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Soil C and N minimum detectable changes and treatment differences in a multi-treatment forest experiment

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Abstract

Detecting changes in forest soil C and N is vital to the study of global budgets and long-term ecosystem productivity. Identifying differences among land-use practices may guide future management. Our objective was to determine the relation of minimum detectable changes (MDCs) and minimum detectable differences between treatments (MDDs) to soil C and N variability at multiple spatial scales. The three study sites were 70–100-year-old coniferous forests in Washington and Oregon. Area- and volumetric-based soil measurements were made before implementation of 7 treatments on 2-ha experimental units, replicated in 3 or 4 blocks per site. In the absence of treatment effects, whole-site MDCs are ~10% for mineral soil C and N masses and concentrations and ~40% for O-horizon C and N masses. When treatment differences occur, MDDs are ~40% for mineral soil and ~150% for O-horizon. MDDs are reduced as much as two-thirds by evaluating change from pre- to post-treatment rather than only post-treatment values, and by pairing pre- and post-treatment measurements within small subplots. The magnitude of MDD reduction is quantitatively related to pre-treatment soil variability at multiple spatial scales, with the greatest reductions associated with the largest within-block:within-plot and within-plot:within-subplot variability ratios. These quantified benefits can be weighed against costs and challenges to make informed decisions when selecting the most appropriate sampling design.

Keywords: Soil nitrogen; Soil carbon; Minimum detectable change; Minimum detectable difference; Change detection

1. Introduction

Detecting change in forest soil C and N and differences between treatments is paramount to understanding alterations in soil fertility, C sequestration, and N impacts on C cycling (Homann et al., 2001b; Johnson and Curtis, 2001; Post et al., 2001; Conen et al., 2003; Swanston et al., 2004; Lal, 2005; Jandl et al., 2007; Woodbury et al., 2007). In investigations of these issues, minimum detectable changes (MDCs) in soil properties and minimum detectable differences between treatments (MDDs) provide valuable information during all phases of study design, implementation, and interpretation. During study design, MDCs and MDDs based on previous studies or low-intensity preliminary sampling can guide experimental and sampling designs, including issues of replication and sampling intensity. Following experimental layout, MDCs and MDDs from comprehensive pre-treatment sampling, combined with estimates of rates of change (Conen et al., 2003; Smith, 2004), can guide timing, intensity, and design of post-treatment sampling. After termination of an experiment, MDCs and MDDs indicate magnitudes of change or differences that could have occurred but remain undetected (Homann et al., 2001b).

Forest soil C and N MDCs and MDDs have been determined for several experimental designs. MDCs have been quantified for *single* experimental units, such as an individual plot, stand or watershed (Huntington et al., 1988, O-horizon and mineral soil C and N) and *single* treatments represented by *multiple* experimental units (Conant et al., 2003, mineral soil C). Substantial differences in MDCs exist between these two experimental designs (Yanai et al., 2003, O-horizon C). MDDs have been determined for more complex experiments that

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compare *multiple* treatments represented by *multiple* experimental units (Garten and Wullschleger, 1999, mineral soil C; Homann et al., 2001a, and Rothe et al., 2002, O-horizon and mineral soil C and N).

MDCs and MDDs are typically large for forest soils (Johnson et al., 1990; Homann et al., 2001a; Conant et al., 2003; Yanai et al., 2003). Large MDCs and MDDs may be reduced by increasing the number of observational or experimental units (Johnson et al., 1990; Conant et al., 2003; Yanai et al., 2003). However, detecting changes and differences on the order of 20 to 30% may require a substantial, and often impractical, number of observations (Johnson et al., 1990; Conant et al., 2003; Yanai et al., 2003; Schoning et al., 2006).

MDCs and MDDs may also be reduced by selecting advantageous experimental and sampling designs (Homann et al., 2001a; Conant et al., 2003; Yanai et al., 2003), but results have varied among studies and sites. Considerable decreases in MDCs were forecast for resampling the same experimental units vs. sampling an independent set of experimental units (Ellert et al., 2002; Yanai et al., 2003), but Conant et al. (2003) found substantial decreases in only three of four sites, which they attributed to differences in soil spatial variability. In examining change, Yanai et al. (2003) suggested the resampling of established subplots would presumably increase statistical power (i.e., lower MDC) compared with sampling an independent set of subplots, but did not have information to test this presumption. In comparing treatments, Homann et al. (2001a) demonstrated a broad range of reductions in MDDs resulting from pre- and post-treatment sampling vs. only post-treatment sampling, a pattern attributed to differences in soil spatial variability. These sampling strategies are implicitly linked to the spatial dependence of forest soil variability, i.e., that proximal points tend to be more similar than distant points (Grigal et al., 1991; Kirwan et al., 2005; Schoning et al., 2006). However, a quantitative assessment between multi-scale variability and sampling strategies is lacking for forest soils.

Our goal in this study was to quantitatively relate MDCs and MDDs for forest soil C and N to soil variability at multiple spatial scales. Our analysis is based on comprehensive pretreatment sampling from a large-scale, complex, multi-treatment experiment at three coniferous forests of the Pacific Northwest USA (Homann et al., 2001a). We compare several relevant MDCs and MDDs (Fig. 1):

MDC_{unit}—minimum detectable change over time in a single unreplicated experimental unit.

MDC_{treat}—minimum detectable change in a single treatment with replicated experimental units.

$MDC_{multiple}$—minimum detectable change in multiple treatments, when magnitude of change does not differ between treatments.

MDD_{change}—minimum detectable difference between treatments, when magnitude of change does differ between treatments, based on pre- and post-treatment sampling of independent subplots.

$MDD_{change*}$—minimum detectable difference between treatments, when magnitude of change does differ between treatments, based on pre- and post-treatment sampling of the same subplots.

MDD_{post}—minimum detectable difference between treatments for a single post-treatment sampling.

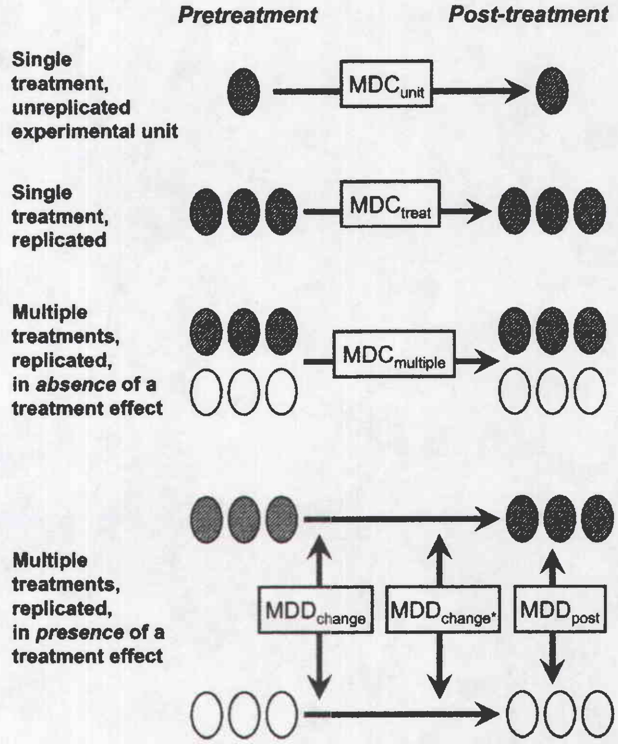

Fig. 1. Conceptual types of minimum detectable change (MDC) and minimum detectable difference between treatments (MDD) considered in this analysis. MDD_{change} and $MDD_{change*}$ differ in their subsampling designs.

