Harvest intensity and competing vegetation control have little effect on soil carbon and nitrogen pools in a Pacific Northwest Douglas-fir plantation

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Abstract

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Increasing demand for timber as well as current interest in the use of woody biomass for energy and chemical production may result in higher quantities of organic matter removal from plantation forests than currently occurs during harvesting. Two practices that can increase the yield of woody biomass from a harvest site are (1) the application of herbicides to control competing vegetation and improve crop tree growth and (2) the removal of branches and foliage (slash) in addition to the bole during harvest. The potential of these practices to change pools of soil carbon and nitrogen necessitates an evaluation of how management practices affect soil quality and carbon sequestration. In this study, soil carbon and nitrogen were measured to a depth of one meter in a 12-year-old Douglas-fir (*Pseudotsuga menziesii*) plantation at the Fall River Long-term Soil Productivity site in western Washington. The effects of vegetation control (bole-only harvest with versus without annual herbicide application, BO+VC vs. BO-VC) and harvest intensity (bole-only harvest with vegetation control versus total tree plus harvest with vegetation control, BO+VC vs. TTP+VC) on soil carbon and nitrogen were compared. Forest floor and mineral soil samples in six depth increments (forest floor, 0-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, and 60-100 cm) were collected at 12 years following planting of seedlings. Carbon and nitrogen concentrations for the forest floor and the fraction of mineral soil <4.75 mm were obtained and contents calculated. Deep soil (60-100 cm) carbon concentration was significantly higher in the treatment with vegetation control (1.60% C for BO+VC, 1.17% C for BO-VC, α=0.10), and forest floor nitrogen concentration was greater in the treatment without vegetation control (1.21% N for BO-VC vs. 1.06% N for BO+VC), however surface mineral soil (0-15 cm) nitrogen content was higher in plots with vegetation control than those without (2890 kg N ha^{-1} for BO+VC vs. 2760 kg N ha^{-1} for BO-VC). No other significant differences were found for the vegetation control, bole-only harvest comparison. In the harvest intensity comparison, forest floor carbon and nitrogen concentrations and contents were lower in total tree plus compared to bole-only harvest (5.28 Mg C ha^{-1} for TTP+VC vs. 9.52 Mg C ha^{-1} and 133 kg N ha^{-1} for TTP+VC vs. 247 kg N ha^{-1} for BO+VC), but no differences existed in the mineral soil. There were no significant differences in total carbon or nitrogen content to 100 cm for either the vegetation control or the harvest intensity comparisons, which suggests that, at this site, neither the use of vegetation control nor whole-tree harvest is likely to have a negative impact on forest productivity or soil quality in the long-term management of the plantation.

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1. INTRODUCTION

Concern over increasing demand for forest resources has received much attention in the early 21st century, eliciting publications by World Wildlife Fund (WWF), the United Nations Food and Agriculture Organization, and the United Nations Environment Programme among others. These reports draw attention to the need for sustainable forest management; use of woody biomass for bioenergy; and, in order to meet demand for renewable forest products while allowing other land to be preserved, increased biomass yields from land currently used for wood production (e.g. WWF's "Zero Net Deforestation and Forest Degradation" proposition (WWF International 2011)). In North America, the North American Forest Sector Outlook Study 2006-2030 published by the United Nations Economic Commission for Europe (2012) projects a 53% to 357% increase in U.S. production of woody biomass for fuel by 2030 based on estimates of future biofuel use by the Intergovernmental Panel on Climate Change. The Billion-Ton biomass study (U.S. Department of Energy 2011) estimates that 1.4-1.6 billon tons of biomass can be harvested from US land annually, and forests are a large part of this potential production.

Increased demand for forest biomass will likely necessitate higher intensity harvests from land currently in timber production through methods such as whole-tree harvesting and use of herbicides to control competing vegetation early in crop tree regeneration. It is important to assess any potential environmental consequences of such harvest intensification (WWF International 2011). Concern over the degradation of soils from timber harvesting has been an issue for decades as the health of forest soils is key to sustainable timber production. Without care, managing plantation forests intensively to meet high global wood demands may degrade soil quality, consequently making timber production unsustainable in the long term (Nambiar 1996). The effects of harvest intensification on soil carbon and nitrogen pools are of particular concern in the Pacific Northwest where forest fertilization is not practiced as commonly as in the US southeast.

Pacific Northwest forest ecosystems have the potential to sustain some of the largest annual productivities and total pools of biomass in the world (Smithwick et al. 2002). These forests contain more combined aboveground tree biomass and belowground soil carbon than many forests in the contiguous United States (Kern 1994; Smithwick et al. 2002). Soils can potentially store carbon for long periods of time, reducing the rate at which carbon is released into the atmosphere; thus, management for increased soil carbon content has been proposed as a method to help mitigate global climate change (Lorenz et al. 2011; Peng et al. 2008). In the Pacific Northwest, estimates of the fraction of ecosystem carbon in the soil, including forest floor, of a Douglas-fir – western hemlock forest range from 15 to 25% (Harmon and Marks 2002). The potential for large amounts of carbon sequestration in these forests necessitates a careful investigation of the ways in which carbon stocks are altered by forest management. In timber harvesting situations, especially, management to maintain and enhance soil organic carbon is necessary. Given that soil carbon stores are driven by biomass accumulation (Sun et al. 2004), enhancing site productivity is a step toward increasing soil carbon stores (Jandl et al. 2007).

Not only is soil carbon an important factor in global carbon cycling and carbon budgets, it is also important for sustaining ecosystem biomass production. Soil organic matter enhances soil water-holding capacity and aeration, and also contains nutrients that can enhance nutrient availability when mineralized, all of which are key factors for plant growth (Brady and Weil 2002). The carbon in soil organic matter is also an energy source for microbes that drive nutrient cycling. The accumulation of soil carbon reflects a balance of organic matter inputs from forest litterfall and outputs from decomposition. Long-term storage of carbon in the soil is a result of the accumulation of humic compounds formed during decomposition of organic matter, leaching of particulate and dissolved organic matter from litter, and adsorption to soil solids. Rates of decomposition, leaching, and adsorption vary with soil type and environmental factors including soil moisture and temperature, and there is high variability in the response of soil carbon to timber harvesting practices due to variations in these factors (Schlesinger 1997).

Soil carbon stores post-harvest can be affected through management of the regenerating forest stand. Within the first few years post-harvest, there is often a spike in soil carbon content as roots and harvest slash decompose into forest floor and mix with soil, but soil carbon levels often then begin to decline until new vegetation becomes established and begins contributing substantial new root growth, litter, and dissolved and particulate organic matter into the soil (Johnson and Curtis 2001; Sanchez et al. 2006). The litter production and root turnover of regenerating vegetation is a significant contributor to the re-accumulation of soil carbon, and intensive management that increases tree growth can, in turn, increase soil carbon through production of coarse roots (Fox 2000). The use of herbicides to control any vegetation competing with crop trees for moisture, nutrients, and sunlight generally increases crop tree survival and growth, however the effect of vegetation control on soil carbon is unclear and may vary with soil type and climate. Slesak et al. (2011b) suggest that vegetation control may reduce the amount of recent organic matter inputs to the soil and that soil microbes may consume more pre-existing soil organic matter as a result. Results of a study in the U.S. Southeast did, indeed, indicate that soil carbon decreased with use of vegetation control treatments (Shan et al. 2001), however this may not always be the case if increased tree growth and production of longer-lived organic matter is greater than any additional decomposition of organic matter in soil.

Harvest intensity (e.g. bole-only versus total tree harvest) can also influence soil carbon stores. Studies evaluating harvest intensity in the short term generally show enhancement of soil carbon for bole-only harvests when compared to more intensive harvesting, however longer term studies have shown little difference in soil carbon with harvest intensity except in soils that are initially very low in organic matter (Tonon et al. 2011). Harvesting may alter environmental conditions that influence organic matter decomposition rates, often increasing soil temperature and decreasing soil moisture, leading to higher rates of microbial decomposition (Slesak et al. 2010). Powers et al. (2005) suggest that under cool, wet conditions more carbon becomes incorporated into the soil and less is respired as carbon dioxide. After bole-only harvest, increases in soil temperature may be mitigated by leaving logging debris distributed across the harvest site to shade the soil, reducing respiration rates (Devine and Harrington 2007; Roberts et al. 2005; Slesak et al. 2010). In addition, mineral soil and forest floor carbon contents tend to respond differently to harvest intensity. Forest floor is more sensitive to harvest due to the more rapid turnover time of carbon in this pool compared to mineral soil carbon and the fact that mineral soil is less disturbed by harvesting machinery. A meta-analysis of post-harvest mineral soil carbon by Johnson and Curtis (2001) indicated an average six percent decrease in mineral soil carbon with whole tree harvesting while bole only harvesting led to an 18 percent increase. Including forest floor in the analysis, however, can change the observed results. A meta-analysis accounting for changes in forest floor carbon (Nave et al. 2010), suggests an average 10 percent decrease in soil carbon regardless of the harvest intensity. The forest floor carbon content was a significant contributor to this result, decreasing by an average of 30 percent post-harvest. Nearly all of the soils included in the Nave et al. (2010) meta-analysis were sampled to relatively shallow depths, and each soil was given equal weight in calculating the average soil carbon loss post-harvest, regardless of the sampling depth and total amount of soil carbon.

Soil nitrogen, in addition to carbon, plays a major role in determining forest productivity, and nitrogen is a limiting nutrient for plant growth in many soils in the Pacific Northwest. Litterfall and root turnover are considered the most important sources from which nutrients return to the soil (Schlesinger 1997). As biomass left on site post-harvest (i.e. branches, foliage, and roots) decomposes, carbon is converted to carbon dioxide and lost from the site while nitrogen can be retained through the process of immobilization (Schlesinger 1997). Mineralization and nitrification convert immobilized nitrogen into ammonium and nitrate ions, forms of nitrogen that are more mobile and may be taken up by plants, adsorbed to soil solids, or leached out of the soil in soil solution (Vitousek et al. 1979). The relative amounts of ammonium and nitrate taken up, sorbed, or leached depend on numerous factors including climate, soil properties, vegetation type, and timing of vegetative growth relative to nitrogen availability (Kimmins 1976).

