Effects of organic matter removal and soil compaction on fifth-year mineral soil carbon and nitrogen contents for sites across the United States and Canada[1]

Felipe G. Sanchez, Allan E. Tiarks, J. Marty Kranabetter, Deborah S. Page-Dumroese, Robert F. Powers, Paul T. Sanborn, and William K. Chapman

Abstract: This study describes the main treatment effects of organic matter removal and compaction and a split-plot effect of competition control on mineral soil carbon (C) and nitrogen (N) pools. Treatment effects on soil C and N pools are discussed for 19 sites across five locations (British Columbia, Northern Rocky Mountains, Pacific Southwest, and Atlantic and Gulf coasts) that are part of the Long-Term Soil Productivity (LTSP) network and were established over 5 years ago. The sites cover a broad range of soil types, climatic conditions, and tree species. Most sites showed increased soil C and N levels 5 years after study establishment; however, the rate and magnitude of the changes varied between sites. Organic matter removal, compaction, or competition control did not significantly affect soil C and N contents at any site, except for the Northern Rocky Mountain site, where competition control significantly affected soil C and N contents. The observation that, after 5 years, the soil C and N contents were not negatively affected by even the extreme treatments demonstrates the high resiliency of the soil, at least in the short term, to forest management perturbations.

Résumé : Cette étude décrit les effets de l'enlèvement de la matière organique et de la compaction du sol en parcelles principales ainsi que les effets du contrôle de la compétition en sous-parcelles sur les pools de carbone et d'azote dans le sol minéral. Les effets des traitements sur les pools de carbone et d'azote sont discutés pour 19 stations réparties dans cinq endroits (la Colombie-Britannique, les Rocheuses septentrionales, le Pacific Southwest, la côte de l'Atlantique et la côte du golfe du Mexique) qui font partie du réseau de productivité des sols à long terme et qui ont été établies il y a plus de 5 ans. Les stations couvraient une large gamme de types de sol, de conditions climatiques et d'espèces d'arbre. Les niveaux de carbone et d'azote dans le sol avaient augmenté dans la plupart des stations 5 ans après l'établissement de l'étude. Cependant, le taux et l'ampleur des changements variaient d'une station à l'autre. L'enlèvement de la matière organique, la compaction du sol ou le contrôle de la compétition n'ont pas significativement affecté le contenu en carbone et en azote du sol dans aucune des stations à l'exception de la station des Rocheuses septentrionales où le contrôle de la compétition a significativement affecté le contenu en carbone et en azote du sol. Le fait que le contenu en carbone et en azote du sol n'ait pas été affecté après 5 ans, même par les traitements extrêmes, démontre que le sol est hautement résilient, au moins à court terme, face aux perturbations causées par l'aménagement forestier.

[Traduit par la Rédaction]

Received 14 March 2005. Accepted 22 October 2005. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 9 March 2006.

F.G. Sanchez.[2] USDA Forest Service, Southern Research Station, P.O. Box 12254, Research Triangle Park, NC 27709, USA.
A.E. Tiarks.[3] USDA Forest Service, Southern Research Station, Alexandria Forestry Center, 2500 Shreveport Highway, Pineville, LA 71360, USA.
J.M. Kranabetter. British Columbia Ministry of Forests, Bag 6000, Smithers, BC V0J 2N0, Canada.
D.S. Page-Dumroese. USDA Forest Service, Rocky Mountain Research Station, Moscow Forestry Sciences Laboratory, 1221 South Main Street, Moscow, ID 83843, USA.
R.F. Powers. USDA Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96001, USA.
P.T. Sanborn. University of Northern British Columbia, 3333 University Way, Prince George, BC V2N 4Z9, Canada.
W.K. Chapman. British Columbia Ministry of Forests, Southern Interior Forest Region, Williams Lake, BC V2G 4T1, Canada.

[1] This article is one of a selection of papers published in the Special Issue on Long-Term Soil Productivity.
[2] Corresponding author (e-mail: fsanchez@fs.fed.us).
[3] Retired.

doi:10.1139/X05-259

Introduction

Careful management of soils is essential to achieving optimal sustainable productivity of forested ecosystems. Although we know a large proportion of the forest carbon (C) cycles occur below ground, far less is known about belowground C response to forest management practices. Thus, we cannot predict impacts of different management practices on C dynamics, nor do we understand the linkages between above- and below-ground productivity. Soil compaction, residual surface detritus, fertilization, and competition control all impact soil C mineralization and stand productivity by altering soil nutrient, moisture, and temperature levels (Henderson 1995). In addition to logging impacts on C inputs and distribution within a site, overstory removal and subsequent understory vegetation control may alter the soil moisture, temperature, and aeration regimes, thus affecting decomposition (Edwards and Ross-Todd 1983; Henderson 1995). These effects on the soil environment (i.e., moisture, temperature, aeration, etc.) are most evident in soils that are low in initial C and nutrient levels and are dependent on continuous organic matter (OM) decomposition for part of their nutrient supply (Ellert and Gregorich 1995).

In 1990, the Long-Term Soil Productivity (LTSP) study was initiated to examine the effects of soil porosity and OM levels on net primary productivity (NPP) (Powers et al. 1990). The study design calls for three levels of OM removal (bole, whole tree, and whole tree plus forest floor) and three levels of compaction (none, moderate, and severe) being imposed on harvested sites prior to planting. Additionally, the effect of understory control on NPP was examined as a split-plot treatment. The study has been installed on 62 sites covering a range of climates, soil types, and tree species across the United States and Canada. The inclusion of 46 closely related affiliated sites has created the world's largest coordinated research network devoted to investigating the relationship between land management and sustainable forest productivity.

A critical component of the LTSP study is the treatment effects on soil organic matter (SOM). International efforts to develop criteria and indicators for sustainable forest management have recognized the importance of SOM. In the Santiago Declaration, the fourth criterion calls for "conservation and maintenance of soil and water resources", with SOM being one of the indicators (Ramakrishna and Davidson 1998). SOM is important because it affects water retention, soil structure, and nutrient cycling (Powers et al. 1990; Paul 1991). Additionally, SOM is the major source of plant available nitrogen (N) and as much as 65% of total soil phosphorus (Bauer and Black 1994). Forest productivity may be sensitive to soil perturbations that alter SOM decomposition rates, particularly those associated with the highly labile fractions (Ruark and Blake 1991; Wander et al. 1994).