These MDCs and MDDs were chosen to represent possible sampling designs and outcomes of our experiment, to allow comparison with less complex experiments, and to address several specific questions. Our presentation of MDC_{unit} and MDC_{treat} allows comparison with evaluations of basic experimental designs (Yanai et al., 2003). Our unique analysis of a more complex multi-treatment experiment recognizes multiple possible outcomes. If there is no difference between treatments, then change can be assessed across all treatments simultaneously ($MDC_{multiple}$). Conversely, if there is a difference between treatments, detecting the difference in change may be affected by sampling design (MDD_{change}, $MDD_{change*}$). Finally, rather than evaluating change, treatment differences may be evaluated at a single post-treatment point in time (MDD_{post}).

In carrying out our assessment, we provide quantitative answers to the following specific questions: What is the relation of MDCs for experimental designs that have different scopes of inference: an unreplicated experimental unit vs. a single treatment with multiple experimental units vs. multiple treatments with multiple experimental units (MDC_{unit} vs. MDC_{treat} vs. $MDC_{multiple}$)? How much is MDD reduced by examining change vs. quantifying only post-treatment properties

(MDD_{change} vs. MDD_{post})? How much is MDD reduced by the resampling of established subplots vs. sampling independent subplots ($MDD_{change*}$ vs. MDD_{change})?

2. Materials and methods

2.1. Experimental approach and design

Our analysis is based on comprehensive pre-treatment sampling, which follows the practice of many studies of forest soil MDCs and MDDs (Huntington et al., 1988; Homann et al., 2001a; Conant et al., 2003; Yanai et al., 2003). We describe the subsequent treatments to provide context for interpretation of results. The three study sites differ in their geology, topography, and vegetation (Table 1). Descriptions of the forest and soils at the Siskiyou site have been reported previously (Little et al., 1995; Homann et al., 2001a).

Seven treatments were assigned in 3 replicate experimental blocks at Willamette and Siskiyou, and in 4 experimental blocks at Olympic. Each block is at least 42 ha. At Willamette and Siskiyou, reconnaissance soil surveys guided placement of blocks on separate mountain slopes in areas of relatively homogeneous soil and vegetation. At Olympic, the blocks are contiguous on an outwash plain. Following pre-treatment sampling and beginning in 1997, treatments were implemented on 2-ha treatment plots plus their surrounding 4-ha buffers. One treatment is a no-disturbance control. The other treatments are 3 vegetation systems (early, mid, or late-successional vegetation), each of which is combined with large and small quantities of woody debris. The vegetation was manipulated by complete or selective harvesting, followed by planting selected tree species. Tree stems were removed from Siskiyou and Willamette by helicopter logging, and from Olympic by grapple logging, which used a tracked machine with a grapple at the end of a long arm. Large quantities of woody debris were created by leaving fallen stems equivalent to 15% of the pre-harvest standing volume, in addition to other harvest residues. Small quantities of woody debris were produced by removing fallen pre- and post-harvest stems greater than 10-cm diameter and 3-m length.

2.2. Soil sampling and analysis

Pre-treatment soil sampling was conducted during June–October in 1992–1994. Within each treatment plot, soil sampling was attempted at 10–16 points on a 25-m × 25-m grid. If a point fell on a tree, large root, log, or large rock, up to two additional attempts were made within 1 m. Of the points attempted, 86% were successfully sampled at Willamette, 85% at Siskiyou, and 68% at Olympic, resulting in an average of 14 successfully sampled points per plot at Willamette, 13 at Siskiyou, and 8 at Olympic. In addition, a second pre-treatment sampling was conducted on one Willamette plot to assess within-subplot variability; this second sampling was taken within 2 m × 2 m subplots that contained the initial sampling points. Also, post-treatment soil sampling of one block at Siskiyou in September 2003 allowed assessing potential change in variance of soil properties.

Area-based sampling of the O-horizon and volumetric-based sampling of the underlying mineral soil were conducted at all sites, although sampling techniques varied among the sites because of different rock contents and soil depths. At each sampling point, slope angle was measured. Samples were taken perpendicular to the surface slope. At Siskiyou, the O-horizon, excluding surface wood >2.5-cm diameter, was collected from within a 30-cm diameter ring. Then a 10-cm × 15-cm box corer, with one open and three solid sides, was driven into the underlying mineral soil to 35-cm depth. After removal of the corer, three strata of mineral soil were extracted from the open side: A-horizon, bottom of A-horizon to 15-cm depth, and 15–30-cm depth. Similar sampling was conducted at Willamette, except the sampling depths were 20 and 40 cm. At Olympic a 30-cm × 30-cm steel square was driven through the O-horizon into the mineral soil. From the top of the square, the O-horizon,

Table 1
Characteristics of the three forest research sites in Oregon and Washington

	Sites		
	Willamette	Siskiyou	Olympic
Location	Cascade Mountains, OR	Siskiyou Mountains, OR	Olympic Peninsula, Sappho, WA
Latitude and longitude	44°03′N, 122°24′W	42°22′N, 124°11′W	48°03′N, 124°27′W
Slope (°)	16	16	0
Geologic substrate	Volcanic	Metamorphic	Glacial outwash
Soil texture	Clay loam	Loam	Gravelly loam
Elevation (m)	700	800–1100	100
Annual precipitation (cm)[a]	197	364	296
Annual temperature (°C)[a]	10.9	11.9	10.2
Dominant tree species[b]	Douglas-fir, western hemlock, western red cedar	Douglas-fir, tanoak	Douglas-fir, Sitka spruce, western hemlock
Tree age (year)	80	90–100	70
Stand history	Stand replacement following wildfires with variable survival of residuals	Stand replacement following wildfires, few surviving residuals	Railroad logged; blowdown prevalent from previous stand

[a] For 1990–2005, derived from data provided by PRISM Group, Oregon State University, http://www.prismclimate.org, 6 Dec 2006.

[b] Scientific names: Douglas-fir, *Pseudotsuga menziesii* Franco (Mirb.); Sitka spruce, *Picea sitchensis* (Bong.) Carr.; tanoak, *Lithocarpus densiflorus* (Hook & Arn.) Rehd.; western hemlock, *Tsuga heterophylla* (Rafn.) Sarg.; western red cedar, *Thuja plicata* Donn.

excluding surface wood >6 mm in diameter, and three strata of mineral soil were extracted: A-horizon, bottom of A-horizon to 15-cm depth, and 15–30-cm depth.