Changes in nitrogen cycling can result from the use of herbicides to control vegetation that competes with crop tree regeneration, and these changes have the potential to reduce soil nitrogen (Shan et al. 2001). Most soils have high cation exchange capacities but lower potential for anion exchange, thus when there is an excess of nitrate ions present in the soil, the ions that are not taken up by vegetation are often leached out of the soil profile. However, uptake of nitrogen by vegetative growth can retain nitrogen near the soil surface and in plant biomass (Marks and Bormann 1972; Vitousek et al. 1979). Control of competing vegetation has the potential to reduce nitrogen uptake on a site, and studies by Smethurst and Nambiar (1995) and Vitousek and Matson (1985) have observed increases in nitrate leaching when competing vegetation is controlled. However, other studies in the Pacific Northwest indicate that there is a substantial ability of some soils to adsorb nitrate (Strahm and Harrison 2006).

The amount and type of organic matter removed during harvest (i.e. stem only versus whole tree harvest) determines the proportion of nutrients removed from the site. Because the nitrogen concentration of tree branches and foliage is higher than that of tree boles, the removal of branches and foliage through whole tree harvest decreases total nitrogen stores on the site relative to the total amount of biomass removed. Removal of these nitrogen-rich tree components could result in a loss of nutrients (Harmon and Marks 2002); thus, in order to maintain forest productivity, care should be taken to make sure that the rate of nitrogen removal does not exceed the rate of replacement (Kimmins 1976; Fox 2000).

The accumulation of carbon and nitrogen at the soil surface reflects a balance of organic matter inputs from litterfall and root turnover and outputs from decomposition.

Rates of decomposition, leaching, and adsorption vary with both soil type and environmental factors, and there is high variability in the response of soil carbon and nitrogen to harvesting due to these factors as well as differences in harvesting practices and harvest intensity. While there have been many studies relating harvest practices and forest productivity in many parts of North America (Powers et al. 2005; Yanai et al. 2003; Johnson and Curtis 2001), few have investigated these relationships in coniferous forests of the Pacific Northwest. The objectives of this study are to evaluate (a) the effects of using vegetation control and (b) the effects of increasing the amount of biomass removed during harvest (whole tree harvest versus bole-only harvest) on soil carbon and nitrogen.

2. MATERIALS AND METHODS

2.1 SITE DESCRIPTION

Research was conducted at the Fall River research area, which is part of the Long Term Soil Productivity (LTSP) network (Powers 2006). The site is located in western Washington (46°44 N, 123°24 W) and has a maritime climate with an elevation between 300 and 375 meters. Slopes are gentle with a 10 – 15 percent grade (Ares et al. 2007b). The soil at Fall River is of the Boistfort Series, a very deep and well-drained soil with few rocks, developed from weathered basalt. Soil texture ranges from silt loam in the A horizon to silty clay below 21 inches depth (Soil Survey Staff 1999). Old growth forest on the site was logged in 1952-1953 and replanted with Douglas-fir (Ares et al. 2007b). The Fall River study site installation began in 1999 with four replicates of twelve treatments in a randomized block design. Plots are 30 X 85 meters and have an internal measurement plot of 15 X 70 meters (0.10 ha). Pre-harvest forest composition and slope position determined blocking. Soil sampling near the time of plot installation (1998) revealed that mineral soil carbon and nitrogen contents to 80 cm were 249 Mg ha^{-1} and 13,140 kg ha^{-1} respectively (Ares et al. 2007b), which is higher than average for igneous parent materials in the Pacific

Northwest. Littke et al. (2011) found that the average soil nitrogen content to 100 cm of 60 different Douglas-fir stands in the Pacific Northwest ranged from 7,327 kg N ha^{-1} for glacial parent materials to 9,483 kg N ha^{-1} for igneous parent materials and 13,254 kg N ha^{-1} for sedimentary parent materials. Fall River nitrogen content to 100 cm is higher than this at approximately 15,100 kg ha^{-1} (Ares et al. 2007b). Fall River carbon content to 100 cm is also above average for igneous parent materials at 276 kg ha^{-1} (Ares et al. 2007b); Littke et al. (2011) found that average carbon contents were 125, 137, and 196 Mg ha^{-1} for glacial, igneous, and sedimentary soils respectively.

Treatment plots were installed to test a wide variety of harvest conditions ranging from soil compaction to harvest intensity to control of competing vegetation in the regenerating stand. In this study, the effects of vegetation control on soil carbon and nitrogen were assessed by sampling soil in both the bole-only harvest with competing vegetation control (BO+VC) treatment and bole-only harvest without competing vegetation control (BO-VC). The harvest intensity treatments sampled in this study represented two extremes: bole-only harvest with competing vegetation control (BO+VC) and total tree plus harvest with competing vegetation control (TTP+VC). No plot treatment for total tree plus harvest without competing vegetation control was installed. In bole-only plots, tree boles to an 8-13 cm top were cable-yarded and all remnant coarse woody debris was distributed evenly across the plot area. For total tree plus harvest, all live aboveground portions of the tree were removed (cable-yarded). Live and dead branches greater than 0.6 cm diameter were removed as well as all coarse woody debris except for rotten material that could not be taken in one piece, old growth stumps and snags, and new stumps. The plots were planted with Douglas-fir seedlings in 2000 at a spacing of 2.5 m by 2.5 m (1600 trees/ha). All plots specified for the vegetation control treatment received five years of intensive vegetation control (herbicide) from 2000 to 2004, applied through a combination of backpack sprayers and spot application. This vegetation control treatment was not intended to simulate standard operational vegetation control but rather to completely eliminate competing vegetation (Ares et al. 2007b). At the time of soil sampling for this study, the trees on site were 12 years old and approaching canopy closure. Figure 1 shows the layout of the Fall River site and plots sampled. A more detailed description of the Fall River study installation is provided by Ares et al. (2007b).

2.2 PLOT SAMPLING

Forest floor and mineral soil samples were collected from February to May 2012. For each of the three treatments (BO+VC, BO-VC, TTP+VC), one plot per block was sampled for a total of twelve plots. Within each plot, six 1.0 m^2 subplots were randomly selected for sampling. When surface obstacles such as stumps or red rot obstructed sampling at one of the randomly selected subplots, a new random subplot location was chosen. Forest floor and mineral soil samples were collected at each subplot.

2.3 FOREST FLOOR SAMPLE COLLECTION

Within each subplot, forest floor samples were collected in three locations in a 0.05 m^2 area and composited into one sample to reduce variability. In this study, forest floor material included all identifiable plant detritus (rotten wood, needles, twigs, etc.) less than 5 cm in diameter. When detritus such as rotten wood extended outside the sampling area, only the portion within the area was collected. Forest floor depth was recorded around the edge of the sample area at four equally spaced points, and the average of these depths was used to calculate forest floor volume.

2.4 MINERAL SOIL SAMPLE COLLECTION

Mineral soil was sampled in 15 cm depth intervals to 60 cm (0-15 cm, 15-30 cm, 30-45 cm, and 45-60 cm) using a Giddings hammer corer with four 6-inch (15.24 cm) sleeves. An additional 40 cm sample (60-100 cm) was collected with a punch corer to reach 100 cm depth. For the 0-15 cm and 15-30 cm intervals, soil was collected in three locations within each subplot and composited to reduce variability (Holub 2011). Due to the difficulty of collecting deep soil samples, only one sample was collected for depth increments below 30 cm. Soil collected in the 5 cm tip of the hammer corer was included in the 30-45 cm interval (for two cores per subplot) and the 45-60 cm interval (one core per subplot). The additional 10 cm of depth in the 45-60 cm interval was collected using the punch corer. Bulk density samples for the 60-100 cm depth interval were collected by digging a soil pit to 60 cm at the center of each treatment plot and taking a vertical bulk density core. For mineral soil samples containing more than 50 percent red rot by volume in any depth interval, all samples in that core were discarded and a new core was collected.

2.5 SAMPLE PROCESSING AND ANALYSIS

All samples were oven dried at 60°C, and bulk density was calculated based on dry weight and sample volume. Dry mineral soil samples were sieved with a 4.75 mm sieve. Although the fraction of material <2mm is generally considered to be the most reactive soil containing the majority of carbon, soil carbon sampling by Holub (2011) and Zabowski et al. (2011) indicates that a significant amount of carbon is contained in the 2 mm to 4.75 mm portion, and trees are able to uptake nutrients from this coarser fraction in addition to <2mm soil (Kimmins 1976). The larger sieve size also helped to reduce variability in the amount of each sample that went through the sieve due to processing method.

Forest floor and the <4.75 mm fraction of mineral soil samples were subsampled, ground, and analyzed in a PerkinElmer CHN Analyzer (Model 2400, Waltham, MA) to determine total carbon and nitrogen concentrations. Carbon and nitrogen content on an areal basis was determined by multiplying the bulk density by concentration and sample depth interval. Total soil carbon and nitrogen to a depth of 100 cm was calculated by adding the carbon and nitrogen contents of all depth intervals, including forest floor.

2.6 STATISTICAL ANALYSIS

Treatment differences in soil carbon and nitrogen concentrations and contents were tested using two-way (randomized block) ANOVA with an alpha value of 0.10. Each depth interval was tested separately, and total carbon and nitrogen contents to a depth of 100 cm were also tested (R Studio, Version 2.10.1, 2009).

3. RESULTS

3.1 VEGETATION CONTROL

3.1.1 Carbon

Carbon concentration values for the vegetation control comparison were 40.6% C for BO+VC and 42.4% C for BO-VC in the forest floor, while mineral soil concentrations decreased from 10.3% for BO+VC and 13.1% for BO-VC in the surface (0-15 cm) mineral soil to 1.60% and 1.17% for BO+VC and BO-VC respectively in the 60-100 cm section (Table 1). There were no significant differences ($\alpha=0.10$) in carbon concentration between vegetation control treatments in the forest floor or in the mineral soil down to 60 cm depth. In the 60-100 cm section, BO+VC carbon concentration (1.60%) was significantly higher than BO-VC (1.17% C, $P=0.06$; Figure 2). In the 0-15 cm section, BO-VC carbon concentration (13.1%) was slightly higher than BO+VC (10.3%, $P=0.15$).