The objectives of this manuscript are to (1) determine whether, after 5 years, the OM removal, soil compaction, or competition control treatments have significantly affected soil C and N pools, and if so, (2) determine whether these effects are site specific across a wide array of managed forest systems. The results of this study will provide information on the resiliency of SOM to harvesting practices and intensive stand management. This information will be essential in our efforts to maintain forest soils and not negatively impact forest productivity and sustainability.

Materials and methods

Study design

Data from 19 sites across five locations belonging to the LTSP network (Powers et al. 1990) were used in this analysis. The sites described in this paper are in the Sub-Boreal Spruce zone of British Columbia (three sites), the Northern Rocky Mountains in Idaho (one site), the Pacific Southwest in California (eight sites), the lower Atlantic Coastal Plains in North Carolina (three sites), and the Gulf Coastal Plains in Louisiana (four sites). After treatment installation, each site was regenerated with the tree species indicative of surrounding native forest types (see next section on site descriptions).

The core LTSP study design is a series of nine treatments that stress two key factors related to site productivity commonly altered during harvest: OM removal and soil compaction. Nine 0.42 ha plots within each site were randomly assigned to a 3 × 3 factorial design with three levels of OM removal: stem only (OM_0), whole tree (OM_1), and whole tree plus forest floor (OM_2) and three levels of compaction: none (C_0), intermediate (C_1), and severe (C_2). Each treatment plot was split in half, with one split plot receiving complete weed control (U_-), while vegetation on the other split plot was allowed to grow freely with the planted trees (U_+). Weed control treatments were applied annually until crown closure. Competing vegetation was eliminated with repeated chemical application in combination with mechanical removal.

Site descriptions

Brief descriptions of the study sites are presented next. Additional description of the sites is presented elsewhere (see Powers (this issue) and Fleming et al. (this issue)). The LTSP installations in central British Columbia are located in the Sub-Boreal Spruce zone, which is characterized by severe, snowy winters and relatively warm, moist, and short summers. Mean annual temperatures range from 1.7 to 5 °C, with temperatures below 0 °C for 4–5 months per year and at approximately 10 °C for 2–5 months. Mean annual precipitation ranged from 415 to 1650 mm, with 25%–50% falling as snow. Climax tree species are hybrid white spruce (*Picea engelmannii* Parry ex Engelm. × *Picea glauca* (Moench) Voss) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.). Lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), trembling aspen (*Populus tremuloides* Michx.), and paper birch (*Betula papyrifera* Marsh.) are seral species common in maturing climax forests. The soils are typically Luvisols, Podzols, or Brunisols (Canadian Soil Survey Committee 1987) developed on extensive deposits of coarse to fine loamy textured glacial till. A site was installed in each of three subzones to cover the range in climatic conditions within sub-boreal spruce forests: moist, cold (SBSmc); wet, cool (SBSwk); and dry, warm (SBSdw). Each site has deep, medium-textured soils, derived from morainal blankets, with average soil moisture and nutrients for the subzone (Banner et al. 1993).

The Idaho site is on a bench adjoining the Priest River at the Priest River Experimental Forest, Idaho. The area receives 840 mm of precipitation annually (80% as snow), and the mean annual temperature is 6.6 °C. The major timber and understory species before harvest were western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and queens cup bead lily (*Clintonia uniflora* (Menzies ex Schultes) Kunth). The soil has a silt loam surface (28–38 cm thick) derived from Mount Mazama volcanic ash. The subsoil is a silty clay loam (50–75 cm thick) derived from glacial lacustrine sediments; these are underlain at depths of 60–100 cm by gravelly to very gravelly sands and sandy loams deposited by alluvial processes. The soil is a Mission series (medial, frigid, Ochreptic Fragixeralf).

At the California sites, daily temperatures range from 0–8 °C in January to 15–28 °C in July. These sites have an annual precipitation of 1600 mm, with 20% falling as snow and 85% occurring between October and March. The growing season is warm and dry. The soil is in the Cohasset series (fine-loamy, mixed, superactive, mesic, Ultic Haploxeralfs) derived from a Pleistocene volcanic mudflow. The planted tree species are white fir (*Abies concolor* (Gord. & Glend.) Lindl.), ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.), sugar pine (*Pinus lambertiana* Dougl.), and giant sequoia (*Sequoiadendron giganteum* (Lindl.) Buchh.).

The Louisiana sites are characterized by an annual rainfall of 1050 mm and an average daily temperature of 19 °C. The soils are in the Malbis (fine-loamy, siliceous, subactive, thermic Plinthic Paleudults), Glenmora (fine-silty, siliceous, thermic Glossaquic Paleudalfs), Metcalf (fine-silty, siliceous, semiactive, thermic Aquic Glossudalfs), and Mayhew (fine-smectitic, thermic Chromic Dystraquerts) series. The sites were previously occupied by loblolly pine (*Pinus taeda* L.), slash pine (*Pinus elliottii* Engelm.), and longleaf pine (*Pinus palustris* Mill.) and were replanted with loblolly pine.

The North Carolina sites are in the Croatan National Forest and receive an average of 1360 mm of rainfall annually. The average air temperature is 16 °C. The soils are predominantly Goldsboro (fine-loamy, siliceous, subactive, thermic, Aquic Paleudults) and Lynchburg (fine-loamy, siliceous, semiactive, thermic, Aeric Paleaquults). The previous stand was primarily loblolly pine and was replanted with the same species.

Methods

In British Columbia, soil samples were taken with a stony soil auger from the entire 0–20 cm depth in the mineral soil (forest floor removed). At the SBSwk site, the samples were located on each plot by a stratified technique, where five transects were located across the plot, from which five random subsamples were bulked together. At the SBSdw site, samples were collected from 18 systematic points and then bulked into three subsamples. At the SBSmc site, 25 points were systematically located in each plot and then randomly bulked into five samples. Plot means were used in the statistical analysis of soil properties to allow for the differences in subsampling regimes among sites. The soil samples were air dried, ground, and sieved through a 100-mesh screen sieve before chemical analysis. The material passing through the sieve was analyzed for total C and N using combustion elemental analysis.

Soil samples at the Idaho site were collected with a large-core sampler (10 cm diameter, 30 cm deep) at each of 16 subplots in each treatment plot. Each soil component (forest floor, humus, mineral at depths of 0–10, 10–20, and 20–30 cm) was field separated into individual bags. Each horizon and depth was composited separately, resulting in four samples per plot each for forest floor, humus, and each of the mineral soil-sampling depths. Samples were sieved to pass a 2 mm sieve and then ground to uniform size before being analyzed for C and N on a LECO CHN analyzer (LECO Corp., St. Joseph, Michigan).

