOH treatment on mineral soil C storage, when compared to WTH treatment; and (2) identify the site and soil conditions under which SOH treatment is most likely to have a higher mineral soil C storage compared to WTH treatment. In addition to the responses of mineral soil C to harvest residue management, we compiled a database of soil respiration measurements in SOH and WTH treatments in forest plantations in this meta-analysis. In some cases, harvest residue retention was reported to lead to declines in mineral soil C contents, which were attributed to the accelerated microbial decomposition of soil organic matter and associated CO_2 efflux (Gordon et al., 1987; Webster et al., 2016). The soil respiration data were examined to determine how treatment effect on mineral soil C were linked to differences in mineral soil respiration.

2. Materials and methods

2.1. Data compilation

Publications that studied C stocks or concentrations under SOH and WTH treatments were collected by searching ISI Web of Science and CAB Direct (1980–2016). Keyword search strings were combinations of terms such as: forest, logging, harvest, clearcut, whole-tree harvest, stem-only harvest and soil C. In this review, the effect of SOH treatment on soil C storage are interpreted relative to WTH treatment. It is not an assessment of the impacts of harvesting per sé relative to a control (e.g. unharvested sites). Rather, our aim is to examine the site and soil conditions under which harvesting with residue retention is most likely to increase soil C storage relative to residue removal. We also screened previous reviews and meta-analyses on soil C changes due to harvest residue management (Thiffault et al., 2011; Achat et al., 2015a). Publications were selected according to the following criteria: (1) The publication reported mineral soil C values (C or organic matter, stocks in $Mg\,ha^{-1}$ or concentration in $g\,kg^{-1}$ soil) in SOH and WTH plots; (2) The SOH and WTH treatment plots in each study were well-paired and hosted the same dominant tree species and soil types; (3) The measurements of soil C in the SOH and WTH plots were performed at the same temporal and spatial scales. Given the variety of sampling depths used in the various studies, and in order to facilitate comparison among the results, the data collected were divided into two depth categories: 0–20 and > 20 cm depth; (4) If the SOH and WTH plots did not have the same initial soil C concentration before harvesting, we used the differences between harvested and unharvested (sometimes pre-harvest) treatments to assess the relative impact of the SOH and WTH treatments on soil C storage; (5) The means, standard deviations or standard errors and samples sizes of our chosen variables were directly reported or could be calculated from the chosen papers; (6) Experimental treatments that included forest floor removal were excluded; and (7) Data used for model development studies were excluded. Raw data were either obtained from tables or extracted from graphs using the GetData Graph Digitizer (version 2.24, Russian Federation). This selection stage led to a list of 51 study sites from 33 primary articles (Fig. 1 and Supplementary Table S1).

In addition to soil C data, we compared soil respiration rates (Supplementary Table S2) between SOH and WTH plots and we also collected data for the variables we used to investigate the factors affecting the differences in mineral soil C stocks between harvesting residue retention (SOH) and residue removal (WTH). These variables included: mean annual temperature (MAT) and precipitation (MAP), pre- and post-harvest vegetation, soil sampling year or time since harvest, soil sampling depth, and soil texture. We recorded soil order (FAO taxonomy) and soil clay content for each study site. If data were unavailable for a given study, we cross-referenced studies from the same location to search for the missing information.

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