Carbon content values for the forest floor were 9.52 Mg ha^{-1} for BO+VC and 8.75 Mg ha^{-1} for BO-VC (Table 1). There were no significant differences in carbon content for individual depth intervals, though treatment average carbon values were slightly higher for the BO+VC treatment in the deeper intervals (Figure 3). There was no significant difference in total carbon content to 100 cm between vegetation control treatments. Total carbon content to 100 cm depth, including forest floor, was 270 Mg ha^{-1} for BO+VC and 254 Mg ha^{-1} for BO-VC (Figure 4).

3.1.2 Nitrogen

Nitrogen concentration values were significantly higher in the forest floor treatment without vegetation control (1.06% N for BO+VC, 1.21% N for BO-VC, $P=0.04$). The 0-15 cm mineral soil depth also had higher nitrogen concentration in the BO-VC treatment (0.48% N vs. 0.42% N for BO+VC), though this difference was not significant at an alpha level of 0.10 ($P=0.16$). Nitrogen concentrations decreased throughout the soil profile, from >1% in the forest floor to less than 0.5% in the surface (0-15 cm) mineral horizon and 0.07-0.08% in the 60-100 cm interval (Figure 5).

There was no difference in forest floor nitrogen content with values of 247 and 239 kg N ha^{-1} for BO+VC and BO-VC respectively (Table 1). The BO+VC nitrogen content was, however, significantly higher ($P=0.05$) in the surface (0-15 cm) mineral soil (2890 kg ha^{-1} vs. 2680 kg ha^{-1} for BO-VC, Figure 6). Soil nitrogen content to 100 cm was not significantly different between vegetation control treatments (Figure 7). Nitrogen contents to 100 cm depth, including forest floor, were 12,500 kg N ha^{-1} in the BO+VC treatment and 12,200 kg N ha^{-1} for BO-VC (Table 1).

3.2 HARVEST INTENSITY

3.2.1 Carbon

Soil carbon concentration in the harvest intensity comparison showed significant differences in the forest floor (40.6% for BO+VC and 36.0% for TTP+VC, $P=0.04$) but not in the mineral soil. Mineral soil carbon concentration ranged from approximately 10% in the surface (0-15 cm) mineral soil to 1.60% for BO+VC and 1.31% for TTP+VC in the 60-100 cm depth interval (Figure 8).

Forest floor carbon content was significantly different ($P=0.002$) between harvest intensity treatments (BO+VC content was 9.52 Mg C ha^{-1} while TTP+VC content was 5.28 Mg C ha^{-1}; Figure 9). However, this significant difference in the forest floor was very small in relation to the carbon content of the mineral soil. The cumulative carbon content to 100 cm was not significantly different between treatments, though the content of BO+VC harvest (270 Mg ha^{-1}) was 18 Mg ha^{-1} greater than TTP+VC harvest (252 Mg ha^{-1}; Figure 10). Even taking into account only the surface 20 cm of the mineral soil, there was no significant difference between treatments, with a cumulative carbon content to 20 cm of 99.3 Mg ha^{-1} for BO+VC harvest and 91.8 Mg ha^{-1} for TTP+VC harvest. While there were no significant differences in carbon contents of the individual mineral soil sampling depths, the 30-45 cm and 45-60 cm intervals showed the largest absolute differences in content, with 4.1 Mg C ha^{-1} more for BO+VC harvest in the 30-45 cm interval and 5.0 Mg C ha^{-1} more in BO+VC harvest in the 45-60 cm interval (Table 1).

3.2.2 Nitrogen

Nitrogen concentration was significantly lower in the TTP+VC forest floor than BO+VC forest floor (P=0.03), with a concentration of 0.90% N in the TTP+VC treatment and 1.06% N for BO+VC. There were no significant differences between treatments in the mineral soil. Values decreased with depth from 0.41% N in the 0-15 cm interval to 0.08% N in the 60-100 cm interval (Figure 11).

Nitrogen content was significantly higher in BO+VC forest floor than TTP+VC forest floor (247 and 133 kg N ha^{-1} respectively, P=0.001), but there were no significant differences between treatments in the mineral soil (Figure 12). As with carbon, the differences in the forest floor were insignificant compared to the greater nitrogen content of the mineral soil; cumulative nitrogen content to 100 cm, including forest floor, was not significantly different between treatments, with 12,500 kg ha^{-1} for BO+VC vs. 12,700 kg N ha^{-1} for TTP+VC (Figure 13). Cumulative nitrogen content to 20 cm was 4100 kg ha^{-1} in the BO+VC harvest and 3900 kg ha^{-1} in the TTP+VC harvest, a difference that was not statistically significant.

3.2.3 Coarse Woody Debris

The carbon and nitrogen stores in coarse woody debris at a site are easily overlooked, as coarse woody debris is part of neither the soil nor the aboveground living biomass. While coarse woody debris was not sampled in this study, the biomass and carbon and nitrogen contents of coarse woody debris (harvest detritus 0.6–60 cm diameter), recent stumps, and old-growth logs were measured post-harvest at the time of plot installation. The estimated total carbon content of these components at that time was 66.7 Mg C ha^{-1} for bole-only harvest and 3.6 Mg C ha^{-1} for total tree plus harvest. Nitrogen content was 206.1 kg N ha^{-1} for bole-only harvest and 8.3 kg N ha^{-1} for total tree plus harvest (Ares et al. 2007b). Based on the total decay rate suggested by Harmon and Hua (1991) for Douglas-fir in western Washington — a loss rate of 3% per year, which includes loss due to biomass fragmentation and decomposition — an estimated 2012 coarse woody debris carbon content at Fall River is 45 Mg ha^{-1} for bole-only harvest and 2.4 Mg ha^{-1} for total tree plus harvest. Harmon and Hua also suggest that 10-20% of coarse woody debris nutrients are released from dead trees relatively rapidly while the rest are released much more slowly. Based on this assumption, the estimated 2012 coarse woody debris nitrogen content in bole-only plots is approximately 175 kg N ha^{-1} while the total tree plus treatment may have contained only 7 kg N ha^{-1} at the time of our sampling.

4. DISCUSSION

4.1 VEGETATION CONTROL

While there were few significant differences between vegetation control treatments, the results did show carbon content increasing with depth in the plots with vegetation control relative to those without, mostly due to the higher BO+VC carbon content of the 30-100 cm mineral soil. This difference was especially evident in the higher carbon concentration and content of the BO+VC treatment in the 60-100 cm depth interval. Though the BO+VC carbon content of the 60-100 cm depth was 6.7 Mg ha^{-1} greater than BO-VC content, this difference was not significant due to high variability of the data in this depth interval. The high variability at depth was likely due to the fact that fewer deep soil samples were collected. While this study was not designed to assess the mechanisms leading to changes in carbon and nitrogen content, one explanation for the higher carbon values in BO+VC at depth is that greater root growth and turnover in this treatment contributed more carbon to the deep soil. A study by Devine et al. (2013) at the Fall River LTSP site found that the 11-year aboveground growth of the trees was greater in the BO+VC treatment than that of trees in the BO-VC treatment, with 8.2 Mg ha^{-1} more carbon in plots with vegetation control. Belowground tree growth generally correlates to aboveground growth (Peichl and Arain 2007; Zerihun and Montagu 2004); thus, given the greater aboveground biomass of the BO+VC treatment, the belowground contribution of carbon by roots was likely higher in the BO+VC treatment than BO-VC. Indeed, the root concentration by weight in our soil cores was higher in the BO+VC treatment of both the 30-45 cm and 45-60 cm depth intervals (0.15% for BO+VC vs. 0.08% for BO-VC in the 30-45 cm interval and 0.16% for BO+VC vs. 0.05% for BO-VC in the 45-60 cm interval). Root data for the 60-100 cm interval was not available in this study due to the small diameter of the soil corer used to collect this sample depth.

As with carbon, the total soil nitrogen content to 100 cm was slightly, though not significantly, higher in the BO+VC treatment overall (12,500 kg N ha^{-1} for BO+VC vs. 12,200 kg N ha^{-1} for BO-VC). The greatest differences between treatments were seen in the 0-45 cm mineral soil, with significantly higher nitrogen content in the 0-15 cm sampling interval for the BO+VC treatment (2890 kg ha^{-1} in BO+VC vs. 2680 kg ha^{-1} in BO-VC; $P=0.05$). It is possible that the observed difference in nitrogen distribution between treatments is due to retention of nitrogen in both the shallow roots and aboveground biomass of regenerating vegetation in the BO+VC treatment.

In the past, studies have shown a loss of nitrogen with vegetation control (e.g. Smethurst and Nambiar (1995) and Vitousek and Matson (1985)). More recently, Miller et al. (2006), in a study of loblolly pine plantations in the southeast United States 15 years post-harvest found that more nitrogen was lost when competing vegetation was controlled. These results contrast with our results, which showed a greater (though not significant) decrease in nitrogen content in the BO-VC treatment at the Fall River site. This study also contrasts with our study in regard to carbon: the Miller et al. study found that carbon concentration was lower in plots with vegetation control relative to those without while results at Fall River show more soil carbon in the plots with vegetation control. The improved growth of BO+VC trees at Fall River likely increased both soil carbon and nitrogen with vegetation control in our study, and in addition, the unique soil properties of the Boistfort soil may have reduced nitrogen loss through leaching in the plots with vegetation control, which did not have herbaceous vegetation taking up excess soluble nitrogen. Strahm and Harrison (2007) found that Fall River soils have a capacity for anion sorption more than twice that of other Pacific Northwest soils. In addition, a study by Strahm et al. (2005) found that NO_3^- was the dominant form of leached N during the first five years post-harvest at Fall River, and there is a high sorption capacity for NO_3^- in the 2Bw1 and 2Bw2 horizons (40-100+ cm depth) relative to shallower horizons at Fall River (Strahm and Harrison 2007). This high retention capacity may have reduced the amount of leaching that occurred in the BO+VC treatment.

The effect of vegetation control on soil carbon and nitrogen may be both site-specific and dependent on initial carbon and nutrient content of the soil. Though the Fall River results did not support those of the Miller et al. (2006) study, they were more similar to the results of a study by Slesak et al. (2011a) in the Pacific Northwest who found that, five years after harvest at a nutrient-rich site (Molalla), neither soil carbon nor nitrogen had changed based on vegetation control treatment. At a lower-nutrient site, however, the carbon content in plots with an annual application of vegetation control treatment was lower than that of plots with just one initial application of vegetation control. The same was true for nitrogen content. The degree to which a change is significant may be determined by the carbon and nitrogen nutrient pool pre-harvest such that sites with higher initial carbon and nitrogen are less likely to show significant changes (Slesak et al. 2011a; Kimmins 1976; Compton and Cole 1991).

