Carbon and nitrogen storage following repeated urea fertilization of a second growth Douglas-fir stand in western Washington

by

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ABSTRACT

Carbon and nitrogen storage following repeated urea fertilization of a second growth Douglas-fir stand in western Washington

by Jana D. Canary

Chairperson of the Supervisory Committee: Associate Professor Robert B. Harrison
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Burning of fossil fuels and land use changes continue to raise the levels of CO_2 in the Earth's atmosphere. It has been suggested that increasing the C sequestered in forest systems through fertilization could reduce atmospheric CO_2 levels and mitigate potential global change (Johnson and Kern, 1991; Smith et al., 1993). Three, 62-69 year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands in western Washington, originally established as forest fertilization research sites, were used to test this possibility. The sites contained control plots, as well as treated plots which received 448 kg/ha of urea-N in 1969, and 224 kg/ha in 1977 and 1981 for a total of 896 kg N/ha over a 12 year period. One site received an additional 224 kg/ha of urea-N in 1985 for a total of 1120 kg/ha over a 16 year period.

In the spring of 1993, three soil pits at each plot were excavated to a depth of 85 cm. Determining bulk density in rocky forest soils is difficult, therefore individual horizons were excavated and horizon volumes calculated using a grid system. Samples were taken at specific depths and analyzed for total C and N. The non-parametric, Wilcoxan distribution-free signed rank test was used to analyze the data.

There was significantly ($p=0.125$) more C stored in the sum of all forest system components of the fertilized plots. There was also significantly more C stored in the live trees and snags of the fertilized plots. There was no significant difference between the understory vegetation, coarse woody debris, and all sampled soil horizons

and depths to 85 cm ha in the control and fertilized plots. On average, the entire forest system of the fertilized plots contained 13.8% more C than the control plots (527 vs. 463 Mg of C ha^{-1})(p=0.125). When CWD was excluded the fertilized plots contained 19.2% more C than the control plots (502 vs. 421 Mg of C ha^{-1}).

A large portion of soil C was found below the surface soil to 85 cm. When sampling to a depth of 85 cm, 71% of soil C was found below the A horizon and 40% below 25 cm. This illustrates how failing to sample at depth can grossly underestimate soil C.

In the past 10 years there have been between 40,000 and 60,000 hectares of commercial forest land in Washington and Oregon have been fertilized annually with N fertilizer. The data from this study suggests that this fertilization would increase C stored in these forest ecosystems.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Introduction

Greenhouse gases play an important role in sustaining life on Earth. These gases are more transparent to the short-wave radiation of the sun than they are to the long-wave radiation of the energy reradiated from the Earth and without them the Earth's average temperature would be 33°(C) cooler (Houghton, 1991). Human activities, such as the burning of fossil fuels and changes in land use, have raised the atmospheric CO_2 levels (Gammon et al., 1986; Oeschger and Stauffer, 1986; Houghton, 1986). Several models have been developed to predict how elevated CO_2 levels in the atmosphere would affect global temperatures and weather patterns. Different models give conflicting predictions because of factors such as the changes in evaporation from the oceans, changes in cloud cover, and interactions of CO_2 with other atmospheric constituents. Although it is unclear how higher concentrations of greenhouse gases would affect the global climate, accelerated global climate change is a possibility. Because a rapid climate change could have an adverse effect on delicate ecosystems, slowing the increase of CO_2 in the Earth's atmosphere has been a goal of both policy makers and scientists in recent years.

It has been suggested that by increasing the productivity of forest systems, more C may be removed from the atmosphere and stored in the terrestrial systems (Sedjo, 1989; Johnson and Kern, 1991; Smith et al., 1993; Dixon et al., 1994). Forests are often growing below their potential productivity level and show increased productivity after N fertilization, thus increasing C stored in plant biomass. If forest productivity is increased, there may also be an increase in C stored in the forest soil. Increased storage of C in soils would be important as they have a much longer potential storage time than live trees. Organic matter stored in soils may remain there for hundreds or thousands of years (Wilding et al., 1983).

The purpose of this study was: 1) to quantify C sequestered in control and urea fertilized, 62-69 year-old Douglas-fir stands which showed significant aboveground growth after urea fertilization, and 2) to determine whether urea fertilized stands sequestered more C in live trees, snags, understory vegetation, coarse woody debris (CWD), forest floor, and mineral soil than corresponding adjacent control stands.

Literature Review

Global C cycle

The global C cycle has three main reservoirs: the atmosphere, the oceans, and the terrestrial system (figure 1). In 1958 Charles Keeling began work at the Mauna Loa Observatory in Hawaii which continues to provide accurate estimates of atmospheric C. When the study began the atmosphere contained 315 μL of CO_2 L^{-1} of air. By 1988 the level had risen to 351 μL of CO_2 L^{-1} of air. (Post et al., 1990) In addition, atmospheric CO_2 levels of the past have been estimated by analyzing air trapped in polar ice cores. The ice core records agree with the Mauna Loa records of preindustrial (1750-1800) atmospheric CO_2 levels which were estimated to be about 279 μL of CO_2 L^{-1} of air (Post et al., 1990).

The oceans play a large role in determining the CO_2 content in the atmosphere (figure 1). In the surface waters of the oceans, atmospheric CO_2 is consumed during photosynthesis. Some of the organic and inorganic C created during this process sink, removing C from the surface waters. To maintain equilibrium, CO_2 from the atmosphere dissolves into the surface waters. Carbon is also carried into deeper waters when atmospheric CO_2 comes in contact with the cool, dense waters of the polar regions and sinks. Over time carbon is cycled back out of the deep waters through upwelling in tropical latitudes and, on a large time scale, through volcanic eruptions after subduction and metamorphism of sedimentary rocks and through the dissolution of limestone (Post et al., 1990; Schlesinger, 1991).

On land, CO_2 is also transferred from the atmosphere to the terrestrial system through the process of photosynthesis (Figure 1). Terrestrial C is stored mainly in living plant material, organic debris, and soil organic material. Burning, plant respiration, and the decay of residues release terrestrial C to the atmosphere. Some C

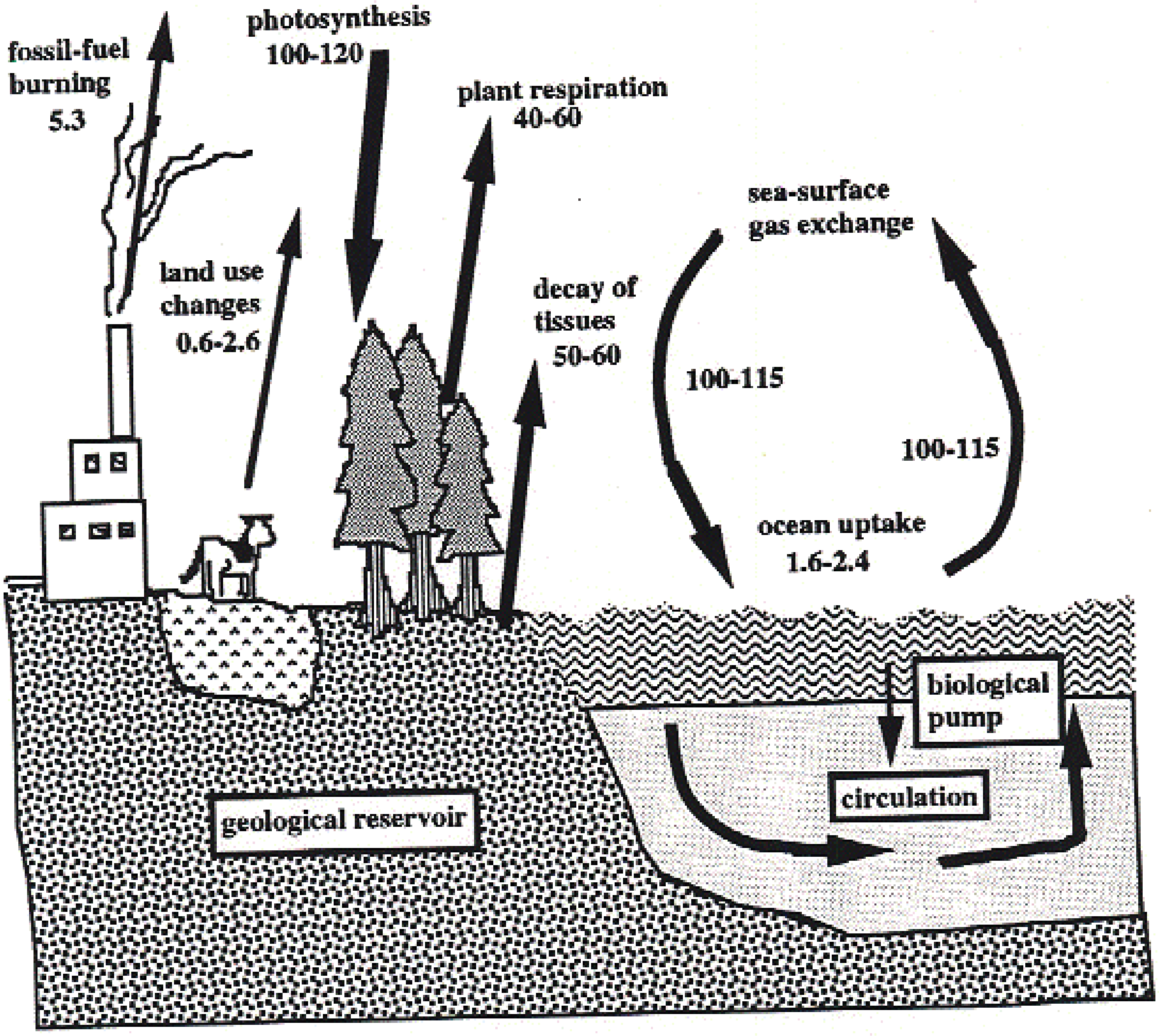

Figure 1. The global carbon cycle. All fluxes are 1980 estimates, in petagrams. Adopted from Post et al., 1990.

is transported to the oceans through organic material entering streams and rivers (Downing et al., 1993) and through the leaching of dissolved organic C into ground water. There is an estimated 2000 Pg (10^{15} g) of C contained in the Earth's terrestrial system (Johnson and Kern, 1991; Smith et al., 1993). Forest systems have been estimated to contain about 1146 Pg of C, with about 787 Pg in forest soils (Dixon et al., 1994).

