AN ABSTRACT OF THE THESIS OF

Suzanne Marie Remillard for the degree of Master of Science in Forest Science presented on April 30, 1999. Title: Soil Carbon and Nitrogen in Old-Growth Forests in Western Oregon and Washington.

Abstract approved: ______________________________________

Peter S. Homann and Bernard T. Bormann

Soil organic carbon (SOC, kg C m^{-2}) is an important component in evaluating global C stores. The nitrogen (TN, kg N m^{-2}) cycle is closely linked to C and understanding its role is also important. Contents and distributions of SOC and TN in soil profiles, to 1-meter depth, were estimated from 79 soils pits, in old-growth forests, in 7 physiographic provinces in western Oregon and Washington. Soils were sampled in four layers, forest floor, 0- to 20-cm, 20- to 50-cm, and 50- to 100-cm, and analyzed on a LECO CN Analyzer. Material <2-mm was analyzed, as well as C-bearing material >2-mm. Forest floor SOC ranged from 0 to 14 kg C m^{-2} (mean = 2.7) and forest floor TN ranged from 0 to 0.4 kg N m^{-2} (mean = 0.07). The SOC of mineral soil ranged from 1.0 to 18 kg C m^{-2} (mean = 6.6) for 0- to 20-cm depth and 2.2 to 57 kg C m^{-2} (mean = 17) for 0- to 100-cm depth. The TN of mineral soil ranged from 0.04 to 1.0 kg N m^{-2} (mean = 0.31) for 0- to 20-cm depth and 0.12 to 3 kg N m^{-2} (mean = 1.0) for 0- to 100-cm depth. Up to 66% of SOC and TN measured was found below 20-cm, illustrating how failing to sample at depth can grossly underestimate SOC. As much as 44% of SOC and TN measured was found in C-bearing material >2-mm, material for which many methods neglect to account. Longitudinal differences in SOC and TN contents were evident between

Coastal, Cascade, and Eastside Cascade sites, implying effects from site and climatic factors. Regression analysis was used to quantify relationships of SOC and TN to site and climatic factors. Response variables included forest floor, forest floor plus 0- to 20-cm, 0- to 20-cm, and 0- to 100-cm layers. Moisture and soil texture played important roles in most cases examined. The results of this study, and of other studies assessing the effects of site and climatic characteristics on the factors controlling soil organic matter accumulation, suggest the relationships are regionally specific.

Soil Carbon and Nitrogen in Old-Growth Forests in Western Oregon and Washington

by

Suzanne Marie Remillard

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APPROVED:

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Suzanne Marie Remillard, Author

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I am truly grateful for the support, encouragement, mentoring, and prodding of Dr. Peter Homann. Without his guidance, I would still be sieving soils. I would like to also acknowledge and thank my other committee members. Dr. Bernard Bormann, Dr. Mark Harmon, and Dr. Herb Huddleston for their help in various aspects of this project. I am very thankful for the funding provided initially through an interagency agreement (DW 12936179) from the USFS Pacific Northwest Research Station, the EPA Environmental Research Laboratory, and Oregon State University via the Long-Term Ecosystem Productivity Program and subsequent support from the Oregon State University Wind River Canopy Crane Project. Permanent Reference Stand data was obtained through research supported by NSF grant #s DEB-76-11978, DEB-79-25939, DEB-80-12162, BSR-83-00370, BSR-85-14325, BSR-90-11663 and the PNW RS, Portland, OR grant #s PNW 86-398, PNW 87-412, PNW 87-415, PNW 88-440, PNW 89-466, PNW 89-470.

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Namaste.

CONTRIBUTION OF AUTHORS

Dr. Peter Homann was involved in the experimental design, data collection, data analysis, and writing of each manuscript. Dr. Homann also provided review and advice on the theory and logic of the study. Dr. Bernard Bormann contributed to the experimental design and also provided review and advice on the theory and logic of the belowground portion of the study. Dr. Mark Harmon contributed to the experimental design, data collection, and provided review and advice on the theory and logic of the aboveground portion of the study. As first author on these papers, I was responsible for study design, data collection, processing, analysis, report writing, and ensuring project success.

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PREFACE

This study is part of an interagency cooperation project between the Pacific Northwest Research Station of the US Forest Service (PNW - USFS), Environmental Protection Agency (EPA), and Oregon State University (OSU) evaluating the effects of management practices on ecosystem carbon. Studies within this project measure pools and fluxes of the ecosystem carbon budget. Projects in this program include both long-term, short-term, and retrospective studies. Retrospective studies enable comparisons of carbon pools in previously manipulated and/or natural stands. Short-term studies focus on specific processes of ecosystem productivity with results in relatively short amounts of time. Long-term ecosystem productivity studies are being initiated to evaluate factors influencing site productivity with plans for monitoring for the next 200 years.

The results of this study contribute to a total ecosytem carbon budget estimation for old-growth forests in the Pacific Northwest. These estimations serve as potential bounds for ecosystem carbon in these forests as net primary productivity is assumed to be in a steady state.

DEDICATION

This thesis is dedicated to my father, the loving memory of my mother, and the Shona river god, Gnami gnami, and Aztec god of old age, wind, and fire, Huehueteotl.

Soil Carbon and Nitrogen in Old-Growth Forests in Western Oregon and Washington

1. INTRODUCTION

Soils are an important component of the global carbon (C) cycle. They store the largest non-fossil reserve of C within the terrestrial system and account for more than two thirds of the approximately 2100 Pg circulating C within terrestrial ecosystems (Johnson and Kern, 1991). Forest soils are particularly important, representing almost 50 percent of terrestrial soil carbon stores (Schlesinger, 1984). An intensely debated question has been whether changes in climate and atmospheric CO_2 might alter the C balance of forest soils (Schlesinger, 1984; Schimel et al., 1994). That is, will forest soils be a net sink or net source of CO2 to the atmosphere during the coming decades, thereby mitigating or exacerbating predicted increases in this 'greenhouse' gas? Simulation models of ecosystem C dynamics are increasingly being used to address this question (e.g., Pastor and Post, 1986; Parton et al., 1995; McKane et al., 1997). However, the application of these models is often severely limited by the availability of detailed data describing the total amounts and distribution of C in soils and the relationship of these variables to environmental factors. To better understand and evaluate the role of forest soils in regional and global C cycles, quantifying belowground C pools and their relation to key climatic and site factors is required.

1.1 Terrestrial Carbon Cycle

Within the global C cycle, C circulates between three major pools: oceanic, atmospheric, and terrestrial (Figure 1.1). Human land-use, through land clearing and fires, transfers C from the terrestrial to atmospheric stores (Post et al., 1990). Land-use and fossil fuel burning amount to an annual addition of about 7.0 Pg C yr^{-1} to the atmosphere. Oceanographers estimate that about 2.0 Pg C yr^{-1} is absorbed into the oceans. Similarly, atmospheric scientists can account for about 3.0 Pg C yr^{-1} retained in the atmosphere. The difference between these values leaves about 2.0 Pg C yr^{-1} transferred out of atmospheric C that is unexplained (Dixon et al., 1994). Terrestrial ecosystems may be significant sinks of this imbalance in the C budget (Johnson, 1992; Dixon et al., 1994).

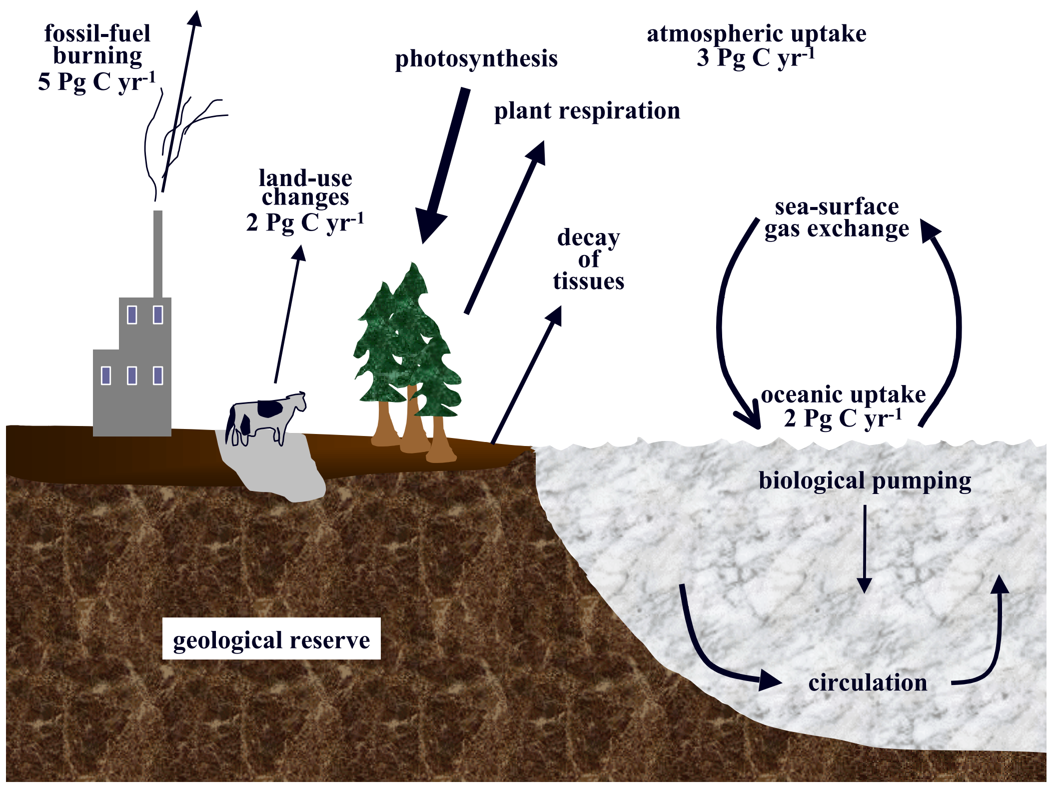

Figure 1.1. The global carbon cycle. All fluxes are in petagrams (Pg=10^{15}g) and are 1980 estimates. Adapted from Post et al. (1990).

Terrestrial vegetation contains approximately 550 Pg of organic C, while soils contain approximately 1500 Pg of organic C globally (Johnson and Kern, 1991), although there is much uncertainty in this latter value. Of this, forests contain up to 80% of the global aboveground C (Dixon et al., 1994) and 50% of the belowground C (Schlesinger 1984).

In addition to its importance in the global C budget, soil C is the major constituent of organic matter, which plays an important role in forest ecosystems in terms of soil structure. It has a tremendous impact on water penetration, root development, and resistance to erosion (Kern 1994). Soil organic matter increases infiltration rate and water-holding capacity, which increases aggregate stability, encourages root development, and protects the soil from erosion. Organic acids associated with organic matter are responsible for the release of nutrient elements from mineral structures, thus increasing availability to plants. Together these soil characteristics influence forest productivity, which affects detrital inputs into soils, and consequently soil organic matter amounts.

The amount of soil C in a specific forest depends on the long-term imbalance between the fluxes of C into and out of soils, which are controlled by numerous processes (Fig. 1.2). Although several processes are responsible for C entering the terrestrial ecosystem, it is mainly a result of photosynthesis, which yields live organic matter. Upon death, the organic matter is deposited as detritus on or within the soil and becomes part of the active soil organic C pool. The organic matter is decomposed by heterotrophic microbes and other soil animals, during which the CO_2 produced through microbial respiration is released to the atmosphere. Fires are also responsible for the release of terrestrial C to the atmosphere. The C in the active pool that is not respired is recirculated into both microbial biomass and a stable soil organic C pool. Thus, soil organic C consists of materials in various states of decomposition from recent inputs of plant litter to highly decomposed humus (Killlham 1994).

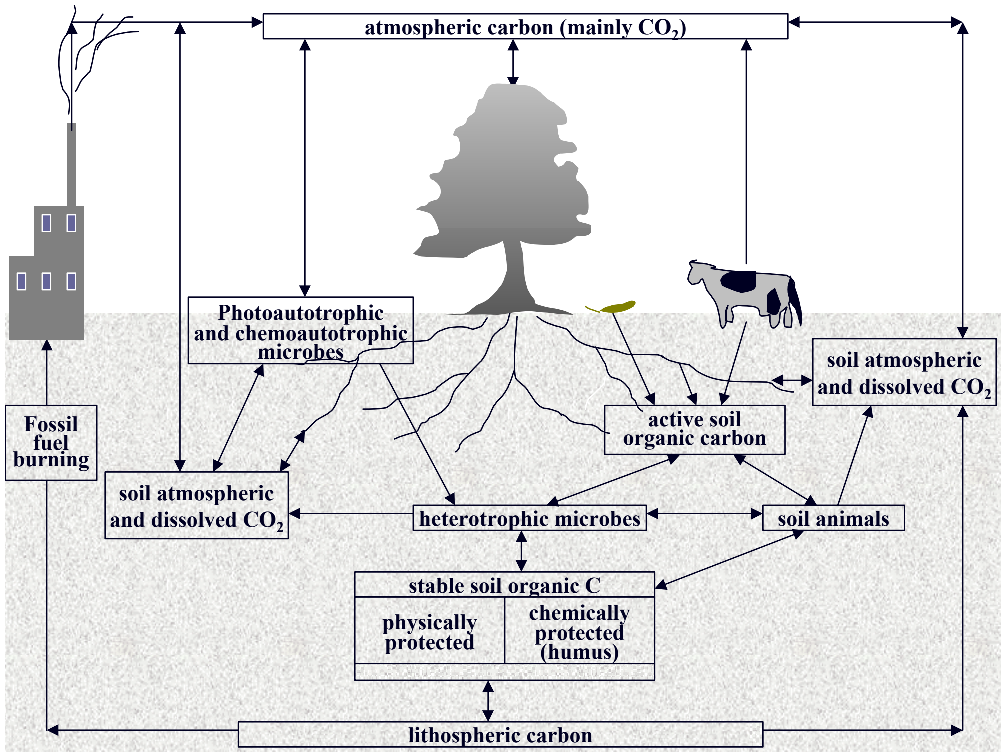

Figure 1.2. The soil carbon cycle. Adapted from Killham, 1994.

1.2 Terrestrial Nitrogen Cycle

The nitrogen cycle is intricately linked with the carbon cycle. Litter and soil humus are the primary reservoirs of N in ecosystems (Perry et al., 1991). Microorganisms responsible for cycling nutrients within the soil ecosystem depend on carbon compounds as their energy source. Changes in both litter quantity and quality affect the rate of decomposition and the amount of C sequestered in the soil. Immobilization of N occurs in substrates with high C/N ratios (Figure 1.3). Microbial decomposition releases CO_2 and reduces substrate C/N ratio, lessening competition for N among microorganisms. Mineralization of N occurs and becomes available for plant uptake as N is no longer tied up in microbial biomass.

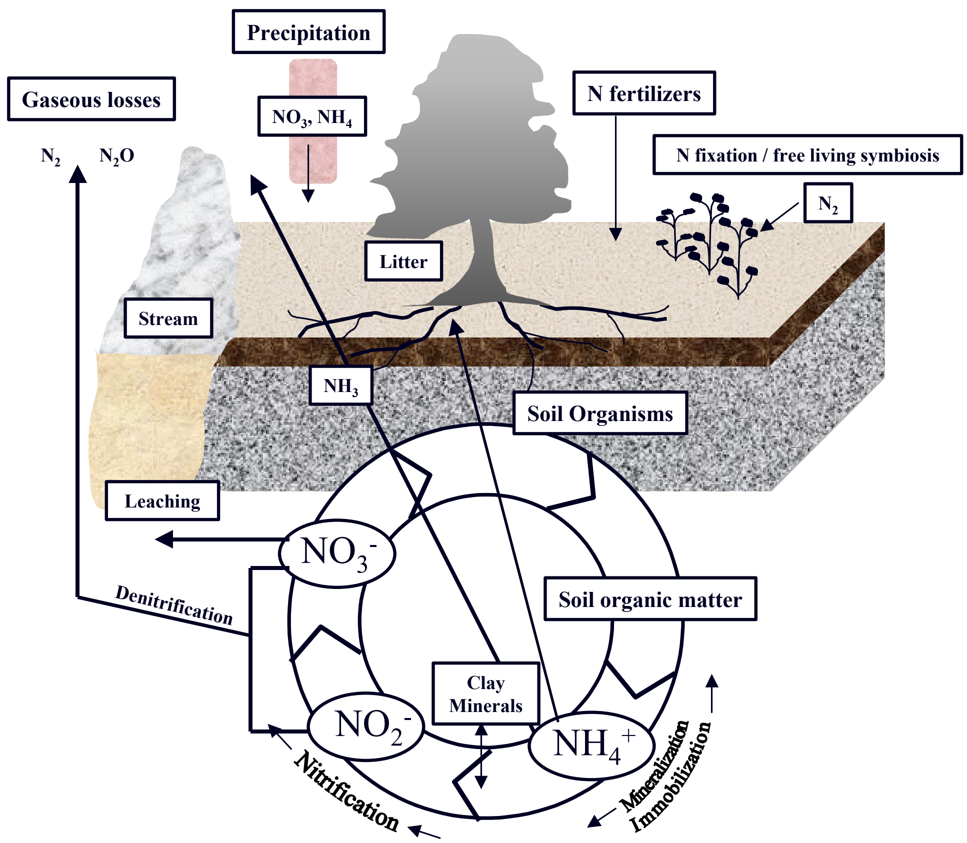

Figure 1.3. The soil nitrogen cycle of a coniferous forest ecosystem. Adapted from Brady (1990) by Canary (1994).

By increasing productivity, more C from the atmosphere can be stored in terrestrial systems (Sedjo, 1989 and Dixon et al., 1994). The supply of N influences primary production and decomposition rates, and thus SOM accumulation and C cycling (Brady and Weil, 1996). Forest productivity is often limited by the supply of available N (Binkley et al., 1986; Perry et al., 1991) and enhanced by N fertilization (Billings et al., 1984; Oberbauer et al., 1986; Edmonds and Hsiang, 1987). An increase in biomass plays a role in SOM accumulation by influencing detrital inputs both above- and belowground. Gower et al. (1992) found that increased water and nutrient inputs shifted the allocation of C from below- to aboveground. More C was allocated to leaf- and canopy-level processes. They also found that fine root production decreased, but fine root turnover increased. As more C is allocated aboveground and production of fine root biomass decreases, production of large root biomass may actually increase.

Fertilization with N in Douglas-fir stands may increase foliar and litter N concentrations. Higher N concentrations in forest floor litter inputs could lower C/N ratios. Several studies have observed increased N concentrations in litter of N fertilized Douglas-fir stands (Turner, 1977; Trofynow, 1991; Prescott et al., 1993). As C/N ratios decrease due to increases in detrital N concentration, microbial activity would be expected to increase, thus increasing decomposition rates and N availability to plants. Some studies have suggested that decomposing woody residue may be a good souce of N (Larsen et al., 1978; Harvey et al., 1989). In general, the larger the total N pools, the more N available for plant uptake.

1.3 Estimates of Soil Organic C and N

Considerable uncertainty is associated with estimates of soil C and N pools at all scales: plot, regional, and global (Johnson et al. 1990, 1991; Eswaran et al., 1993; Homann et al. 1998). For example, estimates of global soil C stores vary from as low as 700 Pg C (Bolin, 1970) to as high as 2946 Pg C (Bohn, 1976) with an average value around 1576 Pg C (Eswaran et al., 1993). Other reported values include 1080 Pg C (Baes et al., 1977), 1184 Pg C (Kimble et al., 1990), 1392 Pg C (Bazilevich, 1974), 1395 Pg C (Post et al., 1982), 1427 Pg C (Buringh, 1984), 1456 Pg C (Schlesinger, 1977), 1500 Pg C (Houghton et al., 1990), 2070 Pg C (Ajtay et al., 1979), and 2200 Pg C (Bohn, 1982). These estimates differ because they have been attained by numerous methods and across various ecosystems and scales.

Rigorous evaluation of soil C and N pools (kg m^{-2}) requires careful measurement of rock volume and bulk density, in addition to C and N concentrations. Each of these measurements has associated uncertainty, which contributes to the overall uncertainty of estimates of C and N pools (Homann et al., 1995). In addition, many studies may not measure whole-soil C and N. Most values report C and N estimates on <2-mm material only (Covington, 1981; Post et al., 1982; Alban, 1982; Huntington et al., 1988; Mattson and Swank, 1989; Johnson et al, 1991; Grigal and Ohmann, 1992; Soil Survey Staff, 1992; National Soil Survey Center, 1996; and Amelung et al., 1998), assuming larger material is inert or insignificant. However, in some ecosystems a significant amount of C and N stores may be in larger soil fractions. For example, in a coastal Oregon Douglas-fir forest, about one-third of the C was stored in the 2- to 6-mm size fraction (Cromack et al., 1999). Ugolini et al. (1996) and Corti et al. (1998) also showed that the fragments >2-mm were not chemically inert and displayed physical and chemical properties that can equal or surpass those of <2-mm material.

Regional analyses of soil C and N stores that account for rock volume, bulk density, and C and N concentrations in multiple size fractions will contribute to better global assessments. Finer scale assessments of soil C and N stores serve to calibrate and evaluate global models. By improving measurements of C and N stores, improvements can also be made on statistical analysis between soil C and site characteristics.

1.4 Controls on Soil Organic Matter

Specific physical, chemical, and biological processes that control the amount of SOM are influenced by classic soil-forming factors such as climate, biota, topography, parent material, and time (Jenny, 1941, 1980). These processes include additions to, and losses from, the soil, translocation of material through the soil, and transformations of organic and inorganic material within the soil. It is through the interaction of the soil forming factors that lead to differences in soil development. Primary production and decomposition are primarily controlled through climate. Net primary production is also influenced by vegetation inputs and microorganisms present. Rates of microbial processing and the nature of the material synthesized are influenced by the chemical composition of the organic materials. Translocation of water and nutrients are influenced by topography. The mineral composition of the soil, resulting from differences in parent material, controls transformation or both organic and inorganic material. Finally, the influence of time is relevant to successional changes in vegetation and soil characteristics.

Differences in vegetation type, climate, and land-use lead to differing net primary productivity (NPP) rates, respiration rates and turnover times among ecosystems (Post et al., 1990 and Melillo et al., 1993), and thus different amounts of soil C and different distributions of soil C with depth. Lower temperatures tend to inhibit decomposition allowing for higher C accumulations in forests at high altitudes or in boreal forests (Schlesinger, 1984). Grasslands contain large amounts of organic C deep in the soil profile due to root turnover while temperate forest soils derive most detritus from litter on the forest floor (Schlesinger, 1984). Fisher et al. (1990) showed that some introduced grasses in converted pastures in the tropical South American savannas do sequester C deep in the soil, far below the plow layer. However, often detrital layers in grasslands are burned, serving as a source of CO_2 to the atmosphere.

Many chronosequence, comparative, and manipulative studies suggest forest management practices have the potential to alter forest soil C and N concentrations (mg g^{-1}) and contents on an areal basis (kg m^{-2}) and, consequently, forest productivity (Schiffman and Johnson, 1989; Schlesinger, 1990; Powers et al., 1990; Johnson, 1992; Cole et al., 1995; Henderson, 1995). Forest floor organic matter several years after harvest may be greater (Mattson and Swank,1989), the same (Hendrickson et al., 1989), or less than preharvest levels (Covington 1981; Snyder and Harter,1987). Total soil organic matter did not change within the first 3 years after harvest of a northern hardwood forest, but organic matter was redistributed in the soil profile (Johnson et al., 1991).

Greater soil C results from the introduction of N-fixing vegetation. Compared to Douglas-fir, N-fixing alder yields higher soil C (Cole et al., 1990; Binkley et al., 1992a; Cole et al., 1995). Non-N-fixing species also influence soil C storage differently (Alban, 1982; Amundson and Tremback, 1989; Grigal and Ohmann, 1992). Species-related differences are also evident in nutrient contents of both the mineral soil and forest floor (Alban, 1982).

Regional studies of SOM relationships with climate and site characteristics are important to help understand the mechanisms involved in C accumulation, distribution and other soil ecosystem processes. Soil ecosystems develop differently across landscapes and the roles of soil-forming factors vary with scale. Not only are the landscapes complex, but the interactions among controls over SOM properties are as well (Burke et al., 1989). Assessing important climate and site characteristics at a local scale can contribute to the formulation of mechanistic models to better understand the dynamics of global C stores.

To predict changes in ecosystem function and climate on C storage, simulation modelling can attempt to integrate concepts of SOM formation and turnover (Parton et al., 1987; Rastetter et al., 1991; Harmon et al., 1996). To accurately simulate changes occurring across a landscape, these models must be calibrated and tested against detailed data describing spatial patterns and relationships among soils, vegetation, and climate. For many regions, including the Pacific Northwest, these data are either not available or have not been sufficiently organized to adequately analyze or model landscape- to regional-scale patterns in ecosystem C and N dynamics. Once accurate estimates of C stores for specific regions exist, models can incorporate the differences to better represent the processes occurring across regions.

1.5 Thesis Objectives

In this thesis, I examine soil C and N in old-growth forests in western Oregon and Washington. In old-growth forests, ecosystem composition, structure, and function are characterized by successionally advanced forests with important components like large standing dead trees, large accumulations of downed wood, and a shade tolerant understory (Spies and Franklin, 1996). Thus, these ecosystems have been relatively unaffected by substantial recent human disturbances. The results of this study contribute the important belowground component to a total ecosystem C budget estimation for old-growth forests in the Pacific Northwest. The general objectives for this thesis research are: (1) To determine total soil C and N in selected old-growth forests of the Pacific Northwest. This is presented in Chapter 2. This chapter addresses the role, significance and storage of C and N to 1-meter depth, and the importance of the greater than 2-mm size fraction in C and N storage. (2) To determine the relation of soil C and N to site factors and climate factors. This is presented in Chapter 3. This chapter provides useful information for calibration or testing of process models.

2. DISTRIBUTION OF SOIL CARBON AND NITROGEN IN OLD-GROWTH FORESTS IN WESTERN OREGON AND WASHINGTON

2.1 Introduction

Soils are an important component of the global carbon (C) cycle. They store the largest non-fossil reserve of C within the terrestrial system and account for more than two thirds of the approximately 2100 Pg circulating C within terrestrial ecosystems (Johnson and Kern, 1991). Forest soils are particularly important, representing almost 50 percent of terrestrial soil carbon stores (Schlesinger, 1997). An intensely debated question has been whether changes in climate and atmospheric CO_2 may alter the C balance of forest soils (Schlesinger, 1984; Schimel et al., 1994). That is, will forest soils be a net sink or net source of CO_2 to the atmosphere during the coming decades, thereby mitigating or exacerbating predicted increases in this ‘greenhouse’ gas? Simulation models of ecosystem C dynamics are increasingly being used to address this question (e.g., Pastor and Post, 1986; Parton et al., 1995; McKane et al., 1997). However, the application of these models is often severely limited by the availability of detailed data describing the total amounts and distribution of C in soils and the relationship of these variables to environmental factors. To better understand and evaluate the role of forest soils in regional and global C cycles, further research needs to focus on quantifying belowground C pools in relationship to key climatic and site factors.