4.2 HARVEST INTENSITY

Comparing harvest intensity treatments at Fall River, carbon content was significantly lower in the forest floor of the total tree plus treatment than in bole-only forest floor. This 4.24 Mg C ha^{-1} difference was small in comparison to the high carbon content of the mineral soil. While there was not a significant difference in the carbon contents to 20 cm or to 100 cm, the TTP+VC carbon values were slightly lower than BO+VC throughout the mineral soil, and the cumulative carbon content to 100 cm including the forest floor was also slightly, though not significantly, lower in the TTP+VC treatment (270 Mg C ha^{-1} in BO+VC vs. 252 Mg C ha^{-1} in TTP+VC; P = 0.33). Though this study did not test the mechanisms driving change in soil carbon content, the slightly lower total TTP+VC carbon content was likely a result of the lower organic matter content in the total tree plus treatment immediately post-harvest. The deficit of forest floor organic matter relative to the BO+VC treatment probably resulted in a lower contribution of organic matter to the O horizon and less movement of both dissolved and particulate organic matter into the mineral soil profile.

While the Fall River results showed no difference in soil carbon content after 12 years between bole-only and total tree harvest, from a total carbon sequestration perspective, Harmon & Marks (2002) suggest that increasing the amount of woody detritus left on a harvest site (i.e. leaving branches and foliage) reduces the amount of carbon lost to the atmosphere. Alternative options, such as processing detritus into forest products or use of slash as a fuel, result in a more rapid loss of carbon than would occur by leaving the slash to decompose on site (Harmon & Marks 2002). A study by Rubino et al. (2010) suggests that movement of carbon in litter into the soil profile is twice the amount released into the atmosphere as carbon dioxide.

At Fall River, different levels of harvest slash removal did not result in a significant difference in total soil nitrogen content to 100 cm. Soil nitrogen content was significantly lower in the forest floor TTP+VC treatment than the BO+VC forest floor due to the removal of nitrogen-containing biomass in the initial treatment setup, however, as with carbon, this small absolute difference in forest floor nitrogen content between treatments was small relative to the high mineral soil nitrogen content. Even if we had sampled to just 20 cm, we would not have seen a difference in nitrogen content. The nitrogen content of the 60-100 cm sample in the TTP+VC treatment was 500 kg ha^{-1} greater than the BO+VC treatment, which was a result of the higher average bulk density value for TTP+VC plots compared to BO+VC (0.91 g cm^{-3} in TTP+VC vs. 0.76 g cm^{-3} in BO+VC). Only one bulk density sample was collected per plot at this depth, and, thus, our dataset for bulk density at this depth is not as robust as it is for the other sampled depths.

Overall, our results are similar to the findings of Slesak et al. (2011a) at the Matlock and Molalla sites in the Pacific Northwest, whose study results showed no difference in mineral soil carbon content between bole-only and whole tree harvest. In their study, nitrogen content was significantly higher for bole-only harvest in the surface (0-15 cm) mineral soil, while at Fall River the only difference in nitrogen content between harvest intensity treatments was in the forest floor. The difference in nitrogen results between these two Pacific Northwest studies may be due to fact that the initial soil nitrogen content at Fall River was much higher than both the Matlock and Molalla initial soil nitrogen contents.

4.3 CHANGES IN SOIL C AND N CONTENT SINCE FALL RIVER LTSP SITE INSTALLATION

Soil carbon storage varies with the amount of time since harvest. Many studies show a spike in content within the first few years as roots and harvest slash decompose, however once this input has mostly decomposed soil carbon levels begin to decline until new vegetation is established (Johnson and Curtis 2001; Sanchez et al. 2006; Tonon et al. 2011). The litter pool, including roots and harvest slash, is generally thought to reach a minimum approximately 10-20 years post-harvest, but litter production and root turnover of regenerating vegetation is a significant contributor to the re-accumulation of soil carbon (Jiang et al. 2002; Yanai et al. 2003; Covington 1981). Soil carbon is thought to fluctuate in a pattern similar to litter, though the magnitude of change in soil carbon is not as large (Jiang et al. 2002; Yanai et al. 2003).

Many studies of soil carbon and nutrient dynamics in the past have taken into account only the forest floor and surface mineral soil rather than sampling deep mineral soil, assuming that carbon deeper in the soil is relatively stable and that treatment differences are most likely to be observed in the surface soil (e.g. Nave et al 2010; Johnson and Curtis 2001; Covington 1981). Currently, the Forest Inventory and Analysis (FIA) program of the U.S. Forest Service samples soil down to just 20 cm (U.S. Department of Agriculture Forest Service 2011). While sampling to this shallow depth gives an indication of how surface conditions change, it does not necessarily indicate changes that may occur in the deep soil (Yanai et al. 2003). The results of our study suggest that, in addition to changes in forest floor and surface mineral soil, Fall River soil is changing at much deeper depths than 20 cm. For example, the BO+VC and BO-VC treatment averages suggest that BO+VC content to 100 cm was 16 Mg C ha^{-1} greater than BO-VC content with most of this difference occurring in soil deeper than 20 cm; the BO+VC content to 20 cm was only 1.4 Mg C ha^{-1} greater than BO-VC content, indicating a 14.6 Mg C ha^{-1}difference in the 20-100 cm mineral soil. Similarly, the observed mineral soil differences in carbon content between harvest intensity treatments were greatest in the 30-45 cm and 45-60 cm sampling depths, with 9.1 Mg C ha^{-1} more soil in the 30-60 cm section of the soil profile of the BO+VC treatment than the TTP+VC treatment. The observed difference in carbon content to 20 cm was only 7.5 Mg ha^{-1} while the difference in carbon content to 100 cm was 18 Mg ha^{-1}. The Fall River results also show changes in nitrogen content of the deep soil by treatment, with 20-100 cm soil nitrogen contents of 8400 kg ha^{-1} in the BO+VC treatment, 8860 kg ha^{-1} in the BO-VC treatment, and 8800 kg ha^{-1} in the TTP+VC treatment (Table 2).

We compared the results of this study to data collected near the time of Fall River installation (forest floor carbon and nitrogen contents from 2000 and mineral soil carbon and nitrogen contents from 2001; Ares et al. 2007b). While 2001 mineral soil values reflect the fraction of mineral soil <2 mm and the 2012 values are for the fraction of soil <4.75 mm, the fine texture of the Boistfort soil means that there is little mineral material in the 2-4.75 mm fraction of the soil. Any additional carbon or nitrogen contributed by this fraction is mostly from coarse roots or other organic matter such as charcoal or bark. Our comparison suggests that mineral soil carbon increased and forest floor carbon decreased in both BO+VC and BO-VC treatments from the initial post-harvest values to 2012. Total carbon content of BO+VC plots decreased by 4 Mg C ha^{-1} while carbon content of the BO-VC treatment decreased by 19 Mg C ha^{-1} (Table 3). Total carbon content of the TTP+VC treatment was the same in 2012 as it was initially post-harvest, however more of this carbon was stored in the mineral soil in 2012 (246 Mg C ha^{-1} in 2012 versus 229 Mg C ha^{-1} initially post-harvest). While carbon was lost from the forest floor of both treatments from over this time, mineral soil carbon content increased by 31.9 Mg C ha^{-1} in BO+VC and 17.8 Mg C ha^{-1} in TTP+VC. This increase in mineral soil content may be due a combination of carbon contributed through both root turnover and movement of forest floor organic matter into the soil profile. Of the treatments measured in 2012, bole-only harvest without vegetation control showed the greatest soil carbon loss.

Both mineral and forest floor nitrogen content decreased from post-harvest to 2012 in all treatments. Mineral soil nitrogen content decreased by 2040 kg ha^{-1} in BO+VC, 2340 kg ha^{-1} in BO-VC, and 1740 kg ha^{-1} in TTP+VC. Forest floor nitrogen content lost 243 kg ha^{-1} in BO+VC, 251 kg ha^{-1} in BO-VC, and 177 kg ha^{-1} in TTP+VC. Unlike some studies (e.g. Smethurst and Nambiar (1995) and Vitousek and Matson (1985)), total nitrogen losses were greater in plots without vegetation control rather than those with (-2620 kg N ha^{-1} for BO-VC versus -2320 kg N ha^{-1} for BO-VC). Losses were also greater for bole-only harvest in comparison to total tree plus (-2320 kg N ha^{-1} for BO+VC versus -1950 kg N ha^{-1} for TTP+VC). These values represent losses of 18% of the total nitrogen in the pre-harvest soil for BO-VC, 16% for BO+VC, and 13% for TTP+VC.

Our results for carbon are similar to the findings of Slesak et al. (2011a) at the Molalla site where they found no differences in total soil carbon content five years after harvest for both vegetation control and harvest intensity treatments. For nitrogen, however, unlike our study, which showed decreased nitrogen content for all harvest treatments, Slesak et al. (2011a) did not find changes in nitrogen content at Molalla. A study by Grand and Lavkulich (2012) on Spodosols in coastal British Columbia also found similar results to our study. Their study compared a chronosequence of control (non-harvested) stands to harvested and regenerating stands up to 15 years post-harvest, and they found no change in total carbon or nitrogen content due to harvest. Despite a lack of change in total contents, however, they did find that the distribution of both carbon and nitrogen in the profile changed with harvest. Mineral soil carbon was greater in cleared plots relative to the control while mineral soil nitrogen was lower and forest floor nitrogen higher in the regenerating stand compared to the control. Our results also showed a loss of carbon from the forest floor and a gain in mineral soil, however the same did not hold true for nitrogen, which was lost from both the forest floor and mineral soil. Results of a study by Rubino et al. (2010) suggest that redistribution of carbon through the soil profile may help conserve soil carbon post-harvest, and our results seem to fit this idea.