Ten random soil samples per plot were collected with a bucket auger in the California sites. The samples were collected in depth increments of 0–10, 10–20, and 20–40 cm and composited by plot and depth increment. In the fifth year, only the herbicide-treated extreme treatments ($OM_0C_0U_-$, $OM_0C_2U_-$, $OM_2C_0U_-$, and $OM_2C_2U_-$) were collected at the California sites. Subsamples were oven-dried for 24 h at 105 °C. The C concentration was determined by Walkley–Black analysis, and total N was determined by Kjeldahl analysis.

In the North Carolina and Louisiana sites, soil samples were collected with a hammer-driven 6.3 cm × 30 cm soil sampler, and each soil core was divided into three equal sections corresponding to the 0–10, 10–20, and 20–30 cm depths. In North Carolina, samples were collected from three sample points on each plot, while in the Louisiana sites, 10 samples were collected per plot. All soil samples were dried, passed through a 2 mm sieve, weighed, and then analyzed for total C and N by dry combustion with detection by infrared (NA 1500 Carlo-Erba CNS analyzer (Carlo-Erba, Milan, Italy) in North Carolina, and LECO 2000 CNS analyzer in Louisiana). For the Louisiana sites, only the 0–10 cm layer samples were available for the preharvest C and N analysis.

Soil bulk density measurements were done according to published methods (Lichter and Costello 1994; Page-Dumroese et al. 1999), but differed at each location because of differences in rock-fragment amounts and size. Bulk density samples were collected from the 0–10, 10–20, and 20–30 cm depths of the mineral soil except for the British Columbia sites, for which samples were collected from the 0–20 cm depth, and the California sites, for which samples were collected from the 20–40 cm depth. The number of samples per plot collected varied by location: British Columbia (9 samples), Idaho (16 samples), California (5 samples), North Carolina (4 samples), and Louisiana (10 samples). The decision as to the number of samples to be collected was determined by the individual researchers at each location and was based on the availability of personnel and funds. Rock-fragment content was measured by either field estimates or gravimetric laboratory mass. Total bulk density was corrected for rock-fragment content as necessary (Page-Dumroese et al. 1999).

Statistical analysis

Analysis of variance (ANOVA) using the GLM procedure for split-plot design (SAS version 8.0, Cary, North Carolina) was used to test for treatment effects on soil C and N contents. Differences between treatments were determined significant at $\alpha \leq 0.05$ using Tukey's paired comparison procedure. Additionally, a paired comparison *t* test (dependent *t* test) was used to compare the pre- and post-treatment means of the studied variables within each treatment. Each location was analyzed as a separate study. Significant interactions at each location were rare and inconsistent. Additionally, these interactions usually involved a treatment that was highly significant as a "stand-alone" effect, so the interactions will not be presented.

Results and discussion

Mineral C and N pools

Within a given year, there were no significant treatment effects (or interactions) for soil C and N contents for any of the sites (see Table A1), but the soil C and N contents did differ between measurement years. Generally, soil C did not change from the preharvest values after 5 years, except for significant increases at the California and North Carolina sites (Table 1). Similarly, soil N did not change from preharvest measures, except for an increase in the North Carolina sites and a decrease in the Louisiana sites. The increase in C and N contents in the North Carolina sites was dramatic, with rapid increases in soil C (Figs. 1A–1C) and N (Figs. 2A–2C) occurring after the first year and with small additional increases by the fifth year. Only the OM/U_ treatments are presented, but these increases were observed for all treatments and depth increments measured. The trends in soil C contents were similar to those observed following a harvest on a South Carolina Piedmont site (Van Lear et al. 1995). In their study, Van Lear et al. (1995) showed that mineral soil C rapidly increased from preharvest levels for the first 2 years after the harvest. They attributed this observation to C inputs from decomposing roots from the previous stand and incorporation of the forest floor into the soil matrix by soil fauna. A drop in soil C occurred in the third year, as labile C in finely divided OM was mineralized and leached. Soil C then reaccumulated through inputs from root decomposition (both from previous and current stand) and the forest floor. As was observed at the North Carolina LTSP site, fifth-year soil C levels were slightly higher than those observed after the first year at the South Carolina Piedmont site (Van Lear et al. 1995).

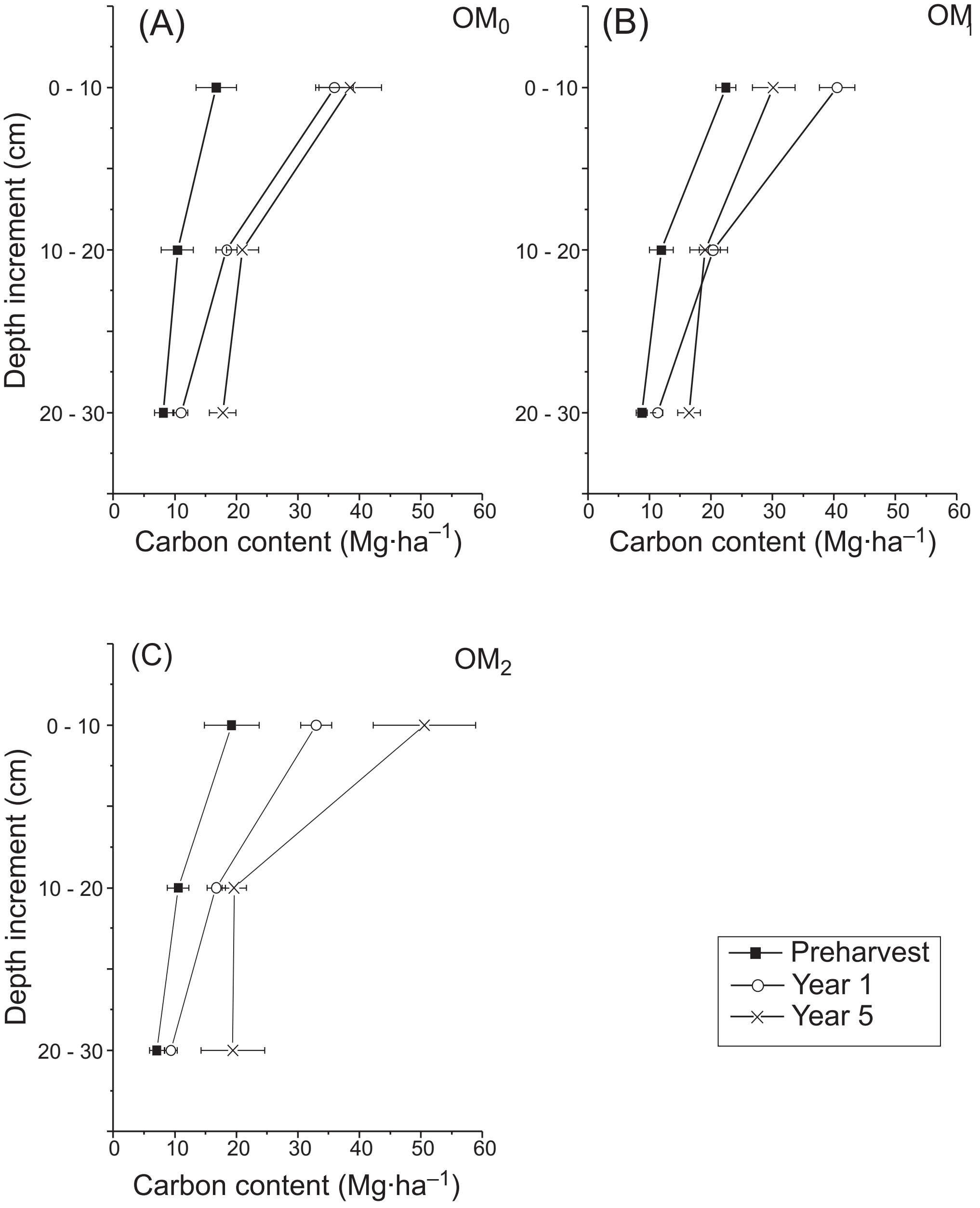
What is particularly remarkable at the North Carolina site is the rate and magnitude of the increases in soil C and N. Tiarks et al. (1999) demonstrated that decomposition processes were very rapid at the North Carolina sites. Some of the increases could be explained by harvest-induced (independent of treatment) increases in soil bulk density (Gordon et al. 1987; Chen et al. 2000). The additional C probably originates from root exudates from the new stand and decomposition of buried organic material, primarily dead roots from the previous stand. Although the relative contribution of the different C sources (i.e., forest floor, roots, etc.) to soil C pools is undetermined, the forest floor seems to be a minor contributor at the North Carolina site, since the largest increases in C were exhibited on plots where all surface OM was removed (Fig. 1C). It is possible that increased soil temperatures on these scalped plots encouraged decomposition of belowground OM, the major C source at this site. Addi-

