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Harvest residue management and fertilisation effects on soil carbon and nitrogen in a 15-year-old *Pinus radiata* plantation forest

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ABSTRACT

Growing interest in the use of planted forests for bioenergy production could lead to an increase in the quantities of harvest residues extracted. We analysed the change in C and N stocks in the forest floor (LFH horizon) and C and N concentrations in the mineral soil (to a depth of 0.3 m) between pre-harvest and mid-rotation (stand age 15 years) measurements at a trial site situated in a *Pinus radiata* plantation forest in the central North Island, New Zealand. The impacts of three harvest residue management treatments: residue plus forest floor removal (FF), residue removal (whole-tree harvesting; WT), and residue retention (stem-only harvesting; SO) were investigated with and without the mean annual application of 190 kg N ha^{-1} $year^{-1}$ of urea-N fertiliser (plus minor additions of P, B and Mg). Stocks of C and N in the forest floor were significantly decreased under FF and WT treatments whereas C stocks and mass of the forest floor were significantly increased under the SO treatment over the 15-year period. Averaged across all harvesting treatments, fertilisation prevented the significant declines in mass and C and N stocks of the forest floor which occurred in unfertilised plots. The C:N ratio of the top 0.1 m of mineral soil was significantly increased under the FF treatment corresponding to a significant reduction in N concentration over the period. However, averaged across all harvesting treatments, fertilisation prevented the significant increase in C:N ratio of the top 0.1 m of mineral soil and significantly decreased the C:N ratio of the 0–0.3 m depth range. Results indicate that residue extraction for bioenergy production is likely to reduce C and N stocks in the forest floor through to mid-rotation and possibly beyond unless fertiliser is applied. Forest floors should be retained to avoid adverse impacts on topsoil fertility (i.e., increased C:N ratio). Based on the rate of recovery of the forest floor under the FF treatment, stocks of C and N in the forest floor were projected to reach pre-harvest levels at stand age 18–20. While adverse effects of residue extraction may be mitigated by the application of urea-N fertiliser, it should be noted that, in this experiment, fertiliser was applied at a high rate. Assessment of the sustainability of harvest residue extraction over multiple rotations will require long-term monitoring.

1. Introduction

The importance of forest soils in the global cycling of carbon (C) and as a potential reservoir for the accumulation and storage of C is well recognised (Peng et al., 2008), as is the vital role of organic matter in sustaining forest productivity and environmental quality (McLaughlin and Phillips, 2006). The ability of forest soils to act as sinks for atmospheric C, sustain commercial biomass production, and provide other environmental services will likely depend on how well these soils are managed (Fox, 2000; Lal, 2005; Vanguelova et al., 2010). Forest management practices affect soil C and nitrogen (N) storage by changing the quantity or quality of organic matter inputs to the soil, causing physical disturbance of the soil profile, or by modifying the soil environment (temperature and moisture regimes) and nutrient levels (Johnson, 1992; Johnson and Curtis, 2001; Jandl et al., 2007; Nave et al., 2009, 2010; Vanguelova et al., 2010). In-line with the increasing demand for renewable energy, interest in the use of planted forests for bioenergy production is growing in New Zealand (Hall et al., 2009) and elsewhere (Vanguelova et al., 2010). This demand could lead to the intensification of forest management with associated reductions in the quantities of residues returned to the site following harvesting and the need to apply fertilisers to maintain site productivity.

Recent studies have suggested that harvest residue removal or forest floor disturbance could have implications for the long-term storage of C or N (or both) in plantation forest soils in New Zealand (Jones et al., 2008; Smaill et al., 2008a) and elsewhere (e.g., Laiho et al., 2003; Chen and Xu, 2005; Powers et al., 2005; Tan et al., 2005; Thiffault et al., 2006). In a recent review and meta-analysis of 75 published studies from around the world, Nave et al. (2010) found that forest harvesting (encompassing a range of

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intensities and residue management practices) resulted in a significant 8 ± 3% decrease in total soil (combined forest floor and mineral soil) C on average in temperate forest soils. Forest floors were found to be more susceptible to C loss than mineral soils with a reduction in forest floor storage of 30 ± 6% over all forest types whereas C storage in mineral soils was not significantly affected overall. Other work in New Zealand has indicated that the fertilisation of plantation forest soils may increase levels of C or N (or both) in forest floors (Smith et al., 1994a; Smaill et al., 2008b) and surface mineral soils (Watt et al., 2008; Huang et al., 2011). Similar findings have also been reported elsewhere (e.g., McFarlane et al., 2009; Rifai et al., 2010), although other studies have found little net effect of fertilisation on soil C and N (e.g., Van Miegroet and Jandl, 2007; Kim, 2008). In a review and meta-analysis of the impacts of elevated N inputs (including N fertilisation) on the storage of C in forest soils based on 72 experimental sites, Nave et al. (2009) found that N inputs increased total soil (combined forest floor and mineral soil) C by 7.7% and decreased the C:N ratio by 4.9%. Stocks of C were increased predominantly in the mineral soil (by 12.2%) whereas the C:N ratio was decreased predominantly in the forest floor (by 7.8%). Internationally, relatively few studies have reported on the combined effects of harvest residue management and fertilisation on C or N (or both) in plantation forest soils (e.g., Smith et al., 1994a,b, 2000; Vanguelova et al., 2010).