4.4 CONCLUSIONS

Fall River five- and ten-year tree growth was greatest in plots with that received the vegetation control treatment compared to those without. The greater growth of BO+VC trees suggests that use of vegetation control may increase carbon storage in both above and belowground biomass. The belowground increase in biomass may be important for longer-term carbon sequestration in soil. While there is often concern over a potential increase in nitrogen leaching with use of vegetation control, the fact that total soil nitrogen and carbon were not significantly different between treatments 13 years after harvest suggests that this was not an issue at Fall River. However, the soil at Fall River has a particularly high anion sorption capacity (Strahm and Harrison 2007) as well as a large store of soil nitrogen. Thus, while loss of nitrogen due to competing vegetation control does not appear to be an issue at this site, leaching may be an important consideration at sites with lower anion sorption capacities. Use of vegetation control is not likely to have a negative effect on productivity at Fall River in the long-term.

As with vegetation control, harvest intensity did not have a significant effect on total soil carbon or nitrogen. The only significant difference between treatments occurred in the forest floor, for which initial carbon and nitrogen contents were intentionally different by study design. Despite a difference in total nitrogen content of 200 kg ha^{-1} between bole-only and total tree plus treatments, the high nitrogen content of the Fall River soil means that this absolute difference represents only an insignificant 1.6 percent of the total BO+VC nitrogen content. Harvest intensity did not affect early growth of the regenerating stand; Ares et al. (2007a) noted that, by year five at the Fall River site, stand stem volume was not significantly different in bole-only than total tree plus plots, and the slight loss of nitrogen should be easily recovered through nutrient accumulation in root and foliage biomass as the stand ages. Similarly, soil carbon stores will likely increase over the next rotation as roots continue to develop and turnover. The redistribution of carbon from the forest floor into the mineral soil suggests there may be longer-term storage of much of this carbon. Mineral carbon content increased more in bole-only harvest than total tree plus harvest, which suggests that bole-only harvest may sequester slightly more carbon in the soil over the long-term. However, total carbon content in the total tree plus treatment was the same in 2012 as it was immediately post-harvest, and the soil can be expected to gain carbon as the trees continue to grow. Thus, while soil carbon sequestration may be slightly higher for bole-only harvest than total tree plus harvest, harvest intensity is not likely to have long-term negative effects on productivity at this site.

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Tables

Table 1 — Treatment average soil carbon and nitrogen values. *Significant difference from the BO+VC treatment (α=0.10).

Depth	Treatment	Bulk density (g cm^{-3})	%C	C content (Mg ha^{-1})	%N	N content (kg ha^{-1})	C:N	pH
Forest Floor	BO+VC	0.08	40.6	9.52	1.06	247	39.2	4.2
	BO-VC	0.07	42.4	8.75	*__1.21__	239	36.5	4.3
	TTP+VC	0.80	*__36.0__	*__5.28__	*__0.90__	*__133__	40.4	4.3
0-15cm	BO+VC	0.46	10.3	70.0	0.42	2890	24.7	4.3
	BO-VC	0.40	13.1	69.6	0.48	*__2680__	26.2	4.2
	TTP+VC	0.48	10.1	67.0	0.41	2810	24.3	4.3
15-30cm	BO+VC	0.65	6.20	59.5	0.30	2890	20.8	4.3
	BO-VC	0.62	6.75	58.6	0.31	2760	21.3	4.2
	TTP+VC	0.62	6.44	58.3	0.32	2870	20.3	4.3
30-45cm	BO+VC	0.72	4.47	47.7	0.23	2430	19.7	4.3
	BO-VC	0.73	4.15	44.0	0.21	2270	19.7	4.3
	TTP+VC	0.71	4.19	43.6	0.22	2300	18.8	4.4
45-60cm	BO+VC	0.84	2.97	34.6	0.14	1640	21.8	4.3
	BO-VC	0.82	2.66	31.3	0.14	1690	18.7	4.3
	TTP+VC	0.79	2.63	29.6	0.15	1670	17.8	4.3
60-100cm	BO+VC	0.76	1.60	48.8	0.08	2410	23.0	4.3
	BO-VC	*__0.89__	*__1.17__	42.1	0.07	2540	17.4	4.3
	TTP+VC	*__0.91__	1.31	47.8	0.08	2900	16.1	4.4
Mineral soil to 100cm	BO+VC	--	--	260	--	12300	--	--
	BO-VC	--	--	246	--	12000	--	--
	TTP+VC	--	--	246	--	12600	--	--
TOTAL to 100cm	BO+VC	--	--	270	--	12500	--	--
	BO-VC	--	--	254	--	12200	--	--
	TTP+VC	--	--	252	--	12700	--	--

Table 2 — Treatment average carbon and nitrogen contents of the forest floor and cumulative contents to 20 cm and 100 cm. *Significant difference from the BO+VC treatment (α=0.10).

Depth	Treatment	C content (Mg ha^{-1})	N content (kg ha^{-1})
Forest Floor	BO+VC	9.52	247
	BO-VC	8.75	239
	TTP+VC	***5.28**	***133**
20 cm	BO+VC	99.3	410
	BO-VC	97.9	384
	TTP+VC	91.8	390
100 cm	BO+VC	270	12500
	BO-VC	254	12200
	TTP+VC	252	12700

Table 3 — Carbon and nitrogen contents of the forest floor and mineral soil at the time of study installation and 2012 results from this study.

Post-harvest carbon and nitrogen contents of the forest floor and mineral soil. Post-harvest mineral soil (2001) and forest floor (2000) contents from Ares et al. (2007b).

Treatment	Mineral soil C to 100cm (Mg ha^{-1})	Forest Floor C (Mg ha^{-1})	Total C to 100cm (Mg ha^{-1})	Mineral soil N to 100cm (kg ha^{-1})	Forest Floor N (kg ha^{-1})	Total N to 100cm (kg ha^{-1})
BO+VC	229	45.1	274	14340	490	14820
BO-VC	229	45.1	274	14340	490	14820
TTP+VC	229	23.5	252	14340	310	14650

2012 Carbon and nitrogen contents of the forest floor and mineral soil

Treatment	Mineral soil C to 100cm (Mg ha^{-1})	Forest Floor C (Mg ha^{-1})	Total C to 100cm (Mg ha^{-1})	Mineral soil N to 100cm (kg ha^{-1})	Forest Floor N (kg ha^{-1})	Total N to 100cm (kg ha^{-1})
BO+VC	260	9.5	270	12300	247	12500
BO-VC	246	8.8	254	12000	239	12200
TTP+VC	246	5.3	252	12600	133	12700

Change from initial post-harvest carbon and nitrogen contents to 2012 carbon and nitrogen contents

Treatment	Mineral soil C to 100cm (Mg ha^{-1})	Forest Floor C (Mg ha^{-1})	Total C to 100cm (Mg ha^{-1})	Mineral soil N to 100cm (kg ha^{-1})	Forest Floor N (kg ha^{-1})	Total N to 100cm (kg ha^{-1})
BO+VC	32	-36	-4	-2040	-243	-2320
BO-VC	17	-36	-19	-2340	-251	-2620
TTP+VC	18	-18	0	-1740	-177	-1950

Figures

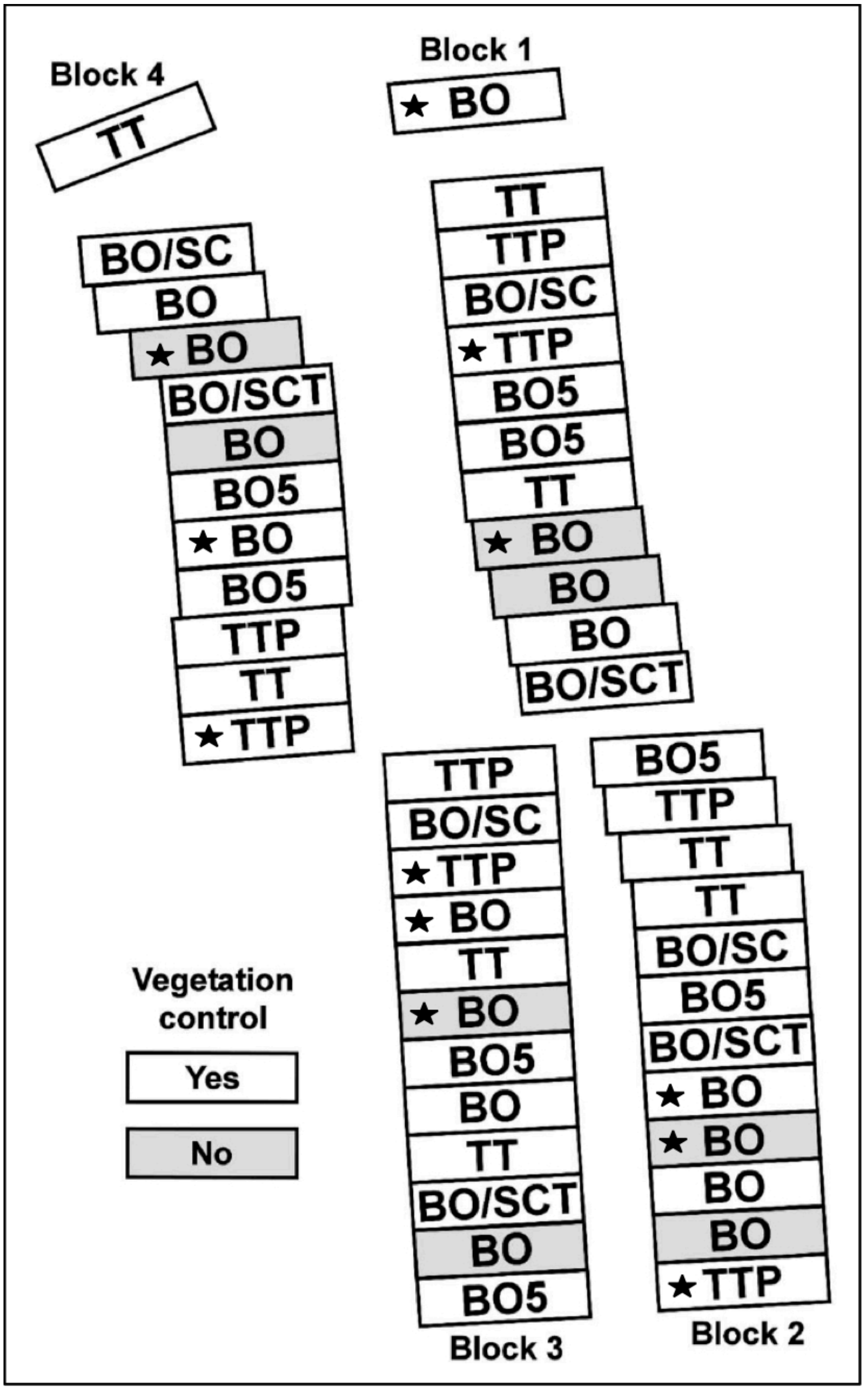

Figure 1. Layout of the Fall River study site. Stars indicate plots sampled in this study. Treatments: bole-only removal “BO”, bole-only removal to 5-cm top “BO5”, total tree removal “TT”, total tree plus removal “TTP”, soil compaction “SC”, soil compaction and tillage “SCT”. Modified from Ares et al. (2007a).