Soil organic carbon (SOC), defined as kilograms C per square meter to a specified depth, has been examined at all scales: plot, regional, and global. However there is considerable uncertainty associated with estimates of soil C (Johnson et al. 1990, 1991; Eswaran et al., 1993;

Homann et al., 1998). More specifically, uncertainty in SOC contents is attributed to factors such as variation in specific analytical techniques used to determine C concentration, selection of sampling locations at a given site, visual estimations of rock content, bulk density measurements, and use of assumed rock density values (Eswaran et al., 1993; Homann et al., 1995). Each of these measurements has associated uncertainty that contributes to overall uncertainty of estimates of C and N pools (Homann et al., 1995). These uncertainties begin with errors associated with plot level estimates that are magnified as data are extrapolated up to regional, continental, and finally global scales. Rigorous evaluation of soil C and N pools requires careful measurement of rock volume, bulk density, and C and N concentrations to arrive at reliable estimates for SOC on regional levels (Schlesinger, 1984; Johnson and Kern, 1991; Eswaran et al., 1993).

Additionally, most SOC estimates are often determined on the <2-mm soil fraction, according to procedures developed for agricultural soils (Cline, 1944; Jackson, 1958; McKeague, 1978; Gaines and Mitchell, 1979; Nelson and Sommers, 1982; Soil Conservation Service, 1984; Soil Survey Staff, 1992; and National Soil Survey Center, 1996). Material >2-mm is traditionally regarded as inert and is therefore discarded. Although many forest soil researchers have adhered to this size threshold (Covington, 1981; Post et al., 1982; Alban, 1982; Huntington et al., 1988; Mattson and Swank, 1989; Johnson et al, 1991; Grigal and Ohmann, 1992; Soil Survey Staff, 1992; National Soil Survey Center, 1996; and Amelung et al., 1998), other studies have not been clear about the size fraction analyzed (Edmonds and Chappell, 1994). Other researchers have analyzed all soil size fractions (Grier and Logan, 1977; Binkley et al., 1992a). In some ecosystems a significant amount of C and N stores may be in larger soil fractions. For example, in a coastal Oregon Douglas-fir forest, about one-third of the C was stored in the 2- to 6-mm size fraction (Cromack et al., 1999). Ugolini et al. (1996) and Corti et al. (1998) also showed that the fragments >2-mm were not chemically inert and displayed physical and chemical properties that can equal or surpass those of <2-mm material. Thus, methods that analyze only the <2-mm soil fraction, may neglect to measure an important pool of SOC in some forest ecosystems. By improving measurements of C and N stores, improvements can also be made on statistical analysis between soil C and site characteristics.

On average, C and nitrogen (N) concentration decreases with depth (Perry, 1994; Brady and Weil, 1996). Canary (1994) showed how failing to sample to a sufficient depth could grossly underestimate soil C. When sampling to a depth of 85 cm, she found 71% of the soil C to be below the A horizon, with 40% between 25 to 85 cm. Other studies also found significant amounts of C at depths of 1-meter or greater (Edmonds and Chappell, 1994; Hammer et al., 1995; and Stone et al., 1993). To obtain more reliable estimates for SOC and total N (TN), these variables must be described to a sufficient depth. The ability to predict vertical distribution of C and N would enable whole-profile estimates of C and N stores to be based on surface measurements, there by saving time and money involved with soil sampling and processing.

As with the C cycle, there is a need to better understand the N cycle in natural soil ecosystems. Available soil N plays an important role in Pacific Northwest soils as it has been shown to limit aboveground productivity in many forests (Edmonds and Hsiang, 1987). Soil N transformations are closely linked to C supply and flow. Thus, N changes in the soil environment may also affect other processes and cycles in that system. Research that evaluates the role of N in forest soils and its relationship to C may improve our understanding of the interactions between these nutrients.

The objectives of this study are to determine (i) the contribution of the C-bearing fraction to soil C and N stores in old growth-forests in western

Oregon and Washington, (ii) the relation of vertical distribution of soil C and N to total C and N stores in the upper meter of mineral soil and (iii) the relation between soil C and N. Each of these objectives contributes to developing improved estimates of soil C and N stores in Pacific Northwest forests and provides a basis for additional analyses of the relationship of these soil variables to important environmental factors.

2.2 Methods

2.2.1 Site Description

Seven study sites were selected in western Oregon and Washington based on physiographic provinces outlined by Franklin and Dyrness (1988), (Figure 2.1, Table 2.1). These sites were located from the Pacific Ocean coast to the eastern slopes of the Cascade Range and were assumed to represent steady-state ecosystems. Therefore, C input to the soil from plant and animal residues in the form of detritus is balanced by oxidation of SOM, in which C is released as CO_2. The sites are associated with the Andrews Long Term Ecological Research (LTER) program (Appendix A). Within each site, 1 to 8 stands were sampled to estimate SOC and TN and their vertical distribution to 1-meter depth in mineral soil. This was accomplished by excavating and sampling 1 to 3 soil pits on the perimeter of each stand. In total, 79 soil pits were sampled to estimate forest floor and mineral SOC and TN contents.

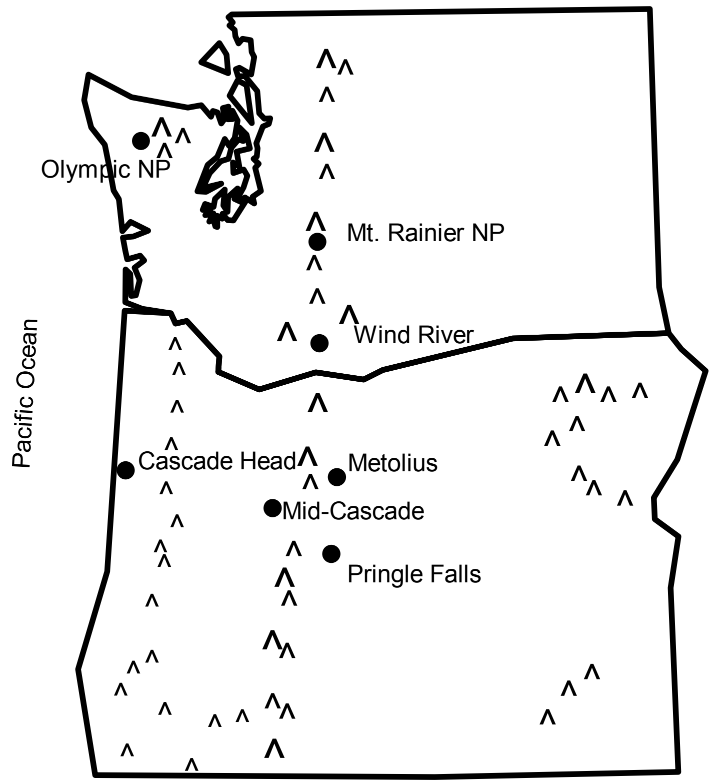

Figure 2.1. Old-growth study sites in Oregon and Washington.

Table 2.1. Location information and data characteristics of the study sites.

Physiographic Province	Study Site*	Stand Locations	North Latitude, West Longitude	Number of Stands	Stand Area (ha)	Managing Agency
Oregon coast	Cascade Head	Cascade Head EF†	45.1,123.9	8	0.4	Hebo District, Siuslaw NF‡
Washington coast	Olympic Peninsula	S. Fork Hoh River	47.8,123.9	4	1.0	Olympic National Park
		Twin Creeks RNA§	47.8,123.9	1	1.0	Olympic National Park
		Quinault RNA	47.4,123.8	2	1.0	Quinault District, Olympic NF
Oregon Cascades	Mid-Cascade	HJ Andrews EF	44.2,122.2	6	0.25 or 1.0	Blue River District, Willamette NF
		EPA/Cascade	44.4,122.3	2	0.6	Sweethome District, Willamette NF
Washington Cascades	Wind River	T.T. Munger RNA	45.8,122.0	1	4.1	Wind River Dist., Gifford Pinchot NF
	Mt. Rainier	Nisqually River	46.7,121.8	4	1.0	Mt. Rainier National Park
		Ohanapecosh River	46.8,121.6	2	1.0	Mt. Rainier National Park
		White River	46.9,121.5	1	1.0	Mt. Rainier National Park
		Carbon River	46.8,121.9	2	1.0	Mt. Rainier National Park
Eastside Oregon Cascades	Metolius	Metolius RNA	44.5,121.6	1	4.5	Sisters District, Deschutes NF
	Pringle Falls	Pringle Falls RNA	43.7,121.6	3	1.0 or 4.0	Bend District, Deschutes NF

* See Appendix A for background information about study sites.

† Experimental Forest

‡ National Forest

§ Research Natural Area

The sites chosen for this study vary widely both physically and climatically (Table 2.2). Climate data was derived from precipitation layers generated by PRISM (Precipitation-elevation Regressions on Independent Slopes Model), a model developed by Oregon Climate Service at Oregon State University (Daly et al. 1994), and temperature layers generated by POTT (Potential Temperature) model (Dodson and Marks, 1997). Both models used a digital elevation model (DEM) to account for topographic differences between grid cell and weather station location (Daly et al., 1994). Precipitation layers were based on 1961 to 1990 data from weather stations within the sampling area and had a grid size of 4-Km. Temperature layers were based on 1981 to 1992 data extracted from 258 weather stations in Oregon and 197 weather stations in Washington (Ohmann and Spies, 1998) and had a grid size of 500-m. From these layers, mean annual precipitation and mean annual temperature were extracted for each plot. Mean annual temperature ranges from 3.8 to 11.4 °C. Mean annual precipitation ranges from 355 to 3669 mm.

Stand age and elevation for most stands were available from the Oregon State University Forest Science Database. Methods for age estimation differed across sites, but were most commonly based on the oldest trees within the stand (Personal communication with Steve Acker and Mark Harmon, OSU, 1998). Both published and unpublished tree core data were available for most sites. Stand ages at Mount Rainier plots were interpolated from age class maps (Franklin et al., 1988). Elevation was checked using topographical maps. Stand age ranges from 105 to over 1200 years. Elevation ranges from 122 to 1430 m. Slope measurements assessed the specific land position of the pit and were collected in the field. Slope ranges from 0- to 70%. Coniferous forests associated with a variety of understory species (Appendix C) dominated all sites.

Table 2.2. Ecological characteristics of study sites. Values are means, with ranges in parentheses, from all the pits within each site. For information on stands within the sites, see Appendix A.

Study Sites	Number of Soil Pits	Temperature (°C yr^{-1})	Precipitation (cm yr^{-1})	Elevation (m)	Slope (%)	Age (years)
Cascade Head	17	8.6 (7.9-9.0)	258 (242-266)	286 (244-396)	17 (0-35)	150
Olympic Peninsula	14	8.5 (8.3-8.9)	336 (289-367)	198 (122-250)	0	254 (200-280)
Mid-Cascades	15	7.8 (3.8-10.4)	215 (186-234)	921 (536-1290)	26 (9-62)	379 (105-460)
Wind River	8	7.8	250	405 (362-461)	15 (0-36)	470
Mt. Rainier	15	6.4 (3.9-8.8)	235 (208-281)	927 (610-1430)	22 (0-55)	747 (300-1200)
Metolius	4	8.1	36	933	1 (0-5)	300
Pringle Falls	6	5.7 (5.6-5.8)	54 (54-55)	1359 (1353-1372)	5 (0-18)	433 (400-500)

2.2.2 Forest Floor Sampling, Processing and Analysis

Forest floor samples were taken, with a 5-cm diameter core sampler, at five points above the sampling face of the soil pit. These samples were composited by pit. The samples included relatively undecomposed aboveground litter whose tissue type was recognizable, as well as decomposed humified material whose tissue type was not recognizable. The forest floor was distinguished from mineral soil by its low content of mineral material (i.e. sand, rocks, and clay). Forest floor samples include woody debris <1-cm in diameter on the surface and all woody debris, irrespective of size, within the forest floor that is not visible from the surface. Sample procedures for treatment in the field, returning to the lab, and greenhouse drying were the same as for the mineral soil samples.

Forest floor samples were oven dried (70°C), weighed, and blended in a kitchen blender (Braun AG, Frankfurt, West Germany) to break up material and ensure homogenous subsampling. A tablespoon of this material was subsampled and more finely ground with an analytical mill (IKA-A 10, Staufen, Germany) to <850μm (<20-mesh). The Central Analytical Laboratory, Oregon State University, Corvallis, analyzed these samples for C and N content using a LECO CNS 2000 analyzer. Samples were randomized for analysis. Quality control samples and replicates represented 20% of the run. Quality control samples (10%) consisted of reference material of known C and N concentration obtained from the EPA Environmental Research Laboratory, Corvallis, Oregon. Replicates (10%) were randomly chosen samples. Total C and N values were reported as g kg^{-1} at 60°C. Mass per sampling area was multiplied by C and N contents to yield kg C or N per sampling area.

2.2.3 Mineral Soil Assessment Strategy

The objective of mineral soil analysis was to determine the mass of SOC and TN in three mineral soil layers (0- to 20-cm, 20- to 50-cm, 50-100-cm depths) of all C-bearing material, which consisted of <2-mm, 2- to 4-mm, and >4-mm size classes. The results of the analysis of all C-bearing material are referred to as the total-soil method. The C and N contents from lab analysis, soil bulk density, soil volume, and layer depth were used to calculate mineral SOC and TN. Each size class was analyzed for total C and N. The thresholds of 2- and 4-mm were chosen to facilitate comparison with other studies. SOC is assumed to be the same as total C. In these acidic forest soils, inorganic C from carbonates does not play a role in the C budgets.

In this text, the subscript “s” represents material expected to bear C. All other material was classified as rock <75 mm or >75 mm. These fractions are denoted by subscripts “r” and “R”, respectively. The subscript “t” denotes the sum of these three fractions. For example, the total sample volume, V_t, is the sum of V_s, V_r, and V_R. Alternatively, the volume of material *x* as a proportion of total, denoted as S, is defined as $S_x = V_x / V_t$, where *x* is either “s”, “r”, or “R”. Thus, SOC (kg C m^{-2}) was calculated on a layer basis:

$$SOC_s = C_s * D_s * S_s * L * 10 \tag{1}$$

where C_s is organic C concentration (g C kg^{-1}) of the C-bearing fraction; D_s is the bulk density (g cm^{-3}) of this fraction; S_s is the C-bearing fraction as a proportion of total sample volume, or V_s/V_t; L is the layer depth (cm); and 10 is the conversion factor (10^4 cm^2 m^{-2} 10^{-3} kg g^{-1}) to obtain volumetric values (kg m^{-2}). The three layers were summed to determine SOC per soil pit.

The TN was calculated using the same equation substituting N_s for C_s, where N_s is total N concentration (g N kg^{-1}) in C-bearing material.

Calculations were also performed on the individual size classes to determine their contribution to the total C content within the profile. Equation 2 was used to perform these calculations.

$$SOC_i = C_i * D_s * S_s * \frac{M_i}{M_s} * L * 10 \qquad (2)$$

where C_i is the total C concentration (g C kg^{-1}) of material in size class i; i refers to the <2-mm, 2- to 4-mm and >4-mm C-bearing size classes; M_i is the mass of material in size class i, and M_s is the mass of all C-bearing material. It is assumed that $D_i = D_s$, as it was not possible to measure D_i for the different size classes; thus $S_i = S_s*M_i/M_s$.

2.2.4 Mineral Soil Sampling

On the perimeter of each plot, one or more 1-meter wide by 1-meter deep soil pits were dug, sampled and described. Pits were located to best represent the stand in terms of slope, aspect, vegetation density and cover. At each pit, three mineral soil layers were sampled (0- to 20-cm, 20- to 50-cm, and 50- to 100-cm). Depth strata, as opposed to horizon, sampling was chosen because it is more repeatable and comparable to other studies.

To ensure a representative sample, mineral soil samples were obtained by collecting material in three swaths, 5- to 10-mm deep, across the face within each layer. For pit faces that were too rocky to make swaths, samples were collected as part of Bulk Density Sampling (Section 2.2.6).

Soil samples were kept in the shade for 4-10 days, brought back to the lab and placed in a cooler (6°C) until they were laid out to air-dry in a greenhouse (within 3 days). The samples were stirred every other day until dry (1-2 weeks) and were then bagged, weighed, and stored until processed.

2.2.5 Mineral Soil Processing and Analysis

Each air-dried sample was sieved and hand-sorted into the following components: <2-mm C-bearing soil fraction, 2- to 4-mm C-bearing soil fraction, >4-mm C-bearing soil fraction, >2-mm rock (non-C bearing), and >2-mm buried wood, roots, charcoal. The C-bearing soil fractions were defined as soil that could not be broken up with a rubber stopper on a sieve. The C-bearing fraction >2-mm were hardened soil aggregates or soft, weathered rocks, which were assumed to be nutrient-rich and should be included in estimating C stores. The >4-mm C-bearing was typically between 4- to 10-mm in size. Each component was weighed. Buried wood, roots, and charcoal accounted for <3% of the sample mass, and they were disregarded. C-bearing fractions >2-mm were only analyzed for C and N if they were greater than 10%, by weight, of the total sample. Otherwise, the weight of any >2-mm C-bearing fraction was incorporated into the rock mass used to estimate soil volume.

Subsamples (50-100 g) of <2-mm, 2- to 4-mm, and >4-mm C-bearing fractions were obtained with a sample splitter (SoilTest Riffles, CL-280 series). These subsamples were ground to 850-µm (<20-mesh) using a 20-cm disc pulverizer (BICO Inc., Burbank, California) and analyzed for total C and N concentration using a LECO CNS 2000 analyzer by the Central Analytical Laboratory, Oregon State University, Corvallis. Samples were randomized for analysis in one of two groups: high C mineral soil or low C mineral soil. Assignment into a group was based on expectation of either a high or a low C concentration. Typically, deeper layers are expected to contain low C concentrations while surface layers are expected to contain high C concentrations. The groups were run in four batches of up to 120 samples in each. Quality control samples and replicates represented 20% of each batch. Quality control samples (10%) consisted of reference material of known C and N concentration obtained from the EPA Environmental Research Laboratory, Corvallis, Oregon. Replicates (10%) were randomly chosen samples from the current and previous batches. Total C and N concentrations were obtained from the lab as g kg^{-1} at 60°C. A dry weight ratio of 60°C to 105°C was determined on the bulk density samples and applied to these lab values for conversion to a 105°C basis.

The mass-weighted C concentration of all C-bearing material, C_s, was computed as:

$$C_s = \frac{\sum C_i M_i}{\sum M_i} \tag{3}$$

where C_i is the total C concentration (g C kg^{-1}) of material in size class i; i refers to the size classes <2-mm, 2- to 4-mm, and >4-mm C-bearing fractions; and M_i is the oven-dry (105°C) mass of material in size class i, ($\sum M_i = M_s$).

2.2.6 Bulk Density Sampling, Processing and Analysis

Bulk density was determined for each layer with a core sampler for non-rocky soils or by excavating a known volume of soil for rocky soils. For non-rocky soils, a 5-cm diameter x 5-cm deep soil core bulk density sampler with sampling ring inserts (AMS, USA) was used in most cases.

For soils that were too loose for the bulk density sampler to be effective (e.g., the top 35 cm at Pringle Falls), a 5-cm diameter tube was inserted approximately 10 cm into the profile face. Inserting a measuring tape in the open end of the corer confirmed this depth. If the depth was uneven (as with sandy, loose soil) an average was taken. Multiplying the area of the corer by the depth of fill attained a core volume. With both samplers, cores were taken at three locations in each layer.

For rocky pit faces, a cube was cut (approximately 20-cm x 10-cm x layer depth), soil excavated, and dimensions of the hole measured. The volumes of any large rocks protruding into the hole were estimated and subtracted from the volume of the hole to obtain a total sample volume, V_t. The material removed from the hole was sieved and weighed in the field to yield material <20-mm and 20- to 75-mm per layer. Thoroughly mixed subsamples of each fraction were obtained, weighed and brought back to the lab. The <20-mm material was used to determine bulk density and was further subsampled and processed for C and N analysis. The oven-dried mass of the 20- to 75-mm material was necessary to determine the soil volume fraction of the total sample volume, S_s, (Soil Volume, Section 2.2.7).

As with the mineral soil processing, each air-dried bulk density sample was sieved and hand-sorted into the same components: <2-mm C-bearing soil fraction, 2- to 4- mm C-bearing soil fraction, >4-mm C-bearing soil fraction, >2-mm rock (non-C bearing), and >2-mm buried wood, roots, charcoal. The mineral components were oven-dried (5-7 days) and weighed at both 60 and 105°C. This provided a soil moisture conversion factor since the soils at the Central Analytical Laboratory were analyzed at 60°C and values in this text reported on 105°C basis. Since the volume contribution of buried wood, roots, and charcoal was insignificant, it was omitted from the calculations.

In this text, the lower case letters "m" and "v" are used to represent mass and volume of bulk density samples, respectively. Bulk density, D_s, for the total-soil method was calculated as the mass of C-bearing material divided by the volume of this material, m_s/v_s. The volume of C-bearing material, v_s, was derived as the total sample volume minus the volume of >2-mm rocks (non C-bearing) in the sample, v_r. The volume of >2-mm rocks, v_r, was the mass of the rocks, m_r divided by rock density, D_r. Bulk density, D_s, for the standard method was simply calculated as the mass of material <2-mm divided by the volume of this material, $m_{<2}/v_{<2}$. Rock density was assumed to be 2.65 g cm^{-3} for all sites except the pumice at Pringle falls which was assumed to be 2.1 g cm^{-3} (Flint and Childs, 1984).

2.2.7 Soil Volume

Appendix D presents a flow diagram of the soil sampling and processing methodology used to determine soil volume. Soil volume (as a fraction of the total volume), S_s, was calculated using equation 4.

$$S_s = \frac{1 - S_R}{1 + \frac{D_s}{D_r}\frac{M_r}{M_s}} \qquad (4)$$

where S_R (= V_R/V_t), was estimated in the field by either scrutiny of the pit face or, in cases where large rocks were abundant, by visually comparing the amount of rock extracted in each layer to the amount of total material excavated. The ratio of the mass of <75 mm rocks to the mass of soil (M_r/M_s) was calculated using the various soil and rock masses established during sampling and processing. Appendix D also discusses the derivation of equation 4 based on the variables measured in the field and obtained through processing in the lab.

2.2.8 Statistical Methods

Data were analyzed using SAS (SAS Institute Inc., 1998). Summary statistics of means and standard error were obtained for the forest floor, SOC, and TN data. These data were summarized on a regional scale by analyzing each soil pit as an individual experimental unit. This allowed for comparisons between this and other studies.

The sites are located in different physiographic provinces (Franklin and Dyrness, 1988) from the Pacific Ocean to the eastern slopes of the Cascade Range. Thus, the bulk of the analyses were performed grouping by site. Soil pits were summarized on a study site basis; each soil pit within the site was considered an individual without replication (soil pits were not summarized by stands).

Tests for significant differences between site means using analysis of variance (ANOVA) were not determined because there was uneven variance between sites and this test is not appropriate in these cases.

2.3 Results and Discussion

2.3.1 Forest Floor Carbon and Nitrogen Pools

Forest floor SOC averaged 2.7 kg C m^{-2} (range 0-13.6, n=79). This average was higher than values reported by Homann et al., (1995) for western Oregon forests (mean=1.0 kg C m^{-2}, range=0.1-4.5, n=86). These values reported by Homann et al. (1995) consisted of actual measured

SOC where both mass and C concentration was available (Table 2.3). However, they were mainly from young, second-growth stands that had soil disturbance prior to establishment. Homann et al. (1995) reported an average value of 2.0 kg C m^{-2} (n=288), by including additional data where a conversion factor was applied to forest floor depth to obtain SOC. For a northern Hardwood forest in New Hampshire, Huntington et al. (1988) reported an average value of 3.0 kg C m^{-2} (n=55). This is similar to the forest floor SOC measured in this study.

A trend in forest floor SOC is evident when summarized by site (Figure 2.2). This trend is most apparent when evaluating sites by physiographic provinces. The Cascade Head coastal site contains more C in the forest floor than do Mountainous Cascade sites, while the Eastside Cascade sites contain the least amount. An anomalous result occurs at the Olympic Peninsula site where forest floor SOC averages 1.4 kg C m^{-2}. This value is on par with the Eastside Cascade sites. Productivity is lower at higher latitudes (Waring and Schlesinger, 1985) lowering inputs. Lower amounts of fine wood debris (<15-cm in diameter) and forest floor mass were observed at the Olympic Peninsula site than at the Cascade Head site. The Cascade Head site contained almost twice as much SOC in the forest floor as reported in another old-growth, coastal Oregon site reported by Cromack et al. (1999).

Forest floor TN averaged 0.07 kg N m^{-2} (range 0-0.38, n=79). This average was higher than values reported from other studies (Table 2.4). However, the average was within the range of values reported by Wooldridge (1961) in old, high elevation, forest stands in Oregon and Washington. As for forest floor SOC, a trend in forest floor TN is also evident when summarized by site (Figure 2.3). Again, this trend is more apparent when evaluating sites by physiographic provinces. The Cascade Head coastal site contains more N in the forest floor than do Mountainous

Table 2.3. Forest floor soil organic carbon (SOC) values for western Oregon and Washington.