Increasing C sequestration in forest systems through N fertilization

Forest growth is often limited by nutrient deficiencies. Therefore, fertilization could increase productivity and C sequestration. A review by Johnson (1992) cited several studies which observed increases in tree biomass and soil C after N fertilization. Van Cleve and Moore (1978) found increases in both tree growth and soil organic matter after the addition of N and P fertilizers to quaking aspen stands in Alaska (*Populus tremuloides*, Michx.). They also observed an increase in soil biological activity attributed to increased soil organic matter and higher levels of soil N and P. Nohrstedt et al. (1989) also found increases in soil C and productivity of pine forests in Sweden after N fertilization. They found an increase of 10-26% in absolute amount of C per square meter of forest floor (including L, F, H and A1). Baker et al (1986) compared the growth of *Pinus radiata* D. Don on sand dunes in New Zealand when either a mixed fertilizer (including N, P, K, S, Ca and Mg) was added, or when lupine (*Lupinus arboreus* Sims), a N-fixing species was initially present, or both. The tree growth was initially increased by all treatments, but after 14 years of growth only the fertilizer or fertilizer plus lupine treatments continued to increase tree growth. The tree growth in the lupine only treatment stand was similar to the control stand. The fertilizer treated area had a statistically significant increase in soil C, while the lupine and lupine plus fertilizer treatments also showed increases in soil C but they were not statistically significant. Johnson (1992) noted several studies which found increases in soil C with the presence of N-fixing species (Tarrant and Miller, 1963; Binkley et al., 1982; Binkley, 1983; Binkley and Sollins, 1990; Brozek, 1990). Johnson also noted that the presence of N-fixing species generally increased soil C more than fertilization. Nilsson (1993) found increased C sequestration in Norway spruce (*Picea abies* (L.) Karsst) aboveground biomass after N-S fertilization (ammonium sulfate), but soil C was not measured. Others found no increase in soil C after either the presence of N-fixing species (Paschke, 1989) or after N fertilization (Harding and Jokela, 1994).

Nitrogen fertilization in western Washington and Oregon

Western Washington and Oregon have a wet, mild, maritime climate. Although the area is considered wet, with about 1500 to 3000 mm of precipitation per year, the summers are dry with less than 10% of the precipitation falling during this season. Mean annual temperatures average 8° to 9° C., with no temperature extremes in any season (Franklin and Dryness, 1988). This region is predominantly covered by vegetation classified as the *Tsuga heterophylla* Zone. Although this zone is named for the climax species, it is dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), often with some mixture of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* Donn. Red) (Franklin and Dryness, 1988). Nitrogen fertilization of low productivity Douglas-fir stands in the *Tsuga heterophylla* Zone is known to boost stand productivity (Barclay and Brix, 1985; Stegemoeller and Chappell, 1989). To date, there have been no published studies comparing the C sequestration in the vegetation, detritus and soil organic matter of urea fertilized and unfertilized stands in the *Tsuga heterophylla* Zone.

Factors affecting C sequestration after N fertilization

Foliage biomass and litter inputs

An increase in tree growth rates after N fertilization increases C sequestered in tree biomass. Increased tree growth could also affect foliage and litter biomass. If foliage production is increased through N fertilization, litterfall could increase, thus increasing the input of C to the forest floor. Increases in foliage biomass after N fertilization of Douglas-fir stands have been observed (Heilman and Gessel, 1963; Turner, 1977; Friedman-Thomas, 1986; Pang et al., 1987; Gower et al., 1992). Trofynow (1991) found a depression of litter in the first year of fertilization, an increase of 20- 80% above control levels in the second year, and then a slow decline to control levels over time. Prescott et al. (1993) found significantly more litterfall in one of two plots 10 years after N fertilization. Brix (1983) found a relationship between increased stem growth and leaf area index before crown closure in a Douglas-fir forest after N fertilization. Turner (1975) found that foliage biomass reached a steady state after crown closure (between ages 36 and 49).

Foliage and litter N concentrations

Foliage and litter N concentrations may also increase with N fertilization in Douglas-fir stands. An increase in the concentration of N in the litter inputs to the forest floor could lower C/N ratios and increase decomposition rates and N availability to plants. An increase in decomposition would reduce the amount of C in the soil. However, increased N availability to plants could increase plant growth and litter inputs to the soil, thus increasing soil C. Heilman and Gessel (1963) and Turner (1977) found higher foliage N concentrations while Pang et al. (1987) found lower concentrations after N fertilization. Turner (1977), Trofynow (1991), and Prescott et al. (1993) all found higher N concentrations in litter of N fertilized Douglas-fir stands.

Trofynow observed a decrease in litter N concentrations to near control levels 3-6 years after treatment. Prescott observed higher concentration of N in the litter at two plots, one of which was significantly higher, 10 years after N fertilization.

Decomposition rates and the N cycle

Changes in both litter quantity and quality could affect the rate of decomposition and the amount of C sequestered in the soil. As decomposition occurs, C is released to the atmosphere as CO_2. In substrates with high C:N ratios, any N is immobilized by the decomposers. As C:N ratios are reduced through the release of CO_2, the competition for N among microbes lessens. Because N is no longer tied up in microbial biomass, the NH_4^+ mineralized is available to higher plants (Figure 2). Nitrogen may be lost from the soil system through direct volatilization of NH_4^+ to NH_3 gas. Nitrogen can also be lost through oxidation of $NH4^+$ to NO_3^- followed by denitrification of NO_3^- to N_2 or N_2O gas, or through leaching of water soluble NO_3 (Binkley, 1986; Brady, 1990). Although little research has been done on the subject, denitrification is thought to be uncommon in coniferous forests of the Pacific Northwest because the forests are N limited (Blew, 1993).

If N fertilization increases the litter inputs and litter N concentration, microbial activity would be expected to increase. If the decomposition rates increase to the point that additional C from litter inputs is consumed and released to the atmosphere, less C would be sequestered in the forest system. Evidence has been found of increased decomposition after N fertilization (Turner, 1977; Van Cleve and Moore, 1978;). Microbial activity in N fertilized stands has also been observed to be similar (Theodorou and Bowen, 1990; Prescott et al., 1992; Prescott et al., 1993) or retarded (Nohrstedt et al., 1988) when compared to control sites. Also, with an increase in litter N concentrations, the immobilization time of N by microbes could decrease. An acceleration of N mineralization could increase the amount of available N, potentially increasing productivity and increasing C stored in tree biomass. Although Prescott et al. (1993) found increased N in the litter of Douglas-fir stands 10 years after fertilization, they found no difference in microbial activity and N turnover.

Belowground productivity

Nitrogen fertilization may also affect belowground productivity. A change in annual belowground production of fine roots would affect the amount of C sequestered in the soil. Friedman-Thomas (1986) compared the fine root and mycorrhizal production at another urea fertilized, 50 year-old Douglas-fir RFNRP stand. Within four months of urea fertilization, total fine root and mycorrhizal biomass in the fertilized plot was 35% lower than in the control plot. Decreased fine roots and mycorrhizal biomass would decrease C inputs to the soil. Friedman-Thomas did observe an increase in aboveground productivity however, and larger trees would probably produce more large root biomass. This was observed by Keyes and Grier (1981) who compared belowground productivity in 40 year-old Douglas-fir stands on low and high aboveground productivity sites. Keyes and Grier found that although the high productivity sites had "less annual belowground dry matter biomass" (8.1 t ha^{-1} in low productivity vs. 4.1 t ha^{-1} in high productivity), they contained more total root biomass (57.6 t ha^{-1} in low productivity vs. 88.1 t ha^{-1} in high productivity). Annual fine root turnover in the low productivity sites was higher (5.2 t ha^{-1} in low productivity vs. 1.6 t ha^{-1} in high productivity), but because of variability it was not significant. In contrast to these studies, Vogt et al. (1983) found that during and following canopy closure, high productivity Douglas-fir stands had significantly more live fine conifer root biomass in the forest floor than less productive sites. They found

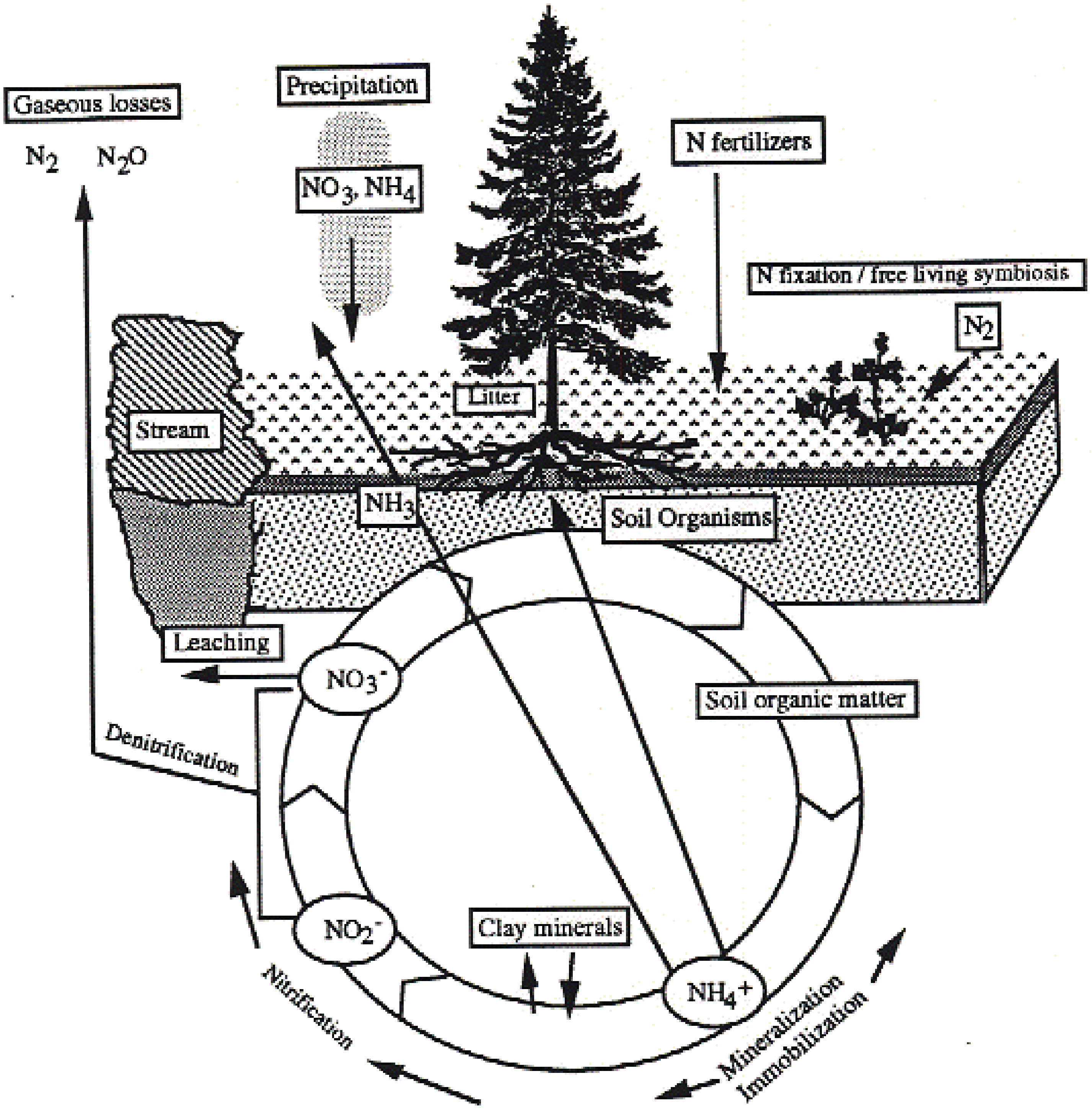

Figure 2. Nitrogen cycle of a coniferous forest ecosystem. Adapted from Brady, 1992.

that after canopy closure, root biomass decreased significantly in only the low productivity stands. They observed less root turnover in the low productivity stands.