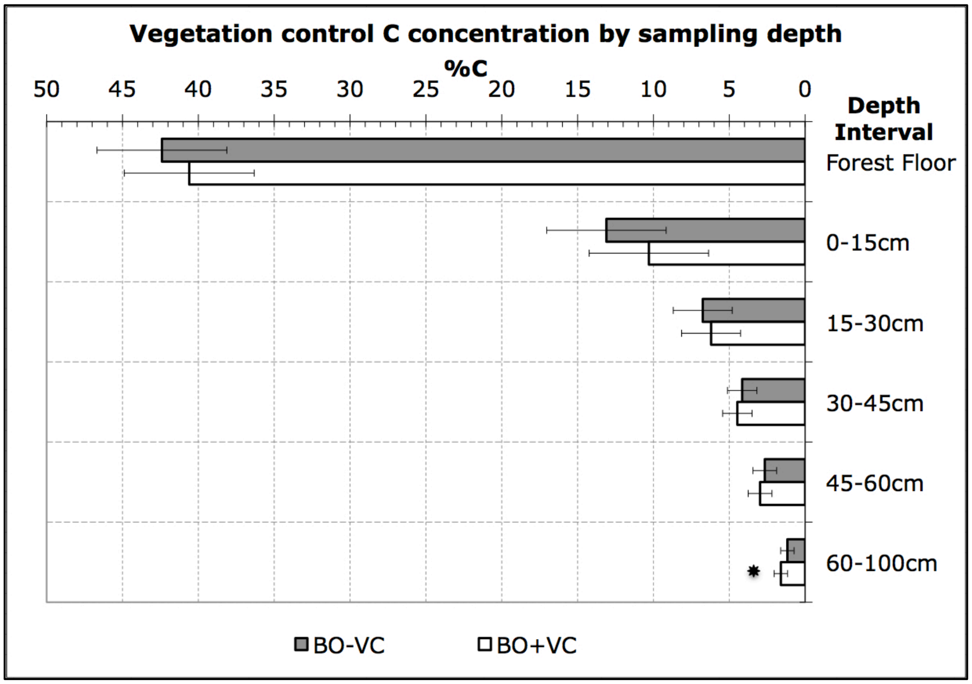

Figure 2. Mean treatment values for carbon concentration by depth interval for the vegetation control comparison. Error bars represent the 90% confidence interval around the mean. *Significant difference (α=0.10) between BO+VC and BO-VC at each depth.

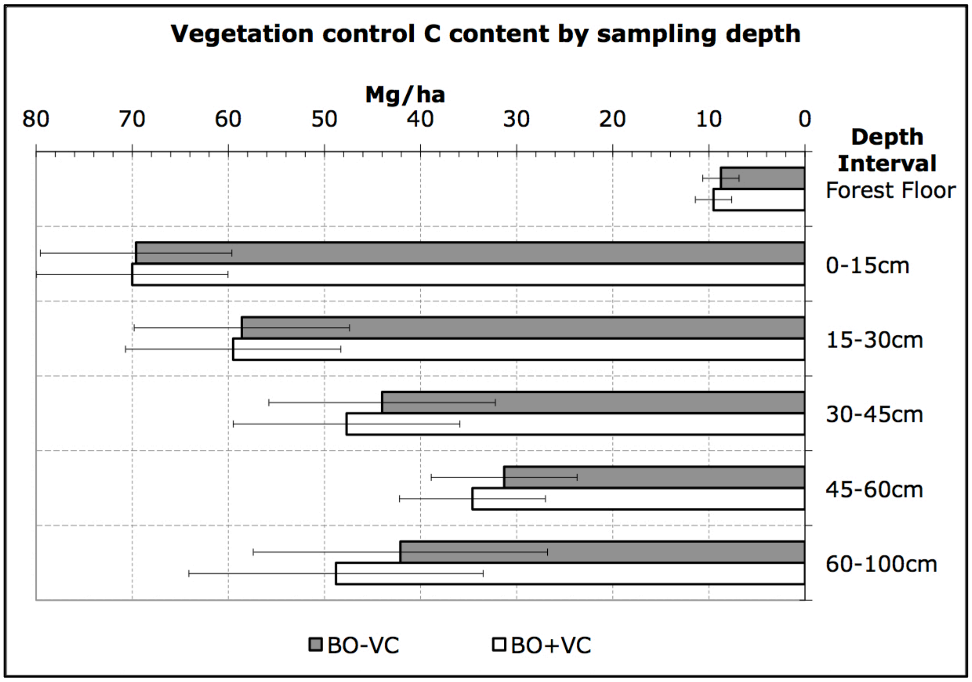

Figure 3. Mean treatment values for carbon content by depth interval for the vegetation control comparison. Error bars represent the 90% confidence interval around the mean. There were no significant differences (α=0.10) between BO+VC and BO-VC.

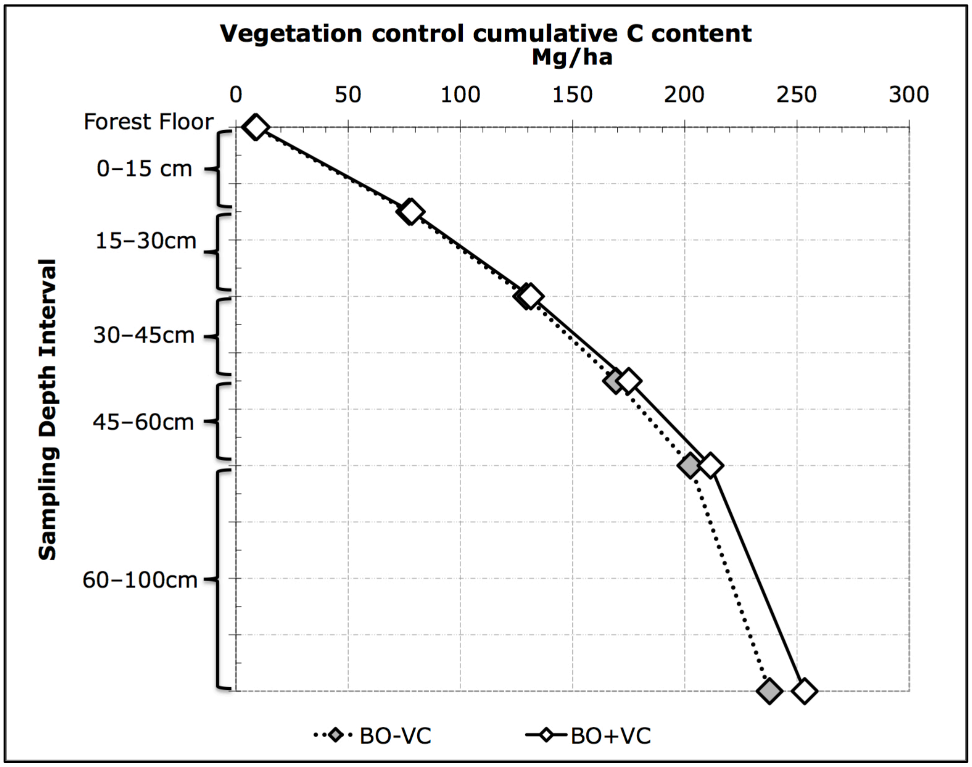

Figure 4. Cumulative carbon content to 100 cm for the vegetation control comparison. Each point represents the sum of contents for all sampling intervals above the indicated depth. Forest floor content is represented by the value at 0 cm depth. There was no significant difference between treatments in total content to 100 cm (α=0.10).

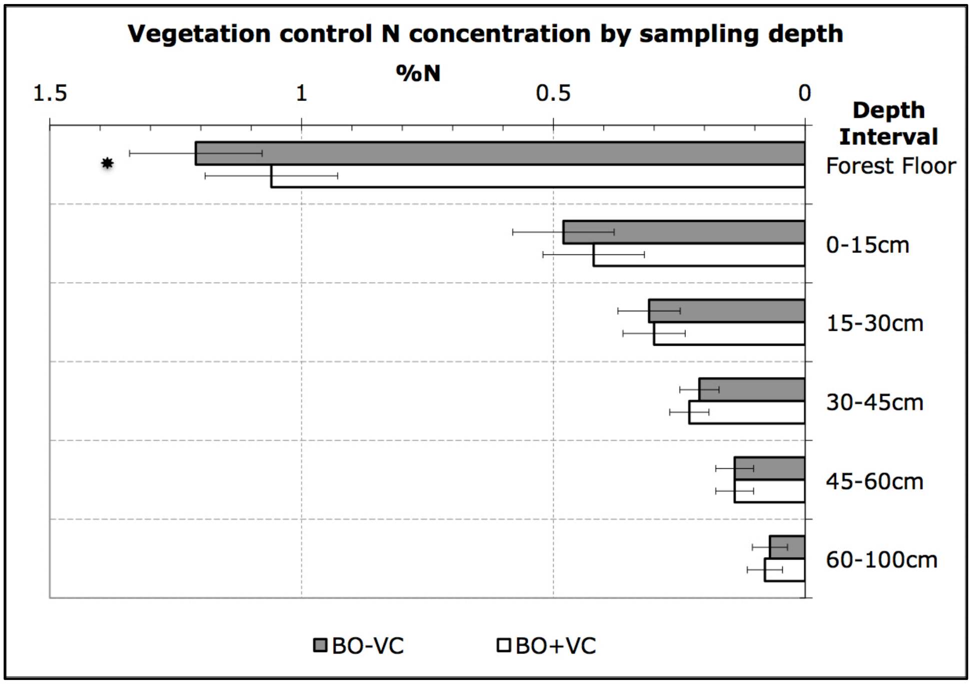

Figure 5. Mean treatment values for nitrogen concentration by depth interval for the vegetation control comparison. Error bars represent the 90% confidence interval around the mean. *Significant difference (α=0.10) between BO+VC and BO-VC at each depth.