Table 1. Mean carbon (C) and nitrogen (N) contents and mean C/N ratios for all locations for years 0 and 5.

	C ($Mg \cdot ha^{-1}$)			N ($kg \cdot ha^{-1}$)			C/N ratio		
Location	Year 0	Year 5	*P* >*F*	Year 0	Year 5	*P* >*F*	Year 0	Year 5	*P* >*F*
Idaho	19.67 (2.31)	19.33 (0.68)	0.89	1222 (225)	1498 (107)	0.27	28.41 (1.96)	15.89 (1.41)	<0.0001
Louisiana	16.94 (0.42)	16.51 (0.27)	0.40	796 (13)	677 (15)	0.00014	21.35 (0.76)	24.47 (0.80)	0.02
North Carolina	12.40 (0.84)	28.20 (1.68)	<0.0001	294 (15)	659 (36)	<0.0001	46.26 (3.57)	48.30 (3.96)	0.70
British Columbia	29.38 (0.96)	32.54 (1.96)	0.18	1630 (52)	1800 (109)	0.24	17.81 (0.16)	18.08 (0.22)	0.34
California	87.94 (5.02)	106.36 (5.08)	0.02	4578 (391)	5176 (218)	0.20	19.68 (0.58)	20.58 (0.54)	0.27

Note: Data encompass all site, treatment, and depth combinations. Standard errors are shown in parentheses.

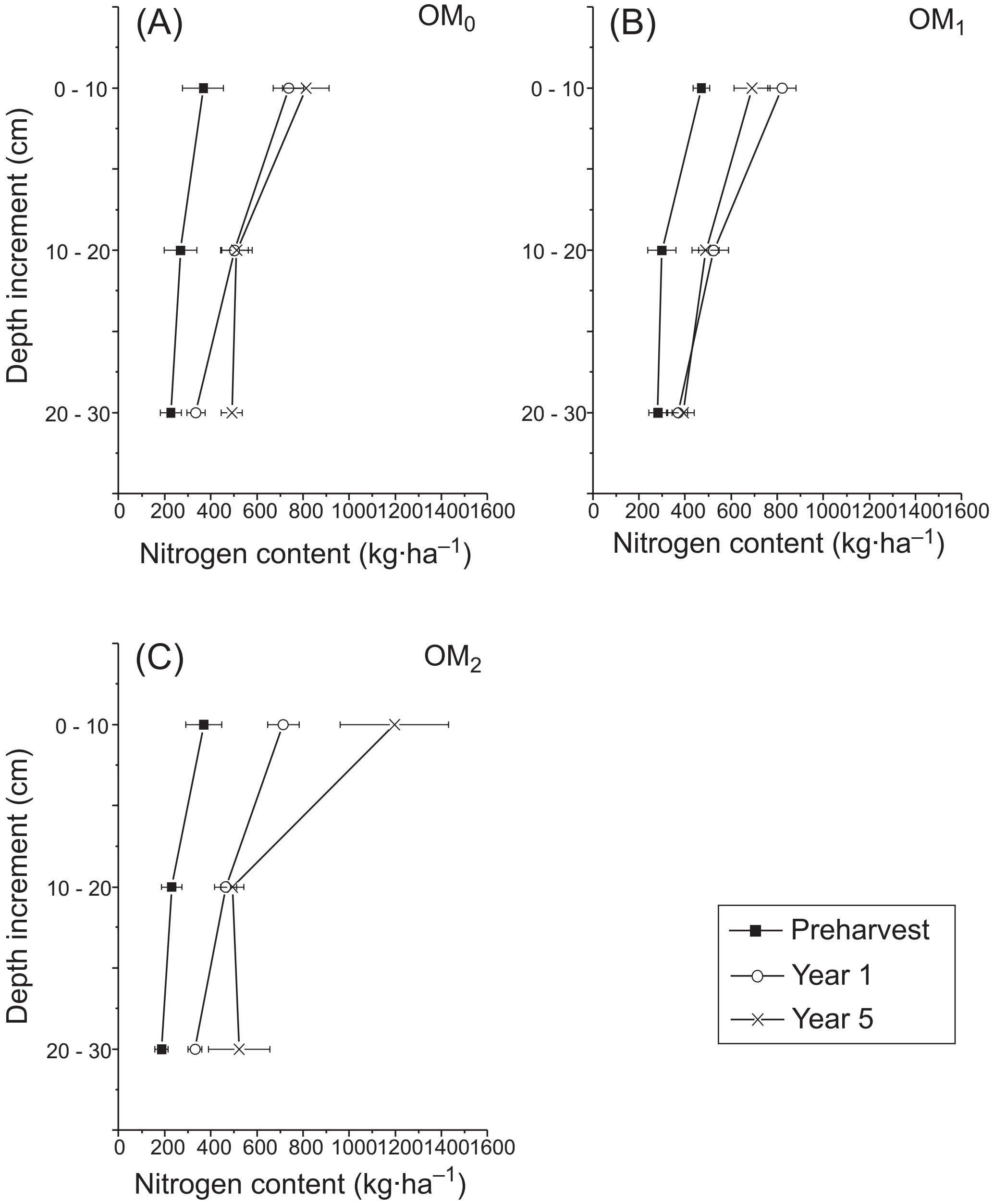
Fig. 1. Carbon distribution for the herbicide – organic matter removal treatments at the North Carolina sites.