Methods

Site description

The study sites were located in the Cascade Mountains of western Washington, U.S.A. Sites 1 and 2 were in the Cedar River Watershed (121° 45', 47° 40') and Site 3 was near the town of Skykomish (121° 15', 47° 45'). (Figure 3) These sites were located in the *Tsuga heterophylla* Zone described by Franklin and Dyrness (1988). Stands at sites 1 and 2 contained (by basal area) over 90% Douglas-fir, with the remaining trees being western hemlock. The stand at site 3 contained 51% Douglas-fir, 35% western hemlock and 14% western redcedar.

Table 1 contains a description of the site understories. Understory vegetation at sites 1 and 2 was much denser than at site 3. Stumps and charcoal found at all sites indicate that these areas were previously logged and burned. Re-establishment probably occurred by natural regeneration, although this is not known for certain. Stands were unthinned. Table 2 contains additional site information.

Soil description

Soils of site 1 were described by the Soil Conservation Service (1973) as Inceptisols of the Alderwood series, a dystric entic Durochrept. Alderwood soils were formed from glacial deposits. They are moderately to well drained with a weakly to strongly consolidated substratum at a depth of 60 to 100 cm. Site 3 was very flat with no detectable slope.

The soils of site 2 were described by the Soil Conservation Service (1973) also as Inceptisols but of the Everett series, a dystric Xerochrept. Everett soils were formed from very gravelly glacial outwash deposits. They are somewhat excessively

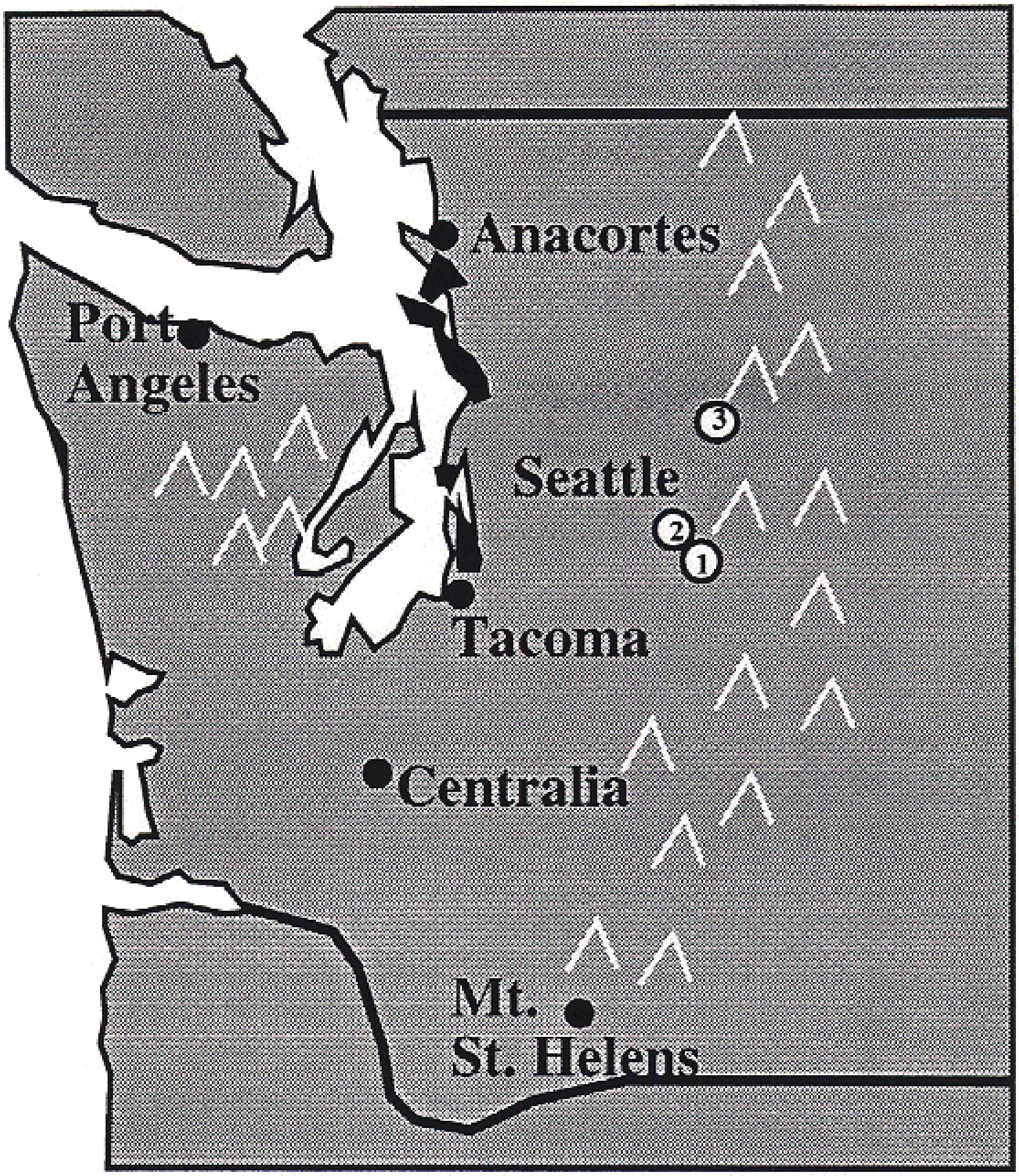

Figure 3. Map of western Washington with locations of study sites.

Table 1. Understory species found at study sites.

	Latin name	Common name
Site 1	*Berberis nervosa* Pursh	Oregongrape
	Eurynchium oreganum (Sull.)	Moss (from Turner Dissertation, 1975)
	Gaultheria shallon Pursh	Salal
	Polystichum munitum (Kaulf.) Presl	Sword-fern
	Vaccinium parvifolium Smith	Red huckleberry
Site 2	*Acer circinatum* Pursh	Vine maple
	Berberis nervosa Pursh	Oregongrape
	Eurynchium oreganum (Sull.)	Moss (from Turner Dissertation, 1975)
	Gaultheria shallon Pursh	Salal
	Holodiscus discolor (Pursh) Maxim.	Ocean-spray
	Linnaea borealis L.	Twinflower
	Menziesia ferruginea Smith	Fool's huckleberry
	Polystichum munitum (Kaulf.) Presl	Sword-fern
	Pteridium aquilinum (L.) Kuhn	Bracken fern
	Rubus ursinus Cham. & Schlecht.	Trailing blackberry
	Trillium ovatum Pursh	Trillium
	Tsuga heterophylla (Raf.) Sarg. (seedling)	Western hemlock
Site 3	*Berberis nervosa* Pursh	Oregongrape
	Eurynchium oreganum (Sull.)	Moss (from Turner Discertation, 1975)
	Pteridium aquilinum (L.) Kuhn	Bracken fern

TABLE 2. Site characteristics. Data taken from RFNRP report (unpublished), Stand Management Cooperative reports (unpublished), and Soil Conservation Service Soil Surveys (1973, 1992).

	site 1 control / treated	site 2 control / treated	site 3 control / treated
Site index (m @ 50 years)	34.7	30.8	26.2
Trees / ha, 1993	725 / 925	1350 / 1250	2125 / 1300
Quadratic mean dbh in cm, 1993	37 / 36	26 / 30	22 / 28
Age in 1993	67	62	69
Elevation (m)	344	274	457
Mean annual precipitation (mm)	2032	1778	2667
Soil series	Alderwood	Everett	Teneriffe
Location	S8 T22N R8E	S8 T22N R8E	S22 T22N R7E
	121° 45', 47° 40'	121° 45', 47° 40'	121° 15', 47° 45'

Table 3. Profile descriptions of soils at study sites.

Site 1. Alderwood, dystric entic Durochrept, slope 5%

Horizon	Depth (cm) in control	Depth (cm) in fertilized	Description
O	3.25-0	2.75-0	fresh and decomposed moss, needles, twigs, logs, etc.
A	0-4.75	0-4.00	10YR 2/3, gravelly loam
Bw1	4.75-18	4.00-18	10YR 3/3, very gravelly sandy loam
Bw2	18-48	18-48	10YR 3/4, very gravelly sandy loam
BC	48-85	48-depth	10YR 4/4, very gravelly, coarse OS?

Site 2. Everett, dystric Xerochrept, slope 10%

Horizon	Depth (cm) in control	Depth (cm) in fertilized	Description
O	2.75-0	3.00-0	fresh and decomposed moss, needles, twigs, logs, etc.
A	0-2.75	0-2.25	10YR 2/2, loam
Bw	2.75-25	2.25-25	10YR 3/3, gravelly sandy loam
BC	25-85	25-85	10YR 3/4, very gravelly sandy loam

Site 3. Teneriffe, typic Haplorthod, slope 10%

Horizon	Depth (cm) in control	Depth (cm) in fertilized	Description
O	5.25-0	2.25-0	fresh and decomposed moss, needles, twigs, logs, etc.
A	0-1.50	0-2.00	7.5YR 4/2, fine silt
E	1.5-7.25	2.00-4.00	7.5YR 6/2, fine silt
Bw1	7.25-34	4.00-34	10YR 4/6, sandy loam
Bw2	34-59	34-59	10YR 3/4, loamy sand
BC	59-85	59-85	10YR 4/4, loamy sand

drained soils that are underlain by very gravelly sand at a depth of 45 to 90 cm. Site 2 was also very flat with no detectable slope.