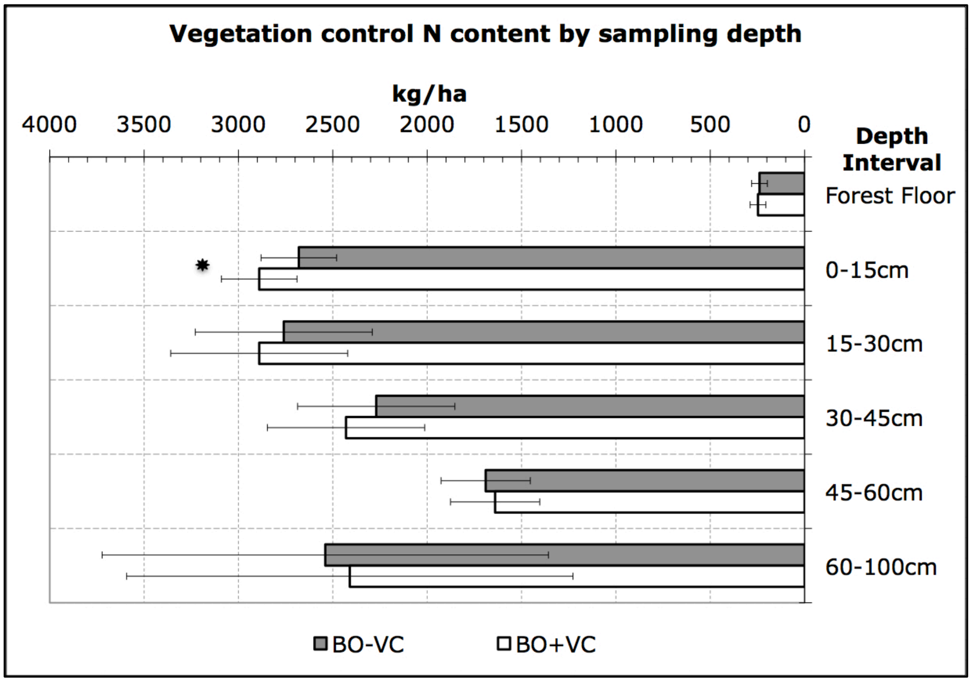

Figure 6. Mean treatment values for nitrogen content by depth interval for the vegetation control comparison. Error bars represent the 90% confidence interval around the mean. *Significant difference (α=0.10) between BO+VC and BO-VC at each depth.

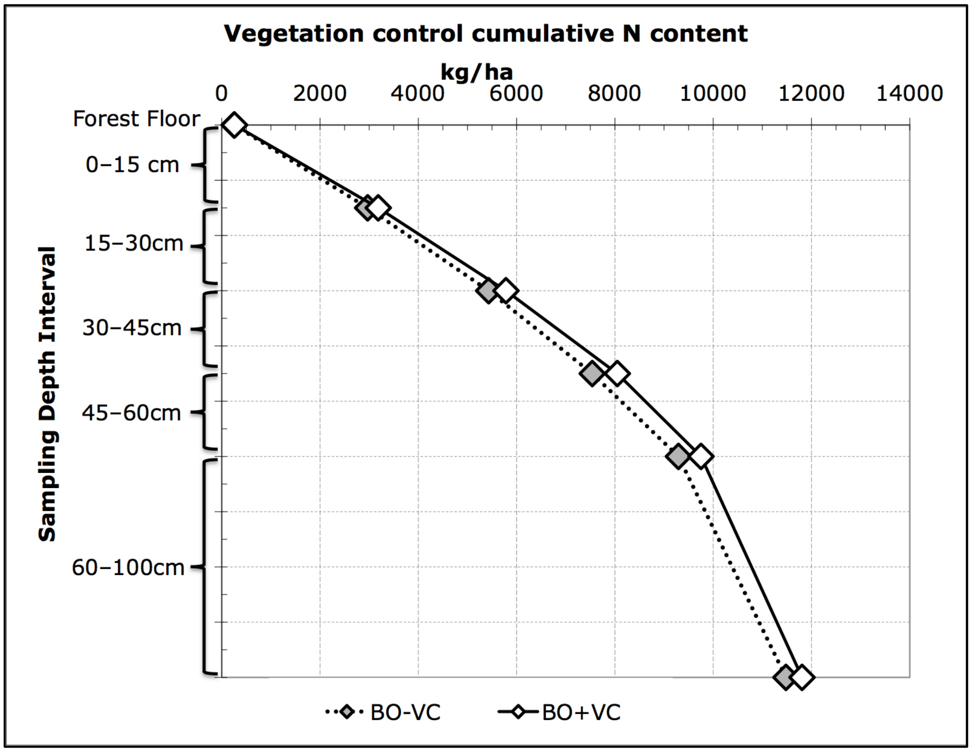

Figure 7. Cumulative nitrogen content to 100 cm for the vegetation control comparison. Each point represents the sum of contents for all sampling intervals above the indicated depth. Forest floor content is represented by the value at 0 cm depth. There was no significant difference between treatments in total content to 100 cm (α=0.10).

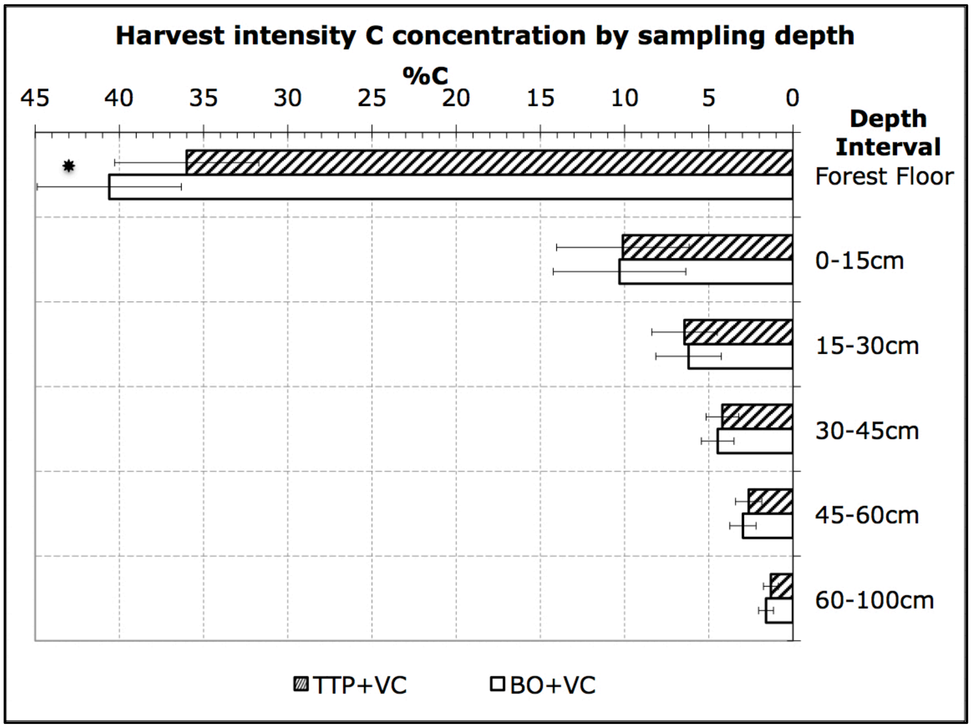

Figure 8. Mean treatment values for carbon concentration by depth interval for bole-only and total tree plus harvest. Error bars represent the 90% confidence interval around the mean. *Significant difference (α=0.10) between BO+VC and TTP+VC at each depth.

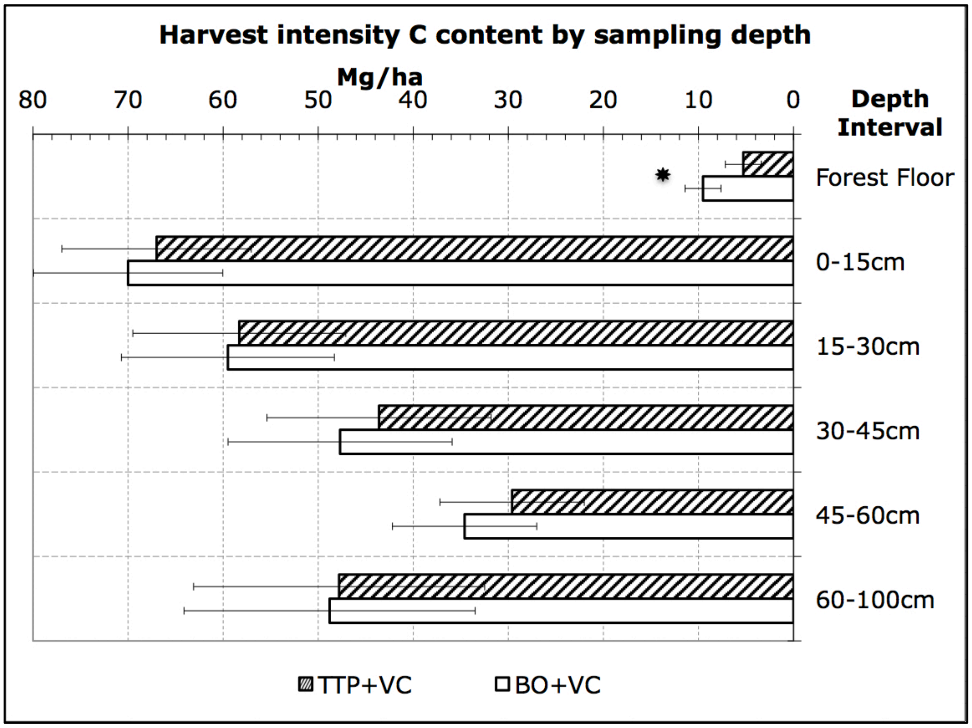

Figure 9. Mean treatment values for carbon content by depth interval for bole-only and total tree plus harvest. Error bars represent the 90% confidence interval around the mean. *Significant difference (α=0.10) between BO+VC and TTP+VC at each depth.