Samples were dried at 40–60 °C. The O-horizon samples were hand-sorted to remove rocks >4 mm, roots, and wood >6 mm in diameter, leaving the residual material, which we call soil. Mineral samples were sieved with a 4-mm sieve to yield <4-mm soil. A 4-mm sieve, rather than the standard 2-mm sieve, was used because of our inability to efficiently break up 2–4-mm organic-containing aggregates (Cromack et al., 1999; Homann et al., 2004). The >4 mm material was hand-sorted into >4-mm rocks and >4-mm wood plus roots. The components were dried at 55–65 °C and weighed. Willamette and Siskiyou soil and rock masses were converted to 105 °C equivalents based on moisture contents.

The O-horizon soil was ground to <0.8 mm (20 mesh) and subsamples of <4-mm mineral soil were ground to <0.25 mm (60 mesh). They were analyzed for total C and N by the following methods. Olympic O and mineral soil and Willamette O-horizon were analyzed by LECO CNS 2000 Analyzer (LECO Corporation, St. Joseph, MI; CV for replicate analyses = 2.0% for C and 3.6% for N). Willamette and Siskiyou mineral soils were analyzed by Carlo-Erba NA 1500 Series 2 analyzer (Carlo Erba Strumentazione, Rodano, Italy; CV for replicate analyses = 5.2% for C and 5.6% for N). Siskiyou O-horizon was analyzed by loss-on-ignition at 550 °C for >12 h (Homann et al., 2001a; CV for replicate analyses = 1.0%) and Kjeldahl N (Bremner and Mulvaney, 1982; CV for replicate analyses = 5.1%); empirical factors converted these results to values equivalent to Carlo-Erba measurements (Homann et al., 2001a).

We expect the O-horizon and surface mineral soil to exhibit the greatest changes and treatment differences in the future; therefore, we limit our analysis to those layers. Masses of soil, rock, and wood-plus-roots per m^2 were calculated by dividing their masses in a sample by the slope-corrected cross-sectional area of the sample. Masses of O-horizon soil or <4-mm mineral soil multiplied by corresponding C and N concentrations yielded C and N masses (kg m^{-2}) for each sampled stratum. Because of the difficulty in consistently defining their boundaries, the A-horizons were not considered separately in this analysis. Instead, masses for a slope-corrected 0–15 cm mineral soil layer for Siskiyou and Olympic, or a 0–20 cm mineral soil layer for Willamette, were determined by summing the masses of the sampled strata within these depths. Concentrations of C and N in these aggregated mineral soil layers were calculated as masses of C and N divided by mass of <4-mm soil.

2.3. Statistical analysis

Some properties, as noted in the results, were log-transformed prior to analysis to yield more normal distributions, and back-transformed to original units for presentation of results. Variability was characterized with standard deviations at three spatial scales: among sampling points within blocks, pooled across blocks (s_{block}), for each site; among sampling points within plots, pooled across plots (s_{plot}), for each site; and among sampling points within subplots, pooled across subplots ($s_{subplot}$), for the Willamette site. In calculating MDCs and MDDs, we used $\alpha = 0.05$ and $\beta = 0.2$.

The plot is the experimental unit. The MDC_{unit} is based on a two-sample t-test with equal sample sizes (Zar, 1999), where the two samples represent independent sampling-point measurements taken pre- and post-treatment.

$$MDC_{unit} = s_{plot}\left(\frac{2}{p}\right)^{0.5}(t_{0.05(2),df} + t_{0.2(1),df}) \quad (1)$$

where p is the average number of points sampled per plot during pre-treatment sampling and assumed to be the same post-treatment, and df = $2p - 2$.

The MDC_{treat} is based on a paired t-test of replicate plots (Zar, 1999), where a pair consists of the pre- and post-treatment means of a plot.

$$MDC_{treat} = s_d\left(\frac{1}{n}\right)^{0.5}(t_{0.05(2),df} + t_{0.2(1),df}) \quad (2)$$

where s_d = standard error of the difference between plot means at two sampling times, $n = 3$ experimental units for Siskiyou and Willamette or 4 for Olympic, and df = $n - 1$. s_d was calculated as $s_d = s_{plot}(2/p)^{0.5}$.

The $MDC_{multiple}$, for circumstances when treatment does not influence the magnitude of change, is based on a repeated-measures, three-factor ANOVA (block is a random factor with 3 or 4 levels, treatment is a fixed factor with 7 levels, and time is a fixed factor with 2 levels). Change is quantified by the difference between the two times. Lack of a treatment effect on the magnitude of change is indicated by a non-significant time × treatment interaction, which allows the subsequent testing of the main effect time (Zar, 1999). Time is tested with $MS_{time \times block}$ in the denominator of the F-ratio, and the $MDC_{multiple}$ is calculated from the following equation:

$$MDC = \left(MS_{denominator} \times 2 \times \frac{k}{b}\right)^{1/2} \times \phi \quad (3)$$

where $MS_{denominator}$ is the mean square of the F-ratio denominator, k = the number of levels of the factor being examined, b = the number of experimental units in each level, and the value of ϕ is a function of degrees of freedom of the F-ratio numerator and denominator (Zar, 1999).

Because $MS_{time \times block}$ cannot be calculated directly from pre-treatment data, it is simulated based on the t distribution:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{(s_p^2/p_1 + s_p^2/p_2)^{0.5}} \quad (4)$$

where $\bar{x}_1$ and $\bar{x}_2$ are means of random samples from the same normal population, s_p^2 is the pooled variance of the observations within the samples, and p_1 and p_2 are the numbers of observations in each sample (Zar, 1999). Rearranging the equation, assigning 1 = pre-treatment and 2 = post-treatment, recognizing $s_p = s_{plot}$, and assuming p sampling points for both pre- and post-treatment, yields a possible post-treatment mean for a single plot:

$$\bar{x}_{post} = \bar{x}_{pre} + s_{plot}\left(\frac{2}{p}\right)^{0.5} \times t \qquad (5)$$

The value for t is randomly selected from the two-tailed t distribution with degrees of freedom associated with s_{plot} and entered into Eq. (5) to yield one of an infinite number of possible post-treatment means for a single plot. From measured $\bar{x}_{pre}$ and simulated $\bar{x}_{post}$ values for each of the plots at a site, we calculated the $MS_{time\times block}$. We repeated this process a total of 250 times, and used the average $MS_{time\times block}$ to determine the $MDC_{multiple}$ with Eq. (3).

For the situation when treatment does influence the magnitude of change, the minimum detectable difference in change between extreme treatments (MDD_{change}) was determined by a similar simulation, except the change ($\bar{x}_{post} - \bar{x}_{pre}$) from Eq. (5) was evaluated in a two-factor ANOVA (treatment and block), and the $MS_{residual}$ was used in Eq. (3) (Homann et al., 2001a). We repeated the analysis to calculate MDD_{change^*} for the scenario where post-treatment measurements would be paired with pre-treatment measurements within 2 m × 2 m subplots; in doing so, we replaced s_{plot} in Eq. (5) with $s_{subplot}$, which was available only for Willamette.