tionally, the wet–dry cycle typical of the North Carolina site may promote the rapid growth and turnover of a sizable mass of fine roots that may contribute a large amount of C to the soil (Eissenstat and Caldwell 1988; Megonigal and Day 1992).

At the Idaho sites, there was a decrease in soil C in the upper 10 cm of the mineral soil, 1 and 5 years after harvest (Figs. 3A–3C). Only the herbicide–compaction (C/U_-) treatments are presented in Figs. 3A–3C for visualization of the trends; however, all the other treatment combinations (i.e., OM/U_+, OM/U_-, C/U_+) have similar trends (data not shown). There was also a concurrent increase in soil C in the 10–20 and 20–30 cm depths, indicating that there was a downward movement of dissolved organic C. Following a disturbance, such as harvesting, a significant amount of OM can be solubilized from the forest floor and the surface mineral horizon (Kalbitz et al. 2000). Dissolved organic matter (DOM) can then be adsorbed onto the mineral surface and accumulate at lower depths, where there are more available active adsorption sites (Kalbitz et al. 2000). This is especially true in fine-textured soils or soils rich in iron or aluminum oxides and hydroxides (Moore et al. 1992), such as those at the Idaho site. Soil N followed a similar trend to that of soil C, except that it was more mobile, penetrating to the 20–30 cm depth after the first year (Figs. 4A–4C). After 5 years, soil N dropped in the 20–30 cm depth, whereas it remained essentially constant (i.e., no statistical difference) in the 0–10 and 10–20 cm depths, suggesting that it was penetrating even deeper into the profile and not being lost through plant uptake. This is consistent with the observations of Kaiser and Zech (1998), who demonstrated that hydrophilic DOM, which contains the majority of the dissolved N, was less

Fig. 2. Nitrogen distribution for the herbicide – organic matter removal treatments at the North Carolina sites.



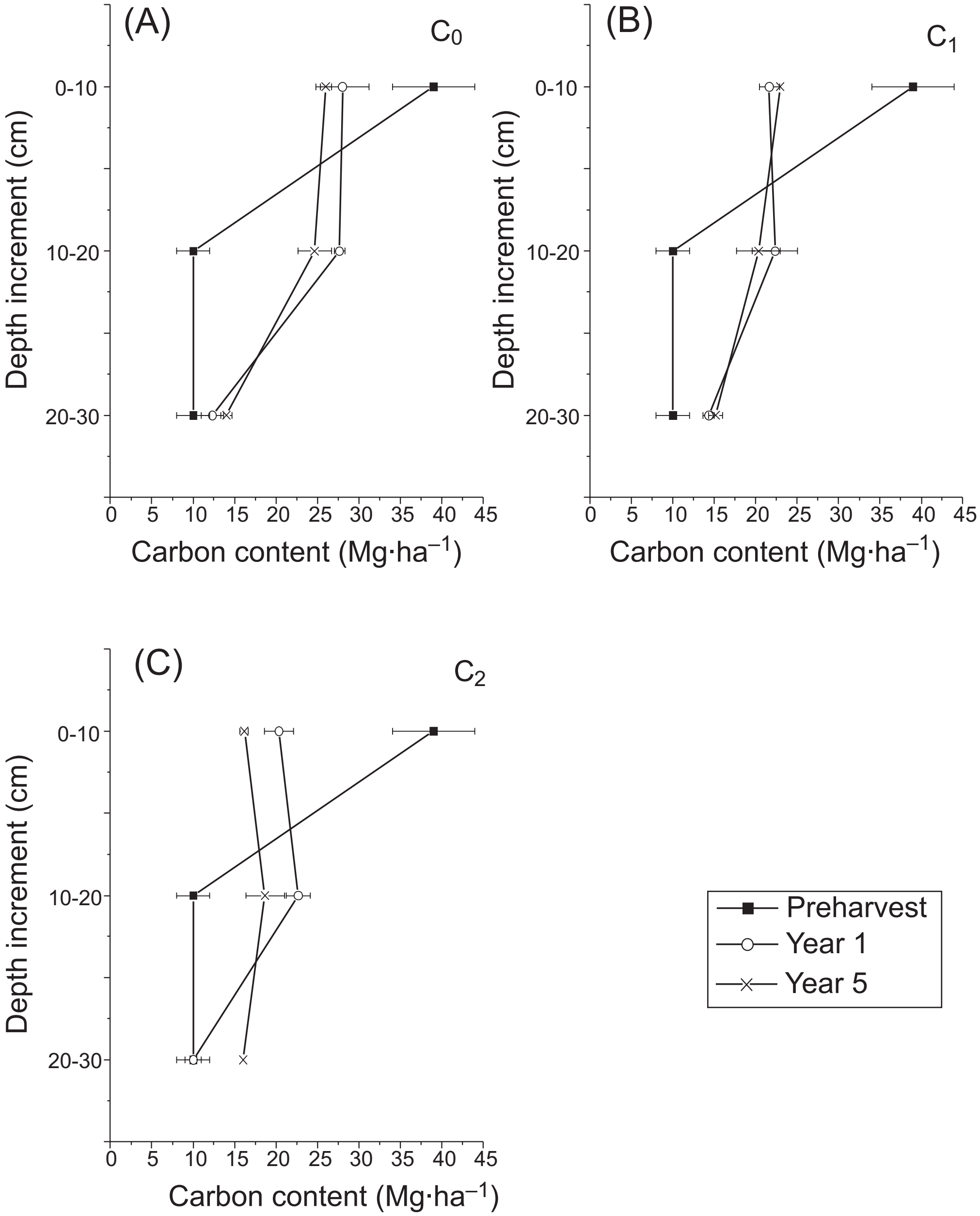
strongly adsorbed and thus penetrated deeper than hydrophobic DOM, which is mostly dissolved C.