Location	SOC (kg C m^{-2})	n	Source	Comments
Western OR & WA	2.7	79	This study	old-growth forests
Western OR	2.0	288	Homann et al., 1995	mountainous forest; all samples
Western OR	1.0	86	Homann et al., 1995	young, mountainous forests; measured SOC
Western OR	2.4	202	Homann et al., 1995	mountainous forest; thickness based SOC
OR coast	4.9	17	This study	old-growth forests
OR coast	2.7	6	Cromack et al., 1999	old-growth forests
OR coast	0.4	18	Cromack et al., 1999	young Douglas-fir plantations
OR coast	1.1	6	Edmonds & Chappell, 1994	young Hemlock stands
OR coast	0.8	14	Edmonds & Chappell, 1994	young Douglas-fir stands
WA coast	1.4	14	This study	old-growth forests
WA coast	1.4	14	Edmonds & Chappell, 1994	young Hemlock stands
WA coast	1.0	22	Edmonds & Chappell, 1994	young Douglas-fir stands
OR Cascade	2.1	15	This study	old-growth forests
OR Cascade	0.7	17	Edmonds & Chappell, 1994	young Douglas-fir stands
WA Cascade	3.3	15	This study	old-growth forests
WA Cascade	1.2	16	Edmonds & Chappell, 1994	young Hemlock stands
WA Cascade	0.9	26	Edmonds & Chappell, 1994	young Douglas-fir stands

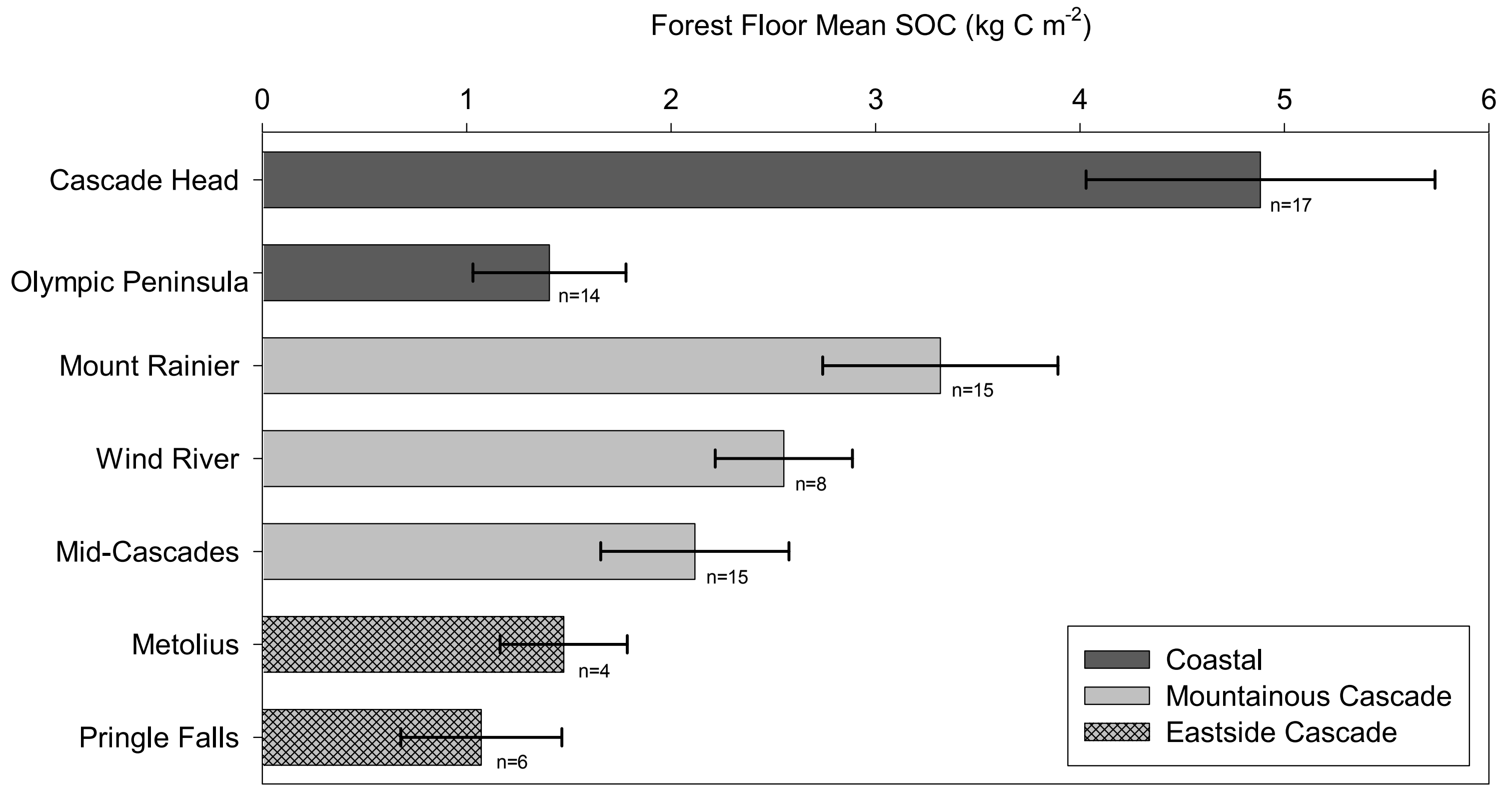

Figure 2.2. Mean forest floor soil organic carbon (SOC) by study site in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

Table 2.4. Forest floor soil total nitrogen (TN) values for western Oregon and Washington.

Location	TN (kg N m^{-2})	n	Source	Comments
OR & WA	0.01-0.20	n.i.*	Wooldridge, 1961	old, high-elevation forest stands
Western OR & WA	0.07	79	This study	old-growth forests
Western OR & WA	0.03	16	Edmonds & Chappell, 1994	young Hemlock stands
Western OR & WA	0.02	17	Edmonds & Chappell, 1994	young Douglas-fir stands
OR coast	0.14	17	This study	old-growth forests
OR coast	0.10	6	Cromack et al., 1999	old-growth forests
OR coast	0.01	18	Cromack et al., 1999	young Douglas-fir plantations
Olympia, WA	0.05	13	Bormann & DeBell, 1981	young alder stands

* not indicated

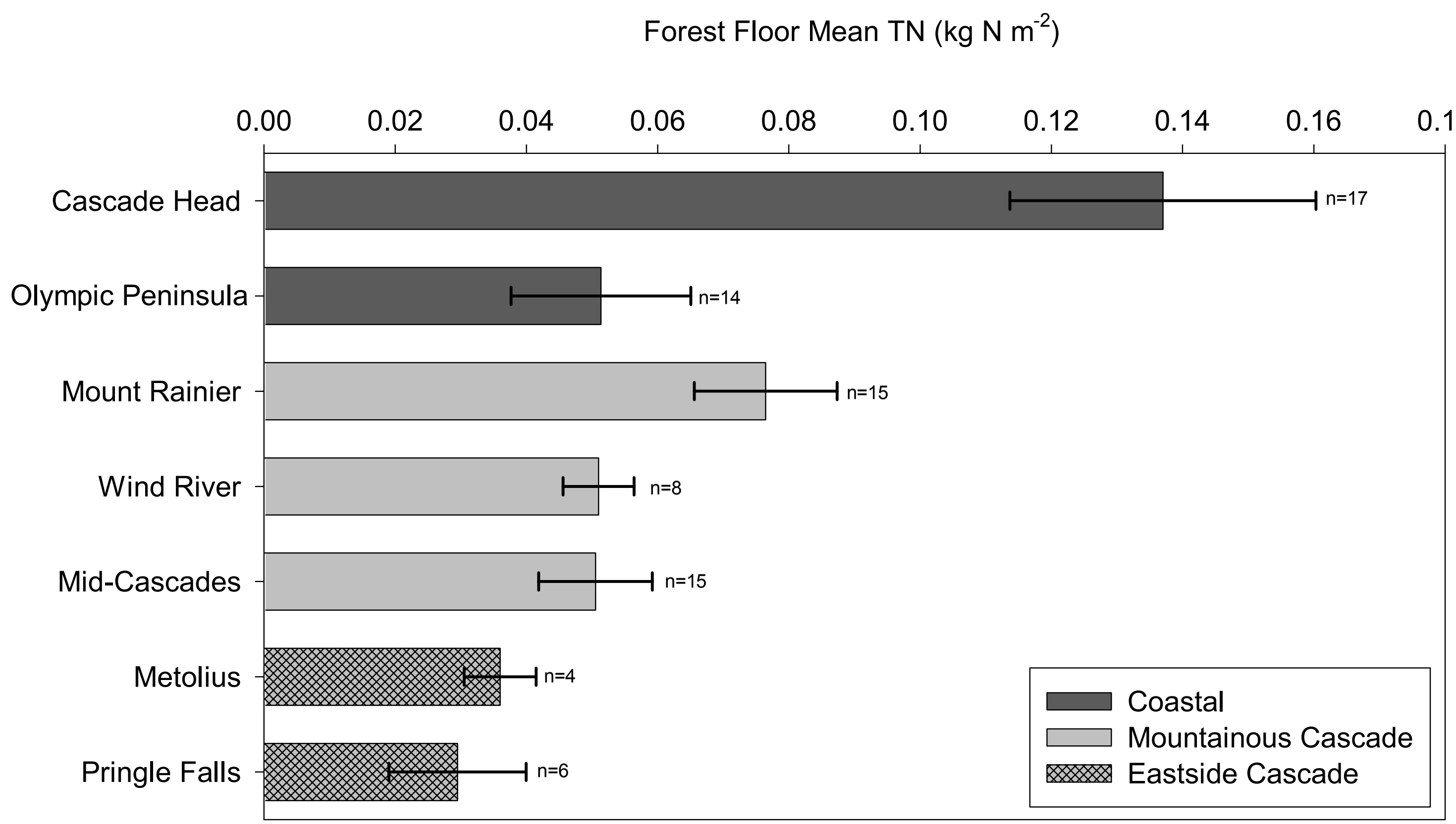

Figure 2.3. Mean forest floor total nitrogen (TN) content by study site in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

Cascade sites, while the Eastside Cascade sites contain the least amount. As with SOC, an anomalous result occurs at the Olympic Peninsula site where forest floor TN averages 0.05 kg N m^{-2}. This value is on par with the Mountainous Cascade sites (rather than the Eastside Cascade sites, as for SOC). The Cascade Head site contained about the same amount of TN in the forest floor as reported in another old-growth, coastal Oregon site reported by Cromack et al., (1999). For a northern hardwood forest in New Hampshire, Huntington et al. (1988) reported 0.13 kg N m^{-2} (n=55). This is similar to what was measured in this study at Cascade Head on the Oregon coast.

Many factors could affect the rates of production and decomposition in forest soils. These factors influence the main mechanisms by which energy flows and nutrients cycle within the soil ecosystem. Decomposition of soil organic matter is controlled by biological and environmental factors. Of the studies summarized in Table 2.3 and Table 2.4, higher amounts of SOC and TN were reported in older forests. Therefore, stand age may have an effect on the amount of forest floor C and N that accumulates. In older forests, where there is limited disturbance and plenty of time has occurred, deeper forest floors were able to accumulate and contribute more C and N. Some studies (Grier and Logan 1977; Bormann and DeBell, 1981; Edmonds and Chappell, 1994) have noted that differences in forest floor C and N contents are associated with forest type. Substrate quality, or the inherent susceptibility of the substrate to microbial degradation, can greatly influence the amount and rate that the substrate is incorporated into the soil system. Finally, the effect of climate plays a major role in the processes occurring in the soil system and affects the rate of turnover. A general trend of high SOC and TN at coastal sites to low SOC and TN at the Eastside Cascade sites is observed (Figures 2.2 and 2.3). This is a longitudinal effect due to different climate. Coastal temperatures are mild and precipitation is high while the Eastside Cascade sites experience extreme temperatures throughout the year and precipitation comes mainly in the form of snow during the winter months.

Forest floor C/N ratios average 38 (range 18-63, n=79). This average was similar to a C/N ratio of 40 reported by Edmonds and Chappell (1994) for young Douglas fir stands from western Oregon and Washington. For young western Hemlock stands they reported C/N ratios of 36 (n=6), 43 (n=14), and 38 (n=16) in coastal Oregon, coastal Washington, and Washington Cascades, respectively.

Summarized by site, Figure 2.4 shows that Mountainous Cascade sites had slightly higher ratios than the other sites. Wind River had the highest mean ratio at 49 and the Olympic Peninsula had the lowest at 27. Given similar vegetation types, the differences in mean C/N ratio across the sites gives an indication of substrate quality. Low C/N ratios are generally associated with high resource quality and rapid rates of decomposition. Likewise, higher C/N ratios are associated with low resource quality and slow decomposition.

2.3.2 Mineral Soil Carbon and Nitrogen Pools

Mineral SOC averaged 6.7 kg C m^{-2} (range 1.0-18, n=79) for 0- to 20-cm depth and 18 kg C m^{-2} (range 2.2-57, n=79) for 0- to 100-cm depth. These values are very similar to those reported by Homann et al. (1995) for western Oregon (Table 2.5). Although higher than contents from other forested regions, mean SOC from this study corresponds to the national average of 17.7 kg C m^{-2} presented by Birdsey (1992), (Table 2.6). The average value for cool, coniferous forest in North America reported by Kern (1994) was 15.8 kg C m^{-2}. Cool, temperate, wet forests classified by the Holdridge Life Zones (Post et al., 1982) averaged 13.9 kg C m^{-2}.

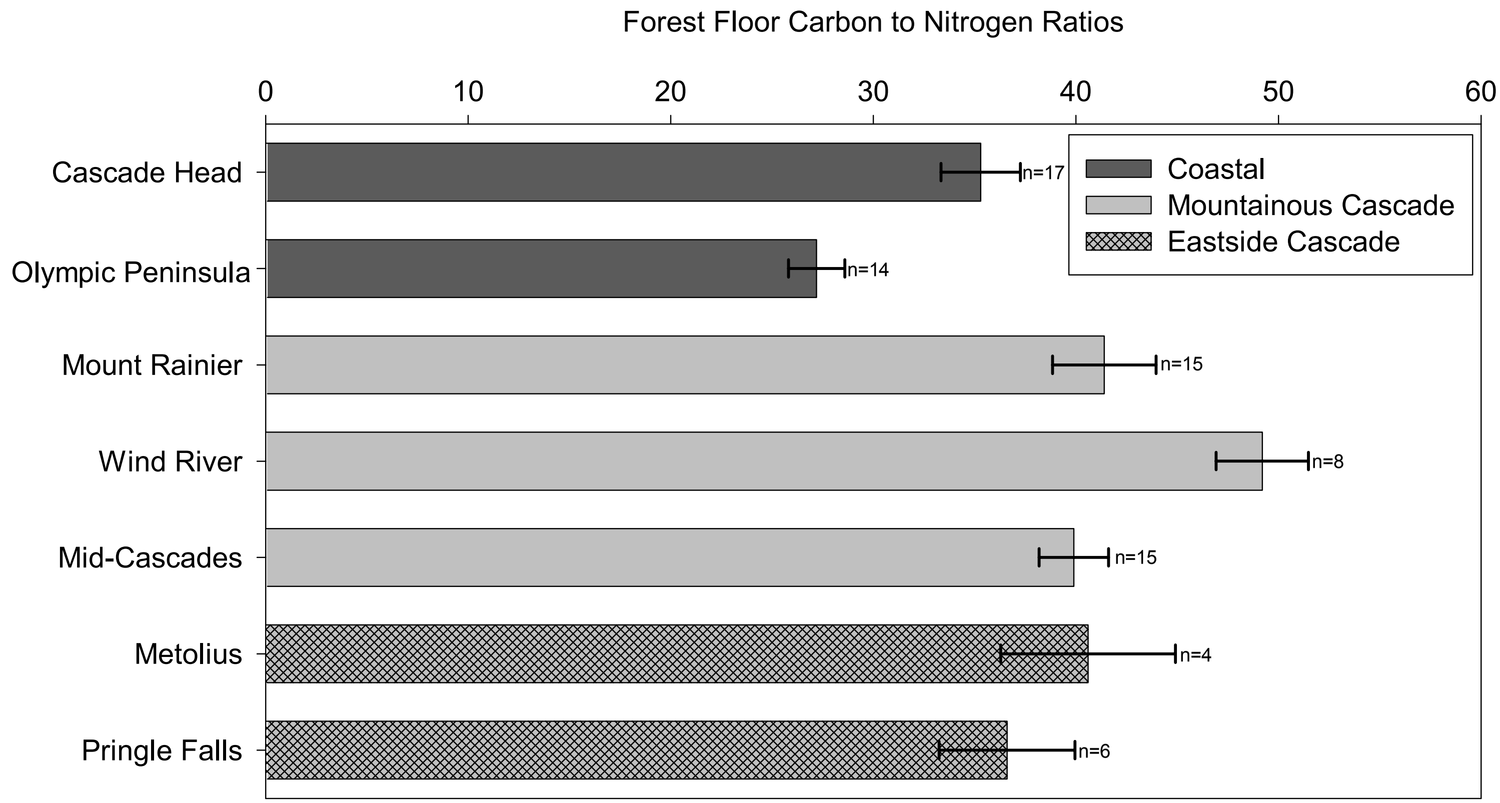

Figure 2.4. Mean forest floor C/N ratios by study site in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

Table 2.5. Mineral soil organic carbon (SOC) values for western Oregon and Washington.

Location:	Mean SOC (kg C m^{-2})	n	Depth (cm)	Source:	Comments:
Western OR	6.3	348	20	Homann et al., 1995	mountainous forest
Western OR & WA	6.7	79	20	This study	old-growth forests
OR Cascade	5.7	4	15	Means, et al., 1992	old-growth forests
OR Cascade	5.4	15	20	This study	old-growth forests
Western OR	15.0	330	100	Homann et al., 1995	mountainous forest
Western OR & WA	17.5	79	100	This study	old-growth forests
OR Cascade	21.3	4	100	Means, et al., 1992	old-growth forests
OR Cascade	12.5	15	100	This study	old-growth forests
OR Cascade	17.7	26	180 (max)	Edmonds & Chappell, 1994	young Douglas-fir stands
WA Cascade	24.1	16	240 (max)	Edmonds & Chappell, 1994	young Hemlock stands
OR coast	27.6	18	100	Cromack et al., 1999	Young Douglas-fir plantations
OR coast	36.6	17	100	This study	old-growth forests
OR coast	16.4	14	180 (max)	Edmonds & Chappell, 1994	young Douglas-fir stands
OR coast	28.2	6	240 (max)	Edmonds & Chappell, 1994	young Hemlock stands
WA coast	19.5	14	100	This study	old-growth forests
WA coast	12.4	22	180 (max)	Edmonds & Chappell, 1994	young Douglas-fir stands
WA coast	30.9	14	240 (max)	Edmonds & Chappell, 1994	young Hemlock stands
Southeast AK	18.5	149	150	Alexander et al., 1989	

Table 2.6. Global mineral soil organic carbon (SOC) values.

Location:	Mean SOC (kg C m^{-2})	n	Depth (cm)	Source:	Comments:
Western OR & WA	6.7	79	20	This study	old-growth forests
N. Central, USA	4.9	~250	20	Franzmeier et al., 1985	all vegetation types
Lake states; MN, WI, MI	4.0	169	20	Grigal & Ohmann, 1992	hardwood forests
Hubbard Brook Exp. For., NH	5.9	59	20	Huntington et al., 1988	northern hardwood forest
Hubbard Brook Exp. For., NH	13.0	59	54	Huntington et al., 1988	northern hardwood forest
Western OR & WA	17.5	79	100	This study	old-growth forests
Pacific coast; WA,OR,CA,AK	23.0		100	Birdsey, 1992	forest lands
n.i.*	11.8	n.i.	n.i.	Schlesinger, 1977	temperate forest
N. Central, USA	11.7	~250	100	Franzmeier et al., 1985	all vegetation types
Lake states; MN, WI, MI	10.5	169	100	Grigal & Ohmann, 1992	hardwood forests
Florida	10.4	244	100	Stone et al., 1993	Spodosols
n.i.	68.6	n.i.	n.i.	Schlesinger, 1977	swamps & marshes
N. Central, USA	75.0	n.i.	100	Franzmeier et al., 1985	Histosols
USA	17.7	n.i.	100	Birdsey, 1992	forest lands
N. America	15.8	803	100	Kern, 1994	Cool, coniferous forests
World	13.9	344	100	Post et al., 1982	Cool, temperate, wet forest zones
World	11.7	>16,000	100	Eswaran et al., 1993	15,000 pedons from USA

* not indicated

Summarized by site, Figure 2.5 exhibits a trend in mineral soil SOC. Coastal sites store twice as much soil carbon as the mountainous Cascade sites and five times that of Eastside Cascade sites. Means et al. (1992) reported almost twice as much SOC in their Oregon Cascade site as was measured from this study, however, they had a very small sample size which all came from a single stand. Their mean is at the high end of the range from the mid-Cascade site in this study (4 to 21 kg C m^{-2}). Values reported by Edmonds and Chappell (1994) are from young stands and were measured to the C-horizon, rather than a specific depth. The maximum depth measure was 180-cm in Douglas-fir stands and 240-cm in western hemlock stands.

Mineral soil TN averaged 0.31 kg N m^{-2} (range 0.04-0.97, n=79) for 0- to 20-cm depth and 0.92 kg N m^{-2} (range 0.12-2.53, n=79) for 0- to 100-cm depth. The ranges and means reported in this study were similar to a variety of studies in the Pacific Northwest summarized by Gessel et al. (1973).

Summarized by site, Figure 2.6 exhibits a similar trend for nitrogen as was seen with carbon. Averages stores for the Coastal sites are more than twice that of the Mountainous Cascade sites and four times the stores of the Eastside Cascade sites. Similar values of mean mineral nitrogen contents have been reported in various studies, which evaluated similar physiographic provinces within the region (Table 2.7). From this study, an average of 1.9 kg N m^{-2} was measured at the coastal Oregon site. Similarly, Cromack et al. (1999) reported 1.3 kg N m^{-2} in their old-growth coastal Oregon site. However, Means et al. (1992) reported more than twice the N content in their Oregon Cascade site than was measured in this study. Again, they had a very small sample size which all came from a single stand where this study covered a much larger sampling area.

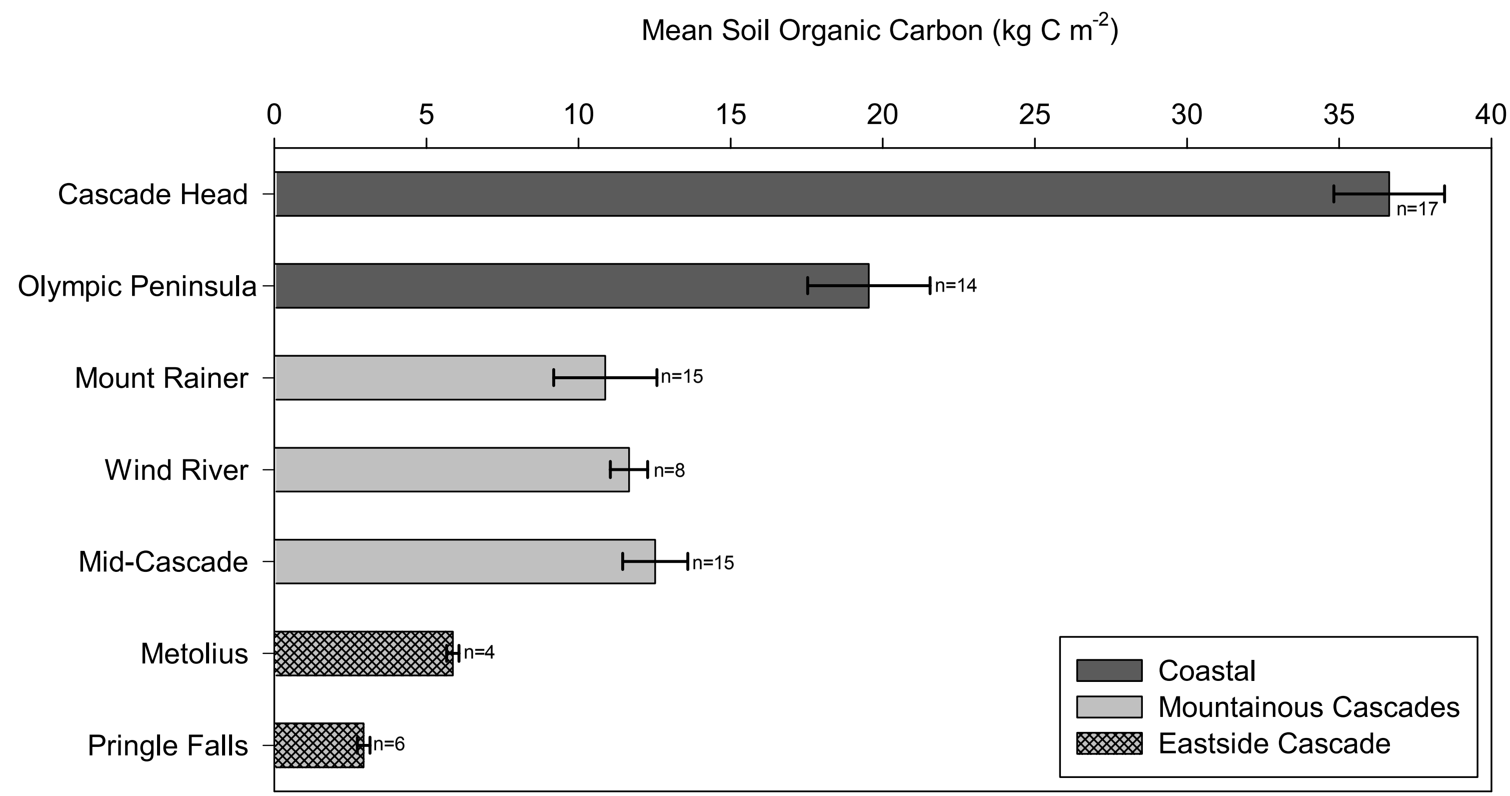

Figure 2.5. Mean mineral soil organic carbon (SOC) to 1-meter depth by study site in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

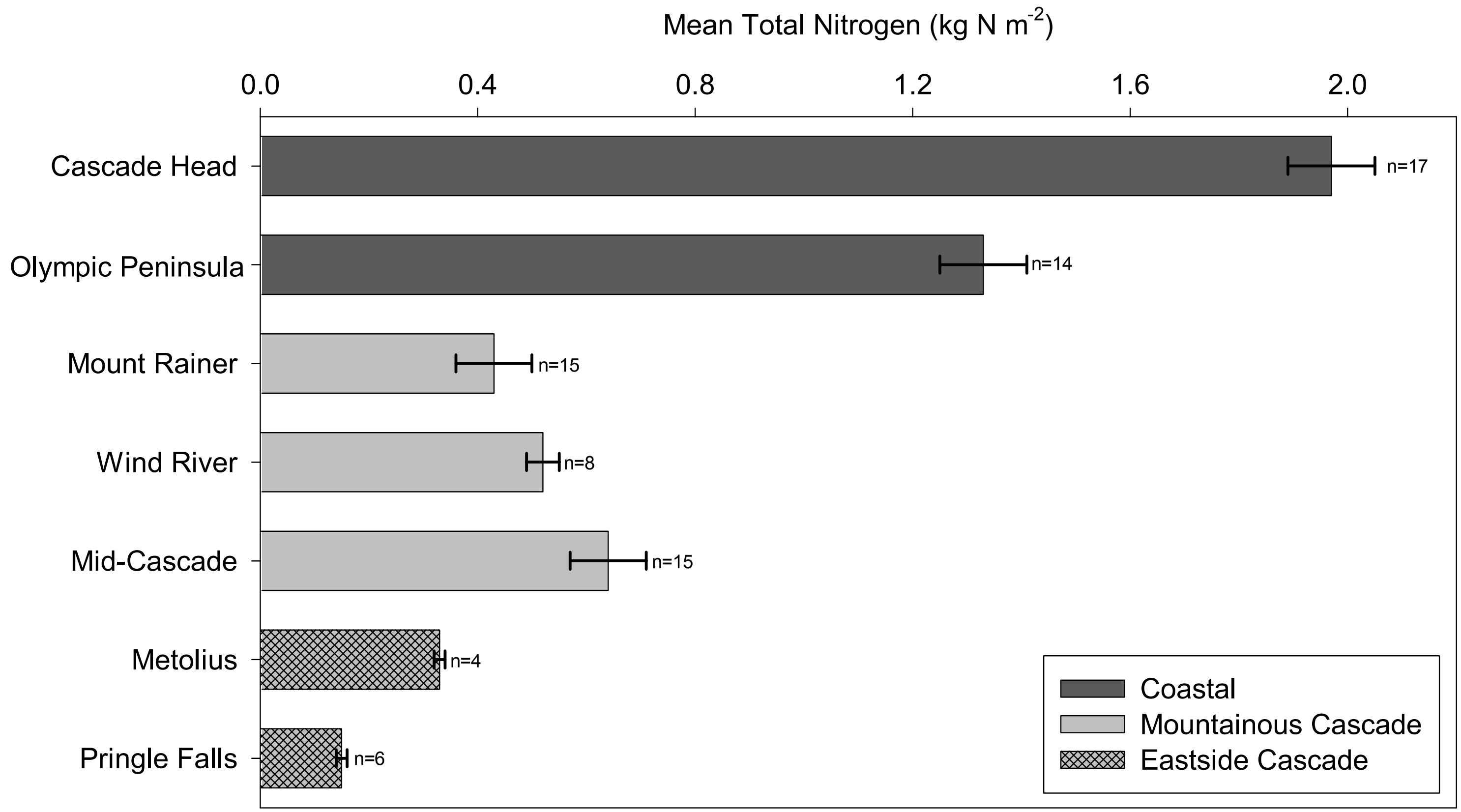

Figure 2.6. Mean mineral soil total nitrogen (TN) to 1-meter depth by study site in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

Table 2.7. Mineral soil total nitrogen (TN) values for western Oregon and Washington.