For calculating MDD_{post} in which only post-treatment sampling would occur, we assumed post-treatment variation among replicate plots would be similar to the pre-treatment variation; then the appropriate $MS_{denominator}$ for Eq. (3) is the $MS_{residual}$ from the two-factor ANOVA (treatment and block) of the $\bar{x}_{pre}$ values (Homann et al., 2001a).

3. Results and discussion

3.1. Soil variability

The three sites differ substantially in surface substrate composition (Table 2). The O-horizon mass is four to five times greater at Olympic than at the other sites due to greater masses of all components: soil, wood and rock. Olympic also has larger amounts of rock in the mineral layer, and smaller amounts of soil.

O-horizon C and N masses vary considerably at all sites, with relative standard deviations ranging from 50 to 150% (Table 3). Willamette has the largest relative standard deviations and Siskiyou the smallest. Mineral soils have less than half the variability of the O-horizons at all sites (Table 3).

3.2. Minimum detectable changes

The MDCs of O-horizons are ~50–150% for both a single experimental unit and a single treatment; they are substantially smaller for multiple treatments in the absence of a treatment effect (Fig. 2). Mineral soil MDCs are typically less than half of the O-horizon MDCs (Fig. 2).

The MDCs of the different experimental designs are all are based on s_{plot} (Eqs. (1), (2), (5)). Hence, soil properties with large s_{plot}, e.g. O-horizon C and N (Table 3), also have large

Table 2
Pre-treatment soil properties at the three coniferous forest research sites, Oregon and Washington

Site	Layer[a]	Property[b]	Mean[c]	Min	Max
Willamette	O-horizon	Soil mass (kg m^{-2})	4.8	0.0	35.7
		Wood-plus-root mass (kg m^{-2})	0.1	0.0	1.9
		Rock mass (kg m^{-2})	0.5	0.0	3.9
	Mineral	Soil mass (kg m^{-2})	114	49	195
		Wood-plus-root mass (kg m^{-2})	1.8	0.2	49.2
		Rock mass (kg m^{-2})	19	0	98
		Rock volume (% of total volume)	4.0	0.0	20.5
Siskiyou	O-horizon	Soil mass (kg m^{-2})	2.7	0.2	13.2
		Wood-plus-root mass (kg m^{-2})	0.6	0.0	6.9
		Rock mass (kg m^{-2})	1.8	0.0	22.6
	Mineral	Soil mass (kg m^{-2})	91	32	170
		Wood-plus-root mass (kg m^{-2})	0.58	0.01	7.24
		Rock mass (kg m^{-2})	52	16	179
		Rock volume (% of total volume)	14.5	4.6	49.8
Olympic	O-horizon	Soil mass (kg m^{-2})	8.0	0.5	57.8
		Wood-plus-root mass (kg m^{-2})	5.3	0.0	58.6
		Rock mass (kg m^{-2})	7.7	0.0	84.0
	Mineral	Soil mass (kg m^{-2})	53	19	114
		Wood-plus-root mass (kg m^{-2})	2.6	0.0	22.4
		Rock mass (kg m^{-2})	101	0	192
		Rock volume (% of total volume)	28.1	0.1	53.4

[a] Mineral-layer depth is 0–20 cm for Willamette and 0–15 cm for Siskiyou and Olympic.
[b] O-horizon soil is residual material after removing the >4-mm rocks and >6-mm diameter wood plus roots. O-horizon wood plus roots for Willamette and Siskiyou includes surface fine woody debris 6–25 mm in diameter, which was excluded from Olympic. Mineral-layer soil is material that passed through a 4-mm sieve, while rocks and wood plus roots did not.
[c] Based on 284 total sampling points for Willamette, 276 for Siskiyou, and 221 for Olympic.

Table 3
Pre-treatment variability of soil C and N at the three forest research sites, Oregon and Washington

Site	Layer[a]	Soil property[b]	Mean[c]	Min	Max	s_{block}[c] (% of mean)	s_{plot}[c] (% of mean)	$s_{subplot}$[d] (% of mean)
Willamette	O-horizon	C mass[e] (kg m^{-2})	0.98	0.00	19.56	158	156	151
		N mass[e] (kg m^{-2})	0.018	0.000	0.156	144	143	139
	Mineral	C mass[e] (kg m^{-2})	4.23	1.94	7.71	25	23	22
		N mass (kg m^{-2})	0.201	0.076	0.395	28	24	18
		C conc.[e] (g kg^{-1})	37.8	17.0	88.9	30	28	21
		N conc. (g kg^{-1})	1.79	0.72	3.98	28	24	15
Siskiyou	O-horizon	C mass[e] (kg m^{-2})	0.93	0.00	6.44	62	53	N/A
		N mass[e] (kg m^{-2})	0.019	0.000	0.099	71	62	
	Mineral	C mass[e] (kg m^{-2})	4.41	2.42	8.84	19	19	
		N mass (kg m^{-2})	0.147	0.062	0.267	23	20	
		C conc.[e] (g kg^{-1})	50.2	25.0	134.9	28	27	
		N conc.[e] (g kg^{-1})	1.62	0.91	3.39	20	18	
Olympic	O-horizon	C mass[e] (kg m^{-2})	2.41	0.17	26.45	98	100	N/A
		N mass[e] (kg m^{-2})	0.052	0.004	0.466	84	86	
	Mineral	C mass (kg m^{-2})	4.13	1.60	7.07	23	22	
		N mass (kg m^{-2})	0.128	0.049	0.288	29	25	
		C conc.[e] (g kg^{-1})	79.0	23.6	197.3	35	34	
		N conc. (g kg^{-1})	2.52	0.68	5.08	30	29	

[a] Mineral-layer depth is 0–20 cm for Willamette and 0–15 cm for Siskiyou and Olympic.
[b] Soil properties of O-horizon are for the residual material after removal of >4-mm rocks and >6-mm wood. Soil properties of mineral layer are for <4-mm material.
[c] Based on 284 sampled points distributed over 7 treatment plots replicated in 3 blocks at Willamette, 276 sampled points distributed over 7 treatment plots replicated in 3 blocks at Siskiyou, and 221 sampled points distributed over 7 treatment plots replicated in 4 blocks at Olympic. s_{block} is standard deviation among sampled points within 42–60-ha blocks. s_{plot} is standard deviation among sampled points within 2-ha plots.
[d] Based on resampling within twelve 2-m × 2-m subplots in one treatment plot at Willamette. NA, not available, for other sites. $s_{subplot}$ is standard deviation among sampled points within 2-m × 2-m subplots.
[e] Original data were log-transformed for analysis and back-transformed to yield the reported summary values.