Generally, for all treatments and depths, the U_+ plots had significantly higher C and N than the U_- plots by the fifth year (see Table A1). This difference is probably due to additional inputs from roots (i.e., decomposition products, exudates, etc.) from understory vegetation that is present on the U_+ plots but absent in the U_- plots. This effect was not captured at the other sites, partly because of differences in sampling intensity (see Methods). However, the properties of the Idaho soils (i.e., fine texture coupled with high aluminum oxide and hydroxide concentrations) favor adsorption and retention of these organic inputs, whereas in other sites the additional OM may not be appreciably stabilized by adsorption and thus is susceptible to decomposition or leaching. Although the soils at the California sites are also fine textured and of volcanic origin, they have higher initial levels of C and N than the Idaho sites (Table 1) and potentially fewer free adsorption sites in the soil matrix.

Effect of soil texture and drainage on soil C and N pools

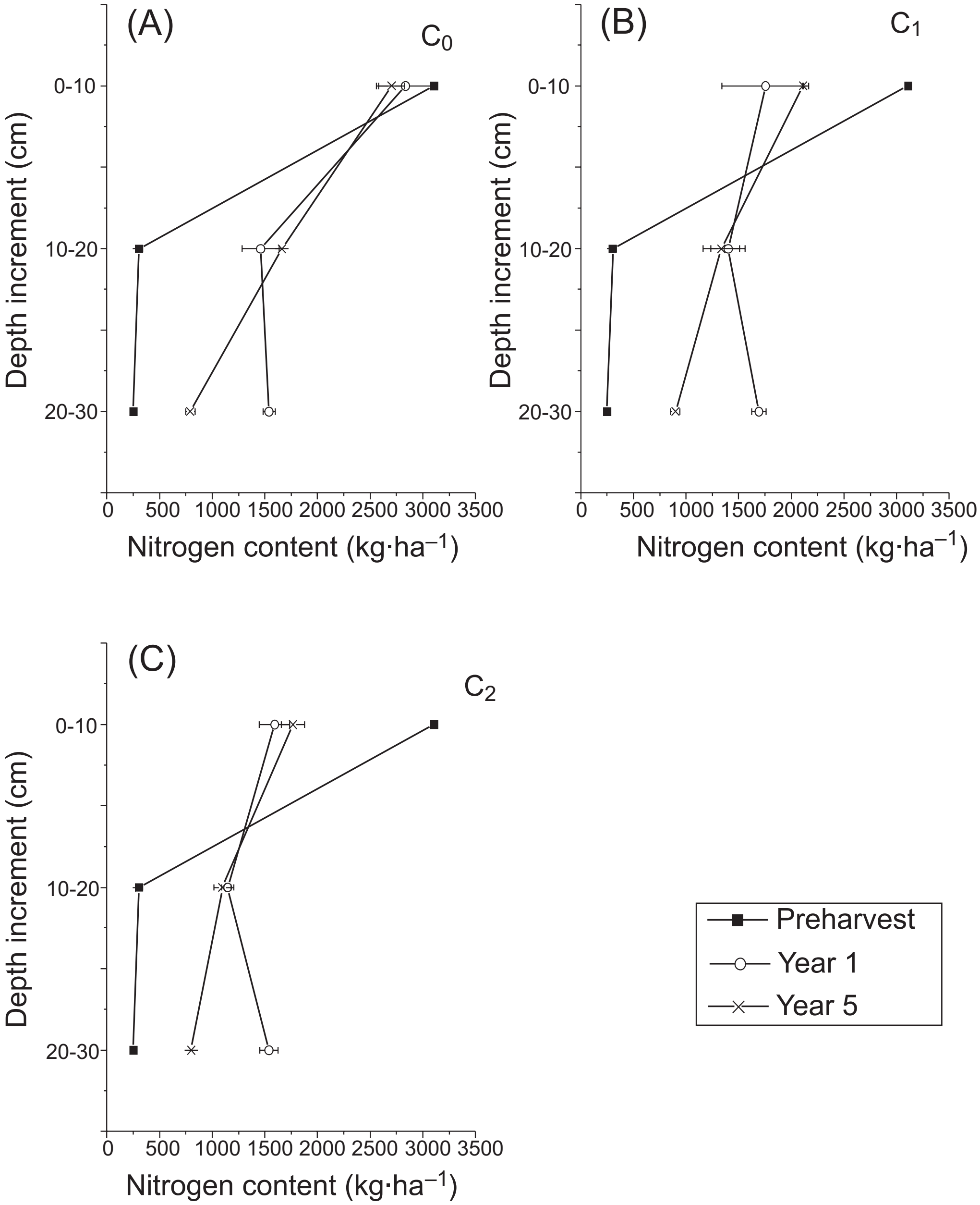
Variations in rates of C and N accretion were observed in our study sites. In long-term ecosystem studies conducted in the upper Piedmont of South Carolina, the rate of accretion of soil C seemed dependent on soil properties, particularly texture and drainage. Richter et al. (1999) showed only a small accretion of soil C (0.07 Mg C·ha^{-1}·year^{-1}) on a 44-year-old loblolly pine plantation planted on abandoned agriculture land. This study was located at the Calhoun Ex-

Fig. 3. Preharvest, year 1, and year 5 carbon distribution for the herbicide – compaction treatments at the Idaho sites.



perimental Forest on well-drained sandy loam. In contrast, Van Lear et al. (1995) demonstrated a much larger rate of soil C accretion (0.47 Mg C·ha^{-1}·year^{-1}) on a 55-year-old loblolly pine plantation on a Pacolet soil (fine, kaolinitic, thermic Typic Kanhapludult), where the A and B horizons had been eroded, leaving an exposed clayey C horizon. The clayey C horizon with low initial C levels allowed for considerable adsorption of SOM and resulted in high rates of accretion. Although the North Carolina and Louisiana sites have similar climates, the response patterns of soil C and N pools differed considerably between them. Soil C and N accretion was substantial at the North Carolina sites and was nonexistent in the Louisiana sites (Table 1). This observation may be due to the differences that exist in soil drainage and relative site moisture levels between the sites. The water deficit is 1 and 82 mm·year^{-1} for the North Carolina and Louisiana sites, respectively (Tiarks et al. 1999), where the water deficit is defined as the difference between potential evapotranspiration and actual evapotranspiration. High levels of C can be solubilized from the forest floor and mineral soil on sites with poor drainage (Kalbitz et al. 2000). Soils at the North Carolina site range from moderately to poorly drained, whereas the Louisiana sites are primarily moderately well drained, with exceptions for the Metcalf (somewhat poorly drained) and Mayhew (poorly drained) soil series. Additionally, extended wet soil periods during the growing season are more prevalent at the North Carolina site because of the differences in rainfall distribution patterns. Ten years after establishment of a second-rotation loblolly pine plantation on the Atlantic coast, soil C increased on a