Location	Mean TN (kg N m^{-2})	n	Depth (cm)	Source	Comments
Western OR & WA	0.31	79	20	This study	old-growth forests
OR Cascade	0.2	4	15	Means, et al., 1992	old-growth forests
OR Cascade	0.22	15	20	This study	old-growth forests
Olympia, WA	0.31	13	20	Bormann & DeBell, 1981	young alder stands
Olympia, WA	0.28	6	20	Bormann & DeBell, 1981	young Douglas-fir stands
Western OR & WA	0.9	79	100	This study	old-growth forests
OR Cascade	1.0	4	100	Means, et al., 1992	old-growth forests
OR Cascade	0.42	15	100	This study	old-growth forests
OR Cascade	0.7	17	180 (max)	Edmonds & Chappell, 1994	young Douglas-fir stands
WA Cascade	0.9	26	180 (max)	Edmonds & Chappell, 1994	young Douglas-fir stands
WA Cascade	1.0	16	240 (max)	Edmonds & Chappell, 1994	young Hemlock stands
OR coast	1.5	18	100	Cromack et al., 1999	old-growth forests
OR coast	1.9	17	100	This study	old-growth forests
OR coast	0.8	14	180 (max)	Edmonds & Chappell, 1994	young Douglas-fir stands
OR coast	1.5	6	240 (max)	Edmonds & Chappell, 1994	young Hemlock stands
WA coast	0.7	22	180 (max)	Edmonds & Chappell, 1994	young Douglas-fir stands
WA coast	1.5	14	240 (max)	Edmonds & Chappell, 1994	young Hemlock stands

Mineral soil C/N ratios averaged 20 (range 9-46, n=79). Summarized by site, Figure 2.7 shows that Mountainous Cascade sites had higher ratios than either Coastal or Eastside Cascade sites. This implies that mountainous Cascade sites were more limiting in N than the other sites. Mount Rainier had the highest mean ratio of 27 and the Olympic Peninsula had the lowest mean ratio of 15.

For young Douglas-fir stands, Edmonds and Chappell (1994) reported mineral soil C/N ratios of 19, 24, 20, and 21 from coastal Oregon, coastal Washington, Oregon Cascade, and Washington Cascade sites, respectively. For young western hemlock stands, they reported mineral soil C/N ratios of 19, 21, and 23 in coastal Oregon, coastal Washington, and Washington Cascade sites, respectively. These averages are very similar to those obtained in this study. The exception is their Coastal Washington site, whose average was higher than from the Olympic Peninsula site in this study. One difference between these sites being compared is that their Coastal Washington site, defined by Edmonds and Hsiang (1987), encompassed the coast all the way to the Columbia River. The sites in this study were all specifically from the Olympic Peninsula. Northwest and southwest Washington are different in terms of their geology and climate, which could explain the discrepancy between the two studies.

The trends comparing the C/N ratio in the forest floor and mineral soil are very similar across the sites. Generally, the mean mineral soil C/N ratio at each site is about half that of the forest floor C/N ratio.

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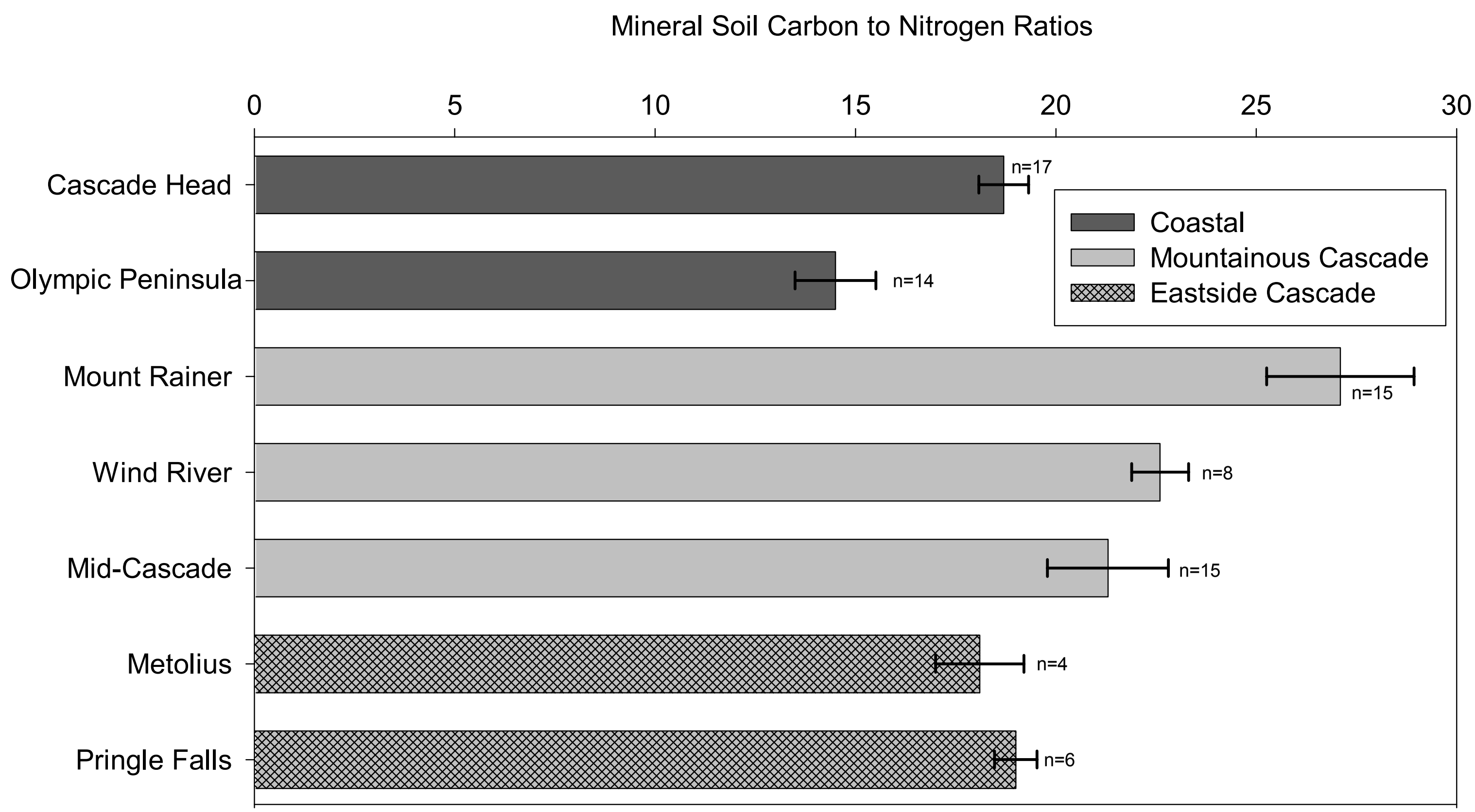

Figure 2.7. Mean mineral soil to 1-meter depth C/N ratio by study site in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

2.3.3 Contribution of the >2-mm C-bearing Soil Fraction to Carbon and Nitrogen Pools

Results from this study show that a large portion of the C and N pool at some of the sites measured occurred in the C-bearing fraction >2-mm. Of the 79 soil pits sampled, 27 had C in this fraction. As much as 52% more SOC was measured by including the >2-mm C-bearing fraction (total-soil method), used in this study, than traditional methods that only consider the <2-mm material (Figure 2.8).

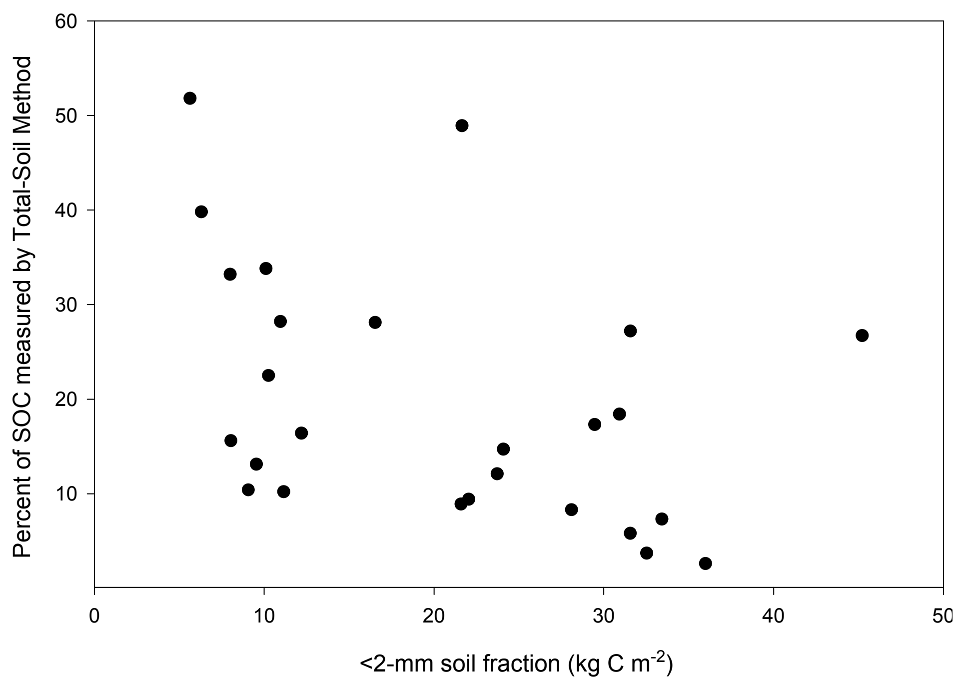

Figure 2.8. Additional Amount of soil organic carbon in the >2-mm C-bearing soil fraction in soil pits to 1-meter depth in old-growth forests in western Oregon and Washington. The graph shows the difference in SOC between the total-soil method, calculated in this study, and traditional methods, which analyze the <2-mm fraction only, as a proportion of the amount calculated by traditional methods.

For soils with a high proportion of >2-mm nutrient rich material, such as hardened aggregates, weathered rock, or shotty soils, this fraction may be an important contribution to the total nutrient stores. By not including C-bearing material >2-mm, measurements using traditional method underestimated SOC.

The >2-mm C-bearing measured in this study proved to contain a significant amount of C and N. Figure 2.9 summarizes SOC distribution as a percentage of the total for soil pits with C-bearing soils that contained all three size classes. Surprisingly, up to 44% of the C measured was contained in C-bearing material >2 mm. As much as 30% of the C measured was contained in the >4 mm C-bearing size class and 34% was found in the 2- to 4-mm C-bearing size class. Figure 2.10 summarizes the SOC distribution as a percentage of the total for only those soil pits with C-bearing soils up to 4-mm. In these soil pits, the 2- to 4-mm C-bearing size class constituted up to 23% of the C measured.

The trend for N in this >2-mm C-bearing material practically mirrored that of C. Figure 2.11 summarizes TN distribution as a percentage of total for soil pits with C-bearing soils that contained all three size classes. Like SOC, up to 41% of the N measured was contained in C-bearing material >2- mm. Up to 26% of the N measured was contained in the >4-mm C-bearing size class and 32% was found in the 2- to 4-mm C-bearing size class. Figure 2.12 summarizes the TN distribution for only those soil pits with C-bearing soils up to 4 mm. In these soil pits, the 2-4 mm C-bearing size class accounted for up to 22% of the N measured.

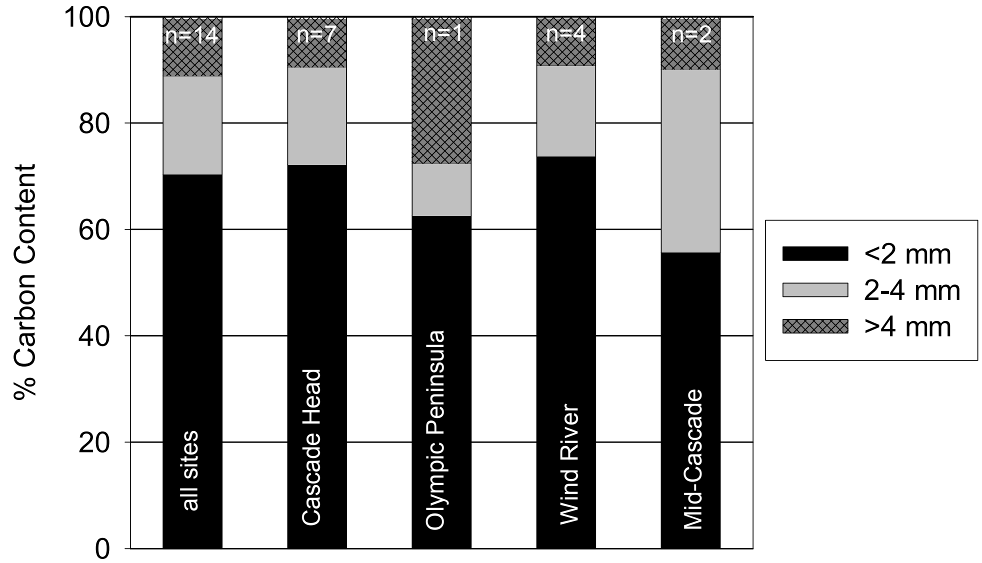

Figure 2.9. Soil organic carbon distribution by size class for soil pits with C-bearing soils in all three size classes. Percent contribution of SOC for each size class to total amount present.

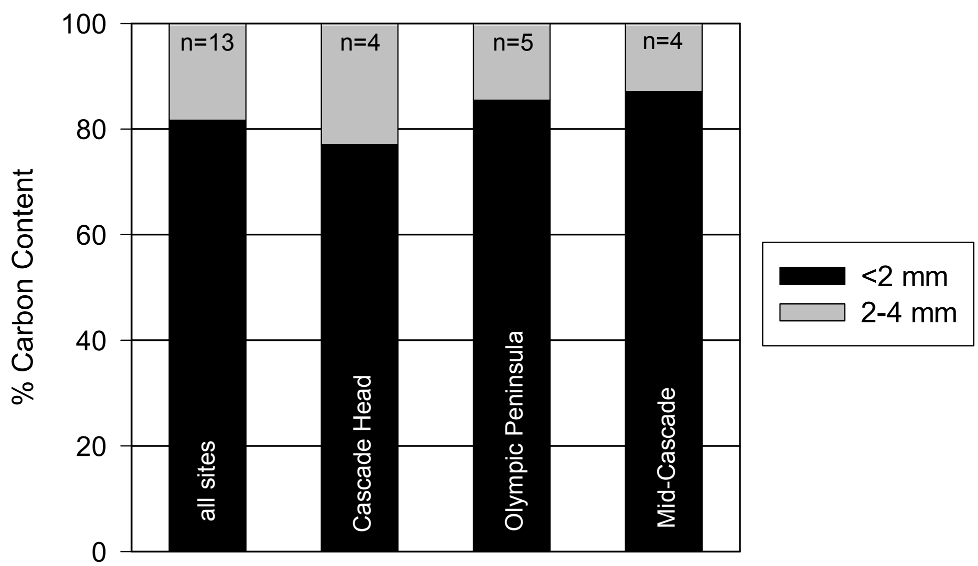

Figure 2.10. Soil organic carbon distribution by size class for soil pits with C-bearing soils up to 4-mm. Percent contribution of SOC for each size class to total amount present.

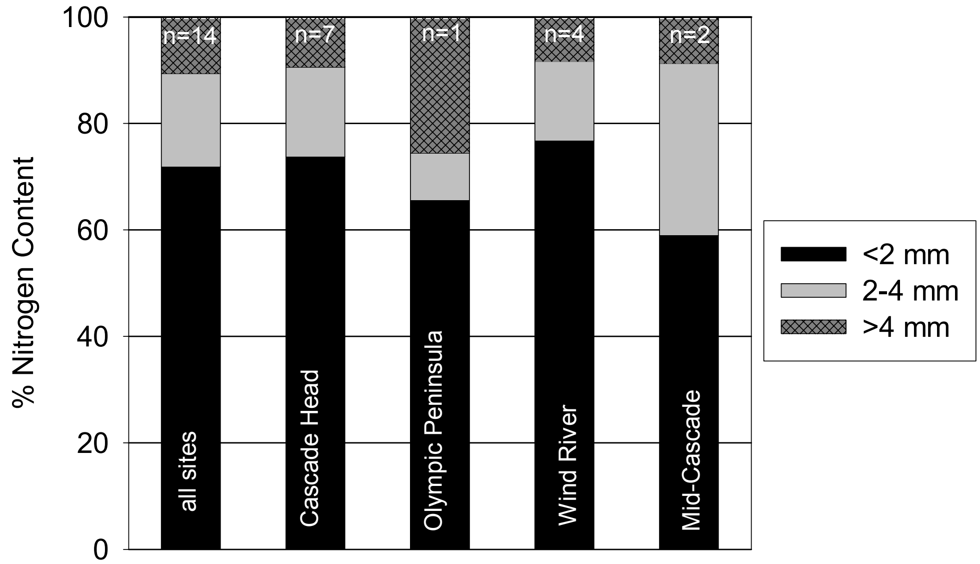

Figure 2.11. Soil total nitrogen distribution by size class for soil pits with C-bearing soils in all three size classes. Percent contribution of TN for each size class to total amount present.

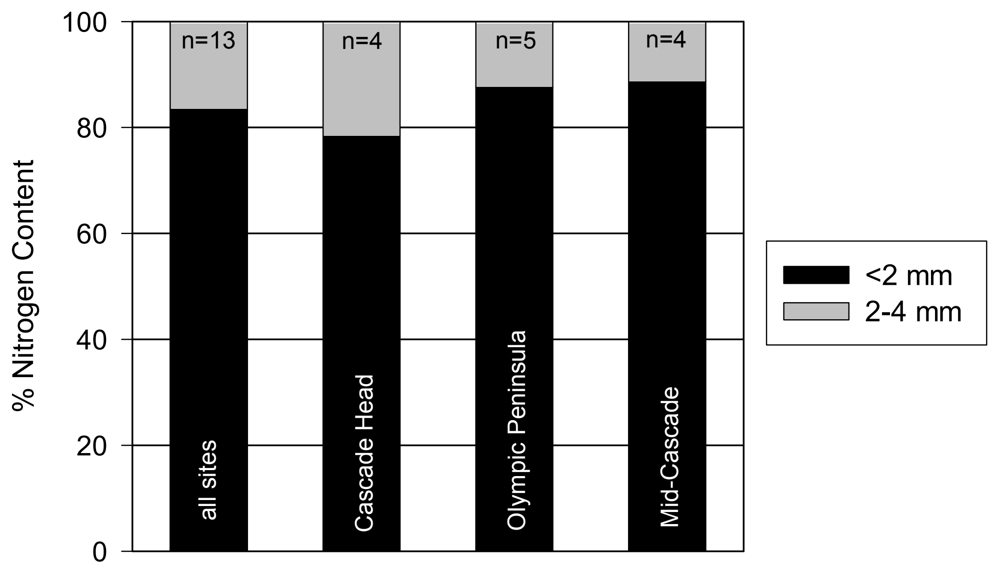

Figure 2.12. Soil total nitrogen distribution by size class for soil pits with C-bearing soils up to 4-mm. Percent contribution of SOC for each size class to total amount present.

Examining the contribution of the >2-mm C-bearing fraction of SOC and TN from the 0- to 20-cm layer reinforces the importance of this pool. Figure 2.13 summarizes SOC distribution as a percentage of the total in the 0- to 20-cm layer for C-bearing soils that contained all three size classes. For this layer in a soil pit in the Olympic Peninsula, up to 64% of the C measured was contained in C-bearing material >2-mm. As much as 52% of the C measured was contained in the >4-mm C-bearing size class. At the Mid-Cascade site, 35% of the C measured was found in the 2- to 4-mm C-bearing size class. Figure 2.14 summarizes the SOC distribution as a percentage of the total in the 0- to 20-cm layer for only those layers with C-bearing soils up to 4 mm. In these soil pits, the 2-4 mm C-bearing size class constituted up to 36% of the C measured.

As with the whole soil pit (to 1-meter depth) analyses, the trend for N in this C-bearing material practically mirrored that of C. Figure 2.15 summarizes TN distribution as a percentage of the total in the 0- to 20-cm layer for C-bearing soils that contained all three size classes. Like SOC, up to 63% of the N measured was contained in C-bearing material >2-mm. Up to 53% of the N measured was contained in the >4-mm and 36% was found in the 2- to 4-mm C-bearing size classes. Figure 2.16 summarizes the TN distribution in the 0- to 20-cm layer for only those layers with C-bearing soils up to 4-mm. In these soil pits, the 2- 4-mm C-bearing size class accounted for up to 35% of the N measured.

This study demonstrates how routinely discarding >2-mm soil material before chemical analyses can underestimate C and N mass in some soils. Sites with a high proportion of soil which is highly cemented, strongly aggregated or shotty in structure warrant separation and chemical analyses of soil fractions >2-mm for better estimates of C and N stores.

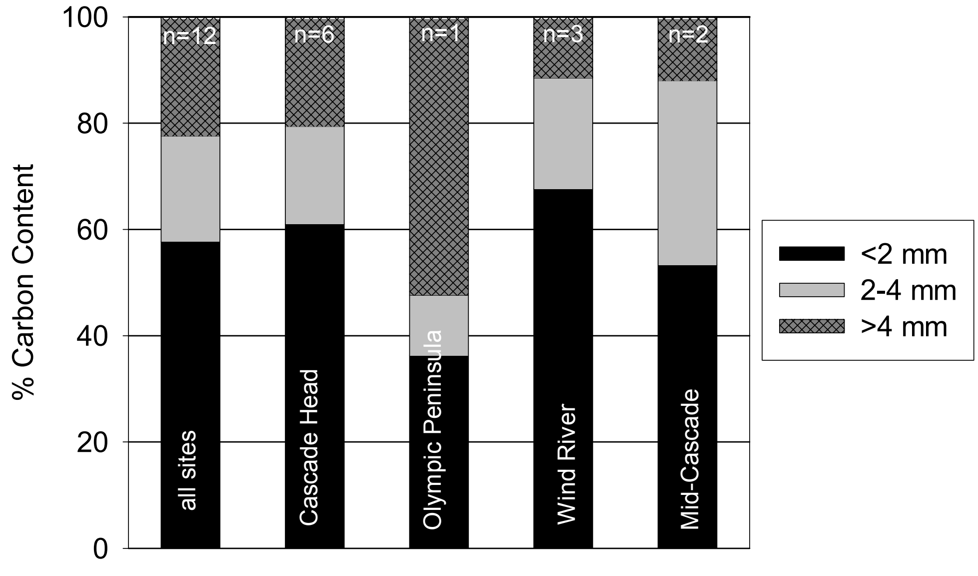

Figure 2.13. Soil organic carbon distribution in the 0- to 20-cm depth by size class for soil pits with C-bearing soils in all three size classes. Percent contribution of SOC for each size class to total amount present.

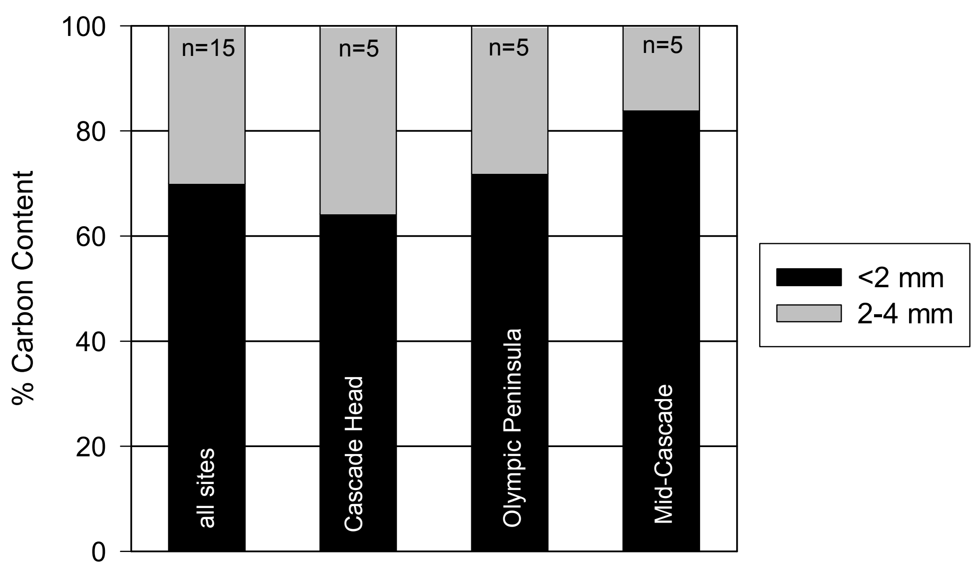

Figure 2.14. Soil organic carbon distribution in the 0- to 20-cm depth by size class for soil pits with C-bearing soils up to 4-mm. Percent contribution of SOC for each size class to total amount present.

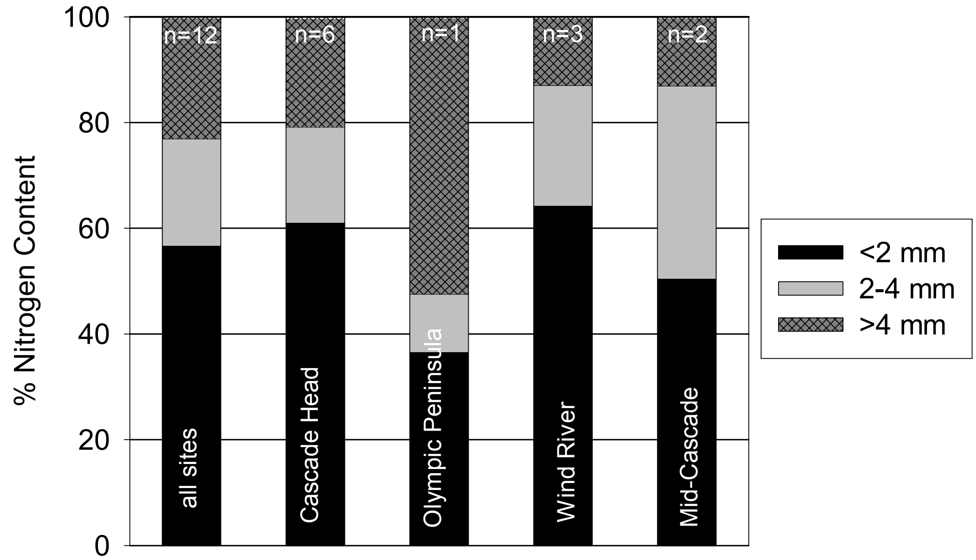

Figure 2.15. Soil total nitrogen distribution in the 0- to 20-cm depth by size class for soil pits with C-bearing soils in all three size classes. Percent contribution of TN for each size class to total amount present.