MDCs (Fig. 2). The relation between MDCs for a single experimental unit vs. a single treatment differs among sites. At Willamette and Siskiyou MDC_{treat} and MDC_{unit} are similar, whereas at Olympic MDC_{treat} is smaller than MDC_{unit} (Fig. 2). Yanai et al.'s (2003) analysis of O-horizon C also demonstrates that relations between MDC_{treat} and MDC_{unit} vary among sites. These differences occur because numbers of experimental units and sampling points per unit differ among sites; they are explained quantitatively by combining Eqs. (1)–(2) to yield

$$\begin{aligned}\frac{MDC_{treat}}{MDC_{unit}} &= \left(\frac{1}{n}\right)^{0.5} \frac{(t_{0.05(2),n-1} + t_{0.2(1),n-1})}{(t_{0.05(2),2p-2} + t_{0.2(1),2p-2})} \\ &= \sim 0.68(\text{Olympic})\text{ or} \\ &\quad \sim 1.07(\text{Willamette and Siskiyou})\end{aligned} \tag{7}$$

The $MDC_{multiple}$ is substantially smaller than MDC_{treat} (Fig. 2), because more plots contribute to the multiple treatment analysis, albeit in a complex way (see 2.3 Statistical analysis). The relation between $MDC_{multiple}$ and MDC_{unit} is relatively constant, irrespective of soil property and site:

$$\frac{MDC_{multiple}}{MDC_{unit}} = 0.35\text{–}0.43 \tag{8}$$

These equations can be applied at our sites to other soil properties, such as exchangeable cations or heavy metals. For example, MDC_{unit} is easily calculated from s_{plot} (Eq. (1)) and can then be used in Eq. (8) to approximate $MDC_{multiple}$ without conducting the more complex statistical simulations.

The various MDCs we present are applicable under different circumstances. In the absence of a treatment effect in our multi-treatment experiment, the mineral soil $MDC_{multiple}$ is about 10% (Fig. 2). The potential to detect changes this subtle may allow testing projections of the role of forest soils in global C sequestration (Post et al., 2001; Lal, 2005) and may reduce uncertainties in broadscale terrestrial C budgets (Gingrich et al., 2007; Woodbury et al., 2007). Unfortunately, the MDCs for O-horizons are three to five times larger than for the mineral soil (Fig. 2), a common problem of assessing O-horizon dynamics (Yanai et al., 2003).

The MDC_{unit} and MDC_{treat} allow comparison with studies that are less complex than ours. Our large MDCs for O-horizon C (Fig. 2) are in the middle of the 20 to >300% range reported in a synthesis of many studies covering a wide variety of forest types (Yanai et al., 2003). Our MDCs for mineral soil C and N masses (Fig. 2) are consistent with those for a Washington-State second-growth conifer forest (Conant et al., 2003), assuming a sampling intensity similar to our study. Additionally, in long-term experiments, unforeseen circumstances may alter the original experimental design. For unplanned disturbances by flood, wildfire, windthrow, landslides or insect outbreaks on individual plots, MDCs for a single experimental unit or treatment may be applicable.

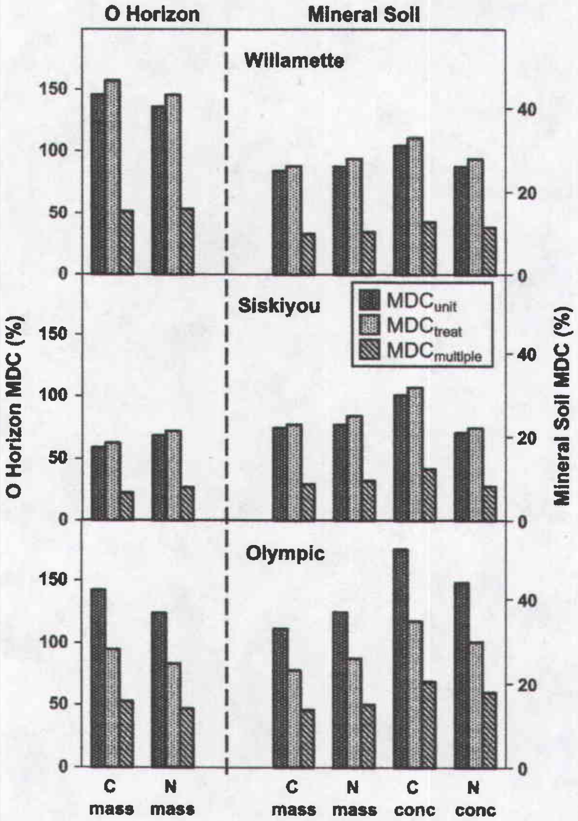

Fig. 2. The minimum detectable changes for an unreplicated experimental unit (MDC_{unit}), a treatment with multiple experimental units (MDC_{treat}), and multiple treatments in the absence of a treatment effect ($MDC_{multiple}$). Note the different scales for O-horizon and mineral soil.

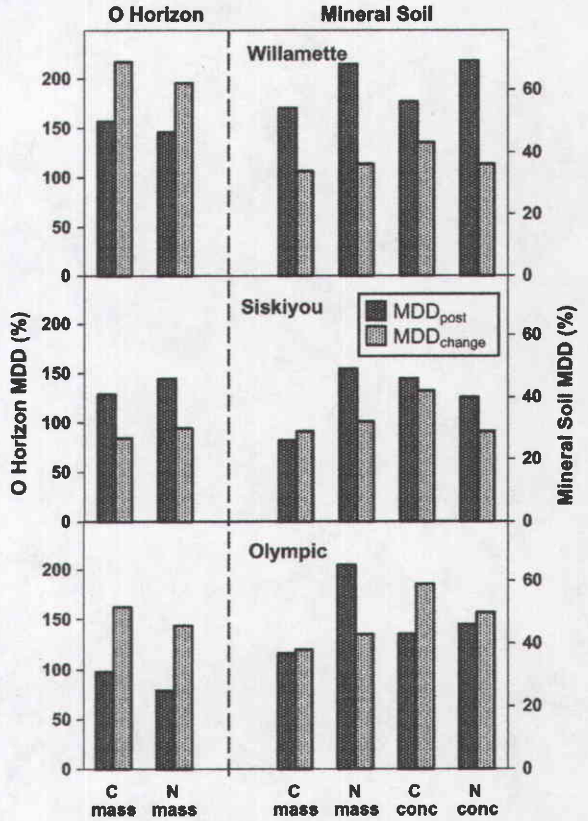

Fig. 3. The minimum detectable differences for a single post-treatment sampling (MDD_{post}) and for a change between pre- and post-treatment samplings (MDD_{change}). Note the different scales for O-horizon and mineral soil.

3.3. Minimum detectable differences

To enhance the probability of detecting a treatment effect, consideration of different sampling strategies is appropriate. Treatment differences may be examined at a single post-treatment point in time (MDD_{post}), or by evaluating changes, which may be assessed with different pre- to post-treatment sampling strategies (MDD_{change} and $MDD_{change*}$).