Fig. 4. Preharvest, year 1, and year 5 nitrogen distribution for the herbicide – compaction treatments at the Idaho sites.



poorly drained soil, while it had not changed on a somewhat poorly drained soil (Gresham 2001). Additionally, the litter layer developed more slowly on the poorly drained, more productive site than on the somewhat poorly drained site. While poor drainage – wet summer combinations may impede mineral soil C and N loss (Bridgham et al. 1991), it may accelerate the rate of forest-floor decomposition and solubilization of organic C and N (Kalbitz et al. 2000). This was demonstrated on our sites, whereby Tiarks et al. (1999) found that coarse woody debris decomposed slower on the Louisiana sites (by approximately half) than on the wetter North Carolina sites. Since the coarse woody debris originated from a single source in the Tiarks et al. (1999) experiment, differences in decomposition rates were determined by differences in site characteristics.

Soil C/N ratios

Models describing soil C and N dynamics emphasize the role of the soil C/N ratio in driving C mineralization and sequestration (Jenkinson and Rayner 1977; Ågren and Bosatta 1987; Parton et al. 1988), with lower values suggesting a greater potential for C mineralization. Management practices that result in long-term alterations of the soil C/N ratio may have major implications in determining whether a forest soil is a C sink or source. After 5 years, mineral soil C/N ratios did not change from preharvest values for the North

Table 2. Within-block variation in carbon (C) and nitrogen (N) measurements for the North Carolina sites and the Louisiana site.

Site	No. samples per plot	Mean	SE†	CV	CI	%Δ
C ($Mg \cdot ha^{-1}$)						
North Carolina	3	20.09	1.33	0.48	5.72	28
Louisiana	3	19.56	0.67	0.25	2.90	15
Louisiana	10	19.01	0.38	0.27	0.86	5
N ($kg \cdot ha^{-1}$)						
North Carolina	3	421.1	29.1	0.50	125	30
Louisiana	3	623.4	19.6	0.23	84	14
Louisiana	10	645.0	10.6	0.22	24	4

Note: SE, standard error; CV, coefficient of variation; CI, confidence interval; %Δ, percent change detected at $\alpha = 0.05$.

Carolina, British Columbia, and California sites, decreased for the Idaho site, and increased slightly at the Louisiana sites (Table 1). There were no discernable trends in the soil C/N ratio based on the main and split-plot treatments for any of the sites, except the Idaho sites. At each depth, the mineral soil C/N ratios for plots on the compaction and the OM_0 treatments were not different from each other but were consistently lower than the C/N ratios on the OM_1 and OM_2 plots. Early in a rotation, surface detritus can immobilize a large amount of N (Sanchez 2001). The immobilized N in the detritus can come from endogenous and exogenous sources, such as fertilization, throughfall, and nutrient importation from lower in the forest floor (Griffin 1972; Berg 1988). Thus, it could be expected that in plots where the surface detritus was higher (OM_0 and OM_1) there would be a lower influx of N into and lower potential immobilization of N from the mineral soil. However, the Idaho sites have a large amount of snowmelt, which results in OM (especially hydrophilic OM rich in N) being solubilized from the forest floor (Kalbitz et al. 2000). The influx of N into the soil results in lower soil C/N values for plots with surface detritus (OM_0). This effect was not seen on the plots with intermediate amounts of detritus (OM_1). OM_0 and OM_1 differ in that the OM_0 plots have larger amounts of detritus but also larger amounts of leaf litter than the OM_1 plots. We postulate that leaf litter, because of its chemistry and surface area, may be more effective than woody debris at immobilizing N. To our knowledge, this hypothesis has not been tested in the literature.

Sampling protocol

A problem evident in this manuscript was the different sampling intensities for the different locations: British Columbia (5 composite samples from 5 transects; 3 composite samples from 18 random locations; 5 composite samples from 25 random locations); Idaho (16 stratified samples composited to 4 samples per horizon per plot); California and Louisiana (10 samples composited to 1 sample per plot); and North Carolina (3 samples per depth per plot). Table 2 shows the within-plot spatial variation in soil C and N for the North Carolina and Louisiana sites. Taking into account the within-plot variation and the number of samples taken, the Louisiana sites picked up approximately 4%–5% of the confidence for the mean soil C and N content in the 0–10 cm layer ($\alpha = 0.05$), whereas the North Carolina sites were picking up approximately 30% of the confidence. Given the low within-plot spatial variation (25%) for the Louisiana plots, three samples per plot could have been collected and a reasonable level of confidence (15%) in the soil C and N content still achieved. Thus, the Louisiana plots were probably oversampled and the North Carolina plots undersampled. The sampling intensity must be carefully considered to achieve a reasonable (and consistent with other LTSP installations) level of confidence in the measures of soil C and N contents.

Conclusions

The results described in this manuscript are of a short-term nature (i.e., 5 years), and sampling intensity may not have been adequate to detect treatment effects for some sites. Nevertheless, in general, OM removal, compaction, and competition control did not have a significant effect on mineral soil C and N pools for the different sites after 5 years. Even on the most severe treatments, scalped soils (OM_2) with bulk densities approaching root-limiting levels (C_2), there was no detrimental effect to soil C and N contents or the soil C/N ratio. Although each location was treated as a separate experiment, the results were fairly consistent among the sites, suggesting that the treatment effects are not site specific. The only exceptions were the large increases in C and N contents in North Carolina and the transport of DOM in the Idaho site. These results coupled with the observations of Johnson (1992) — which showed that except for cases of severe disturbance or wet soils, harvesting does not have a deleterious effect on soil physical properties — speak to the resiliency of the soil to land management practices. This may be particularly true for forested ecosystems not occurring on extreme slopes, where parental root systems provide structural protection and a large source of OM. Caution must still be taken with soils with high adsorption capabilities (i.e., fine-textured soils). Soils with high adsorption capabilities, such as those at the Idaho sites in this study, may result in absorption of DOM (thus protecting the DOM from leaching or microbial decomposition) and may build up in lower horizons. This condition would result in a depletion of OM in the surface horizon and the rooting zone. Any benefit from the buildup of C and N in the lower horizons may be negated by the loss of productivity due to diminished levels of C and N in the rooting zone. Unlike the rapid detection of changes in C and N contents for the different horizons, changes in productivity due to a depletion of C and N in the rooting zone may not be detectable until late in the rotation, especially on sites characterized by slow growth rates. Analyses of the soil C and N pools coupled with changes in stand productivity, at a sufficiently long enough time after harvest to detect productivity changes, will help us to ascertain whether the effects of OM removal, soil compaction, and competition control have a long-term effect on the overall site C and N pools. This information will be essential in our efforts to maintain forest soils and not negatively impact forest productivity and sustainability.