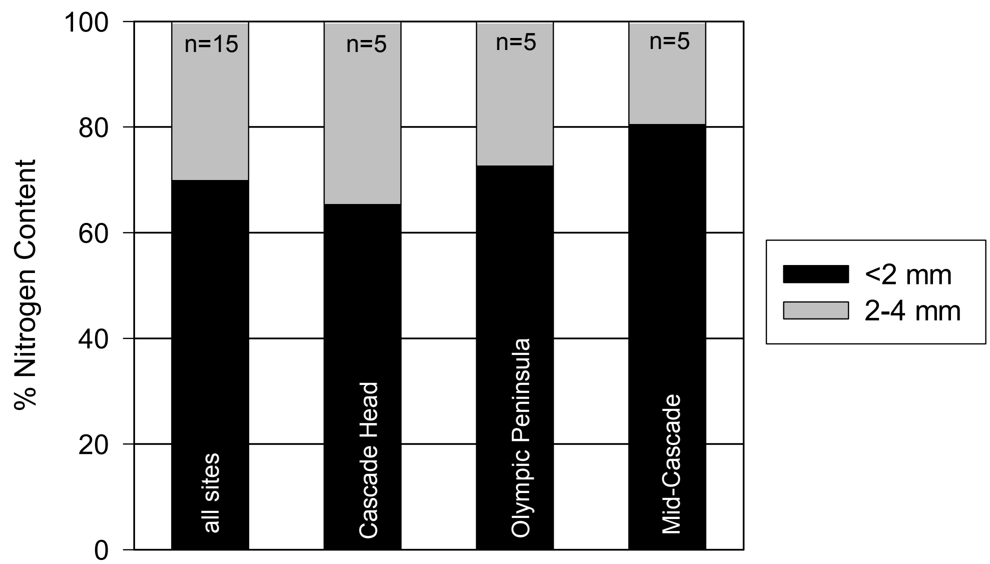

Figure 2.16. Soil total nitrogen distribution in the 0- to 20-cm depth by size class for soil pits with C-bearing soils up to 4-mm. Percent contribution of SOC for each size class to total amount present.

2.3.4 Vertical Distribution of Carbon and Nitrogen

Quantifying the SOC and TN distribution by layer to 1-meter depth by site is important to better understand the contribution of each layer to the overall pool. In most cases, the 0- to 20-cm layers have the highest carbon content of the three layers measured (Figure 2.17). However, the carbon contents from 20- to 100-cm contribute to more than half of the total C measured (Pringle Falls being the exception). Within the Cascade Head site, 66% of the carbon measured was found below 20-cm.

A closer evaluation of the distribution of SOC and TN throughout the 1-meter profile across the sites reveals an interesting phenomenon. Soil pits at Pringle falls contained 59% of the total SOC in the 0- to 20-cm layer. In contrast, the 0- to 20-cm layer in pits at Cascade Head comprised only 34% of the total SOC (Figure 2.18). The SOC content in the 0- to 20-cm layer as a proportion of the total meter depth was higher at sites with lower overall SOC contents (compare Figure 2.5 to Figure 2.18), implying that profiles profuse with SOC store this C deeper in the profile. This result emphasizes processes that promote greater accumulation of this material through greater nutrient and water-holding capacities, reduced rates of organic matter oxidation, and protection from degradation.

Several factors promote the transport of C through the soil profile. One factor is the root distribution in the soil profile. Fine root growth, death, and turnover are very important in the internal nutrient cycle of forest ecosystems (Waring and Schlesinger, 1985). More than half of the total biomass production in forests may be in the form of tree roots (Brady and Weil, 1996). Vogt et al., (1982) found that roots comprised 59-67% of NPP in coniferous forests in Washington. The bulk of the root system of most plants is in the upper 25- to 30-cm of the soil profile. More stable humus

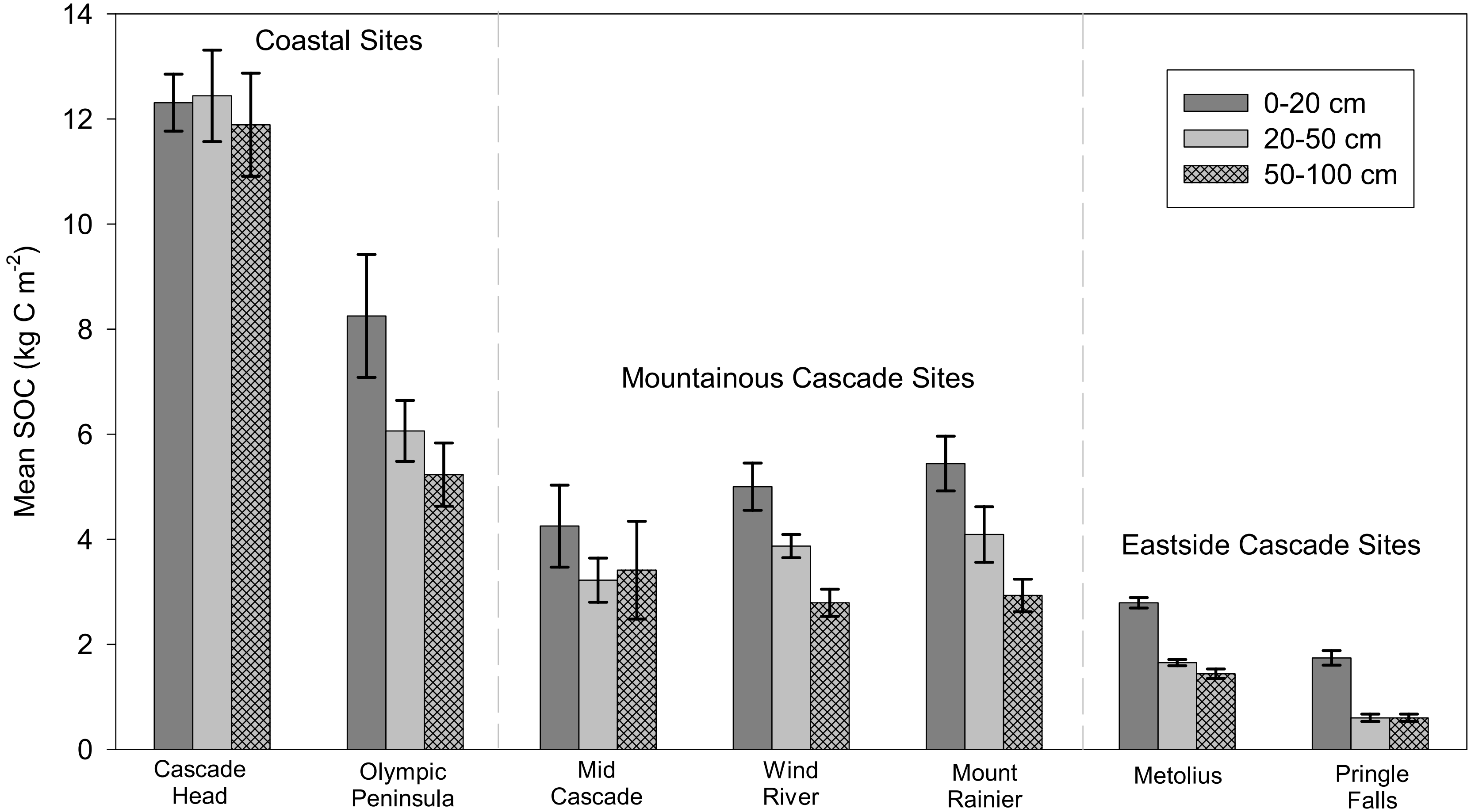

Figure 2.17. Distributions of mean soil organic carbon (SOC) by layer to 1-meter depth in soil pits in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

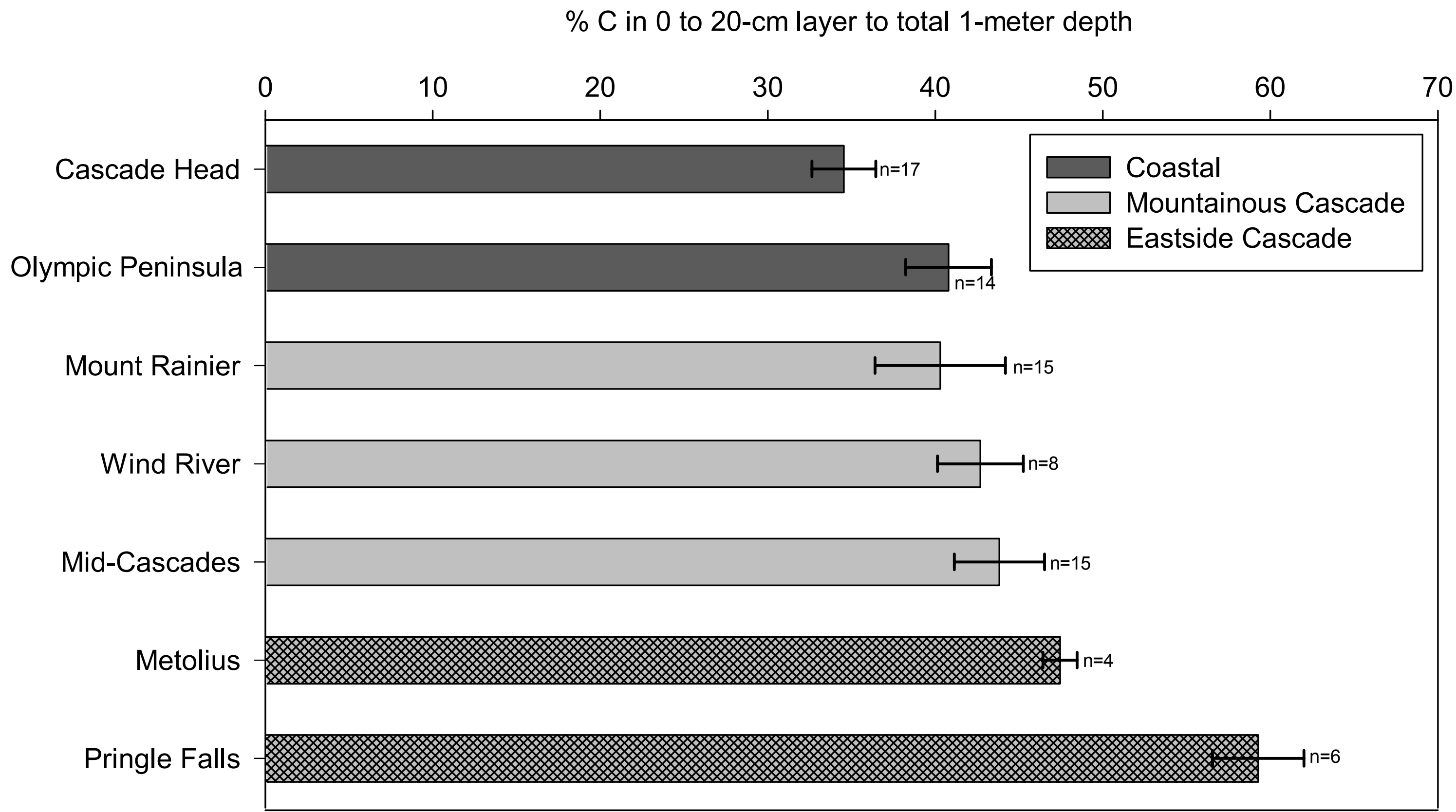

Figure 2.18. Percent contribution of C in the 0- to 20-cm layer to total 1-meter depth in soil pits in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

compounds accumulate in the lower soil profile and comprise the bulk of SOM (Schlesinger, 1977). Other factors promoting the transfer of C through the soil profile are soil age and parent material. These factors contribute to different stages of soil development and differences in soil texture. Soil texture influences several properties of the soil, like its physical structure, aeration, and moisture holding capacity. Higher contents of fine-textured materials (silts and clays) stabilize organic matter by forming complexes, thus increasing inflitration rates, and water availability (Brady and Weil, 1996). In addition, the microbial community plays an important role in the mixing of the forest floor with the mineral soil (Schlesinger, 1991).

Figure 2.19 presents mean soil TN distribution by layer to 1-meter depth by site. Although the layers are not constant in depth (20, 30, and 50 cm), each layer contains roughly the same amount of TN. At each site, 68% of the nitrogen measured was found below 20-cm.

The pattern of TN contribution from the 0- to 20-cm layer, as a proportion to the total meter depth was different from that for SOC (Figure 2.20). There was not much difference among the sites. Between 29-37% of the TN was found in the 0- to 20-cm layer, as a proportion of total depth, at all the sites. For some reason, the distribution of TN seems to be more evenly dispersed in the soil profile than SOC. Surface SOC may be subject to loss through respiration at a greater rate than TN is lost through leaching or root uptake. Although TN is less abundant with depth for a given volume of mass, it is more evenly conserved throughout the soil profile.

Regression analysis was used to relate SOC to 1-meter depth to SOC in the 0- to 20-cm layer (Figure 2.21). This analysis exhibited a strongly significant relationship (R^2 = 0.83). The relationship is polynomial, suggesting that SOC to 1-meter depth increased with increasing SOC in the 0- to 20-cm depth to 21.7 kg C m^{-2}, then decreased at higher SOC in the 0-

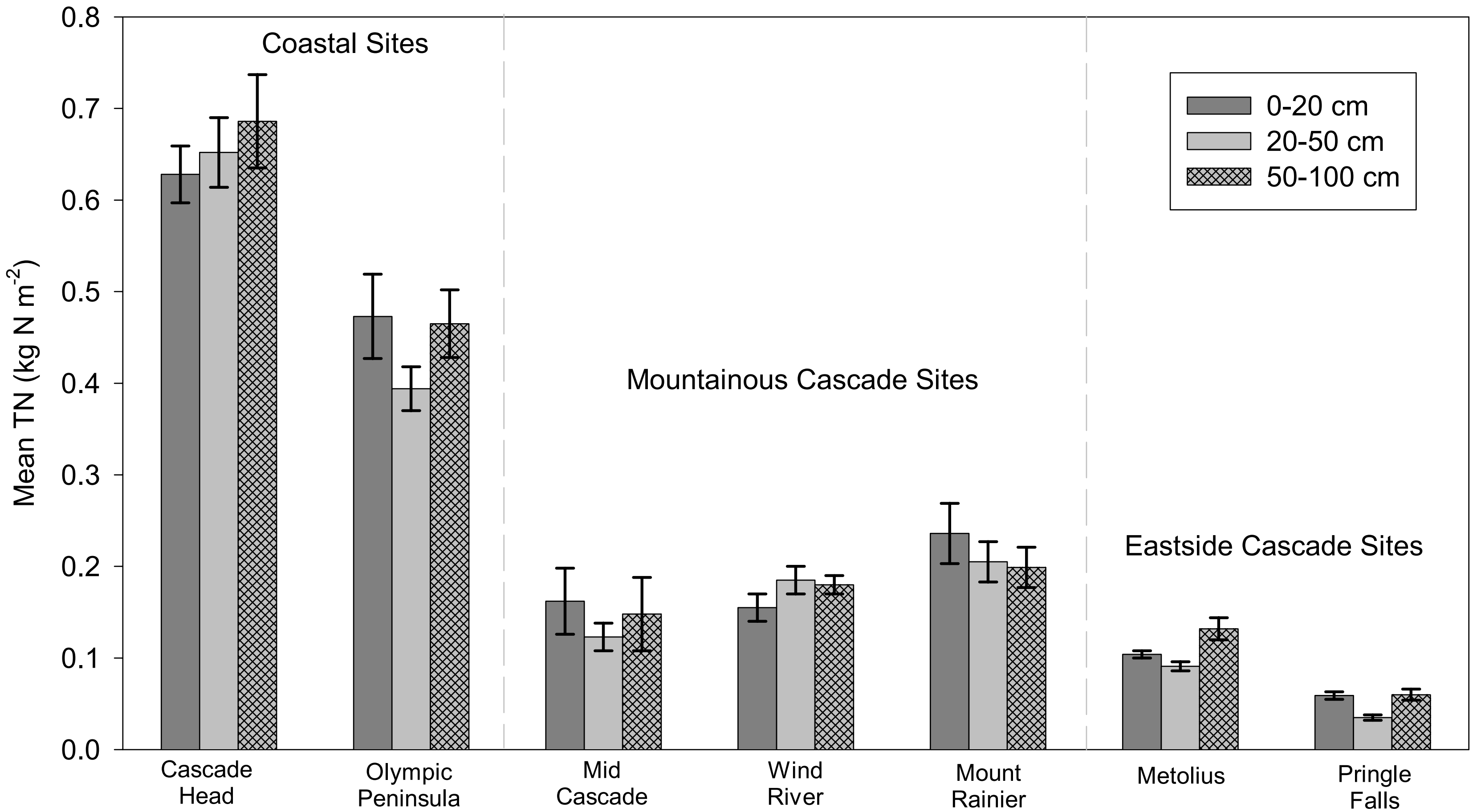

Figure 2.19. Distributions of mean total nitrogen (TN) by layer to 1-meter depth in soil pits in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

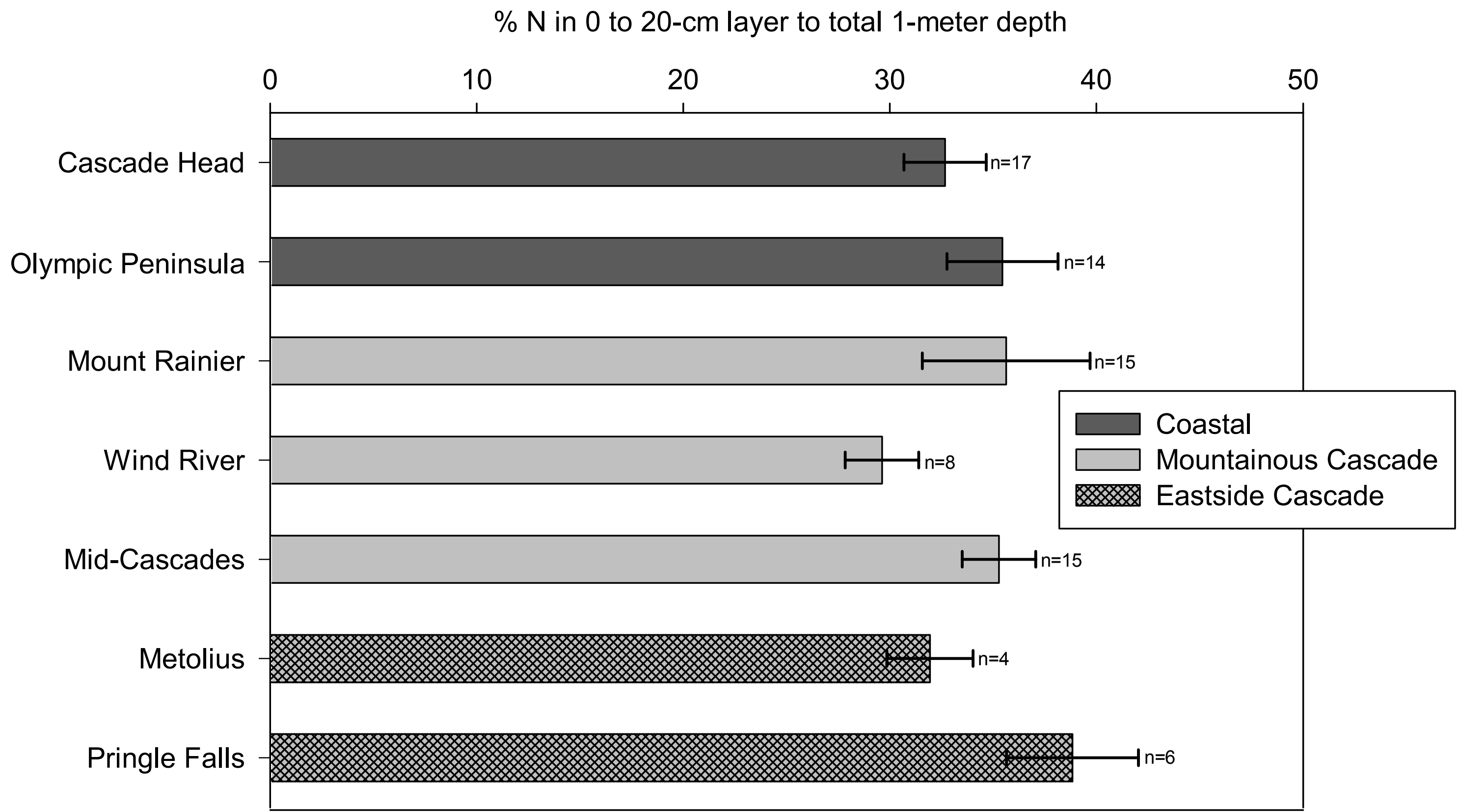

Figure 2.20. Percent contribution of TN in the 0- to 20-cm layer to total 1-meter depth in soil pits in old growth forests in western Oregon and Washington. Error bars indicate standard errors of the mean.

to 20-cm depth. However, all the SOC to 1-meter depth measure in this study falls on the increasing portion of this relationship. This relationship was also tested with data from Homann et al. (1995) which included SOC from various land uses (forested, cultivated, pasture-orchard, and undesignated) in a mountainous region of western Oregon. Again, a significant relationship resulted (R^2 = 0.80). Due to uneven scattering of the residual plots, both models required a transformation of the response variable (SOC to 1-meter). However, data from this study were best represented by a square root transformation while data from Homann et al. (1995) were better represented using a log transformation. The strength of these relationships indicates that SOC to 1-meter depth can be estimated from the content found in the upper 20-cm.

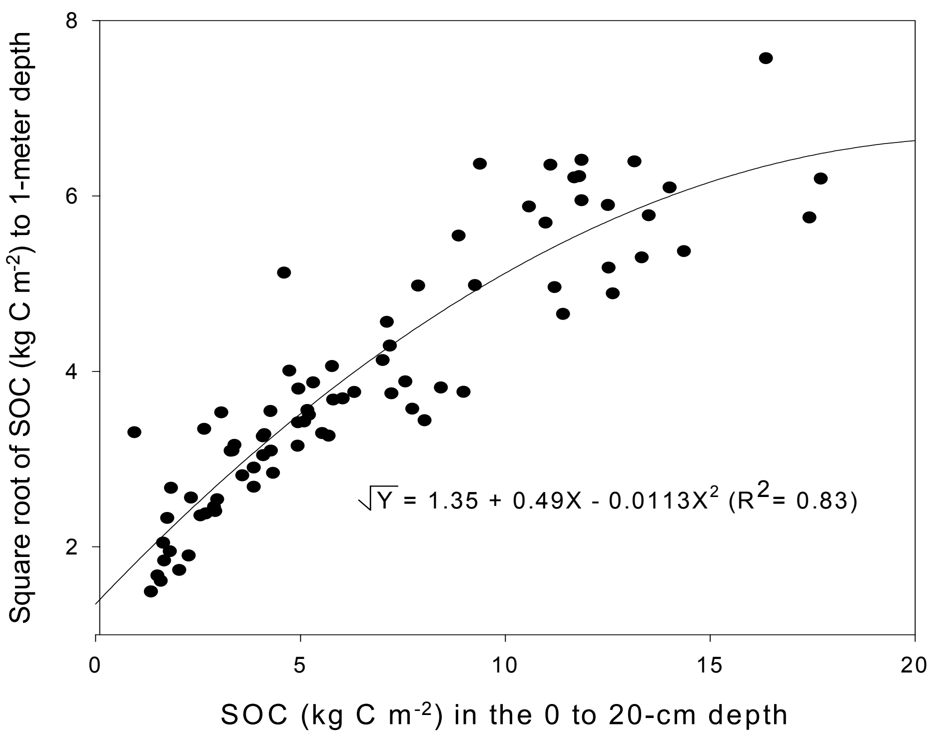

Figure 2.21. Relationship of the square root of SOC to 1-meter depth as a function of SOC in the 0- to 20-cm depth.

Regression analysis was also used to evaluate the relationship of TN to 1-meter depth as a function of TN in the upper 20-cm depth (Figure 2.22). The same significant polynomial relationship was found with the square root of TN to 1-meter depth (R^2 = 0.88). The square root of TN to 1-meter depth increased with increasing TN in the 0-to 20-cm depth to 0.9 kg N m^{-2}, then decreased at higher TN to 20-cm depth. Most of the data from this study falls below this value of decline. As for SOC, the strength of this relationship also indicates that TN to 1-meter depth can be estimated from the content found to 20-cm.

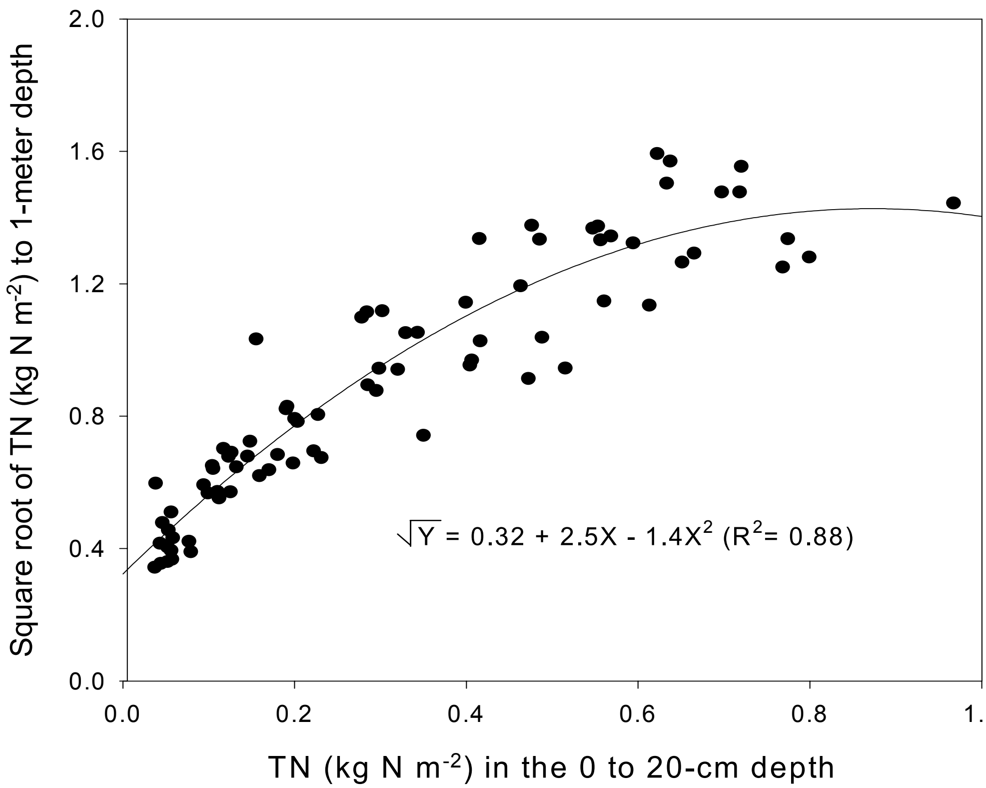

Figure 2.22. Relationship of the square root of TN to 1-meter depth as a function of TN in the 0- to 20-cm depth.