The soils of site 3 were described by the Soil Conservation Service (1992) as Spodosols of the Teneriffe series, a sandy-skeletal, mixed, frigid Typic Haplorthod. Teneriffe soils are deep, well drained soils formed in volcanic ash and pumice over colluvium derived from granitic and low-grade metamorphic rocks. In all pits at site 3 evidence of a buried soil at approximately 30 cm was found, which was also formed from volcanic ash and pumice shot. The source of the ash is most likely Glacier Peak, located north of the site. In one pit bedrock was reached at 85 cm. Both the control and fertilized plots were located on the summit of a flat-topped hill. This hill seemed to be formed from material resistant to the movement of the glaciers. Table 3 contains further description of these three soils.

Fertilization

All three sites were established by the RFNRP in 1969 as part of a N fertilization study. This previous study provided a number of study sites to chose from. At each site a control and two fertilized plots measuring 20 m by 20 m were installed. Plots were duplicated for a total of 6 plots at each site. This study utilized one control and one fertilized plot at the 3 sites selected. All of the sites selected originally had low productivity and responded to urea fertilization. .Douglas-fir stands in western Washington and Oregon have on average a 20% growth increase for 8 to 10 years after urea fertilization. This degree of response can be expected at 70% of fertilized sites, 95% of the time. (Chappell, 1992) All of the fertilized plots received 448 kg/ha of N in the form of urea in 1969, and 224 kg/ha of N in 1977 and 1981. The fertilized plot in site 3 received an additional 224 kg/ha of N in 1985. Sites 1 and 2 received a total of 896 kg/ha of N over 12 years while site 3 received a total of 1120 kg/ha of N over 16 years. Plot names were abbreviated as either ctrl for control or fert for fertilized, followed by the site number (i.e., fert-3, ctrl-2).

Soil sampling and calculations

Bulk density and gravel content

Soil samples were collected from February to April 1993. Because of the rocky nature of the soils at Sites 1 and 2, bulk density could not be determined using a soil core. Instead a method similar to the one described by Huntington et al. (1989) was used at all sites. Three pits at each plot were selected by locating 3 randomly selected coordinates on a 20 by 20 m grid. The pit excavation method was as follows. Each pit was excavated manually and measured 50 cm x 50 cm x 85 cm. The O (including moss), A, and E (when present) horizons were individually removed and all material brought back to the laboratory at the University of Washington. The B horizon was excavated by depth rather than by genetic horizon using the following sampling depths: the bottom of the A or E horizon to 25 cm, 25 to 55 cm and 55 to 85 cm (Figure 4). The B horizon was removed by measured depth rather than genetic horizon because during excavation it was nearly impossible to detect the difference between different B horizons. After each measured layer of the B horizon was excavated, the material was weighed using a hand-held scale, and representative, 7 L sub-samples brought back to the lab for bulk density analysis. After excavation, the horizon or layer volume was estimated by placing a grid with sixteen 12.5 cm x 12.5 cm squares over each pit and depths measured at the corners of each square. The volume of each box was determined by first averaging the depths at the four corners of the box; this average was then multiplied by 12.5 cm^2 (Figure 4). The volumes of the boxes were summed and upper horizon volumes subtracted to determine the horizon volume. When large rocks protruded from the pit wall, they and the material below them were not excavated and their volume was not included. The material excavated

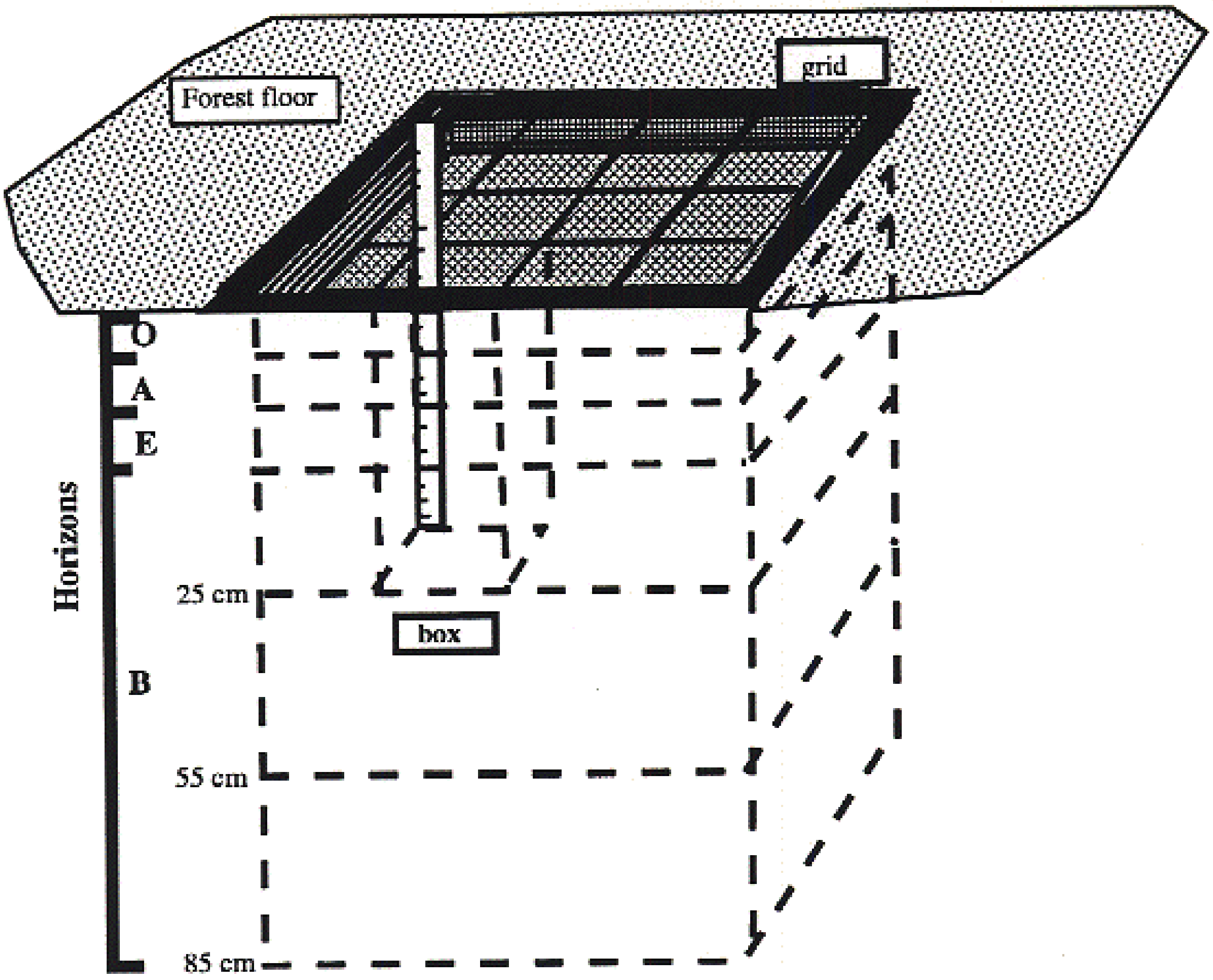

Figure 4. Diagram of the pit excavated to determine soil bulk density. Individual horizons and depths were removed. The horizon volumes were estimated by measuring the depth of each box and multiplying by the boxes known length and width (12.5 x 12.5 cm).

from the O, A and E horizons and the subsamples from the other layers were oven dried at 70°C. Because only a sub-sample of the layers was brought back, the oven dried weight of the entire material excavated had to be calculated. This was done by multiplying the wet weight of the entire material by the ratio of the dry subsample weight to the wet sub-sample weight. All but the O horizons were sieved to 2 mm and weighed. It was assumed that material >2 mm was inorganic, thus organic material which did not pass through the sieve was combined with the <2 mm material. Large tree roots were excluded because they were included in the tree biomass equations. The oven dried weight of the < 2 mm material in each layer was calculated.

Carbon and N concentrations and contents

An equal amount of material from the entire depth of each horizon or layer of each pit was sampled. Samples were oven dried at 70° C. O horizons were ground in a Wiley mill using a 1 mm sieve. All other samples were sieved to 2 mm and coarse tree roots removed. The < 2 mm material was finely ground with a mortar and pestle and analyzed for total C and N using a CHN analyzer (Perkin-Elmer 2400, Norwalk, CT). Equation 1 was used to determine the Mg of C ha^{-1} and kg of N ha^{-1} in the soil.

$$X = \frac{\text{Mg of oven dried} < 2\text{ mm material}}{\text{Horizon volume (m}^3\text{)}} * \frac{10{,}000\text{ m}^2}{1\text{ ha}} * \text{Horizon depth (m)} * \text{Soil \%C or \%N} \qquad [1]$$

Soil pH

Soil at 25° C was weighed and then mixed with deionized water in the following concentrations: O horizon 2g/ 20 ml, A horizon 5 g/ 25 ml, all other horizon material 5 g/ 10 ml. The solutions were left for 10 minutes and was measured according to the methods of McLean (1982).

Understory C

Six understory samples were taken at each plot in July, 1993. A metal frame one meter square was placed on the forest floor and all understory plants cut at the base. Roots were not sampled as they were included in the soil samples. Samples were oven dried at 70°C. Because many samples were very small, the six samples from each site were combined into 3 composite samples (2 original samples for each composite sample) and ground to 1 mm using a Wiley mill. Samples were analyzed for C concentration using a CHN analyzer. The C concentration of each composite sample was then applied to the separate weights of the 2 original samples.

Tree C

Live tree C

The dbh of all live trees on each plot was measured in July 1993 and their biomass, including coarse roots and foliage, estimated using allometric equations developed by Gholz et al. (1979). When allometric equations were unavailable to estimate the coarse roots or small trees of western redcedar or western hemlock the equations for Douglas-fir were used. The total live tree biomass was then multiplied by an average C concentration of Douglas-fir trees in the Pacific Coast and Rocky Mountain regions, which is approximately 0.512 g C/ g of tree (Koch, 1989 as quoted by Birdsey, 1992), to determine the kg of C per plot.