Insufficient attention has been given to the change in soil C and N over time in response to forest harvest residue management and fertilisation in New Zealand. Although some studies have examined treatment difference at mid-rotation (e.g., Jones et al., 2008; Smaill et al., 2008a,b), changes relative to pre-treatment (pre-harvest) levels at mid-rotation have not been well established. Based on treatment effects at mid-rotation, some studies suggest that the effects of harvest residue manipulations and fertilisation on soil C and N may persist for up to 25–30 years (Smaill et al., 2008a,b). Schipper et al. (2011) have reported complex temporal changes (inter-annual trends) in soil C and N storage under long-term pastoral grazing of hill-country which highlights the likely difficulties in establishing long-term trends with infrequent re-measurement and the need for more long-term, and more frequent, monitoring.

The primary objective of this study was to determine the change in forest floor and mineral soil C and N in response to harvest residue management and fertilisation between pre-harvest and mid-rotation (stand age 15 years) measurements in a *Pinus radiata* D. Don plantation forest. *P. radiata* is the dominant plantation forest species grown in New Zealand, comprising about 90% of the planted forest area. Treatment effects on tree growth (basal area) and the contribution of the mineral soil coarse fraction to total mineral soil C and N stocks were also examined.

2. Materials and methods

2.1. Site location and description

The study was undertaken at the Kinleith Forest trial site which was part of the Long-Term Site Productivity (LTSP) Series I group of trial sites (Smaill et al., 2008b). The Kinleith Forest trial was located in a second rotation *P. radiata* (D. Don) plantation forest situated in the central North Island, New Zealand (latitude 38° 14′S and longitude 175° 58′E). The first rotation stand (*P. radiata*) was established in 1966 at a stocking of 1667 stems ha^{-1}. The stand was production thinned to 500 stems ha^{-1} in 1978 and to a final stocking of 300 stems ha^{-1} in 1985. The first rotation stand at the trial site was clear-fell harvested in 1991 at stand age 25 years. Harvesting of the stand was undertaken using chainsaws, and harvesting machinery was kept off the plots to avoid additional disturbance (Smith et al., 2000).

The trial site was initially planted in 1991 but, due to a high mortality rate, was completely replanted in September 1992. Seedlings were approximately 12 months old when planted and planting was undertaken without mechanical cultivation. Smith et al. (2000) gave a full description of the trial site, only the key points of which are summarised here. The trial was established on an elevated (490 m) and slightly hummocky surface within a deeply incised landscape (Smith et al., 2000). The annual rainfall at the site is 1764 mm $year^{-1}$ and the mean annual temperature is 11.5 °C (Leathwick et al., 2003). The trial was terminated shortly after the mid-rotation sampling (at stand age 15 years) in September 2007 due to the conversion of the forest to dairy-farm pastures.

Smith et al. (2000) described the soil type at the site as a Taupo sandy loam to silt loam. These soils are classified as Typic Udivitrands (Soil Survey Staff, 2003), corresponding to Immature Orthic Pumice Soils of the New Zealand Soil Classification system (Hewitt, 1998).

2.2. Trial design

The trial was a split-plot, randomized complete block design with four replicate blocks. Each block contained three main plots to which three harvest residue management treatments were randomly assigned. Main plots had dimensions of 80 × 40 m and each contained two split-plots, one of which was randomly assigned a fertiliser treatment and the other left unfertilised after replanting. Each split-plot consisted of a 20 × 20 m measurement area surrounded by a 10 m buffer. The measurement area of each split-plot initially contained about 100 trees (2500 stems ha^{-1}) and these were thinned-to-waste – meaning stems were retained on-site – at stand-age five (to 1250 stems ha^{-1}) and again at age 10 (to 625 stems ha^{-1}). The trees were not pruned.

The main harvest residue management treatments were stem-only harvesting (SO), whole-tree harvesting (WT), and whole-tree harvesting plus forest floor removal (FF) (Smith et al., 2000). The FF treatment involved the careful removal of the forest floor (undertaken manually using rakes) in addition to the removal of harvest residues whereas the WT treatment involved the removal of harvest residues while minimising disruption of the forest floor. The WT treatment is effectively what would occur if harvest residues were removed for bioenergy production. With the SO treatment (the conventional approach to forest harvesting), branches and foliage were retained on-site after the removal of merchantable logs. It is estimated that approximately 50 Mg ha^{-1} of residues were retained in SO plots based on the pre-harvest branch and foliage biomass estimates for the first rotation (described in Section 2.6). All treatments received weed control which involved periodic herbicide application through to crown closure. Urea-N fertiliser was applied annually (at a mean rate of 190 kg ha^{-1} $year^{-1}$) to one split-plot within each main plot from stand age 1–6 years (totalling 950 kg ha^{-1} of N). A high rate of Urea-N was applied with a view to ensure an ample supply of N for maximum tree growth. The high rate and timing of application (during early stand establishment) were not common practice in New Zealand forest operations. Total applications of other nutrients applied to each fertilised split-plot from stand age 1–6 years were 100 kg ha^{-1} of P (LL Super/reactive phosphate rock), 12 kg ha^{-1} of B (Ulxite), and 200 kg ha^{-1} of Mg (calmag/$MgSO_4$/dolomite). The other split-plot remained unfertilised (Smith et al., 2000).

2.3. Pre-treatment sample collection

The forest floor and mineral soils at the trial site were sampled in 1991 prior to the harvesting of the previous stand. This sampling is referred to here as the pre-treatment sampling (PT). Forest floor material (combined LFH horizon) was sampled at five randomly selected points across the entire 80 × 40 m main plot area because