2.4 Conclusions

Longitudinal differences in SOC and TN contents were evident between Coastal, Mountainous Cascade, and Eastside Cascade sites. These differences imply climatic and site factors affect SOC and TN accumulation. This longitudinal trend was not observed in the C/N ratios of these sites, where mountainous Cascade sites had higher C/N ratios in both the forest floor and mineral soil. Decomposition is slower at cooler, moist sites allowing for more SOC accumulation. However, sites too extreme in either moisture or temperature will not be as productive and aboveground inputs will be lower. Also, if N is limiting (high C/N ratios), decomposition may be slower and the SOC unavailable to microbes.

Within the upper meter of mineral soil, up to 44% of SOC and TN was found in C-bearing material >2-mm for individual soil pits. These strongly cemented, stable aggregates are not traditionally accounted for during soil processing and analysis. Neglecting to incorporate this material into forest ecosystem estimates can considerably underestimate SOC and TN, which limits our ability to make valid regional estimates of C and N in the Pacific Northwest.

Of the material measured, 39 to 66% of SOC and 34 to 63% of TN in individual soil pits was found below 20-cm. These estimates illustrate how failing to sample at depth can grossly underestimate SOC and TN. The content of SOC in the 0- to 20-cm depth as a fraction of the total depth was less when SOC was abundant. This implies that a profile profuse with SOC stores this C deeper in the profile. Perhaps this is due to specific physical, chemical and biological conditions that promote greater accumulation of this material through greater nutrient and water-holding capacities, reduced rates of organic matter oxidation, and protection from degradation. However, there was no significant difference in the N contents among the layers. The TN content in the 0- to 20-cm depth as a fraction of the total depth was on average 32% for all the sites. There is also strong evidence indicating that SOC and TN to 1-meter depth can be estimated from the content found to 20-cm. Both the square root of SOC and TN exhibited significant polynomial relationships. The relationships were strongly positive until a point at which they began to decline.

3. RELATIONSHIP OF SOIL CARBON AND NITROGEN TO SITE AND CLIMATIC CHARACTERISTICS IN OLD-GROWTH FORESTS IN WESTERN OREGON AND WASHINGTON

3.1 Introduction

Soil organic matter (SOM) is a complex and varied mixture of organic substances, such as plant and animal tissues and residues, dead roots and microorganisms. The constituents of SOM undergo numerous processes and are converted to more stable forms of varying degree. SOM plays a critical role in the global carbon (C) balance because it contains about three times as much C as does aboveground vegetation and double the amount in the atmosphere (Post, et al., 1990; Brady and Weil, 1996). In mature, natural ecosystems, C input to the soil comes from plant and animal residues in the form of detritus. This C input is balanced by oxidation of SOM, where C is released as CO_2. SOM is a dynamic component of the soil that exerts a major influence on soil processes, properties, and function within the ecosystem. Thus, SOM stability, which is influenced by rates of primary production and decomposition, encompasses a variety of physical, chemical, and biological processes. These physical, chemical, and biological processes, which ultimately control the stability of SOM, are influenced by classic soil-forming factors such as climate, biota, topography, parent material and time (Jenny 1941, 1980).

Regional studies of SOM relationships with climate and site characteristics are important to help understand the mechanisms involved in C accumulation, distribution and other soil ecosystem processes. Soil ecosystems develop differently across landscapes and the roles of soil-forming factors vary with scale. Both SOM accumulation and vertical distribution are influenced by climate and site factors. Not only are the landscapes complex, but the interactions among controls over SOM properties are as well (Burke et al., 1989). Assessing important climate and site characteristics at a local scale can contribute to the formulation of mechanistic models to better understand global C stores. To predict changes in ecosystem function and climate on carbon storage, simulation modelling can attempt to integrate concepts of SOM formation and turnover (Parton et al., 1987; Rastetter et al., 1991; Harmon et al., 1996). To accurately simulate changes occurring across a landscape, these models must be calibrated and tested against detailed data describing spatial patterns and relationships among soils, vegetation, and climate.

Many studies have evaluated the relationship of climate and site characteristics to SOM across numerous ecosystems. Temperature and precipitation were important in forested ecosystems. Spain (1990) found that organic C decreased with precipitation and temperature in tropical Australian rain forests. In a northern hardwood, forest ecosystem in New Hampshire, Huntington et al. (1988) C and N concentration were positively related to elevation and negatively to temperature. In temperate hardwood forests in the Lake states, Grigal and Ohmann (1992) reported that soil organic C was positively correlated to precipitation, available water, actual evapotranspiration, and clay. They also determined that forest type and age were important variables. In coniferous forests of the Pacific Northwest, Edmonds and Chappell (1994) reported that total mineral soil C expressed a weak, positive relationship to site index. Also in forested areas in the Pacific Northwest, Homann et al. (1995) found soil organic carbon to be positively related to temperature, precipitation, actual evapotranspiration, available water, and clay whereas it was negatively related to slope.

Similar relationships of SOC to site and climatic characteristics also occur in grassland ecosystems. In the southern Great Plains of the USA, Nichols (1994) found no relationship between organic C and temperature. However, organic C was positively related to clay and, to a lesser degree, precipitation. Also in the Great Plains grasslands, Parton et al., (1987) concluded that soil organic C can be predicted from soil temperature, moisture, texture, and N inputs. In the central Plains grasslands USA, Burke et al. (1989) reported that soil texture and climate were important in predicting soil organic C. They concluded that soil organic C increased with precipitation and clay content and decreased with temperature. In soils of the North Central USA, Franzmeier et al. (1985) found that the effects of climate on soil organic C was expressed primarily through vegetation. Climate, in terms of temperature and precipitation, had little effect on soil organic C contents. In native grasslands in North America, Amelung et al. (1998) found texture to be the primary variable affecting the size of the SOM pool. The clay fraction (<2-µm), which contained abour 43% of the SOC and 56% of TN, incresed with temperature and decreased with precipitation. The opposite trend occurred in the fine sand fraction (20-to 250-µm). McDaniel and Munn (1985) found in Montana and Wyoming that soil organic C was positively related to elevation. They concluded that soil organic C was related to texture, but was sensitive to soil temperature. Colder soils (cryic and frigid) soils had more organic C than warmer soils. In warmer soils (mesic), the effects of texture were more pronounced with organic C positively related to clay and negatively related to sand. In cool soils in Montana, Sims and Nielsen (1986) also found no relationship between soil organic C and clay. However, they did find a soil organic C to be positively related to precipitation and elevation and negatively related to temperature.

Steady-state ecosystems, in which C storage is not changing, are useful for the purpose of developing relationships because they simplify the ecosystem interactions. Within a steady-state ecosystem fluxes of material and energy continue to enter and leave, however, these quantities and fluxes are in balance. For many regions, including the Pacific Northwest, these data are either not available or have not been sufficiently organized to adequately analyze or model landscape- to regional-scale patterns in ecosystem C and N dynamics. Once accurate estimates of C stores for specific regions exist, models can incorporate the differences to better represent the processes occurring across regions.

The objectives of this study are to (i) quantify the relationships of soil organic carbon (SOC) and total nitrogen (TN) to site and climatic characteristics in Pacific Northwest old-growth forests, (ii) compare the relations between SOC and TN, (iii) compare the relations between forest floor and mineral soil, (iv) compare the relations between total-soil and standard methods, (v) compare the relations with those found in other regions.

The stands selected for this study represent steady-state systems. Ecosystem compostition, structure, and function characterize successionally advanced forests and have important old-growth components like large standing dead trees, large accumulations of downed wood, and a shade tolerant understory (Spies and Franklin, 1988). Within these stands, SOC and TN for the mineral soil layers were measured by two methods. The standard method used in this chapter refers to soil processing methods typically used where soil is sieved to <2-mm and analysis of this fraction is used to determine SOC and TN contents. The total-soil method, as estimated and discussed in Chapter 2, included the analysis of C-bearing material >2-mm (indestructible aggregates), which in some of these stands greatly contributed to the SOC and TN measured.

3.2 Methods

3.2.1 Soil Measurements

Carbon and N pools, and other soil properties, were measured in the forest floor, 0- to 20-cm mineral soil, and 0- to 100-cm mineral soil at seven study sites. The seven sites were old-growth forests selected in western Oregon and Washington based on physiographic provinces outlined by Franklin and Dyrness (1988), (Figure 3.1, Table 3.1). These sites were located from the Pacific Ocean coast to the eastern slopes of the Cascade Range and were assumed to represent steady-state ecosystems. Therefore, C input to the soil from plant and animal residues in the form of detritus is balanced by oxidation of SOM, in which C is released as CO_2. The sites are associated with the Andrews Long Term Ecological Research (LTER) program (Appendix A). Within each site, 1 to 8 stands were evaluated, for a total of 45 stands. Within each stand, coarse and fine woody debris were measured. Forest floor and mineral soil C and N to 1-meter depth were estimated from the excavation, sampling, and analysis of 1 to 3 soil pits on the perimeter of each stand (see Chapter 2 for detailed sampling procedures). A total of 79 soil pits were sampled.

In addition to these 79 soil pits, auxiliary data was available for the Mid-Cascade site. Data from Brown and Parsons (1972) were used to incorporate an additional 11 soil pits for the 0- to 20-cm depth and 9 for the 0- to 100-cm depth. SOC (kg C m^{-2}) and TN (kg N m^{-2}) were calculated from organic matter or N concentration, bulk density, rock content and horizon depth. A C to SOM ratio of 58% was assumed. Forest floor N data were not available. Also included in the data were lab analyses of particle size providing percent sand, silt, and clay. In total, data were available for

90 pits for the 0- to 20-cm layer, 88 pits for the 0- to 100-cm layer, and 79 pits for layers including forest floor N.

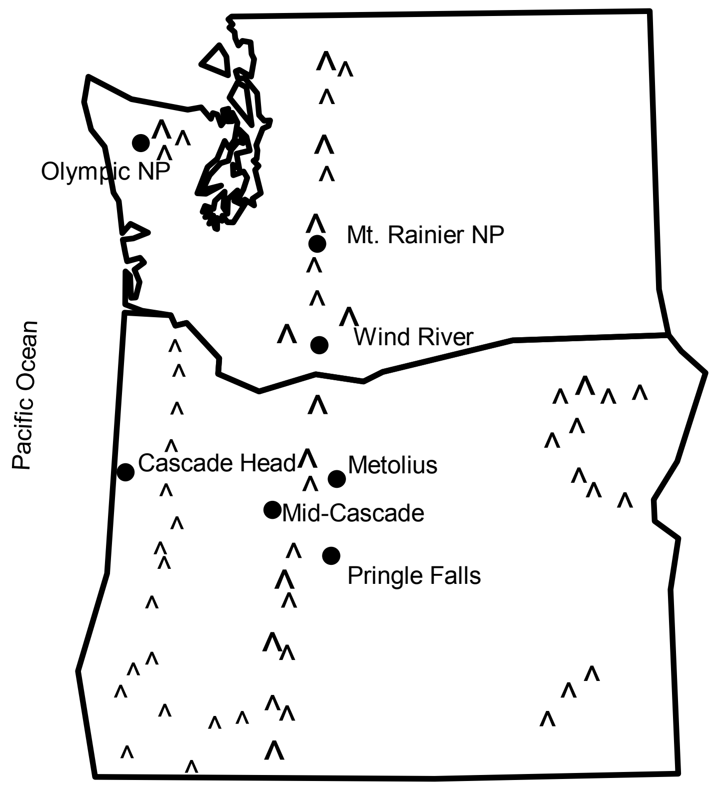

Figure 3.1. Old-growth study sites in western Oregon and Washington.

Two additional stands were added outside of the H.J. Andrews LTER plot network. These sites were established by the EPA Environmental Research Laboratory. The soils were sampled by the author while coarse and fine woody debris, age, latitude, longitude, and mean annual temperature and precipitation were provided by Robert McKane (personal comm., 1997).

Table 3.1. Location information and data characteristics of the study sites.

Physiographic Province	Study Site#	Stand Locations	Approx. Lat., Long.	Number of Stands	Stand Area (ha)	Managing Agency
Oregon coast	Cascade Head	Cascade Head EF†	45.1,123.9	8	0.4	Hebo District, Siuslaw NF*
Washington coast	Olympic Peninsula	S. Fork Hoh River	47.8,123.9	4	1.0	Olympic National Park
		Twin Creeks RNA↕	47.8,123.9	1	1.0	Olympic National Park
		Quinault RNA	47.4,123.8	2	1.0	Quinault District, Olympic NF
Oregon Cascades	Mid-Cascade	HJ Andrews EF	44.2,122.2	6	0.25 or 1.0	Blue River District, Willamette NF
		EPA/Cascade	44.4,122.3	2	0.6	Sweethome District, Willamette NF
Washington Cascades	Wind River	T.T. Munger RNA	45.8,122.0	1	4.1	Wind River Dist., Gifford Pinchot NF
	Mt. Rainier	Nisqually River	46.7,121.8	4	1.0	Mt. Rainier National Park
		Ohanapecosh River	46.8,121.6	2	1.0	Mt. Rainier National Park
		White River	46.9,121.5	1	1.0	Mt. Rainier National Park
		Carbon River	46.8,121.9	2	1.0	Mt. Rainier National Park
Eastside Oregon Cascades	Metolius	Metolius RNA	44.5,121.6	1	4.5	Sisters District, Deschutes NF
	Pringle Falls	Pringle Falls RNA	43.7,121.6	3	1.0 or 4.0	Bend District, Deschutes NF

See Appendix 6.1 for background information about study sites.

† Experimental Forest

* National Forest

↕ Research Natural Area

3.2.2 Site and Climatic Variables

Explanatory variables used in this analysis were measured at either pit- or stand-levels (Table 3.2 and Table 3.3). Variables measured at the pit-level include slope (SL), aspect (AS), soil texture (sand, Sa; silt, Si; and clay, Cl), available water holding capacity (AWH), actual evapotranspiration (AET) and forest floor (FF) when it was not used as a response variable. Variables obtained at a stand-level include stand age (AGE), fine (FWD) and coarse (CWD) woody debris, mean annual temperature (MAT) and precipitation (MAP) and potential evapotranspiration (PET). Other variables available at a stand-level include elevation (ELE), latitude (LAT) and longitude (LON).

Table 3.2. Pit-level variables; units, means, and ranges. See text for source of data.

Variables*	Units	Mean	Minimum	Maximum
Slope	%	19	0	70
Aspect	degrees	-	0	360
Sand	kg m^{-2}	56/263+	0.2/19	163/865
Silt	kg m^{-2}	54/267	2/27	168/703
Clay	kg m^{-2}	21/146	4/6	69/427
AWH	cm $depth^{-1}$	4/18	1/8	6/32
AET	cm yr^{-1}	53/59	22/32	74/80
Forest floor	kg C m^{-2}	3	0	14

* AWH=available water-holding capacity, AET=actual evapotranspiration.

+First number represents 20-cm depth, second number represents 100-cm depth.

Table 3.3. Stand-level variables; units, means, and ranges. See text for source of data.

Variables*	Units	Mean	Minimum	Maximum
Stand age	years	396	105	1200
Fine woody debris	kg C m^{-2}	1.2	0.5	3.3
Coarse woody debris	kg C m^{-2}	7	0.4	25
Temperature	°C yr^{-1}	8	4	11
Precipitation	cm yr^{-1}	227	35	367
PET	cm yr^{-1}	62	42	80
Elevation	m	639	122	1430
Latitude	degrees N	-	43.707	47.834
Longitude	degrees W	-	121.538	123.990

* fine woody debris= woody material, above the surface of the forest floor, between 1- an 15-cm in diameter, coarse woody debris= woody material, including stumps, snags, and downed logs, greater than 15-cm in diameter; PET=potential evapotranspiration.

The SL and AS assessed the specific land position of the pit. AS was transformed to a cosine function to smooth the transition change of north from 360° to 0° (Stage, 1976). Texture was determined in the field, based on horizons, by soil scientists according to the basic soil textural class names established by the USDA Classification system. Relative proportions of Sand, Silt and Clay were interpolated from the USDA-SCS textural triangle. Proportion, on a layer basis, was calculated and converted to content (kg m^{-2}) using bulk density and soil volume. AWH was calculated as the difference between volumetric water content at 10 and 1500 kPa matric pressures (Grigal and Ohmann, 1992) for each layer of mineral soil, summed over the layers to depth of 20 or 100 cm. Volumetric water content was calculated from texture using equations from Rawls et al.

(1982). In the use of Rawls' equations, the assumption of no organic matter was made; therefore, AWH represents an indicator rather than an actual value. This assumption was made because for the regression analysis of SOC as functions of site and climate characteristics, AWH needed to be independent of organic C, so as not to be a function of itself.

The AGE and CWD for most stands were available from the Oregon State University Forest Science Database. CWD, defined as any woody material, including stumps, snags, and downed logs, greater than 15-cm in diameter, was calculated for each stand. Four 625-m^2 plots within a 1-ha stand (totalling 0.25-ha) or the whole stand for stands 0.25-ha in size were inventoried for volume, species and decay class of all CWD. Volume of CWD was converted to mass of C per area based on wood densities for a given species and decay class and nutrient concentration (Harmon and Sexton, 1996). Methods for AGE estimation differed across sites, but were most commonly based on the oldest trees within the stand (Personal communication with Steve Acker and Mark Harmon, OSU, 1998). Both published and unpublished tree core data were available for most sites. AGE at Mount Rainier plots was interpolated from age class maps (Franklin et al., 1988).

The FWD, defined as any woody material, above the surface of the forest floor, between 1- an 15-cm in diameter, was estimated for each stand. Four transects, either 25- or 50-m long (depending on the size of the stand), were sampled. At five fixed points along the each transect, FWD within 1-m^2 was sampled, weighed and subsampled. The five subsamples per transect were composited. The composited subsamples were oven-dried at 60°C. Using a biomass to carbon ratio of 2:1, FWD (kg C per m^2) was calculated for each transect and per stand.

The LAT and LON were available from the Forest Science Database. ELE was also available for most stands, although they were checked using topographical maps.

Climate data was derived from precipitation layers generated by PRISM (Precipitation-elevation Regressions on independent Slopes Model), developed by Oregon Climate Service at Oregon State University (Daly et al. 1994), and temperature layers generated by POTT (Potential Temperature) model (Dodson and Marks, 1997). Both models used a digital elevation model (DEM) to account for topographic differences between grid cell and weather station location (Daly et al., 1994). Precipitation layers were based on 1961 to 1990 data from weather stations within the sampling area and had a grid size of 4-km. Temperature layers were based on 1981 to 1992 data extracted from 258 weather stations within in Oregon and 197 weather stations in Washington (Ohmann and Spies, 1998) and had a grid size of 500-m. From these layers, mean annual precipitation (MAP) and mean annual temperature (MAT), along with their respective 12 monthly means were extracted.

The PET was calculated using mean monthly temperature and an annual heat index (Thornthwaite and Mather, 1955). AET was calculated from monthly water balance using PET, mean monthly temperature and precipitation from the GIS layers, and AWH. As with AWH, AET represents an indicator rather than an actual value.

3.2.3 Statistical Methods

The forest floor and mineral soil to depths of 20- and 100-cm were used to determine the relationships of SOC and TN to site and climatic characteristics. These depths were chosen to facilitate comparison with other studies. Two methods of measuring SOC and TN for the mineral soil layers were also evaluated. The standard method refers to soil processing methods traditionally used where soil is sieved to <2-mm and analysis of this fraction is used to determine SOC and TN contents. The total-soil method, as estimated and discussed in Chapter 2, included the analysis of C-bearing material >2-mm (indestructible aggregates), which in some of these stands greatly contributed to the SOC and TN measured. Therefore, a total of seven response variables for SOC and seven for TN were evaluated against site and climatic characteristics (Table 3.4).

Table 3.4. The seven response variables for SOC or TN used in the regression analysis against site and climatic characteristics. Layers including mineral soil were analyzed by two different methods.

Total-Soil Method (C-bearing soils)	**Standard Method (<2-mm fraction)**
1) Forest Floor	
2) Forest Floor + 0 to 20-cm	5) Forest Floor + 0 to 20-cm
3) 0 to 20-cm	6) 0 to 20-cm
4) 0 to 100-cm	7) 0 to 100-cm

Scatterplots revealed the need to log transform the response variables. Subsequent correlation analysis indicated several explanatory variables that were highly correlated ($r>0.7$) and should not be included in the same model. These variables were PET and AET, PET and MAT, AET and MAP, AWH and Si, and Cl and Si. Therefore, models were run using either PET with MAP or AET without MAP. The Si was often left out of the analysis, which accommodated its high correlation with AWH and Cl. Due to a problem with multicolinearity, all three soil texture variables (Sa, Si, and Cl) were not permitted in the same model.

Forward stepwise linear regression was used to choose models. Models were hand-selected using SAS (SAS Institute, 1998) in a stepwise fashion to select variables. This hand-selecting technique allowed analysis of significant multiple variable models even when the single variables may have been insignificant. Single variable models were first run to determine which variables were most significant using p-values <0.1. This p-value allowed variables that would be excluded at p-values of 0.05 but might form significant interactions with other variables (as was often the case) to be considered. The significant models were re-run with the remaining variables to determine if another variable would play a role in the model taking into account the first variable in the model. If another variable was found significant, then any appropriate interactions between these variables were tested. These significant models were tested with the remaining variables and the process described above repeated until a final model was attained. Variables in final models were accepted at p-values<0.05.

Due to the different scales at which the variables were measured (stand- versus pit-level) and multiple stands being in proximity to one another, there was concern about lack of independence of the response variables (SOC and TN) at the pit-level. To alleviate this dependence, two modelling approaches were evaluated. First, a single-level modelling approach subdivided 45 stands into 18 landscape units (Appendix A) based on similar ecological characteristics (Table 3.5). The response variable from each pit and the stand- and pit-level characteristics were averaged by landscape unit. Models were analyzed based on these landscape units. This approach alleviated over emphasizing the stand-level variables.

Table 3.5. Ecological characteristics of landscape units. Values are means, with ranges in parentheses, from all the pits within each unit. For information on stands within each unit see Appendix 6.2.

Landscape Unit	Number of Pits	Temperature (°C yr^{-1})	Precipitation (cm yr^{-1})	Elevation (m)	Slope (%)	Age (years)
1	7	8.4 (8.3-8.6)	266 (265-266)	287 (280-305)	14 (0-35)	150
2	8	8.9 (8.7-9.0)	255 (255-256)	258 (244-271)	18(10-30)	150
3	2	7.9	242	396	23 (18-27)	150
4	8	8.2	367	247 (244-250)	0	280 (275-285)
5	2	8.9	303	152	0	200
6	4	8.9	290	122	0	230
7	7	6.6 (4.1-8.8)	247 (217-281)	961 (640-1430)	18 (0-55)	671 (300-750)
8	2	6.0 (5.4-6.6)	225 (225-226)	847 (841-853)	20 (14-25)	1000
9	2	7.3	208	1050	26 (25-27)	500
10	4	6.0 (3.9-8.1)	231 (211-250)	845 (610-1080)	29 (9-40)	875 (550-1200)
11	8	7.8	250	405	15 (0-36)	470
12	9	10.2 (5.8-11.4)	185 (172-226)	571 (490-720)	59 (33-70)	460
13	5	7.4 (7.0-8.0)	231 (226-234)	932 (800-1020)	39 (18-62)	460
14	8	7.3 (3.8-10.1)	215 (200-228)	940 (610-1290)	22 (14-36)	460
15	2	7.6	204	1219	9	210
16	2	10.3	201	536	9	105
17	4	8.1	36	933	1 (0-5)	300
18	6	5.7 (5.6-5.8)	54 (54-55)	1359 (1350-1372)	5 (0-18)	433 (400-500)

Secondly, a multi-level modelling approach analyzed models individually at the two scales resulting in two models that work together. The first step in this approach averages the response variable, which was calculated at a pit-level, and all stand-level characteristics into 18 landscape unit (as in the single-level approach). Stand-level models were analyzed based on these landscape units. In the second step of this approach, the predicted values from the stand-level results were subtracted from the pit-level response variables. This yielded new response variables on which pit-level analyses were performed. Equation 3.1 presents a mathematical explanation.

$$Y_p = Y_s - \hat{Y}_s \qquad \text{Equation 3.1}$$

where Y_p is the pit-level response, Y_s is the stand-level response, and $\hat{Y}_s$ is the predicted stand-level response from the model using Y_s. In essence, this method first accounts for the variation in stand-level response and then accounts for any pit-level response.

3.3 Results and Discussion

3.3.1 Soil Organic Carbon

3.3.1.1 Single-Level Models

The final single-level models for SOC are presented in Table 3.6. The log of SOC in the forest floor and forest floor plus 0- to 20-cm layer increased as SL increased to 35 and 45%, respectively, then decreased at higher SL. In the mineral soil, the log of SOC is positively related with SL,

Table 3.6. Single-level analysis for soil organic C content (kg C m^{-2}). Coefficients and p-values for regression equations* for the log of SOC in forest floor, forest floor plus 0- to 20-, 0- to 20-, and 0- to 100-cm depths as functions of most significant site and climatic variables (n=18).

	Forest Floor (FF)		FF + 0- to 20-cm depth				0- to 20-cm depth				0- to 100-cm depth			
	SOC		Total SOC		Standard SOC		Total SOC		Standard SOC		Total SOC		Standard SOC	
Variable†	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P
Intercept	-1.4×10^{-1}	0.6	1.2×10^{-1}	0.6	3.0×10^{-1}	0.3	-8.5×10^{-1}	0.01	-4.7×10^{-1}	0.07	2.0	0.0001	2.0	0.0001
SL	7.0×10^{-2}	0.01	3.6×10^{-2}	0.003	3.6×10^{-2}	0.003	1.1×10^{-2}	0.04						
SL^2	-1.0×10^{-3}	0.04	-4.0×10^{-4}	0.03	-5.0×10^{-4}	0.03								
AWH			4.0×10^{-1}	0.0001	3.4×10^{-1}	0.0001	5.9×10^{-1}	0.0001	4.4×10^{-1}	0.0001				
CWD									4.5×10^{-2}	0.02	1.3×10^{-1}	0.0003	1.4×10^{-1}	0.0001
Sa											-1.0×10^{-3}	0.02	-9.5×10^{-4}	0.02
Cl											3.0×10^{-3}	0.01	2.2×10^{-3}	0.04
AGE											-1.1×10^{-3}	0.03	-1.1×10^{-3}	0.01
Adjusted R^2	0.32		0.77		0.71		0.83		0.80		0.77		0.77	

* Regression equations are of the form log SOC content = intercept + coefficient1 x variable1 + coefficient2 x variable2 +....