Snag C

The dbh of each snag was measured and its decay stage (Maser et al., 1984) recorded in November, 1993. Because no allometric equations exist for the calculation of snag biomass, the following method was used. Using the allometric equations above, tree biomass excluding foliage was calculated using the dbh and species type of the snag. If the decay stage of the snag was higher than 3, then dead branches were not included. If the decay stage of the snag was greater than 4, then live branches and bark were not included. This adjusted tree biomass was then applied to equation 2, using the density of the snag determined by its decay stage and species (Spies et al. 1988), the density of a live tree of the same species (Hartman et al., 1976?) and the C concentration of live Douglas-fir trees (0.512 g C/ g of tree) because the C concentration of decaying wood remains fairly constant (Sollins et al., 1987).

$$X = \left[\text{(Adjusted live tree biomass)} * \frac{\text{(density of snag)}}{\text{density of live tree}} \right] * \text{ (average \%C of tree)} \qquad [2]$$

Snags with broken tops

The biomass of each tree was estimated by calculating the biomass of a dead whole tree as explained above and then subtracting out the biomass of the broken top. Because I had neither the height nor the radius of the broken top piece, these had to be estimated in order to calculate the volume and biomass of the top piece. The height of a similar tree in the stand was subtracted from the height of the snag in order to estimate the height of the broken piece. The radius was calculated using the Law of Cosines, the dbh, and the estimated unbroken tree height. The volume of the broken piece was then converted to mass and multiplied by the carbon concentration of Douglas-fir trees (0.512 g C/ g of tree).

Coarse woody debris

Biomass estimates of CWD were taken from data collected at these sites in the summer of 1992 (Tacey, 1993). Tacey (1993) used a modified form of the planar intersect method (Brown, 1974), "theoretically analogous to the line intersect method" These biomass estimates were multiplied by 0.512 g C/ g of tree, the C concentration of Douglas-fir because the carbon content of decaying wood remains fairly constant (Sollins et al. 1987). Tacey's estimates include all wood greater than 77 mm. When collecting the O horizon samples, all material greater than 5 cm was not included. A consistent over-estimation of forest floor C occurred because material from 0.77 to 5 cm was counted twice.

Statistical analysis

Because the sample size was small, it could not be assumed samples were normally distributed. Therefore a non-parametric test was used, which does not require the assumption of normality. The Wilcoxan distribution-free signed rank test (Hollander and Wolfe, 1973) was used to determine whether there was a significant difference between C and N content and concentrations as well as C/N ratios in the control and fertilized plot. This test pairs the treated and control plots from the same site. Each treated plot value is subtracted from the control plot value and the absolute value taken. The absolute values are then ranked. The rank values from the pairs which were negative before the absolute value was taken are then summed and this value compared to a table. The strongest p value possible given a sample size of 3 was 0.125.

Results

Total ecosystem C pool

The urea fertilized plots contained significantly ($p=0.125$) more C in the entire ecosystem than the control plots (Figure 5). On average the fertilized plots contained 13.8% more C than the control plots (527 vs. 463 Mg of C ha^{-1}). A large portion of the CWD was left after the harvest of previous stands and does not reflect the effect of N fertilization on C sequestration in the present stand. If CWD is not included the urea fertilized plots still contained significantly ($p=0.125$) more C, with the fertilized plots containing on average 19.2% more C than the control plots (502 vs. 421 Mg of C ha^{-1}). (Table 4, Figure 5)

Soil C, N, and pH

There was no significant difference between the C stored in the control and fertilized plot soil sampled to a depth of 85 cm. On average the soil to 85 cm in the fertilized plots contained 4.2% more C then the average soil in the control plots (97.9 vs. 94.0 Mg of C ha^{-1}). On average the fertilized plots contained 34% more C in the O horizon (20.2 vs. 15.1 Mg of C ha^{-1}). Control and fertilized plots contain on average nearly the same amount of C in the A horizon (11.9 vs. 11.8 Mg of C ha^{-1}). Mineral soil below the A horizon in both control and fertilized plots contained similar C contents (67.0 vs. 67.7 Mg of C ha^{-1}). (Table 5; Figure 5).

Carbon and N concentrations in the O horizon and C/N ratios in the A horizon were significantly higher in the control plots (Table 5). On average, C concentrations in the O horizons of the control plots were 7.1% higher (43.7 vs. 40.8) and N concentrations 11.2% higher (1.19 vs. 1.07) than the fertilized plots. In the A

Table 4. Carbon content of forest ecosystem components.

Component	Ctrl-1 Mg C/ha	Fert-1 Mg C/ha	Ctrl-2 Mg C/ha	Fert-2 Mg C/ha	Ctrl-3 Mg C/ha	Fert-3 Mg C/ha	avg Ctrl Mg C/ha	avg Fert Mg C/ha
A horizon-85 cm	86	97	84	71	68	67	79	78
O horizon	14	11	12	13	19	37	15	20
CWD	18	16	75	11	34	49	42	25
Understory	7	8	9	6	0	0	5	5
Snag	30	41	16	23	13	16	20	27
Live tree roots	60	70	46	58	44	54	50	61
Live tree retained	65	76	58	70	64	67	62	71
Live tree removed	224	261	177	224	156	194	186	226
Total C	503	609	476	477	411	496	463	527
Total w/o CWD	485	593	401	466	377	447	421	502

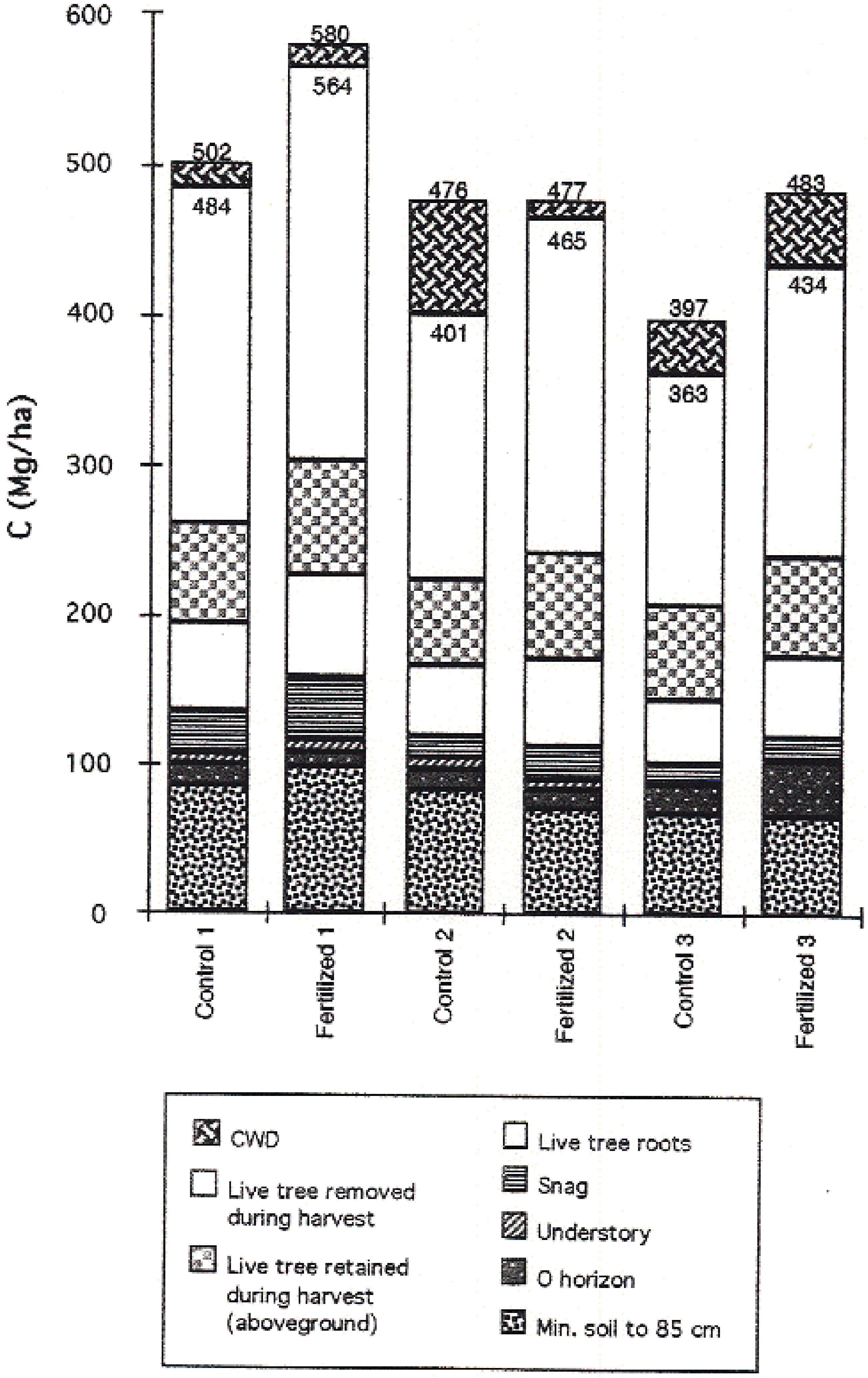

Figure 5. Storage of C in ecosystem components.

Table ~~3~~5. The average soil C and N concentrations, contents, C/N ratios and soil pH. Data from three pits at each site were averaged.