Compared with evaluating treatment differences at a single point in time (MDD_{post}), assessing change (MDD_{change}) decreases MDD by half for Willamette mineral soil N mass and N concentration (Fig. 3). For other properties and sites there is less benefit (Fig. 3) of examining change. The difference between the two sampling strategies is related to variability at two spatial scales. The higher the s_{block}/s_{plot} ratio, the lower the MDD_{change} relative to MDD_{post} (Fig. 4), and the more advantageous it is to examine change rather than only post-treatment values. A high s_{block}/s_{plot} ratio indicates there is substantial pre-treatment variability among plots within a block, and accounting for this by pre-treatment sampling is advantageous. Conversely, if plots within a block are quite similar, as indicated by a s_{block}/s_{plot} ratio approaching 1, pre-treatment sampling does not offer an advantage in detecting treatment differences. Low ratios lead to two interesting and counterintuitive outcomes. First, a s_{block}/s_{plot} ratio less than 1 (Fig. 4) would incorrectly suggest that there can be less variability within a block than within the plots that make it up. Low ratio values occur because of the formulae for sample statistics. The formula for s_{block} uses greater degrees of freedom in the denominator (total sampling points minus 1) than the formula for the pooled s_{plot} (total sampling points minus

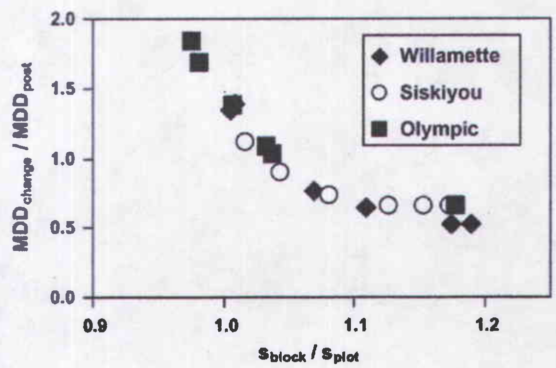

Fig. 4. The relation of relative minimum detectable differences (MDD_{change}/MDD_{post}) to relative variability at two spatial scales (s_{block}/s_{plot}). Each point is a soil C or N property from one of the three sites. The larger the pre-treatment within-block variability (s_{block}) compared to within-plot variability (s_{plot}), the greater the reduction in MDD by examining pre- to post-treatment change (MDD_{change}) compared to measuring only post-treatment values (MDD_{post}).

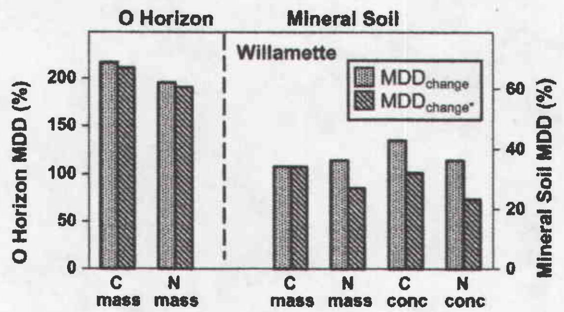

Fig. 5. The minimum detectable differences based on pre- and post-treatment sampling of independent subplots (MDD_{change}) vs. resampling the same subplots ($MDD_{change*}$). Note the different scales for O-horizon and mineral soil.

number of plots), resulting in lower s_{block} when the numerators are similar. Second, at $s_{block}/s_{plot} < 1.03$, the MDD_{change}/MDD_{post} ratio exceeds 1, suggesting that assessing change would increase, rather than decrease, the MDD. This occurs because the resampling analysis incorporates the measurement uncertainties of both the pre- and post-treatment samples, whereas the single sampling analysis has only the measurement uncertainty of the post-treatment samples (Homann et al., 2001a).

Compared with sampling independent subplots to examine change, resampling the same subplots resulted in a one-third reduction in MDD for Willamette mineral soil N concentration (Fig. 5). However, magnitude of improvements for other soil properties varied, including essentially no improvement for O-horizon C and N masses and mineral soil C mass (Fig. 5). The magnitude of the response to resampling the same subplots is related to variability at two spatial scales. The larger the $s_{plot}/s_{subplot}$ ratio, the greater the reduction in MDD by resampling the same subplots, as indicated by the lower $MDD_{change*}/MDD_{change}$ ratio (Fig. 6). A high $s_{plot}/s_{subplot}$ ratio signifies lower variation within a subplot than across an entire plot; resampling within subplots takes advantage of this lower variation and leads to lower MDD. Conversely, when variability within a subplot is similar to that across an entire plot, resampling within a subplot does not confer an advantage.

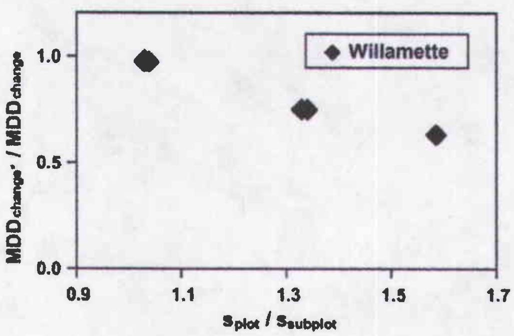

Fig. 6. The relation of relative minimum detectable differences ($MDD_{change*}/MDD_{change}$) to relative variability at two spatial scales ($s_{plot}/s_{subplot}$). Each point is a soil C or N property from the Willamette site. The larger the within-plot variability (s_{plot}) compared to within-subplot variability ($s_{subplot}$), the greater the reduction in MDD by pre- and post-treatment resampling of the same subplots ($MDD_{change*}$) compared to independent subplots (MDD_{change}).

These quantitative relations between MDDs and soil variability at multiple spatial scales provide a refined and expanded explanation of previous qualitative observations and forecasts (Homann et al., 2001a; Ellert et al., 2002; Conant et al., 2003; Yanai et al., 2003).

3.4. Potential changes and differences

The MDCs of our study will allow us to detect changes of the magnitude observed in other studies of forest disturbance and natural processes (Richter et al., 1994; Oliver et al., 2004; Zhou et al., 2006). For example, the N mass in O-horizon plus 45-cm mineral soil increased 32% (95% CI = 14–50%) in an Oregon Douglas-fir/red alder stand over 19 years (Rothe et al., 2002). The C concentration in the upper 10 cm of mineral soil increased 73% (95% CI = 33–127%) in an aggrading Tennessee hardwood forest over 26 years (Kelly and Mays, 2005). The C concentrations in the upper 15 cm of mineral soil increased ~20% in both harvested and mature mixed oak forest over 16 years (Johnson and Todd, 1998). In southern hardwood forests, both increases and decreases in soil C and N occurred (Trettin et al., 1999). Interannual variation of up to 50% occurred in C and N concentrations in the upper 10 cm of mineral soil in regenerating hardwood forests (Knoepp and Swank, 1997). In contrast, other studies have not detected changes in forest soil C and N (Johnson et al., 1995, 2003).

Detectable differences between treatments are unlikely in the near-term (<5 years). The C and N in foliage and branches (Cole et al., 1992) deposited during thinning and harvesting operations are small compared with the large MDDs for O-horizons, precluding the detection of immediate treatment differences. In contrast, different vegetation treatments may be discernible in several decades (Bormann et al., 1994; Rothe et al., 2002).