† SL = slope (%), range = 0 to 70; AWH = available water holding capacity (cm $depth^{-1}$), range = 1 to 6 in 0- to 20-cm depth and 8 to 32 in 0- to 100-cm depth; CWD = coarse wood debris (kg C m^{-2}), range = 0.4 to 25; Sa = mass of sand to either 20- or 100-cm depth (kg m^{-2}), range = 0.2 to 163 in 0- to 20-cm depth and 19 to 865 in 0- to 100-cm depth; Cl = mass of clay to either 20- or 100-cm depth (kg m^{-2}), range = 4 to 69 in 0- to 20-cm depth and 6 to 427 in 0- to 100-cm depth; AGE = stand age (years), range = 105 to 1200.

AWH, CI, and CWD, and negatively related to SA and AGE. Final models of total SOC and standard SOC for each layer were identical in terms of significant variables included, only coefficients varied slightly. For the mineral soil layers, AWH was the single variable that explained the most variation. The variation in total SOC explained by AWH was 56, 78, and 52% in the forest floor plus 0- to 20-cm, 0- to 20-cm, and 0- to 100-cm layers, respectively, and 45, 73, and 49% in standard SOC. It makes sense that AWH is an important variable in explaining carbon content of the soil because it directly influences forest productivity. More moisture available for plant uptake leads to increased productivity, which in turn promotes higher detrital inputs (Waring and Schlesinger, 1985; Brady and Weil, 1996). Soil texture influences the amount of water held in the soil (Donahue et al., 1983; Brady and Weil, 1996). Higher contents of fine-textured materials (silts and clays) increase inflitration rates and increase the water availability (Brady and Weil, 1996). Higher contents of fine-textured materials also stabilize organic matter by forming complexes (Brady and Weil, 1996).

Forest floor SOC exhibited significant relations with only two variables, SL and AS. The most significant single variable model of forest floor SOC was a negative relationship to AS (adj. R^2=0.19). Represented as a linear relationship, SL explained 16% of the variation in forest floor SOC. However, by using a polynomial relationship, SL and SL^2 explained 32% of the variation in forest floor SOC. Both SL and AS describe the orientation of the soil pit and influence the amount of solar radiation reaching the soil surface. This, in turn, would affect the aboveground vegetation and ultimately inputs to the soil.

Grigal and Ohmann (1992) were able to explain 40% of the variability in their forest floor SOC by including forest type, the inverse of age, AET, and clay content to 20-cm in their model. Although my model was able to explain 32% of the variability, there were no similarities to the model derived by Grigal and Ohmann (1992) for the Lake States forests. The data from this study were tested against a model for the Lake States forests excluding forest type. Forest type in the Lake States forests model incorporated an indicator variable to represent various types of hardwood forests. The forest types of the stands in my study were all mixed coniferous and a classification of the stands into forest type was not attempted. The litter from the hardwood forests in the Lake States probably contributes more biomass and nutrients, annually, to the forest than litter from coniferous forests.

Homann et al. (1995) found that forest floor SOC related poorly to site characteristics (R^2=0.12) in largely forested, mountainous regions of western Oregon. The differences between results from this study and those of Homann et al. (1995) are curious since they were developed from data within the same region. Some of the data used in the model by Homann et al. (1995) were from second-growth forests where there may have been some previous disturbance, such as post-harvest fire, resulting in lower forest floor accumulations.

Forest floor plus 0- to 20-cm layer was examined because the forest floor and mineral soil do not act independently, rather they have an intimate interface where the organic matter influences the mineral soil and the processes occurring there. Other studies have treated these layers independently (Grigal and Ohmann, 1992; Edmonds and Chappell, 1994; Homann et al., 1995). However, some researchers may consider the forest floor as part of the mineral soil. Of interest are how the factors that affect the forest floor or the 0- to 20-cm layer differ from the factors that affect the forest floor plus 0- to 20-cm layer. Variables in the models for the forest floor plus 0- to 20-cm layer using the two methods were the same with minor differences in the coefficients. The models included the same quadratic relationship of SL and SL^2 that were in the forest floor model, but also included AWH, which indicates the influence of the 0- to 20-cm layer. The forest floor plus 0- to 20-cm layer did a much better job at explaining the variation than the forest floor alone (77% versus 32%).

Models using SL and AWH for both the total and standard methods explained 83% and 79% of the variation in SOC in the 0- to 20-cm mineral soil, respectively. However, AWH and CWD explained 80% of the variation by the standard method and were included in the final model of that response variable.

Models from this study for the 0- to 20-cm mineral soil layer explained much more of the variation in SOC than other studies. This could be due to aggregating the data into landscape units, which averages out a large portion of the variation. Burke et al. (1989) was able to explain 51% of this variation using MAT and MAP and interactions of MAP with Si and Cl. Homann et al. (1995) explained 44% and Grigal and Ohmann (1992) explained 35% using qualitatively similar models including the variables AET and Cl. However, variables from this study did not fit any of the aforementioned models. This lack of fit could be due to the different methods used to determine SOC or the explanatory variables. Burke et al. (1989) and Homann et al. (1995) compiled data from a variety of studies where the methods may have differed or were even unknown. Grigal and Ohmann (1992) composited samples from a very large sampling area. Alternatively, the production and decomposition processes in the different study areas could be controlled by specific site and climatic factors.

Models explaining variation of SOC for both total and standard methods in the 0- to 100-cm mineral soil were virtually identical. The adjusted R^2 equaled 0.77 for both models and the coefficients were nearly the same. The models included AGE, CWD, Cl, and Sa. The log of SOC was positively correlated to CWD and Cl and negatively correlated to Sa and AGE. It is likely that the negative correlation to AGE is driven by the Cascade Head site, which has the highest SOC contents and the youngest trees. The adjusted R^2 for these models are much higher than for models from other studies. Homann et al. (1995) explained 50% of the variation in SOC using AET^2, MAP^2, and MAP x AWH. Grigal and Ohmann (1992) explained 57% of the variation using MAP, AWH, and CI. Again, variables from this study did not fit into either of these models. In this study, AET and MAP were highly correlated and not permitted in the same equation. As mentioned previously, soil texure is an important in forming stable complexes with organic material (Brady and Weil, 1996) and influencing the available water holding capacity of the soil (Donahue et al., 1983; Brady and Weil, 1996).

The explanatory variables in the models presented in Table 3.6 were chosen because they were able to explain the most variation in the log of SOC. However, they were not the only set of significant variables. Variables selected for the 0- to 100-cm layer were different than those chosen for the 0- to 20-cm layer, based on adjusted R^2. From this analysis, factors controlling the accumulation of SOC in the 20- to 100-cm portion of the soil pit out-weight the important factors to only 20-cm depth. However, models using the variables from the 0- to 20-cm layer, for example AWH and CWD, to explain SOC also explained a large amount of the variation in the 0- to 100-cm layer (64% for total and 69% for standard method).

3.3.1.2 Multi-Level Models

The final multi-level models for SOC are presented in Table 3.7 for the stand-level and Table 3.8 for the pit-level. At the stand-level, the log of SOC in the mineral soil is negatively related with AGE while the other main effect variables are positively related. Models for total SOC and standard SOC are similar with slight differences in their coefficients. For pit-level models, a parabolic relationship explained SOC in all layers except for

Table 3.7. Multi-level analysis for stand-level soil organic C content (kg C m^{-2}). Coefficients for regression equations* for the log of SOC in forest floor, forest floor plus 0- to 20-, 0- to 20-, and 0- to 100-cm depths as functions of most significant site and climatic variables (n = 18).

	Forest Floor (FF)		FF + 0- to 20-cm depth				0- to 20-cm depth				0- to 100-cm depth			
	SOC		Total SOC		Standard SOC		Total SOC		Standard SOC		Total SOC		Standard SOC	
Variables†	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P
Intercept			$7.8x10^{-1}$	0.03	$7.3x10^{-1}$	0.01	1.8	0.0001	1.5	0.0001	1.1	0.01	1.0	0.01
FWD			$4.4x10^{-1}$	0.05	$4.9x10^{-1}$	0.01					$6.4x10^{-1}$	0.01	$6.8x10^{-1}$	0.004
MAP			$3.5x10^{-3}$	0.01	$3.1x10^{-3}$	0.004					$4.9x10^{-3}$	0.002	$4.8x10^{-3}$	0.001
AGE							$-2.2x10^{-3}$	0.001	$-2.0x10^{-3}$	0.0002	$-1.1x10^{-3}$	0.01	$-9.2x10^{-4}$	0.02
CWD							$1.1x10^{-1}$	0.01	$1.2x10^{-1}$	0.001				
Adjusted R^2			0.46		0.58		0.52		0.61		0.67		0.70	

* Regression equations are of the form log SOC content = intercept + coeffient1 x variable1 + coeficient2 x variable2 + …

† FWD = fine woody debris (kg C m^{-2}), range = 0.5 to 3.3; MAP = mean annual precipitation (cm yr^{-1}), range = 35 to 367; AGE = stand age (years), range = 105 to 1200; CWD = coarse wood debris (kg C m^{-2}), range = 0.4 to 25.

Table 3.8. Multi-level analysis for pit-level soil organic C content (kg C m^{-2}). Coefficients for regression equations* for residual stand-level variation in the log of SOC in forest floor, forest floor plus 0- to 20-, 0- to 20-, and 0- to 100-cm depths as functions of most significant site and climatic variables (n = 90 for 0- to 20-cm depth and n = 88 for 0- to 100-cm depth).

	Forest Floor (FF)		FF + 0- to 20-cm depth				0- to 20-cm depth				0- to 100-cm depth			
	SOC		Total SOC		Standard SOC		Total SOC		Standard SOC		Total SOC		Standard SOC	
Variables†	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P
Intercept	-4.1	0.6	$-1.2x10^{-1}$	0.3			-1.8	0.0001	$-7.5x10^{-1}$	.0001	$-3.9x10^{-1}$	0.001	$-3.6x10^{-1}$	.001
AET	$2.0x10^{-1}$	0.01												
AET^2	$-1.9x10^{-3}$	0.04												
AWH							$8.1x10^{-1}$	.001						
AWH^2							$-9.0x10^{-2}$	0.002						
Sa			$-2.1x10^{-3}$	0.05										
Cl			$9.0x10^{-3}$	0.01			$8.4x10^{-3}$	0.03			$4.4x10^{-3}$	0.002	$4.3x10^{-3}$	0.002
Cl^2											$-9.5x10^{-6}$	0.01	$-9.7x10^{-6}$	0.01
Si									$2.7x10^{-2}$	0.0001				
Si^2									$-2.0x10^{-4}$	0.0001				
Adjusted R^2	0.19		0.09				0.28		0.24		0.10		0.09	

* Regression equations are of the form residual stand-level variation = intercept + coeffient1 x variable1 + coeficient2 x variable2 + …

† AET = available water holding capacity (cm $year^{-1}$), range = 22 to 74 in 0- to 20-cm depth and 32 to 80 in 0- to 100-cm depth; AWH = available water holding capacity (cm $depth^{-1}$), range = 1 to 6 in 0- to 20-cm depth and 8 to 32 in 0- to 100-cm depth; Sa = mass of sand to either 20- or 100-cm depth (kg m^{-2}), range = 9 to 163 in 0- to 20-cm depth and 19 to 865 in 0- to 100-cm depth; Cl = mass of clay to either 20- or 100-cm depth (kg m^{-2}), range = 4 to 69 in 0- to 20-cm depth and 6 to 427 in 0- to 100-cm depth; Si = mass of silt to either 20- or 100-cm depth (kg m-2), range = 14 to 168 in 0- to 20-cm depth and 27 to 703 in 0- to 100-cm depth.

standard SOC in the forest floor plus 0- to 20-cm layer, where no significant models resulted.

Forest floor SOC failed to exhibit any relationships with variables at the stand-level. The pit-level variables AET and AET^2 were only able to explain 19% of the residual variability. In this case, the log of SOC increased with increasing AET to 53 cm $year^{-1}$, then decreased at higher AET. These results are similar to Homann et al. (1995) who found that forest floor SOC related poorly (12%) to site and climatic characteristics in western Oregon forests. These results differ significantly from the single-level modelling approach where 32% of the variability in forest floor SOC was explained by SL and SL^2.

As a single stand-level variable, MAP explained the most variability (adj. R^2 = 0.34 [total], 0.37 [standard]) of SOC in the forest floor plus 0- to 20-cm layer. However, a model including FWD and MAP explained the most variation (adj. R^2 = 0.58[total], 0.52 [standard]). The pit-level variables AWH and Sa explained 9% of the residual variation in total SOC. No significant pit-level variables were able to explain any of the residual variation in standard SOC.

As single stand-level variables, MAP and AGE each explained 25% of the variation in total SOC in the 0- to 20-cm. MAP explained 28% of the variation in standard SOC in the 0- to 20-cm. However, models including AGE and CWD explained the greatest amount of variation (adj. R^2 = 0.52[total], 0.61 [standard]) in log SOC. For total SOC, pit-level variables CI, AWH, and AWH^2 explained 28% of the residual variation. In this case, the log of SOC increased with increasing AWH to 4.4 cm per 20-cm depth, then decreased at higher AWH. The same variables did not result in a model for standard SOC. AWH, and AWH^2 explained 23% of the residual variation (CI was not significant in this model). The final pit-level model for standard SOC included Si and Si^2 and explained 24% of the residual variation. The log of SOC increased with increasing Si to 65 kg m^{-2}, then decreased at higher Si.

Models for the 0- to 100-cm layer for the total SOC and standard SOC were nearly identical, with only minor differences in the coefficients. As a single stand-level variable, MAP explained the most variability (adj. R^2 = 0.43 [total], 0.44 [standard]) of SOC in this layer. However, stand-level variables MAP, AGE, and FWD together explained the most variation (adj. R^2 = 0.67 [total], 0.70 [standard]). Pit level variables Cl and Cl^2 explained 10% and 9% of the residual variation in total and standard SOC, respectively. The log of SOC increased with increasing Cl to 23 kg m^{-2}, then decreased at higher Cl.

Stand-level variables between the two methods (total and standard) for a given layer were very similar. However, the significant pit-level variables explaining residual variation in the log of SOC were quite different not only among layers, but between methods too. In all the layers including mineral soil, texture appeared to be significant.

3.3.2 Soil Total Nitrogen

3.3.2.1 Single-Level Models

The final single-level models for TN are presented in Table 3.9. The log of TN is positively related to AWH and AET in the forest floor, positively related to AWH, CWD, SL, and Cl in the mineral soil, and negatively related to AGE, Sa, and FF in the mineral soil. Models of total N and standard N were very similar. For mineral soil layers, CWD was significant in each resulting model. This was surprising as foliar N inputs to the soil are much larger than inputs from CWD (Harmon et al., 1986). However, transfers of organic matter into and out of CWD can be large (Harmon et al., 1986). For the surface layers, AWH was significant in each resulting model. For the

Table 3.9. Single-level analysis for total soil N content (kg N m^{-2}). Coefficients for regression equations* of the log for TN in forest floor, forest floor plus 0- to 20-, 0- to 20-, and 0- to 100-cm depths as functions of most significant site and climatic variables (n=18).

	Forest Floor (FF)		FF + 0- to 20-cm depth				0- to 20-cm depth				0- to 100-cm depth			
	Total N		Total N		Standard N		Total N		Standard N		Total N		Standard N	
Variable†	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P
Intercept	-9.8	0.0001	-5.2	0.0001	-3.8	0.0001	-4.8	0.0001	-4.6	0.0001	$-8.5x10^{-1}$	0.02	$-8.4x10^{-1}$	0.01
SL							$1.6x10^{-2}$	0.01	$1.4x10^{-2}$	0.01				
FF							$-1.0x10^{-1}$	0.04	$-9.6x10^{-2}$	0.04				
AET	$1.2x10^{-1}$	0.003												
AETxAWH	$-2.7x10^{-2}$	0.01												
AWH	1.6	0.01	$9.3x10^{-1}$	0.0001	$5.0x10^{-1}$	0.0001	$7.7x10^{-1}$	0.0001	$6.8x10^{-1}$	0.0001				
CWD			$2.6x10^{-1}$	0.01	$7.3x10^{-2}$	0.001	$4.1x10^{-2}$	0.05	$6.0x10^{-2}$	0.01	$1.4x10^{-1}$	0.0001	$1.4x10^{-1}$	0.0001
CWDxAWH			$-5.6x10^{-2}$	0.02										
Sa											$-9.4x10^{-4}$	0.02	$-9.0x10^{-4}$	0.02
Cl											$3.4x10^{-3}$	0.01	$2.6x10^{-3}$	0.01
AGE											$-1.7x10^{-3}$	0.001	$-1.7x10^{-3}$	0.001
Adjusted R^2	0.48		0.86		0.85		0.91		0.90		0.83		0.84	

* Regression equations are of the form log TN content = intercept + coeffient1 x variable1 + coeficient2 x variable2 + …

† SL = slope (%), range = 0 to 70; FF = forest floor organic carbon content (kg C m^{-2}), range = 0 to 14; AET = available water holding capacity (cm $year^{-1}$), range = 22 to 74 in 0- to 20-cm depth and 32 to 80 in 0- to 100-cm depth; AWH = available water holding capacity (cm $depth^{-1}$), range = 1 to 6 in 0- to 20-cm depth and 8 to 32 in 0- to 100-cm depth; CWD = coarse wood debris (kg C m^{-2}), range = 0.4 to 25; Sa = mass of sand to either 20- or 100-cm depth (kg m^{-2}), range = 9 to 163 in 0- to 20-cm depth and 19 to 865 in 0- to 100-cm depth; Cl = mass of clay to either 20- or 100-cm depth (kg m^{-2}), range = 0 to 69 in 0- to 20-cm depth and 6 to 427 in 0- to 100-cm depth; AGE = stand age (years), range = 105 to 1200.

mineral soil layers, AWH was the single variable that explained the most variation. The variation in total N explained was 74, 82, and 62% in the forest floor plus 0- to 20-cm, 0- to 20-cm, and 0- to 100-cm layers, respectively, and 69, 76, and 62% in standard N. As was mentioned earlier, AWH is an important variable in explaining carbon content of the soil because it directly influences forest productivity.

Not many variables were significant in explaining the variation in forest floor N. The most significant model included AET, AWH and an interaction of AET and AWH (adj. $R^2 = 0.48$). The variables AET and AET^2 were able to explain more variation in forest floor N (adj. $R^2 = 0.42$) than they did in forest floor SOC (adj. $R^2 = 0.29$).

Models using AWH and CWD for both total N and standard N explained 82% and 85% of the variation in the forest floor plus 0- to 20-cm mineral soil, respectively. However, by including an interaction between AWH and CWD, 86% of the variation was explained in total N and was included in the final model.

Models that explained the most variation in TN in the 0- to 20-cm mineral soil for both total N and standard N included AWH, CWD, SL, and FF (adj. $R^2 = 0.91$ [total], 0.90 [standard]). With the exclusion of FF, these same variables were also important in the SOC models for this layer.

Models explaining variation in total N and standard N in the 0- to 100-cm mineral soil were virtually identical. The models and their coefficients were also nearly the same as for SOC. The models included AGE, CWD, Cl, and Sa.

There have not been many papers written on modelling soil TN to determine influential site and climatic factors, thus comparisons are difficult to make. However, Bormann and DeBell (1981) found AGE to be positively related with N to 20-cm depth in red alder stands in western Washington. AGE was only significant in a single-level modelling approach in the 0- to

100-cm layer and it was negatively related to N. The stands examined by Bormann and DeBell (1981) were young alder stands and the difference in vegetation type may have contributed to the discrepancy in results. But as mentioned before, AGE in this analysis is most likely being driven by the Cascade Head site, which has the highest SOC contents and the youngest trees.

3.3.2.2 Multi-Level Models

The final multi-level models evaluated for TN are presented in two separate tables. Stand-level models are presented in Table 3.10 and the pit-level models explaining the residual stand-level variation are presented in Table 3.11. The log of TN is positively related to MAP in the forest floor and positively related to MAP and CWD in the mineral soil. In addition, in the mineral soil, the log of TN decreased with increasing AGE to about 700 years, then increased at higher AGE. Stand-level models of total N and standard N tend to be similar while there are differences in the pit-level models which explain the residual variation in the stand-level models.

Forest floor TN was only explained by the stand-level variable MAP (adj. R^2 = 0.23). No pit-level variables were significant in explaining any of the residual variation. In the single-level approach, AWH and AET came into the model as main effects and as an interaction.

In the forest floor plus 0- to 20-cm layer the models were quite similar except for minor differences in the coefficients. The stand-level variables MAP, AGE, and AGE^2 explained 67% and 64% of the variation in total N and standard N, respectively. Pit-level variables AWH and AWH^2 explained 17% of the residual variation in total N while CI, AWH and AWH^2 explained 21% of the residual variation in standard N. Thus, in both methods, the log of TN increased with increasing AWH to 4.3 cm per 20-cm depth, then decreased at higher AWH.

Table 3.10. Multi-level analysis for stand-level total soil N content (kg N m^{-2}). Coefficients for regression equations* for the log of TN in forest floor, forest floor plus 0- to 20-, 0- to 20-, and 0- to 100-cm depths as functions of most significant site and climatic variables (n = 18).

	Forest Floor (FF)		FF + 0- to 20-cm depth				0- to 20-cm depth				0- to 100-cm depth			
	Total N		Total N		Standard N		Total N		Standard N		Total N		Standard N	
Variables†	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P
Intercept	-4.1	0.0001	-8.7×10^{-1}	0.1	-1.2	0.04	-1.0	0.1	-8.5×10^{-1}	0.05	-1.6×10^{-1}	0.7	3.1×10^{-1}	0.3
MAP	4.6×10^{-3}	0.03	4.6×10^{-3}	0.01	4.5×10^{-3}	0.005	4.9×10^{-3}	0.01			5.1×10^{-3}	0.001		
AGE			-6.4×10^{-3}	0.002	-5.5×10^{-3}	0.004	-6.5×10^{-3}	0.01	-6.3×10^{-3}	0.001	-5.9×10^{-3}	0.001	-6.2×10^{-3}	0.0003
AGE2			5.1×10^{-6}	0.01	4.5×10^{-6}	0.01	4.6×10^{-6}	0.03	3.7×10^{-6}	0.03	4.2×10^{-6}	0.01	3.7×10^{-6}	0.01
CWD									1.4×10^{-1}	0.001			1.3×10^{-1}	0.002
Adjusted R^2	0.23		0.67		0.64		0.63		0.72		0.76		0.72	

* Regression equations are of the form log TN content = intercept + coeffient1 x variable1 + coeficient2 x variable2 + …

† MAP = mean annual precipitation (cm yr^{-1}), range = 35 to 367; AGE = stand age (years), range = 105 to 1200; CWD = coarse wood debris (kg C m^{-2}), range = 0.4 to 25.

Table 3.11. Multi-level analysis for pit-level total soil N content (kg N m^{-2}). Coefficients for regression equations* for the residual stand-level variation of the log of TN in forest floor, forest floor plus 0- to 20-, 0- to 20-, and 0- to 100-cm depths as functions of most significant site and climatic variables (n= 79 for forest floor, n = 90 for 0- to 20-cm depth, and n = 88 for 0- to 100-cm depth).

	Forest Floor (FF)		FF + 0- to 20-cm depth				0- to 20-cm depth				0- to 100-cm depth			
	Total N		Total N		Standard N		Total N		Standard N		Total N		Standard N	
Variables†	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P	Coefficient	P
Intercept			-2.4	0.0001	-2.5	0.0003	$3.5x10^{-1}$	0.0001	$-3.0x10^{-1}$	0.02	$-4.2x10^{-2}$	0.8	$-8.1x10^{-1}$	0.0001
AWH			1.3	0.001	1.4	0.002					$2.1x10^{-2}$	0.01	$4.2x10^{-2}$	0.0001
AWH^2			$-1.5x10^{-1}$	0.0003	$-1.6x10^{-1}$	0.0005								
SL									$8.4x10^{-3}$	0.001			$6.2x10^{-3}$	0.005
AS													$1.4x10^{-1}$	0.01
Sa							$-4.9x10^{-3}$	0.0001			$-2.0x10^{-3}$	0.001		
Sa^2											$2.1x10^{-6}$	0.01		
Si									$1.6x10^{-3}$	0.0001				
FF									$-5.3x10^{-2}$	0.004				
Cl					$-1.4x10^{-2}$	0.001								
Adjusted R^2			0.17		0.21		0.15		0.23		0.28		0.36	

* Regression equations are of the form residual log TN = intercept + coeffient1 x variable1 + coeficient2 x variable2 + …

† AWH = available water holding capacity (cm $depth^{-1}$), range = 1 to 6 in 0- to 20-cm depth and 8 to 32 in 0- to 100-cm depth; SL = slope (%), range = 0 to 70; AS=aspect (degrees), range=0 to 360; Sa = mass of sand to either 20- or 100-cm depth (kg m^{-2}), range = 0.2 to 163 in 0- to 20-cm depth and 19 to 865 in 0- to 100-cm depth; Si = mass of silt to either 20- or 100-cm depth (kg m^{-2}), range = 14 to 168 in 0- to 20-cm depth and 27 to 703 in 0- to 100-cm depth; FF = forest floor (kg m^{-2}), range = 0 to 14 (used as an explanatory variable in the mineral soil models); Cl = mass of clay to either 20- or 100-cm depth (kg m^{-2}), range = 0 to 69 in 0- to 20-cm depth and 6 to 427 in 0- to 100-cm depth.

Significant stand-level variables for explaining the most variation in total N in the 0- to 20-cm layer and the 0- to 100-cm layer include MAP, AGE, and AGE^2. These models are the same as for the forest floor plus 0- to 20-cm layer. The pit-level variable Sa was the only significant variable, explaining 15% of the residual variation, and was negatively related to total N for the 0- to 20-cm layer. For the 0- to 100-cm layer, pit-level variables AWH, Sa, and Sa^2 explained 28% of the residual variation in total N. In this layer, the log of TN decreased as Sa increased to 500 kg m^{-2}, then increased at higher Sa.

Significant stand-level variables for explaining the most variation in standard N in the 0- to 20-cm layer and the 0- to 100-cm layer include CWD, AGE, and AGE^2. These models differ slightly from the forest floor plus 0- to 20-cm layer and the total N models. The pit-level variables SL, Si, and FF explained 23% of the residual variation in total N for the 0- to 20-cm layer. For the 0- to 100-cm layer, pit-level variables AWH, SL, and AS explained 36% of the residual variation in total N.

Being able to explain 15-36% of the variation in the residual variation of TN is substantial, especially when the stand-level models were able to explain 64-78% initially. The AGE was significant in each mineral soil layer analyzed. These results are more consistent with those of Bormann and DeBell (1981), although their relationship was positively related with TN to 20-cm depth in young, red alder stands in western Washington. Except for the 0- to 20-cm layer, the pit-level variable AWH was important in explaining residual variation from stand-level models.