		Site 1				Site 2				Site 3			
		Control		Fertilized		Control		Fertilized		Control		Fertilized	
	Horizon	avg	SD	avg	SD	avg	SD	avg	SD	avg	SD	avg	SD
C %	O	40.9	2.9	39.5	3.6	44.0	1.4	37.7	1.5	46.4	2.2	45.9	3.1
	A	20.7	5.9	17.3	2.3	14.9	6.0	14.3	11.2	15.0	4.4	27.1	10.2
	E									2.2	2.2	2.7	2.8
	E to 25	5.6	1.5	4.8	0.5	3.7	0.9	3.2	0.7	1.7	0.7	2.2	0.6
	25 to 55	3.2	1.5	3.3	0.8	2.6	0.7	1.9	0.3	1.2	0.5	1.9	0.8
	55 to 85	2.7	0.9	1.8	1.1	1.0	0.3	1.4	0.8	1.4	1.0	1.5	0.6
N %	O	1.3	0.1	1.1	0.0	1.2	0.1	1.1	0.0	1.1	0.1	0.9	0.2
	A	0.7	0.1	0.7	0.1	0.5	0.2	0.5	0.4	0.3	0.1	0.7	0.2
	E									0.1	0.1	0.1	0.1
	E to 25	0.2	0.1	0.2	0.0	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.0
	25 to 55	0.2	0.1	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0
	55 to 85	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0
C Mg/ha	O	13.7	1.9	10.9	2.0	12.2	6.2	13.2	3.8	19.4	6.1	30.9	18.6
	A	24.1	14.7	9.9	1.9	4.7	2.6	10.8	3.7	7.0	4.5	11.1	4.2
	E									3.4	3.6	3.3	3.4
	E to 25	24.6	10.4	35.0	5.8	34.5	3.9	27.1	5.0	19.8	9.2	26.0	7.5
	25 to 55	23.4	0.4	30.7	11.0	31.7	10.2	17.5	7.3	17.3	3.0	18.4	8.9
	55 to 85	13.5	7.5	16.4	15.7	12.7	4.3	14.8	7.5	20.2	10.8	12.2	4.9
	total	99.2	31.5	102.9	22.4	95.8	19.9	84.0	14.9	87.0	9.8	101.8	4.0
N kg/ha	O	428	19	300	32	340	214	399	116	474	181	585	214
	A	874	708	376	65	154	100	409	74	146	71	262	75
	E									98	89	78	58
	E to 25	968	231	1733	437	1421	50	1036	205	631	246	781	89
	25 to 55	1119	32	1536	477	1422	429	943	658	791	163	660	302
	55 to 85	620	239	770	480	808	200	850	201	1139	345	665	182
	total	4009	1144	4715	831	4145	653	3650	955	3279	730	3030	144
C/N	O	32	4	36	3	38	5	33	1	42	4	51	15
	A	30	5	26	1	31	5	26	5	48	16	41	5
	E									32	6	27	8
	E to 25	25	6	21	3	24	2	26	2	31	6	33	8
	25 to 55	21	1	20	1	22	1	21	6	23	6	28	2
	55 to 85	21	4	19	7	15	2	17	8	18	7	19	6
pH	O	4.64	0.11	4.58	0.17	4.74	0.03	4.95	0.06	4.45	0.04	4.50	0.27
	A	4.72	0.37	4.66	0.22	4.86	0.27	4.98	0.05	4.54	0.40	4.38	0.17
	E									4.76	0.34	4.28	0.13
	E to 25	5.35	0.23	5.08	0.10	5.13	0.08	5.52	0.11	5.41	0.21	5.07	0.35
	25 to 55	5.40	0.11	5.24	0.14	5.25	0.09	5.32	0.07	5.44	0.12	5.26	0.23
	55 to 85	5.47	0.14	5.15	0.22	5.55	0.20	5.35	0.07	5.29	0.19	5.19	0.21

fertilized?

horizons, C concentrations were 15.5% higher in the control plots (19.5 vs.16.9) and N concentrations 31.8% higher in the fertilized plots (0.65 vs. 0.49). Control and fertilized O horizon C/N ratios were similar (37.3 vs. 36.5). The C/N ratios in the A horizon of the control plots were 34.3% higher than the fertilized plots (39.9 vs. 29.7) (Table 5).

The distribution of soil C content varied among sites. The fert-1 contained less C in the O and A horizons and more C in all depths below the A horizon than ctrl-1. Fert-2 contained more C in the O and A horizons and less in all depths sampled below the A horizon with the exception of the 55-85 cm depth than ctrl-2. Fert-3 contained more C than ctrl-3 in all horizons and depths except the 55-85 cm depth.

Approximately 71% of C in the O horizon and mineral soil to 85 cm was found below the A horizon at both control and fertilized plots. Sampling to only 25 cm would exclude 40% of soil C found to 85 cm. Undoubtedly there was more C below 85 cm, but limitations of time and resources prevented deeper sampling.

The soil results change when sampling is done to different depths. When either the O and A horizons are considered, or when the total soil to 25 cm is considered, plots fert-2 and fert-3 contained more C. When either soil to 55 cm, or the soil to 85 cm is considered, plots fert-1 and fert-3 contained more C.

There was no significant difference found between the kg/ha of N in the control and fertilized plot soil to 85 cm. While fert-1 contained more soil N to a depth of 85 cm (+706 kg/ha), fert-2 and fert-3 contained less than their respective control plots (-495 and -249 kg/ha respectively).

The soil pH levels were generally lower in the fertilized plots at sites 1 and 3, but higher in the fert-2 when compared to the corresponding control plots. The soil generally became less acidic with depth (Table 6).

Carbon stored in understory plants

There was no significant difference (p =0.125) in the amount of C stored in the fertilized plot understory vegetation (Table 4). The control plots contained on average 10% more C than the fertilized plots (5.24 vs. 4.78 Mg of C ha^{-1}) (Table 4, Figure 5).

Carbon stored in trees

There was significantly (p = 0.125) more C stored in the live trees and snags of the fertilized plots. When compared to the control plots, the fertilized plots contained on average 20.1% more C in live trees (358 vs. 298 Mg of C ha^{-1}) and 36% more C in snags (26.9 vs. 19.7 Mg of C ha^{-1}) (Table 4, Figure 5).

Carbon stored in coarse woody debris

Although not significantly different (p=0.125), data from Tacey (1993) shows on average the control plots contained 67% more C in CWD than the fertilized plots at these 3 sites (42.3 vs. 25.3 Mg of C ha^{-1}) (Table 4, Figure 5). Variability was high with a range of 550% more C in ctrl- 2 (74.6 vs. 11.5 Mg of C ha^{-1}) to 43% more in fert-3 (49.0 vs. 34.2 Mg of C ha^{-1}). A visual inspection indicated that some of the CWD found on the plots was from previous stands, as it was too large to be from the current stand. This was especially true of ctrl-2. It was not possible to differentiate between the CWD of past and present stands from Tacey's data.

Table 6. Comparison of soil C concentrations and pH. Carbon concentrations tend to be higher when soil pH is lower.

Site 1	Mg C/ha		pH	
Horizon	Control	Fertilized	Control	Fertilized
A to 25	24.6	**35**	5.35	**5.08**
25 to 55	23.4	**30.7**	5.40	**5.24**
55 to 85	13.5	**16.4**	5.47	**5.15**

Site 2	Mg C/ha		pH	
Horizon	Control	Fertilized	Control	Fertilized
A to 25	**34.5**	27.1	**5.13**	5.52
25 to 55	**31.7**	17.5	**5.25**	5.32
55 to 85	12.7	**14.8**	5.55	**5.35**

Site 3	Mg C/ha		pH	
Horizon	Control	Fertilized	Control	Fertilized
E to 25	19.8	**26**	5.41	**5.07**
25 to 55	17.3	**18.4**	5.44	**5.26**
55 to 85	**20.2**	12.2	5.29	**5.19**

Discussion

Carbon storage

Data from this study indicate that repeated urea fertilization of the three stands significantly increases C stored in trees and snags. Significantly more C was found in the trees and snags of the fertilized plots. Data suggests that there would be no significant difference in C stored in the understory vegetation, CWD, or any combination of soil horizons or layers. Results agree with those of Harding and Jokela (1994) who found no increase in soil organic matter after a single N fertilization produced increased aboveground productivity in a Florida forest. However, findings contrasted with a review of literature cited by Johnson (1992) which found statistically significant increases in soil C after N fertilization (Van Cleve and Moore, 1978; Baker et al. 1986; Nohrstedt et al., 1989). Two of my three sites did show an increase in soil C after fertilization, however this was not found to be significant. It is possible that if the sampling size had been larger, significantly more C in the fertilized plots could have been observed with a stronger statistical test.

Distribution of soil C

Total profile soil C distribution was variable among sites. Fert-1 contained less C in the O and A horizons while fert-2 and fert-3 contained more. Even so, all of the fertilized plots could have had litter inputs equal or higher to those of the control. This has been observed in several studies (Heilman and Gessel, 1963; Turner, 1977; Pang et al., 1987; Gower et al., 1992; Prescott et al., 1993). Fert-1 may have had a decomposition rate fast enough to reduce increased litter inputs, while fert-2 and fert-3 had decomposition rates that did not reduce the additional litter. Because site 1 was lower in elevation (and thus, colder) than site 3 and received more precipitation than site 2, microbial activity and decomposition rates may have been higher at site 1.

Fert-1 and -3 contained higher amounts of C in the mineral soil below the A horizon to a depth of 85 cm, while fert-2 contained less when compared to corresponding control plots. Several factors could be involved in creating these differences. A few worms (*Lunbricus terrestris*), approximately 7 cm long, were found in two pits at fert-1in both the A and B horizons. Earthworms are known to move organic material into the soil. The presence of earthworms may have increased the mixing of organic matter from the O and A horizons into the top of the B horizon, thus decreasing the O and A horizon C and increasing the C in the top of the B horizon.

Another possible cause of larger accumulations of C in the B horizon is through the processes of pedogenesis. The soil pH was somewhat more acidic at fert-1 and fert-3, but less acidic at fert-2 when compared to their corresponding control plots. Urea fertilization is known to lower pH (Brady, 1990). Fert-1 and -3 may have lower soil pH values because of urea fertilization. Ctrl-2 contained a dense understory of salal, a species whose presence is associated with acid soils (Weatherell, 1954; Weetman et al., 1989). The presence of large quantities of salal may have had a more acidifying effect at plot ctrl-2 than the urea fertilization did at plot fert-2. These plots (fert-1, ctrl-2, fert-3) also contained more C below the A horizon. As organic acids are produced in the O and A horizon they are leached into lower horizons. In a more acidic environment both Al and Fe, which are weathered from minerals in the soil, are more available to combine with the organic acids. As more Al and Fe is added to the (Al, Fe)-organic complexes, they become less soluble and precipitate and C accumulates (Wilding, 1983). If more Al and Fe is available at a lower pH, the (Al, Fe)-organic complexes may precipitate sooner and accumulate faster., It is possible that the (Al, Fe)-organic complexes in the less acidic plots did precipitate, but at depths lower than 85 cm.

Another possible cause for increased C in the lower horizons of plot ctrl-2 was higher root production due to nutrient deficiency. Ctrl-2 contained large amounts of CWD, possibly immobilizing N. Ctrl-2 also contained a dense understory of salal, which is in known to flourish at N deficient sites (Prescott et al., 1993). The dense salal understory was reduced at fert-2 after N fertilization. If N is limited in ctrl-2, the trees may be producing more roots, thus increasing the C sequestered in the mineral soil.