3.5. Applying and improving MDCs and MDDs

Our analysis provides valuable perspective when selecting a sampling design—beyond the general guidance of "take more samples". We demonstrate the quantitative advantages of one sampling design vs. another (Figs. 3–6), which can be weighed against their costs and challenges. For example, soil nitrogen dynamics are important in our long-term productivity study. The MDD for mineral soil N mass is substantially lowered by examining change (Fig. 3), and even further by resampling the same subplots (Fig. 5). To implement these resampling approaches, substantial costs are incurred to document and archive sampling protocols in sufficient detail that they can be reproduced years or decades later, to archive pre-treatment soil samples under stable conditions for later comparison with post-treatment soil samples, and to accurately relocate pre-treatment sampling points years or decades later. Because of the potential benefits, we prepared for such challenges by installing professionally surveyed permanent plot corners and semi-permanent grids, developing detailed documentation and protocols for long-term resampling, and archiving >3000 soil samples. Other studies may choose less intensive approaches, depending on specific project goals, soil properties of interest, and trade-offs between costs of various sampling designs and their potential quantitative benefits.

Our MDCs and MDDs, developed from comprehensive pre-treatment soil sampling, will be most useful to guide timing of future post-treatment sampling. In combination with projected rates of soil change (Conen et al., 2003; Smith, 2004), MDCs and MDDs can be used to forecast when sufficient time will have transpired to observe anticipated changes and differences. The future sampling will ultimately determine the validity of those projections. In contrast, MDCs and MDDs developed during the study-design phase are based on previous studies or low-intensity preliminary sampling and allow addressing issues of replication and sampling intensity. MDCs and MDDs calculated after termination of an experiment indicate the magnitudes of change or differences that could have occurred but were not detectable (Homann et al., 2001b).

MDCs and MDDs may be improved by increasing their accuracies. Many studies have used pre-treatment measurements to forecast MDCs and MDDs (Huntington et al., 1988; Garten and Wullschleger, 1999; Homann et al., 2001a; Conant et al., 2003; Yanai et al., 2003), under the implicit assumption that pre-treatment and future variances are the same. But, future sampling may reveal that a treatment has altered the variance. For example, whole-tree harvesting of a small northeastern USA watershed increased variances of the O-horizon C and N masses up to three-fold (Huntington and Ryan, 1990). In our study, resampling several Siskiyou experimental units six years after treatment showed no change in variance for five of the six soil C and N properties we evaluated; in contrast, the observed increase in variance for O-horizon C mass would increase the MDC by about one-third. Refinements such as this enhance the accuracy of MDC estimates and thus their applicability to experimental and sampling design.

Selection of appropriate sampling techniques and soil variables may allow smaller changes and differences to be detected. The use of large soil cores and small soil pits of known area and volume (this study) and other area-based approaches (Johnson et al., 1990; Ellert et al., 2002) allows a more accurate assessment of C and N pools and their uncertainties than the use of C and N concentrations from one set of sampling points, and rock volumes and/or bulk densities from other points or from other studies. Further, the evaluation of pools rather than concentrations can improve sensitivity of detecting differences and changes. In our study, MDDs and MDCs are consistently lower for mineral soil C pools than for C concentrations (Figs. 2 and 3), except for Willamette $MDD_{change*}$ (Fig. 5).

Ellert et al. (2002) suggested that even greater sensitivity could be achieved with area-based sampling by using an equivalent-soil mass basis rather than a depth basis for calculating soil C and N pools. We previously evaluated the equivalent-soil mass basis for the Siskiyou site, but results were inconsistent, sometimes lowering MDDs and sometimes increasing them (Homann et al., 2001a). Although conceptually appealing to account for compaction or expansion of soils, the equivalent-mass basis may be less advantageous in the rocky and wood-containing forest soils of our study compared to the rock-free agricultural soils of Ellert et al. (2002). Spatial variability of rocks and woody roots may confound the assessment of compaction or expansion.

Geostatistical approaches may lead to better estimates of variances within experimental units (Okae-Anti and Ogoe, 2006; Mooney et al., 2007), thereby allowing improved estimates of MDCs and MDDs. However, such approaches are likely to require very intensive sampling across a broad range of spatial scales to develop realistic semivariograms, and the additional sampling intensity may preclude their use in large-scale studies such as ours. In the absence of complete semivariograms, our analysis of variability at three spatial scales – subplot, plot, and block – bridges the gap between classical and geostatistical approaches to demonstrate the relations between variability at multiple spatial scales and detection of change and treatment differences (Figs. 4 and 6).

4. Conclusions

Our study substantially expands previous considerations of MDCs and MDDs in forest soils. In particular, we address the complexity of a multi-treatment experiment; consider multiple relevant MDCs and MDDs; evaluate both soil C and N in both the O-horizon and surface mineral soil; and provide the quantitative link among MDDs, MDCs, and soil variability at multiple spatial scales.

Complex forest experiments simultaneously address multiple questions: Will there be change? Will there be differences? Will there be differences in change? To enhance the efficacy of answering these questions, consideration of several relevant MDCs and MDDs is warranted when designing, implementing and interpreting complex experiments. MDCs and MDDs based on comprehensive pre-treatment soil sampling, combined with forecasted rates of change, can guide the timing and type of effective post-treatment sampling.

The detection of changes and treatment differences are reciprocally linked. Mineral soil C and N changes of ~10% may be detected in our long-term ecosystem productivity experiment, if the various vegetation and woody debris treatments have similar influences on the soil. These subtle changes are relevant in understanding soil C budgets, soil fertility, and how climate change influences soils. However, if soil responses differ between treatments, individual treatment changes would be detected only if they exceeded ~30%.

Detecting differences among treatments may be improved by examining pre- to post-treatment change rather than only post-treatment values, but the magnitude of the improvement varies substantially among soil properties and sites. Greater improvement occurs when there is larger pre-treatment variability among experimental units, and smaller variability within subplots than within experimental units. Information at multiple spatial scales – block, experimental unit, and subplot – allows quantifying the relative benefits of various sampling designs, which can be weighed against costs and challenges to select the most appropriate approach.

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References

Bormann, B.T., Cromack Jr., K., Russell III, W.O., 1994. Influences of red alder on soils and long-term ecosystem productivity. In: Hibbs, D.E., DeBell, D.S., Tarrant, R.F. (Eds.), The Biology and Management of Red Alder. Oregon State University Press, Corvallis, OR, pp. 47–56.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen—total. In: Page, A.L., et al. (Eds.), Methods of Soil Analysis. Part 2, second ed., Agron. Monogr. 9. American Society of Agronomy, Madison, WI, pp. 595–624.

Cole, D.W., Van Miegroet, H., Homann, P.S., 1992. Biomass, nutrient content of the Douglas fir (DF) site. In: Johnson, D.W., Lindberg, S.E. (Eds.), Atmospheric Deposition and Forest Nutrient Cycling. Springer-Verlag, New York, p. 614.

Conant, R.T., Smith, G.R., Paustian, K., 2003. Spatial variability of soil carbon in forested and cultivated sites: implications for change detection. J. Environ. Qual. 32, 278–286.

Conen, F., Yakutin, M.V., Sambuu, A.D., 2003. Potential for detecting changes in soil organic carbon concentrations resulting from climate change. Global Change Biol. 9, 1515–1520.

Cromack Jr., K., Miller, R.E., Helgerson, O.T., Smith, R.B., Anderson, H.W., 1999. Soil carbon and nutrients in a coastal Oregon Douglas-fir plantation with red alder. Soil Sci. Soc. Am. J. 63, 232–239.