3.4 Conclusions

Relationships of SOC or TN to site and climatic variables in western Oregon and Washington were statistically dominated by specific themes in terms of important explanatory variables. In most cases examined, moisture and texture played important roles. The exception to this was with SOC in the forest floor. The factors controlling forest floor SOC and TN accumulation differed from factors controlling the mineral soil. Results of this research indicate that SOM dynamics of the forest floor may be controlled by external organic inputs rather than subsurface processes. The results of the mineral soil from this study agree with those of Homann et al. (1995) who concluded that texture and climate explained much of the variation in SOC.

The two modelling approaches produced different results. The amount of residual stand-level variation explained by pit-level factors varied between layers, on whether C or N was the response variable, and depending on how much variation was accounted for by stand-level factors. Many of the site and climate factors interact causing identification of individual characteristics difficult. Future modelling scenarios would benefit from more complete datasets of site and climate characteristics for measured SOC and TN. For instance, this dataset was limited by a need to estimate the texture components for each soil pit. Detailed lab analyses of particle size distribution would not only furnish measured sand, silt, and clay contents, but also provide more accurate estimates of available water-holding capacity. Grigal and Ohmann (1992) found that forest type to be important in explaining SOC in both the forest floor and mineral soil of forests in the Lake States. Thus, inclusion of aboveground data like forest overstory, understory, and productivity may be useful in evaluating relationships to SOC.

The models for SOC and TN were more similar for mineral soil than for the forest floor. In most cases examined, more of the variability in TN was explained by site and climatic factors than for SOC. Because of the tight link between C and N cycling, the factors correlated to their abundance are similar.

The variables included in models comparing the total-soil and the standard method for each layer analyzed were also similar. There was little discrepancy in explaining the response between the two methods. The exception to this similarity was evident in the pit-level models applying the multi-level approach. The resulting models included different variables, but texture appeared in each case for the mineral soil. It is likely that the sample size of the soil pits with C-bearing material >2-mm was not large enough for these differences to be detected. However, I believe that this fraction does play an important role in specific ecosystems in the Pacific Northwest and that further investigation is warranted.

The results of this study, and of other studies assessing the effects of site and climatic characteristics on the factors controlling SOM accumulation, suggest the relationships are regionally specific. The results from this study indicate texture and climate relate well with either SOC or TN at these specific sites. The processes that control SOM dynamics were not assessed. However, the important factors that related to SOC and TN can support the development of mechanistic models because they influence the more specific processes stabilizing SOM. Improved documentation, measurements, and estimates of SOC, TN, and related site and climatic variables may aid in development of generalizable process models and may contribute to better understanding these processes for western Oregon and Washington.

4. CONCLUSIONS AND SUMMARY

Forest floor SOC averaged 50% higher in the old-growth forests of this study than in second growth forests in western Oregon (Homann et al., 1995). Forest floor TN also averaged 50% higher in the old-growth forests of this study than in young Douglas-fir and hemlock stands in western Oregon and Washington (Edmonds and Chappell, 1994). Mineral SOC and TN for the 0- to 20-cm depth for the 0- to 100-cm depth averaged higher than other studies for the same region, but was within a similar range (Means et al., 1992; Homann et al., 1995; Cromack et al., 1999).

Vertical distribution of SOC and TN to 1-meter depth within soil pits in western Oregon and Washington shows the importance of accounting for SOC and TN at depth and provides patterns of accumulation within the profile. Of the material measured, 39 to 66% of SOC and 34 to 63% of TN in individual soil pits was found below 20 cm. These estimates illustrate how failing to sample at depth can grossly underestimate SOC and TN. The content of SOC in the 0- to 20-cm depth as a fraction of the total depth was less when SOC was abundant. This implies that a profile profuse with SOC stores this C deeper in the profile. Explanations of this may be due to specific physical, chemical and biological conditions that promote greater accumulation of this material through greater nutrient and water-holding capacities, reduced rates of organic matter oxidation, and protection from degradation or to various types of disturbance causing mixing of the soil profile (i.e. windthrow, micro- and macrofauna disturbance). There was no significant difference in the N contents among the layers. The TN content in the 0- to 20-cm depth as a fraction of the total depth was on average 32% for all the sites. For some reason TN seems to be more evenly dispersed in the soil profile than SOC. Surface SOC may be subject to loss through respiration at a greater rate than TN is lost through leaching or root uptake. Although TN is less abundant with deep, the distribution of TN is more evenly conserved throughout the soil profile.

Within the upper meter of mineral soil, up to 44% of SOC and TN was found in C-bearing material >2-mm for individual soil pits. These cemented, stable aggregates are not accounted for by traditional methods of soil processing and analysis. Neglecting to incorporate this material into forest ecosystem estimates can also considerably underestimate SOC and TN, which limits our ability to make valid regional estimates of C and N in the Pacific Northwest.

Longitudinal differences in SOC and TN contents were observed between Coastal, Cascade, and Eastside Cascade sites. These differences imply climatic and site factors affect SOC and TN accumulation. This longitudinal trend was not observed in the C/N ratios of these sites where mountainous Cascade sites had higher C/N ratios in both the forest floor and mineral soil. Decomposition is slower at cooler, moister sites allowing for more SOC accumulation. However, sites too extreme in either moisture or temperature will not be as productive and aboveground inputs will be lower. Also, if N is limiting (high C/N ratios), decomposition may be slower and the SOC unavailable to microbes.

Relationships of SOC or TN to site and climatic variables in western Oregon and Washington were statistically dominated by specific themes in terms of important explanatory variables. In most cases examined, moisture and texture played important roles. The exception to this was with SOC in the forest floor. The factors controlling forest floor SOC and TN accumulation differed from factors controlling the mineral soil. Results of this research indicate that SOM dynamics of the forest floor may be controlled by external organic inputs rather than subsurface processes. The results of the mineral soil from this study agree with those of Homann et al.

(1995) who concluded that texture and climate explained much of the variation in SOC.

The single-level and multi-level modelling approaches produced different results. The amount of residual stand-level variation explained by pit-level factors varied between layers, on whether C or N was analyzed, and depending on how much variation was accounted for by stand-level factors. Many of the site and climate factors interact causing identification of individual characteristics difficult. Future modelling scenarios would benefit from more complete datasets of site and climate characteristics for measured SOC and TN. For instance, this dataset was limited by a need to estimate the texture components for each soil pit. Detailed lab analyses of particle size distribution would not only furnish measured sand, silt, and clay contents, but also provide more accurate estimates of available water-holding capacity. Grigal and Ohmann (1992) found that forest type to be important in explaining SOC in both the forest floor and mineral soil of forests in the Lake States. Thus, inclusion of aboveground data like forest overstory, understory, and productivity may be useful in evaluating relationships to SOC.

As areas of future research, several of the explanatory variables in the analysis could be redressed. A potentially important variable missing from these analyses is age of the soil. It is more likely that soil age rather than stand age would influence soil development. Older soils have been subjected to longer periods of weathering. If Coast Range soils and low elevation Cascade soils are significantly older than high Cascade soils, an influence of age on soil development may be prominent. Secondly, the climate variables used in this study could be evaluated differently. Rather than analyzing mean annual temperature and precipitation, it may be more meaningful to examine growing season temperature and precipitation. Perhaps the differences among the sites would be extreme during the growing season. The seasonal timing of precipitation events in conjunction with the current temperature could certainly influence the biological processes in the soil.

The variables included in models comparing the total-soil and standard method for each layer analyzed were also similar. The total-soil method, as estimated and discussed in Chapter 2, included the analysis of C-bearing material >2-mm (indestructible aggregates), which in some of these stands greatly contributed to the SOC and TN measured. The standard method refers to traditional soil processing methods, where soil is sieved to <2-mm and analysis of this fraction is used to determine SOC and TN contents. There was little discrepancy in explaining the response between the two methods. The exception to this similarity was evident in the pit-level models applying the multi-level approach. The resulting models included different variables, but texture appeared in each case for the mineral soil. Although standard methods underestimated the amount of SOC and TN in western Oregon and Washington (Chapter 2), these underestimations did not have a large effect on the relationship to site and climate factors (Chapter 3). It is likely that the sample size of the soil pits with C-bearing material >2-mm was not large enough for these differences to be detected. However, I believe that this fraction does play an important role in specific ecosystems in the acific Northwest and that further investigation is warranted.

The results of this study, and of other studies assessing the effects of site and climatic characteristics on the factors controlling SOM accumulation, suggest the relationships are regionally specific. The results from this study indicate the variables measured that correlate well with either SOC or TN at these specific sites. The processes that control SOM dynamics were not assessed. However, the important factors that related to SOC and TN can support the development of mechanistic models because they influence the more specific processes stabilizing SOM. Improved documentation, measurements, and estimates of SOC, TN, and related site and climatic variables may aid in development of generalizable process models and may contribute to better understanding these processes for western Oregon and Washington.

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APPENDICES

Appendix A. Background Information about Study Sites

Andrews Long Term Ecological Research (LTER) program was established by the National Science Foundation to support research on long-term ecological phenomena in the United States. H.J. Andrews Experimental Forest is the main research site. Most other sites sampled are part of the Andrews research site and constitute satellite research areas which include Research Natural Areas, other Experimental Forests, and Wilderness areas within either the National Forest or Park systems. The sites comprise reference stands (plots) which have been survey and permanently marked. Each plot has been subject to various degrees of research. Data collected from plots within the permanent reference stands are stored and managed in the Forest Science database, Oregon State University, Corvallis.

Research publications for H.J. Andrews have been compiled by Blinn et al. (1988) and McKee et al. (1987). There is also a web site for H.J. Andrews LTER where a master bibliography of all research since 1948 can be found in addition to other information about the LTER program (http://www.fsl.orst.edu/lter/homepage.htm). Information on the satellite research areas is also available at this website. For information on RNAs in the Pacific Northwest, contact Chair of the Pacific Northwest Natural Areas Committee, Pacific Northwest Research Station, P.O. Box 3890, Portland, OR, 97208. Establishment, maintenance, and remeasurement of the Thornton T. Munger RNA was described by DeBell and Franklin (1987). A detailed description and classification of the forests of Mount Rainier National Park was compiled by Franklin et al. (1988).

The EPA/Cascade plots include a high (1220 m) and low (520 m) elevation plot established by the EPA Environmental Research Laboratory to compare and contrast C and N cycling in Douglas-fir/western hemlock ecosystems along an elevational/climatic gradient. Each plot is approximately 0.6 ha divided into 15-m x 15-m plots. Twelve sub-plots were randomly selected and sampled for C and N stocks and fluxes in vegetation and soil. Meteorological data, including air and soil temperatures, soil moisture, and precipitation were also measured at each site over the 2-year period for which ecosystem C and N cycling were monitored. Since it is within the same physiographic province, the EPA/Cascade plots were grouped with data from the HJ Andrew site to comprise the mid-Cascade site.

Appendix B. Ecological Characteristics of Study Stands and Corresponding Landscape Units for Old-Growth Sites in the Pacific Northwest.

Table A.1. Ecological characteristics of study stands and corresponding landscape units for old-growth sites in the Pacific Northwest. Landscape units classifies the stands based on similar ecological characteristics and is used in regression analysis in Chapter 2.

Unit	Study Site	Location	Stand	Stand size (ha)	Lat. degrees N	Long. degrees W	Ele. (m)	Stand age (yrs)	Temp (C)	Ppt. (mm)	# of soil pits
1	Cascade Head	Cascade Head	CH01	0.4	45.046	123.897	305	150	8.3	2658	2
1	Cascade Head	Cascade Head	CH03	0.4	45.044	123.901	280	150	8.6	2660	2
1	Cascade Head	Cascade Head	CH12	0.4	45.049	123.898	280	150	8.5	2651	3
2	Cascade Head	Cascade Head	CH04	0.4	45.065	123.941	259	150	9.0	2554	2
2	Cascade Head	Cascade Head	CH05	0.4	45.065	123.942	259	150	9.0	2552	2
2	Cascade Head	Cascade Head	CH07	0.4	45.063	123.939	244	150	8.7	2559	2
2	Cascade Head	Cascade Head	CH08	0.4	45.065	123.944	271	150	9.0	2549	2
3	Cascade Head	Cascade Head	CH10	0.4	45.062	123.990	396	150	7.9	2417	2
4	Olympic Peninsula	S. Fork Hoh River	HR01	1.0	47.779	123.908	244	280	8.2	3669	2
4	Olympic Peninsula	S. Fork Hoh River	HR02	1.0	47.779	123.908	244	280	8.2	3669	2
4	Olympic Peninsula	S. Fork Hoh River	HR03	1.0	47.779	123.908	250	280	8.2	3669	2
4	Olympic Peninsula	S. Fork Hoh River	HR04	1.0	47.779	123.908	250	280	8.2	3669	2
5	Olympic Peninsula	Twin Creeks RNA	HS04	1.0	47.834	123.990	152	200	8.9	3026	2
6	Olympic Peninsula	Quinault RNA	HS02	1.0	47.429	123.873	122	230	8.9	2899	2
6	Olympic Peninsula	Quinault RNA	HS03	1.0	47.430	123.873	122	230	8.9	2893	2
7	Mt. Rainier NP	Nisqually River	AE10	1.0	46.768	121.742	1430	300	4.1	2812	1
7	Mt. Rainier NP	Nisqually River	AG05	1.0	46.748	121.803	950	700	6.1	2421	2
7	Mt. Rainier NP	Nisqually River	AV06	1.0	46.777	121.783	1060	750	6.0	2658	2
7	Mt. Rainier NP	Nisqually River	TO04	1.0	46.741	121.887	640	750	8.8	2166	2
8	Mt. Rainier NP	Ohanapecosh River	AO03	1.0	46.827	121.546	853	1000	6.6	2257	1
8	Mt. Rainier NP	Ohanapecosh River	AV02	1.0	46.823	121.551	841	1000	5.4	2249	1
9	Mt. Rainier NP	White River	AB08	1.0	46.919	121.538	1050	500	7.3	2076	2
10	Mt. Rainier NP	Carbon River	AV14	1.0	46.960	121.843	1080	1200	3.9	2500	2
10	Mt. Rainier NP	Carbon River	TO11	1.0	46.995	121.880	610	550	8.1	2112	2
11	Wind River	T.T. Munger RNA	MUNA	4.5	45.828	121.969	411	470	7.8	2496	8
12	Mid-Cascade	H.J. Andrews	RS01	1.0	44.202	122.257	510	460	11.4	1719	*
12	Mid-Cascade	H.J. Andrews	RS02	1.0	44.217	122.243	520	460	10.9	1868	*
12	Mid-Cascade	H.J. Andrews	RS07	0.3	44.213	122.148	490	460	5.8	2260	*
12	Mid-Cascade	H.J. Andrews	RS15	0.3	44.212	122.236	720	460	8.9	1906	*
12	Mid-Cascade	H.J. Andrews	RS16	0.3	44.214	122.241	670	460	10.3	1869	*
12	Mid-Cascade	H.J. Andrews	RS20	1.0	44.222	122.249	700	450	10.4	1859	1
13	Mid-Cascade	H.J. Andrews	RS12	0.3	44.227	122.122	1020	460	7.0	2332	*
13	Mid-Cascade	H.J. Andrews	RS23	1.0	44.227	122.123	1020	450	7.1	2340	2
13	Mid-Cascade	H.J. Andrews	RS29	1.0	44.231	122.146	800	450	8.0	2264	2
14	Mid-Cascade	H.J. Andrews	RS03	1.0	44.260	122.159	950	460	7.8	2202	*
14	Mid-Cascade	H.J. Andrews	RS10	0.3	44.233	122.217	610	460	10.1	2003	*
14	Mid-Cascade	H.J. Andrews	RS22	1.0	44.274	122.140	1290	450	3.8	2282	2
14	Mid-Cascade	H.J. Andrews	RS27	1.0	44.254	122.175	790	450	8.5	2118	2
14	Mid-Cascade	H.J. Andrews	RS31	1.0	44.262	122.181	900	450	8.1	2101	2
15	Mid-Cascade	EPA	EPA-Hi	0.6	44.383	122.167	1219	210	7.6	2040	2
16	Mid-Cascade	EPA	EPA-Lo	0.6	44.391	122.375	536	105	10.3	2010	2
17	Metolius	Metolius RNA	MRNA	4.5	44.488	121.631	933	300	8.1	355	4
18	Pringle Falls	Pringle Falls RNA	PF27	1.0	43.707	121.609	1353	400	5.7	545	2
18	Pringle Falls	Pringle Falls RNA	PF28	1.0	43.709	121.603	1372	400	5.6	539	2
18	Pringle Falls	Pringle Falls RNA	PF29	1.0	43.706	121.613	1353	500	5.8	549	2

*Soil pit data from Brown and Parsons (1972).

Appendix C. Dominant Vegetation at each Study Site

Table A.2. Dominant tree species occurring at each study site.

Study Site	Scientific Name	Common Name
Cascade Head	*Picea sitchensis*	Sitka spruce
	Tsuga heterophylla	western hemlock
Olympic Peninsula	*Picea sitchensis*	Sitka spruce
	Tsuga heterophylla	western hemlock
Mid-Cascade	*Pseudotsuga menziesii*	Douglas-fir
	Tsuga heterophylla	western hemlock
	Abies procera	noble fir
	Thuja plicata	wester redcedar
Wind River	*Pseudotsuga menziesii*	Douglas-fir
	Tsuga heterophylla	western hemlock
Mt. Rainier	*Abies amabilis*	Pacific silver fir
	Chamaecyparis nootkatensis	Alaska-cedar
	Thuja plicata	wester redcedar
	Pseudotsuga menziesii	Douglas-fir
	Tsuga heterophylla	western hemlock
Metolius	*Pinus ponderosa*	ponderosa pine
	Abies grandis	grand fir
Pringle Falls	*Pinus ponderosa*	ponderosa pine
	Pinus contorta	lodgepole pine

Table A.3. Dominant understory species occurring at each study site.

Study Site	Scientific Name	Common Name
Cascade Head	*Oxalis oregana*	Oregon oxalis
Olympic Peninsula	*Oxalis oregana*	Oregon oxalis
	Ceanothus velutinus	snowbrush ceanothus
Mid-cascade	*Berberis nervosa*	Oregongrape
	Cornus canadensis	bunchberry dogwood
	Holodiscus discolor	creambush oceanspray
	Linnaea borealis	twinflower
	Polystichum munitum	swordfern
	Rhododendron macrophyllum	Pacific rhododendron
	Vaccinium alaskaense	Alaska huckleberry
	Vaccinium membranaceum	big huckleberry
	Xerophyllum tenax	common beargrass
Mt. Rainier	*Berberis nervosa*	Oregongrape
	Erythronium montanum	avalanche fawnlily
	Gaultheria shallon	salal
	Oplopanax horrisum	devilsclub
	Rhododendron macrophyllum	Pacific rhododendron
	Vaccinium alaskaense	Alaska huckleberry
Wind River	*Rhododendron macrophyllum*	Pacific rhododendron
Metolius	*Purshia tridentata*	bitterbrush
	Stipa occidentalis	western needlegrass
Pringle Falls	*Ceanothus velutinus*	snowbrush ceanothus
	Purshia tridentata	bitterbrush

Appendix D. Calculation of Soil Organic Carbon and Nitrogen

Due to the actual fractions measured in the field and in the lab, the variables needed need to be calculated from other variables. Figure A.1 diagrams the methodology for estimating the ratio of mass of rock <75-mm to mass of C-bearing material. The capital letters in the boxes across the bottom of the diagram are the variables resulting from processing.

The following derivation of S_s, used in equation 4 (Chapter 2), attempts to explain how the calculations were performed. The derivation of equation 4 is summarized in equations 5-7. The total volume of any profile of a soil is:

$$S_s + S_r + S_R = 1 \quad (5)$$

where S_s is the soil volume of C-bearing fraction as a proportion of total volume, S_r is the <75-mm rock fraction as a proportion of total volume, S_R is the >75-mm rock fraction as a proportion of total volume.

Rearranging equation 5 to separate the >75-mm volume fraction as a proportion of total volume from the rest of the equation gives:

$$S_s + S_r = 1 - S_R \quad (6)$$

Dividing the left side of the equation by S_s

$$S_s\left(1 + \frac{S_r}{S_s}\right) = 1 - S_R \quad (7)$$

As mass of <75-mm and >75-mm fractions were measured, mass was divided by density to obtain volume:

$$S_s = \frac{1 - S_R}{1 + \frac{D_s}{D_r}\frac{M_r}{M_s}} \quad (4)$$

where D_s is the density of the carbon bearing component, D_r is the density of rock <75-mm, M_r is the mass of the rock <75-mm and M_s is the mass of the carbon bearing material.

The ratio of the mass of the rock <75-mm to the mass of the carbon bearing material, M_r/M_s, used in equation 4 is computed using the various soil and rock fractions established during sampling and processing. Equation 8 was used for non-rocky profiles that did not require field sieving.

$$\frac{M_r}{M_s} = \frac{M_{2-20}^{OD} + M_{20-75}^{OD}}{M_s^{OD}} \quad (8)$$

where M is the sample mass taken in the field, the superscript refers to the moisture level (OD is oven-dried at 105°C), and the subscript refers to the various soil and rock fractions established during sampling and processing.

Equation 9 was used for rocky profiles which were sieved in the field and subsampled. This equation partitions the <20-mm field subsample to C-bearing material and rock.

$$\frac{M_r}{M_s} = \frac{\frac{m_{2-20}^{OD}}{m_{<20}^{FM}} M_{<20}^{FM} + \frac{m_{20-75}^{OD}}{m_{20-75}^{FW}} M_{20-75}^{FM}}{\frac{m_s^{OD}}{m_{<20}^{FM}} M_{<20}^{FM}} \quad (9)$$

where m is the mass of the subsample brought back from the field and the superscript FM refers to its field-moist weight.

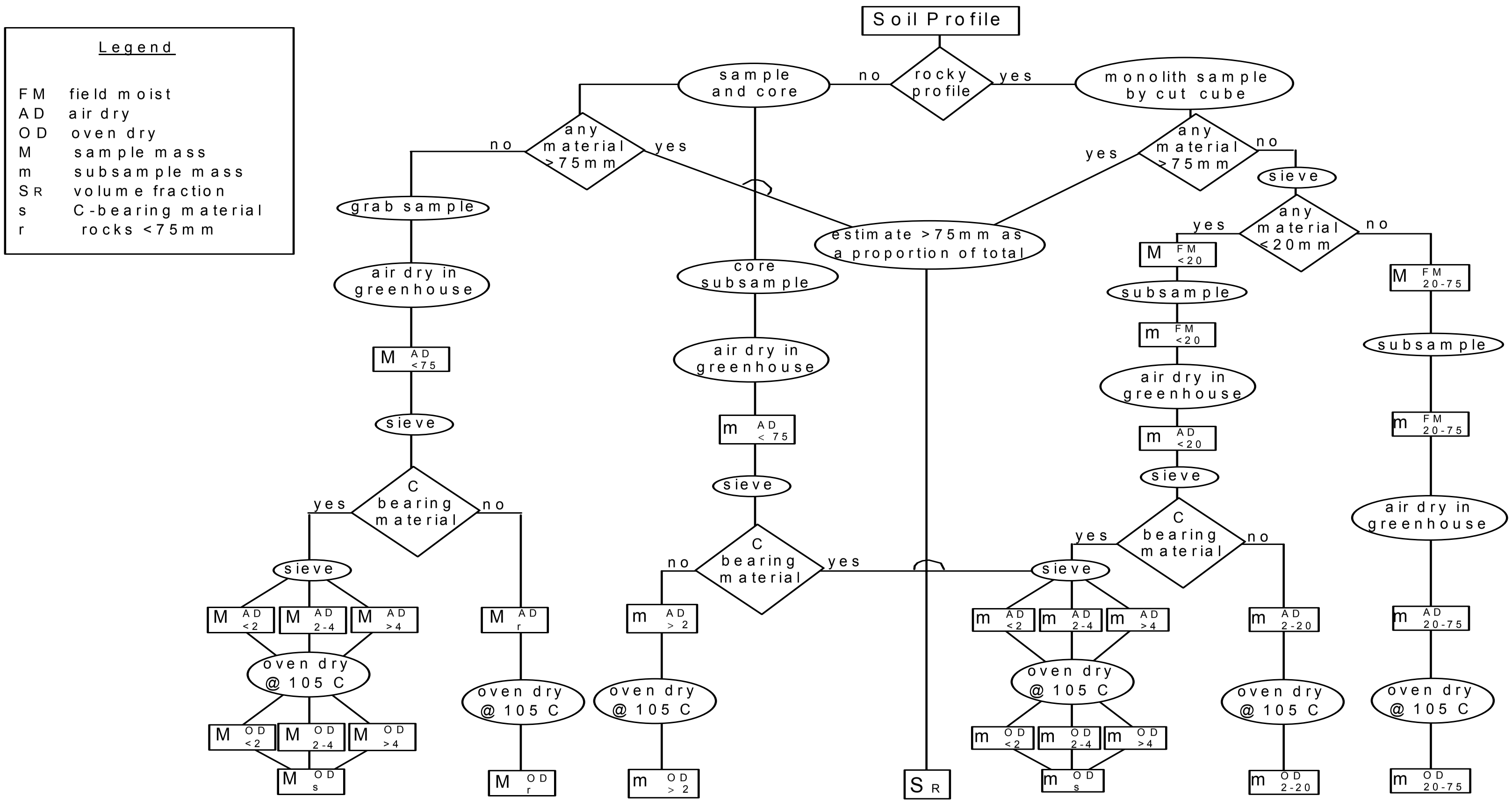

Figure A.1. Methodology for estimating the ratio of mass of rock <75-mm to mass of C-bearing material to use in the determination of soil volume.

Appendix E. Soil Data

Table A.4. Soil and forest floor C and N contents and C/N ratios by site in western Oregon and Washington.

		Mineral Soil to 1-meter depth			Forest Floor		
Site	n	C (kg m^2)	N (kg m^2)	C/N	C (kg m2)	N (kg m^2)	C/N
Cascade Head	17	35.5 (1.8)	1.9 (0.08)	18.7 (0.6)	4.9 (0.9)	0.14 (0.02)	35.3 (2.0)
Olympic Peninsula	14	19.1 (2.0)	1.3 (0.07)	14.5 (1.0)	1.4 (0.4)	0.5 (0.01)	27.2 (1.4)
Mt. Rainier	15	11.8 (1.0)	0.6 (0.07)	27.1 (1.9)	3.3 (0.6)	0.08 (0.01)	41.4 (2.6)
Wind River	8	11.6 (0.6)	0.5 (0.03)	22.3 (0.7)	2.6 (0.3)	0.05 (0.01)	49.2 (2.3)
Mid-Cascades	15	10.6 (1.6)	0.4 (0.07)	21.3 (1.5)	2.1 (0.5)	0.05 (0.01)	39.9 (1.7)
Metolius	4	5.7 (0.2)	0.3 (0.01)	18.0 (0.6)	1.5 (0.3)	0.04 (0.01)	40.6 (4.3)
Pringle Falls	6	2.9 (0.2)	0.2 (0.01)	18.9 (0.6)	1.1 (0.4)	0.03 (0.01)	36.6 (3.4)

Note: Values are means with standard errors given in parentheses.