Comparison of C storage estimates

I compared my estimates of C stored in a 60 year-old Douglas-fir forest to average estimates for forests of Washington (Birdsey, 1992). My understory vegetation and mineral soil C estimates were slightly lower while my live tree C estimates were 3 to 3.5 times higher. Birdsey combined CWD and forest floor estimates. My estimates of the combined O horizon and CWD were about twice as high as their estimates. The differences in estimates may be due to the wide variety of forest types and ages in the state of Washington. Birdsey's estimates included recently replanted clearcuts with low aboveground biomass and eastern Washington forests which have frequent fires consuming some of the understory, CWD, and forest floor.

I also compared my C storage estimates with those of Edmonds and Chappell (in press). They estimated soil C in the control plots of the same RFNRP study. They used the original soil data collected from 1969-1971 during site establishment. The soil was sampled to the C horizon, with pit depths averaging 121 cm. They found on average that mineral soil contained 177.4 Mg of C /ha and the O horizon contained 8.7 Mg of C / ha. Their estimate of average mineral soil C in unfertilized plots was higher than mine (178.4 vs. 78.9 Mg/ha), while their C content estimate for the O horizon was lower (8.7 vs 15.1 Mg/ha). The higher estimates of mineral soil C were probably due to two factors; Sampling to a much lower depth, and differences in bulk density sampling methods. This would indicate that there is a significant amount of carbon in the lower B horizon. Differences in identification of O horizon boundaries may account for differences in the O horizon estimates.

Sampling depth

My results demonstrate how failing to sample deep in the soil may give gross underestimates of soil C. Seventy-one percent of soil C to 85 cm was found below the A horizon and 40% was found below 25 cm. Although the depth at which I could sample was limited by resources, if I had been able to sample deeper I probably would have had higher soil C estimates. Edmonds and Chappell (in press) estimated the soil C at these and other western Cascade RFNRP sites to be nearly a third higher when soil was sampled to the C horizon (121 cm). A study by Hammer et al. (in press) found that subsurface soil C (sampling depth ranged from 94-191 cm) exceeded that of surface C in a forest-prairie ecotone. Stone et al. (1992) found that C stored in Florida Spodosols was underestimated, due largely to shallow sampling. They found that over 50% of soil C was found in the Bh + B'h horizons.

Soil N

Plot fert-1 contained more N in the soil to 85 cm than ctrl-1, while fert-2 and -3 contained less than their respective control plots. Because forests in the Pacific Northwest have tight nutrient cycles (Blew and Parkinson, 1993) and all three fertilized stands showed an increase in aboveground productivity, it is unlikely that a large amount of the additional N from fertilization was lost from the system through leaching or volatilization . It may be that the N taken up by the trees is be cycled back into the soil at fert-1 but is being held in the tree biomass at fert-2 and -3.

Potential C storage in urea fertilized Douglas-fir forests of western Washington

Currently 40,500 - 60,700 hectares of commercial land in western Washington and Oregon are fertilized with N each year (H.N. Chappell, College of Forest Resources, University of Washington, personal communication). My results indicate that multiple urea fertilizations of these forests would increase C stored in live trees and snags, although it is hard to calculate exact estimates because of differences in stand age, density, history, soil type, and variability. As these are commercial forests, the ultimate fate of the C stored in trees must be considered. Harmon et al. (1990) predicted that much of the C stored in harvested wood is released back to the atmosphere in a relatively short period of time. However, my results indicate that not all of the additional C sequestered in urea fertilized stands would be removed from the site after harvest. Of the additional 81 Mg of C/ha stored by the urea fertilized plots, approximately 40 Mg of C per harvested hectare would be removed. The remaining 41 Mg of C/ha found in the tree roots, stumps, slash, snags, and O horizon would be retained unless harvesting were followed by intense burning or cultivation (Johnson, 1992).

One must also consider the release of CO_2 to the atmosphere after the application of urea fertilizers. Urea is derived from fossil fuels. During this process 1 g of C is used for every 2.33 g of N produced. When urea is applied as fertilizer, it reacts chemically releasing C to the atmosphere. On average there was 971 kg of N/ha applied at each of the fertilized plots in this study. The fertilized plots stored on average 81 Mg of C /ha more than the control plots. Thus, for every gram of N applied, an additional 83.5 g of C were stored in the fertilized plots. In other words, for every gram of C released to the atmosphere from the application of urea, an additional 195 g of C was removed from the atmosphere and stored in these forest ecosystems.

Conclusions

- The fertilization of three, 62-69 year-old Douglas-fir stands with urea-N significantly increased C stored in the trees, snags, and sum of all components of the fertilized plots. On average the fertilized plots contained 13.8% more C in the entire system than the control plots (527 vs. 463 Mg of C ha^{-1}). When CWD is excluded, the fertilized plots still contain on average significantly more C than the control plots. They contain 19.2% more C (421 vs. 402 Mg of C ha^{-1}).

- The addition of urea-N fertilizer did not significantly change C content of the understory vegetation, CWD, or any of the sampled soil horizons or depths. On average the fertilized plots contained 34% more C in the O horizon (20.2 vs. 15.1 Mg of C ha^{-1}). The average C content of the mineral soil in the control and fertilized plots was similar (78.9 vs. 79.5 Mg of C ha^{-1}).

- A large portion of the soil C was found below the surface soil. When sampling to a depth of 85 cm, 71% of soil C was found below the A horizon and 40% below 25 cm. This illustrates how failing to sample at depth can grossly under estimate soil C.

- In the past 10 years 40,000 - 60,000 hectares of commercial forest land in western Washington and Oregon were fertilized annually with N fertilizer. Our data indicates that this fertilization would increase C stored in these terrestrial systems. On average there was 971 kg of N/ha applied at each of the fertilized plots in this study. The fertilized plots stored on average 81 Mg of C /ha more than the control plots. Thus, for every g of N used, an additional 83.5 g of C were stored in the fertilized plots. In other words, for every gram of C released to the atmosphere from the application of urea, an additional 195 grams of C was removed from the atmosphere and stored in these forest ecosystems.

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Appendix A. Soil C, N, H and bulk density data for all pits.

Site	Horizon	<2 mm od wt subsmpl (g)	total od wt grams	fld wt+rock grams	horzn vol cm^3	bulk dnsty Mg/m^3	<2mm wt/vol Mg/m^3	C % in <2mm	N % in <2mm	H % in <2mm	horzn hts cm	C Mg/ha	N kg/ha	H kg/ha	C/N
1-Ctrl-A	O	810	810	810	9125	0.09	0.089	37.63	1.35	3.19	3.7	12.2	436	1033	28
	A	7283	15060	40008	19400	2.06	0.375	14.05	0.58	2.15	7.8	40.9	1690	6264	24
	A to 25	1023	83462	83462	51750	1.61	0.407	5.22	0.17	1.43	17.2	36.6	1192	10023	31
	25 to 55	1324	120431	120431	63725	1.89	0.529	1.50	0.07	0.81	30.0	23.8	1111	12855	21
	55 to 85	748	87998	87998	59175	1.49	0.196	3.75	0.15	1.06	30.0	22.0	882	6232	25
									total		88.7	136	5310	36407	
1-Ctrl-B	O	929	929	929	8100	0.11	0.115	42.39	1.19	4.09	3.2	15.8	442	1520	36
	A	1347	3477	3477	5575	0.62	0.242	25.39	0.77	3.29	2.2	13.7	415	1773	33
	A to 25	532	56246	56246	40025	1.41	0.187	4.29	0.23	1.49	22.8	18.3	981	6357	19
	25 to 55	622	61690	61690	35850	1.72	0.183	4.20	0.21	1.55	30.0	23.1	1155	8525	20
	55 to 85	714	87091	87091	50530	1.72	0.156	2.20	0.12	0.99	30.0	10.3	562	4636	18
									total		88.2	81.1	3555	22811	
1-Ctrl-C	O	763	763	763	7285	0.10	0.105	42.75	1.33	4.07	2.9	13.0	406	1242	32
	A	1931	9921	9921	11465	0.87	0.168	22.71	0.67	2.99	4.6	17.6	518	2312	34
	A to 25	535	73937	73937	45547	1.62	0.128	7.26	0.28	1.87	20.4	18.9	730	4875	26
	25 to 55	864	104782	104782	64785	1.62	0.202	3.85	0.18	1.51	30.0	23.4	1092	9160	21
	55 to 85	613	125874	125874	65430	1.92	0.132	2.06	0.11	1.00	30.0	8.1	415	3956	20
									total		87.9	81.0	3161	21545	
1-Trtd-A	O	776	776	776	6508	0.12	0.119	40.90	1.08	2.13	2.6	12.7	335	661	38
	A	1463	5489	5489	17984	0.31	0.081	14.77	0.59	1.94	7.2	8.7	346	1136	25
	A to 25	2753	78019	78019	44942	1.74	0.336	4.83	0.20	1.13	17.8	30.21	1279	7016	24
	25 to 55	1904	77112	77112	44101	1.75	0.416	2.58	0.13	0.88	30.0	32.2	1624	10992	20
	55 to 85	930	74390	74390	38945	1.91	0.240	1.19	0.08	1.48	30.0	8.6	576	10664	15
									total		87.6	92.4	4160	30470	

Appendix A continued.