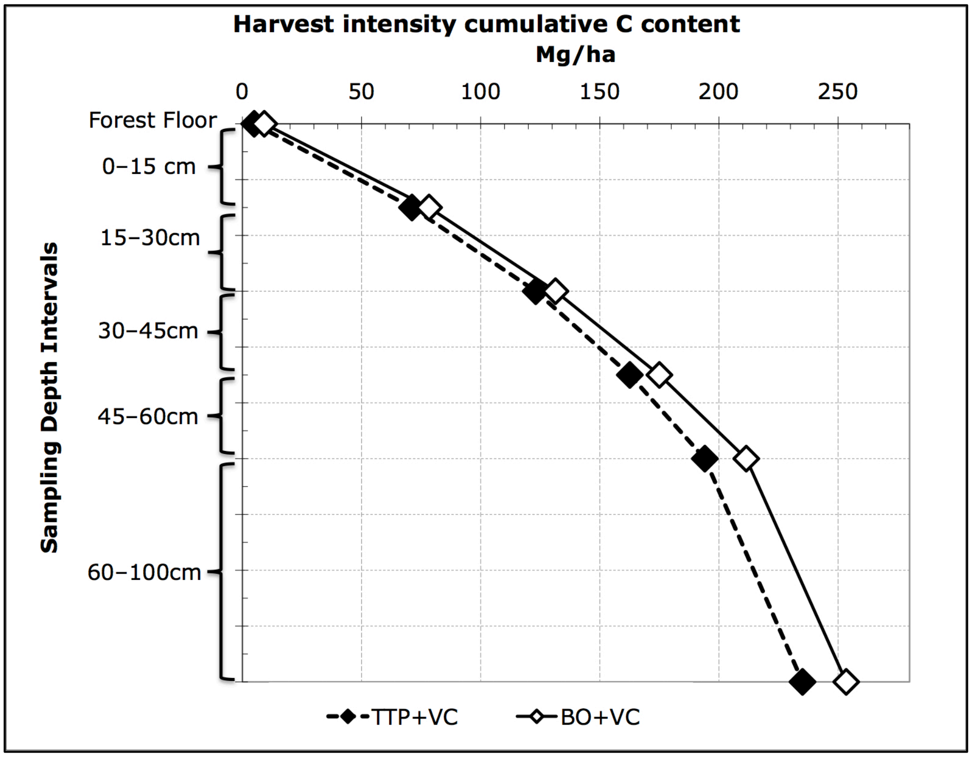

Figure 10. Cumulative carbon content to 100 cm for the harvest intensity comparison. Each point represents the sum of contents for all sampling intervals above the indicated depth. Forest floor content is represented by the value at 0 cm depth. There was no significant difference between treatments in total content to 100 cm (α=0.10).

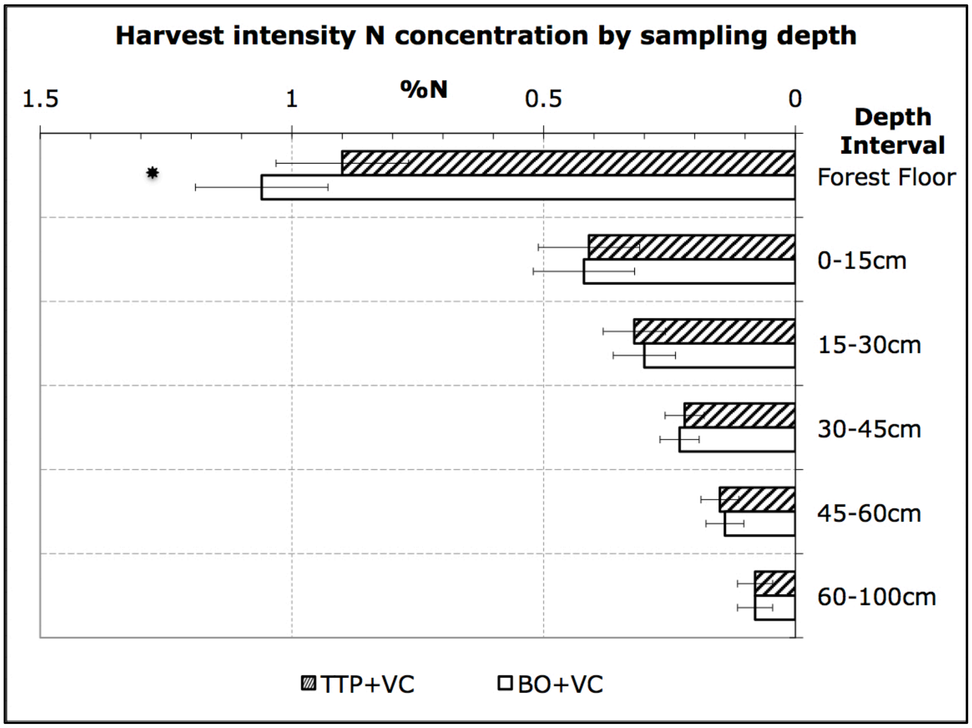

Figure 11. Mean treatment values for nitrogen concentration by depth interval for bole-only and total tree plus harvest. Error bars represent the 90% confidence interval around the mean. *Significant difference (α=0.10) between BO+VC and TTP+VC at each depth.

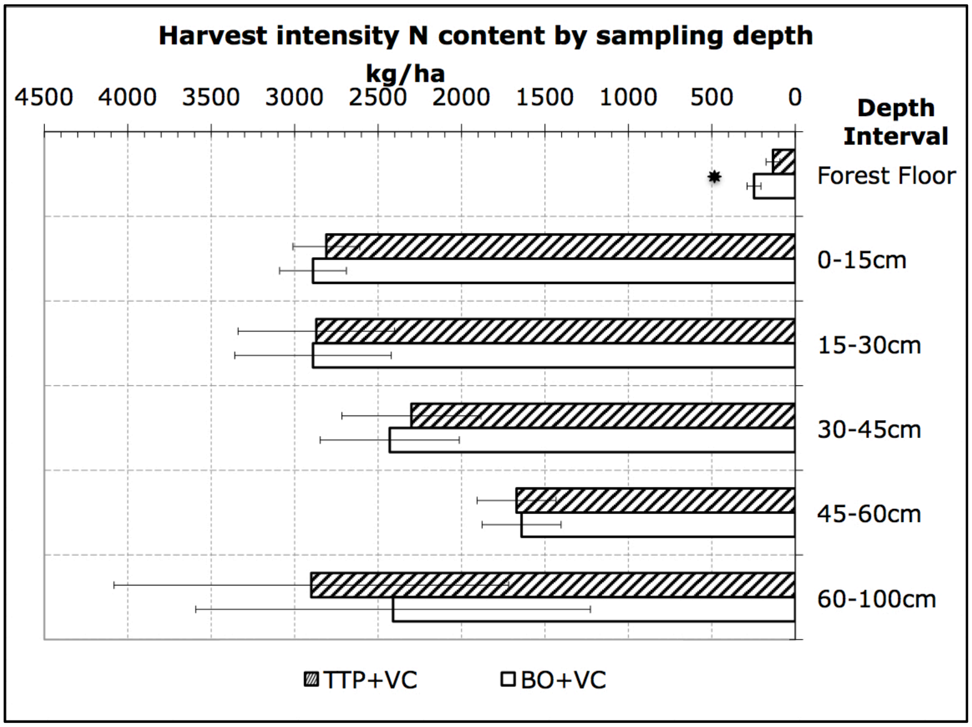

Figure 12. Mean treatment values for nitrogen content by depth interval for bole-only and total tree plus harvest. Error bars represent the 90% confidence interval around the mean. *Significant difference (α=0.10) between BO+VC and TTP+VC at each depth.

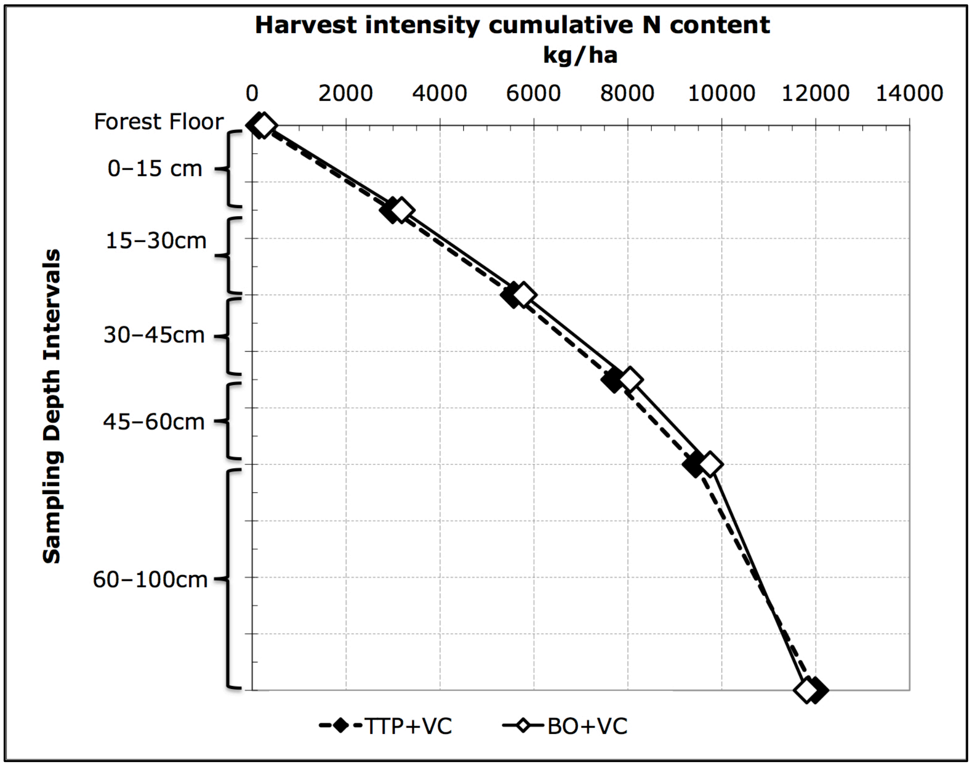

Figure 13. Cumulative nitrogen content to 100 cm for the harvest intensity comparison. Each point represents the sum of contents for all sampling intervals above the indicated depth. Forest floor content is represented by the value at 0 cm depth. There was no significant difference between treatments in total content to 100 cm (α=0.10).