Ellert, B.H., Janzen, H.H., Entz, T., 2002. Assessment of a method to measure temporal change in soil carbon storage. Soil Sci. Soc. Am. J. 66, 1687–1695.

Garten Jr., C.T., Wullschleger, S.D., 1999. Soil carbon inventories under a bioenergy crop (switchgrass): measurement limitations. J. Environ. Qual. 28, 1359–1365.

Gingrich, S., Erb, K.-H., Krausmann, F., Gaube, V., Haberl, H., 2007. Long-term dynamics of terrestrial carbon stocks in Austria: a comprehensive assessment of the time period from 1830 to 2000. Reg. Environ. Change 7, 37–47.

Grigal, D.F., McRoberts, R.E., Ohmann, L.F., 1991. Spatial variation in chemical properties of forest floor and surface mineral soil in the north central United States. Soil Sci. 151, 282–290.

Homann, P.S., Bormann, B.T., Boyle, J.R., 2001a. Detecting treatment differences in soil carbon and nitrogen resulting from forest manipulations. Soil Sci. Soc. Am. J. 65, 463–469.

Homann, P.S., Caldwell, B.A., Chappell, H.N., Sollins, P., Swanston, C.W., 2001b. Douglas-fir soil C and N properties a decade after termination of urea fertilization. Can. J. For. Res. 31, 2225–2236.

Homann, P.S., Remillard, S.M., Harmon, M.E., Bormann, B.T., 2004. Carbon storage in coarse and fine fractions of Pacific Northwest old-growth forest soils. Soil Sci. Soc. Am. J. 68, 2023–2030.

Huntington, T.G., Ryan, D.F., 1990. Whole-tree harvesting effects on soil nitrogen and carbon. For. Ecol. Manage. 31, 193–204.

Huntington, T.G., Ryan, D.F., Hamburg, S.P., 1988. Estimating soil nitrogen and carbon pools in a northern hardwood forest ecosystem. Soil Sci. Soc. Am. J. 52, 1162–1167.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, 253–268.

Johnson, C.E., Johnson, A.H., Huntington, T.G., 1990. Sample size requirements for the determination of changes in soil nutrient pools. Soil Sci. 150, 637–644.

Johnson, C.E., Driscoll, C.T., Fahey, T.J., Siccama, T.G., Hughes, J.W., 1995. Carbon dynamics following clear-cutting of a northern hardwood forest. In: McFee, W.W., Kelly, J.M. (Eds.), Carbon Forms and Functions in Forest Soils. Soil Science Society of America, Madison, WI, pp. 463–488.

Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. For. Ecol. Manage. 140, 227–238.

Johnson, D.W., Todd Jr., D.E., 1998. Harvesting effects on long-term changes in nutrient pools of mixed oak forest. Soil Sci. Soc. Am. J. 62, 1725–1735.

Johnson, D.W., Todd Jr., D.E., Tolbert, V.R., 2003. Changes in ecosystem carbon and nitrogen in a loblolly pine plantation over the first 18 years. Soil Sci. Soc. Am. J. 67, 1594–1601.

Kelly, J.M., Mays, P.A., 2005. Soil carbon changes after 26 years in a Cumberland Plateau hardwood forest. Soil Sci. Soc. Am. J. 69, 691–694.

Kirwan, N., Oliver, M.A., Moffat, A.J., Morgan, G.W., 2005. Sampling the soil in long-term forest plots: the implications of spatial variation. Environ. Monit. Assess. 111, 149–172.

Knoepp, J.D., Swank, W.T., 1997. Forest management effects on surface soil carbon and nitrogen. Soil Sci. Soc. Am. J. 61, 928–935.

Lal, R., 2005. Forest soils and carbon sequestration. For. Ecol. Manage. 230, 242–258.

Little, R.L., Peterson, D.L., Silsbee, D.G., Shainsky, L.J., Bednar, L.F., 1995. Radial growth patterns and the effects of climate on second-growth Douglas-fir (*Pseudotsuga menziesii*) in the Siskiyou Mountains, Oregon. Can. J. For. Res. 25, 724–735.

Mooney, S., Gerow, K., Antle, J., Capalbo, S., Paustian, K., 2007. Reducing standard errors by incorporating spatial autocorrelation into a measurement scheme for soil carbon credits. Climat. Change 80, 55–72.

Okae-Anti, D., Ogoe, J.I., 2006. Analysis of variability of some properties of a semideciduous forest soil. Commun. Soil Sci. Plant Anal. 37, 211–223.

Oliver, G.R., Beets, P.N., Garrett, L.G., Pearce, S.H., Kimberly, M.O., Ford-Robertson, J.B., Robertson, K.A., 2004. Variation in soil carbon in pine plantations and implications for monitoring soil carbon stocks in relations to land-use change and forest site management in New Zealand. For. Ecol. Manage. 203, 283–295.

Post, W.M., Izaurralde, R.C., Mann, L.K., Bliss, N., 2001. Monitoring and verifying changes of organic carbon in soil. Climat. Change 51, 73–99.

Richter, D.D., Wells, C.G., Markewitz, D., Allen, H.L., April, R., Heine, P.R., Urrego, B., 1994. Soil chemical change during three decades in a loblolly pine (Pinus taeda L.) ecosystem. Ecology 75, 1463–1473.

Rothe, A., Cromack Jr., K., Resh, S.C., Makineci, E., Son, Y., 2002. Soil carbon and nitrogen changes under Douglas-fir with and without red alder. Soil Sci. Soc. Am. J. 66, 1988–1995.

Schoning, I., Totsche, K.U., Kogel-Knabner, I., 2006. Small scale spatial variability of organic carbon stocks in litter and solum of a forested Luvisol. Geoderma 136, 631–642.

Smith, P., 2004. How long before a change in soil organic carbon can be detected? Global Change Biol. 10, 1878–1883.

Swanston, C., Homann, P.S., Caldwell, B.A., Myrold, D.D., Ganio, L., Sollins, P., 2004. Long-term effects of elevated nitrogen on forest soil organic matter stability. Biogeochemistry 70, 227–250.

Trettin, C.C., Johnson, D.W., Todd Jr., D.E., 1999. Forest nutrient and carbon pools at Walker Branch Watershed: changes during a 21-year period. Soil Sci. Soc. Am. J. 63, 1436–1448.

Woodbury, P.B., Smith, J.E., Heath, L.S., 2007. Carbon sequestration in the U.S. forest sector from 1990 to 2010. For. Ecol. Manage. 241, 14–27.

Yanai, R.D., Stehman, S.V., Arthur, M.A., Prescott, C.E., Friedland, A.J., Siccama, T.G., Binkley, D., 2003. Detecting change in forest floor carbon. Soil Sci. Soc. Am. J. 67, 1583–1593.

Zar, J.H., 1999. Biostatistical Analysis, fourth ed. Prentice Hall, Upper Saddle River, NJ.

Zhou, G., Liu, S., Li, Z., Zhang, D., Tang, X., Zhou, C., Yan, J., Mo, J., 2006. Old-growth forests can accumulate carbon in soils. Science 314, 1417.