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Appendix A

Appendix appears on following page.

Table A1. Fifth-year mean soil carbon (C) and nitrogen (N) contents for each treatment, depth, and location.

Depth (cm)	Treatment	C (Mg·ha^{-1})	N (kg·ha^{-1})
British Columbia			
0–20	OM$_0$	32.44 (4.34)	1742 (203)
	OM$_1$	39.83 (7.63)	2238 (463)
	OM$_2$	26.46 (3.11)	1535 (147)
0–20	C$_0$	31.37 (6.13)	1800 (366)
	C$_1$	31.18 (4.00)	1711 (189)
	C$_2$	36.19 (6.51)	2005 (367)
California			
0–10	OM$_0$	117.24 (17.18)	5033 (43)
	OM$_2$	110.94 (2.65)	5489 (258)
10–20	OM$_0$	92.37 (4.33)	4452 (335)
	OM$_2$	82.35 (0.76)	4198 (43)
20–40	OM$_0$	127.94 (17.18)	6171 (87)
	OM$_2$	107.35 (0.23)	5715 (291)
0–10	C$_0$	115.66 (2.10)	5363 (378)
	C$_2$	112.52 (4.23)	5154 (78)
10–20	C$_0$	84.82 (3.22)	4179 (62)
	C$_2$	89.90 (6.79)	4471 (316)
20–40	C$_0$	108.94 (1.82)	6045 (39)
	C$_2$	126.35 (18.77)	5841 (417)
Idaho			
0–10	OM$_0$	22.50 (1.95)	2256 (230)
	OM$_1$	22.83 (2.24)	2233 (170)
	OM$_2$	19.83 (2.06)	2138 (131)
10–20	OM$_0$	21.33 (2.20)	1616 (139)
	OM$_1$	22.83 (1.08)	1511 (138)
	OM$_2$	19.50 (2.11)	1492 (114)
20–30	OM$_0$	15.67 (0.61)	804 (42)
	OM$_1$	14.17 (0.31)	765 (54)
	OM$_2$	15.33 (1.02)	669 (74)
0–10	C$_0$	26.00 (0.45)	2700 (92)
	C$_1$	23.00 (1.88)	2108 (11)
	C$_2$	16.17 (0.48)	1820 (106)
10–20	C$_0$	24.67 (1.05)	1701 (31)
	C$_1$	20.33 (2.11)	1553 (133)
	C$_2$	18.67 (1.48)	1365 (152)
20–30	C$_0$	14.00 (0.68)	673 (76)
	C$_1$	15.17 (0.60)	838 (45)
	C$_2$	16.00 (0.73)	728 (37)
0–10	U+	22.11 (1.90)	2224 (144)
	U$_-$	21.33 (1.49)	2194 (145)
10–20	U+	23.56 (1.21)	1715 (68)
	U$_-$	18.89 (1.41)	1365 (99)
20–30	U+	15.00 (0.55)	661 (50)
	U$_-$	15.11 (0.65)	831 (27)
Louisiana			
0–10	OM$_0$	17.03 (0.19)	725 (5)
	OM$_1$	15.94 (1.33)	670 (30)
	OM$_2$	16.56 (0.29)	690 (20)
10–20	OM$_0$	8.46 (0.25)	410 (10)
	OM$_1$	8.16 (0.25)	405 (5)
	OM$_2$	7.55 (0.18)	390 (< 1)
20–30	OM$_0$	5.88 (0.16)	380 (< 1)
	OM$_1$	6.05 (0.06)	380 (< 1)
	OM$_2$	5.79 (0.17)	370 (< 1)
0–10	C$_0$	16.62 (1.04)	685 (25)
	C$_1$	16.41 (0.05)	710 (10)
	C$_2$	16.50 (0.13)	685 (5)
10–20	C$_0$	8.10 (0.55)	390 (10)
	C$_1$	8.43 (0.29)	425 (5)
	C$_2$	7.46 (0.60)	380 (20)
20–30	C$_0$	5.79 (0.25)	370 (< 1)
	C$_1$	5.93 (0.08)	390 (< 1)
	C$_2$	6.00 (0.26)	375 (5)
0–10	U+	16.92 (0.22)	697 (8)
	U$_-$	16.10 (0.35)	692 (14)
10–20	U+	8.28 (0.15)	407 (5)
	U$_-$	7.77 (0.27)	393 (10)
20–30	U+	5.93 (0.07)	377 (3)
	U$_-$	5.88 (0.11)	378 (3)
North Carolina			
0–10	OM$_0$	37.97 (3.32)	799 (79)
	OM$_1$	37.15 (2.79)	837 (73)
	OM$_2$	44.46 (5.12)	980 (137)
10–20	OM$_0$	22.74 (2.06)	572 (55)
	OM$_1$	23.32 (3.00)	595 (82)
	OM$_2$	21.04 (2.12)	517 (36)
20–30	OM$_0$	19.21 (1.75)	513 (39)
	OM$_1$	20.69 (1.79)	510 (42)
	OM$_2$	20.12 (3.05)	545 (76)
0–10	C$_0$	37.72 (4.22)	889 (131)
	C$_1$	38.64 (3.69)	832 (85)
	C$_2$	43.23 (3.72)	895 (79)
10–20	C$_0$	19.07 (1.37)	520 (44)
	C$_1$	22.04 (2.39)	560 (58)
	C$_2$	25.99 (3.12)	604 (75)
20–30	C$_0$	20.62 (3.02)	576 (78)
	C$_1$	19.66 (1.51)	494 (34)
	C$_2$	19.73 (2.04)	499 (40)
0–10	U+	36.93 (2.31)	774 (60)
	U$_-$	42.79 (3.82)	970 (98)
10–20	U+	23.30 (2.39)	586 (60)
	U$_-$	21.44 (1.45)	537 (36)
20–30	U+	20.76 (1.57)	541 (34)
	U$_-$	19.25 (2.10)	505 (53)