Site	Horizon	<2 mm od wt subsmpl (g)	total od wt grams	fld wt+rock grams	horzn vol cm^3	bulk dnsty Mg/m^3	<2mm wt/vol Mg/m^3	C % in <2mm	N % in <2mm	H % in <2mm	horzn hts cm	C Mg/ha	N kg/ha	H kg/ha	C/N
1-Trtd-B	O	656	656	656	12500	0.05	0.053	42.15	1.10	2.09	5.0	11.1	289	549	38
	A	1221	6067	6067	6465	0.94	0.189	18.15	0.68	1.05	2.6	8.9	333	513	27
	A to 25	3002	92761	92761	69199	1.34	0.309	4.33	0.23	1.05	22.4	33.35	1769	8149	19
	25 to 55	1858	58514	58514	42891	1.36	0.327	4.16	0.20	1.01	30.0	40.8	1963	9913	21
	55 to 85	658	27216	27216	17461	1.56	0.366	3.14	0.12	1.10	30.0	34.4	1316	12066	26
									total		90.0	129	5670	31190	
1-Trtd-C	O	623	623	623	2051	0.30	0.304	35.42	1.11	2.43	0.8	8.8	275	605	32
	A	1588	4718	4718	6035	0.78	0.263	19.04	0.71	2.35	2.4	12.1	450	1490	27
	A to 25	2372	56020	56020	49336	1.14	0.350	5.31	0.28	1.27	22.6	41.48	2152	9752	19
	25 to 55	952	51710	74844	62539	1.20	0.206	3.08	0.17	1.09	30.0	19.1	1022	6749	19
	55 to 85	768	92988	92988	73496	1.27	0.173	1.19	0.08	0.88	30.0	6.2	416	4574	15
									total		85.8	87.6	4315	23170	
5-Ctrl-A	O	1101	1101	1101	6503	0.17	0.169	42.74	1.30	1.57	2.6	18.8	573	691	33
	A	956	2620	2620	5762	0.45	0.166	13.36	0.37	2.03	2.3	5.1	141	775	36
	A to 25	3631	62370	62370	56309	1.11	0.327	4.61	0.18	1.17	22.7	38.94	1478	8360	26
	25 to 55	2730	94802	94802	74648	1.27	0.365	3.33	0.15	1.01	30.0	36.5	1644	11067	22
	55 to 85	1753	106596	117936	60195	1.96	0.438	1.22	0.07	0.76	30.0	16.0	920	9990	17
									total		87.6	115	4756	30884	
5-Ctrl-B	O	361	361	361	7950	0.05	0.045	45.45	1.05	1.45	3.2	6.6	151	209	43
	A	220	818	818	2125	0.38	0.104	21.54	0.70	2.57	0.9	1.9	62	226	31
	A to 25	1161	78019	78019	59275	1.32	0.389	3.54	0.15	1.12	24.2	32.98	1389	10368	24
	25 to 55	560	135400	135400	69600	1.95	0.344	1.94	0.09	0.89	30.0	20.0	928	9176	22
	55 to 85	998	128822	138801	55650	2.49	0.441	1.07	0.07	0.71	30.0	14.2	927	9403	15
									total		88.2	75.6	3457	29382	

Appendix A continued.

Site	Horizon	<2 mm od wt subsmpl (g)	total od wt grams	fld wt+rock grams	horzn vol cm^3	bulk dnsty Mg/m^3	<2mm wt/vol Mg/m^3	C % in <2mm	N % in <2mm	H % in <2mm	horzn hts cm	C Mg/ha	N kg/ha	H kg/ha	C/N
5-Ctrl-C	O	640	640	640	5635	0.11	0.114	43.75	1.15	1.74	2.3	11.2	295	446	38
	A	1810	7688	7688	13100	0.59	0.138	9.77	0.36	1.59	5.2	7.1	261	1151	27
	A to 25	2164	93442	93442	59225	1.58	0.553	2.90	0.13	0.91	19.8	31.69	1395	9338	23
	25 to 55	1980	114307	114307	80025	1.43	0.514	2.50	0.11	1.07	30.0	38.5	1696	16495	23
	55 to 85	1469	100472	100472	62975	1.60	0.385	0.68	0.05	0.68	30.0	7.8	577	7848	14
									total		87.3	96.4	4223	35278	
5-Trtd-A	O	650	650	650	6367	0.10	0.102	36.04	1.10	1.55	2.6	9.4	286	403	33
	A	1176	3034	3034	4532	0.67	0.260	17.96	0.78	2.39	1.8	8.4	366	1123	23
	A to 25	1687	67133	67133	49492	1.36	0.351	2.49	0.10	1.03	23.2	21.38	800	8429	27
	25 to 55	602	74844	74844	82109	0.91	0.171	2.09	0.08	0.85	30.0	10.7	411	4362	26
	55 to 85	464	122926	122926	54707	2.25	0.305	1.90	0.08	0.95	30.0	17.4	733	8704	24
											87.6	67.3	2619	22379	
5-Trtd-B	O	1117	1117	1117	7100	0.16	0.157	37.91	1.16	1.67	2.8	16.9	518	746	33
	A	1618	3790	3790	5125	0.74	0.316	19.14	0.67	2.38	2.1	12.4	434	1541	29
	A to 25	2366	81421	81421	58800	1.38	0.325	3.92	0.14	1.14	23.0	29.50	1054	8623	28
	25 to 55	1330	124060	131318	71775	1.83	0.274	2.01	0.09	0.92	30.0	16.5	740	7564	22
	55 to 85	1243	150595	150595	58750	2.56	0.401	1.71	0.09	0.85	30.0	20.6	1082	10219	19
									total		87.8	95.9	3828	28693	
5-Trtd-C	O	844	844	844	8672	0.10	0.097	39.02	1.16	1.66	3.5	13.2	392	561	34
	A	1510	3712	3712	6582	0.56	0.229	22.25	0.78	2.14	2.6	13.4	467	1293	29
	A to 25	2405	81648	81648	59395	1.37	0.429	3.11	0.13	0.97	22.4	30.56	1232	8975	25
	25 to 55	1862	104328	104328	45371	2.30	0.560	1.50	0.10	0.83	30.0	25.2	1679	13932	15
	55 to 85	1950	160348	170327	94570	1.80	0.408	0.52	0.06	0.66	30.0	6.4	735	8084	9
									total		88.5	88.7	4505	32844	

Appendix A continued.

Site	Horizon	<2 mm od wt subsmpl (g)	total od wt grams	fld wt+rock grams	horzn vol cm^3	bulk dnsty Mg/m^3	<2mm wt/vol Mg/m^3	C % in <2mm	N % in <2mm	H % in <2mm	horzn hts cm	C Mg/ha	N kg/ha	H kg/ha	C/N
43-Ctrl-A	O	651	651	651	18550	0.04	0.035	48.70	1.04	2.34	7.4	12.7	271	609	47
	A	1517	1679	1679	4975	0.34	0.305	20.10	0.36	2.29	2.0	12.2	218	1390	56
	E	9860	15026	15026	16900	0.89	0.583	0.55	0.02	0.24	6.8	2.2	79	947	28
	E to 25	2084	44226	44226	37725	1.17	0.561	1.77	0.05	0.88	16.3	16.1	456	8020	35
	25 to 55	847	76205	76205	49800	1.53	0.342	1.61	0.06	1.00	30.0	16.5	616	10259	27
	55 to 85	1362	84823	84823	48775	1.74	0.423	2.56	0.10	0.96	30.0	32.5	1268	12175	26
									total		92.4	92.2	2908	33400	
43-Ctrl-B	O	1178	1178	1178	8106	0.15	0.145	44.40	1.13	1.71	3.2	20.9	533	806	39
	A	833	885	885	2539	0.35	0.328	12.86	0.43	1.72	1.0	4.3	142	570	30
	E	4056	4628	4628	8379	0.55	0.484	4.64	0.12	0.77	3.4	7.5	195	1249	39
	E to 25	3612	73937	73937	58672	1.26	0.631	2.32	0.07	0.65	20.6	30.2	911	8486	33
	25 to 55	1981	103421	103421	70351	1.47	0.781	0.63	0.04	0.55	30.0	14.8	938	12893	16
	55 to 85	2156	66452	66452	45020	1.48	0.778	0.66	0.06	0.67	30.0	15.4	1401	15640	11
									total		88.2	88.2	88	88	
43-Ctrl-C	O	1334	1334	1334	13262	0.10	0.101	46.10	1.16	1.59	5.3	24.6	619	848	40
	A	912	961	961	3164	0.30	0.288	12.18	0.21	1.38	1.3	4.5	77	505	58
	E	142	13608	13608	17344	0.78	0.058	1.41	0.05	0.37	6.9	0.6	20	148	28
	E to 25	3436	40370	40370	39961	1.01	0.781	0.99	0.04	0.36	16.8	13.0	525	4722	25
	25 to 55	2733	48082	48082	54570	0.88	0.547	1.25	0.05	0.80	30.0	20.5	821	13135	25
	55 to 85	1810	43092	48082	40351	1.19	0.416	1.01	0.06	0.84	30.0	12.6	748	10475	17
									total		90.3	90.3	90	90	
43-Trtd-A	O	2703	2703	2703	4746	0.57	0.569	48.38	0.74	3.50	1.9	52.3	800	3784	65
	A	704	716	716	4433	0.16	0.159	24.47	0.68	2.59	1.8	6.9	191	728	36
	E	3132	3920	3920	7149	0.55	0.438	2.09	0.06	0.35	2.9	2.6	75	439	35
	E to 25	2877	37195	37195	41582	0.89	0.592	1.50	0.05	0.67	20.4	18.83	681	7036	28
	25 to 55	1932	62370	62370	63906	0.98	0.410	1.03	0.04	0.52	30.0	12.7	492	6397	26
	55 to 85	1671	52391	52391	56289	0.93	0.280	1.10	0.09	0.63	30.0	9.3	757	5301	12
									total		86.9	103	2996	23685	

Appendix A continued.

Site	Horizon	<2 mm od wt subsmpl (g)	total od wt grams	fld wt+rock grams	horzn vol cm^3	bulk dnsty Mg/m^3	<2mm wt/vol Mg/m^3	C % in <2mm	N % in <2mm	H % in <2mm	horzn hts cm	C Mg/ha	N kg/ha	H kg/ha	C/N
43-Trtd-B	O	1222	1222	1222	6836	0.18	0.179	42.39	1.19	1.50	2.7	20.7	582	733	36
	A	1519	1692	1692	5235	0.32	0.290	18.40	0.42	2.12	2.1	11.2	255	1286	44
	A to 25	2608	38556	38556	50117	0.77	0.556	2.46	0.06	0.55	22.9	33.84	808	6543	42
	25 to 55	1312	28577	28577	46992	0.61	0.229	2.03	0.07	0.72	30.0	13.9	480	4939	29
	55 to 85	997	29030	29030	45234	0.64	0.261	2.28	0.10	1.11	30.0	17.8	782	8679	23
									total		87.7	97.5	2907	22181	
43-Trtd-C	O *	1046	1046	1046	11500	0.09	0.091	46.82	0.89	1.86	4.6	19.6	372	778	53
	A *	993	1024	1024	7300	0.14	0.136	38.34	0.86	2.44	2.9	15.2	341	969	45
	E	3024	3589	3589	7500	0.48	0.403	6.08	0.13	0.80	3.0	7.4	157	968	47
	E to 25	1402	15649	15649	18825	0.83	0.497	2.66	0.09	0.93	19.1	25.2	853	8815	30
	25 to 55	1468	41051	41051	51925	0.79	0.374	2.55	0.09	0.99	30.0	28.6	1009	11098	28
	55 to 85	1484	51257	51257	62525	0.82	0.253	1.24	0.06	0.64	30.0	9.4	455	4852	21
									total		89.6	89.6	90	90	

*There was a class 5 log put in with A instead of O, thus invalid for O, A comparisons