RELATIONSHIPS BETWEEN ANDIC AND SPODIC SOIL PROPERTIES AND ASSOCIATED FOREST COMMUNITIES OF THE NORTHERN ROCKY MOUNTAINS

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AUTHORIZATION TO SUBMIT THESIS

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ABSTRACT

Andisols, Spodosols, and Spodic intergrades are the dominant soils in the steep, volcanic ash-mantled forested terrain of the Northern Rocky Mountain region. The objective of this study was to look at pH, exchangeable Al, and organic carbon distributions in these three soil types as well as the relationships between these soil types and the structure of the forest communities they support across 44 sites in northern Idaho. Results demonstrate that Andisols and Spodosols possess significantly different morphological and chemical properties, and support distinctly different forest communities. Eluvial E horizons of Spodosols exhibit the lowest pH values (3.2) and greatest concentrations of exchangeable Al (8.4 $\mathrm{cmol_c/kg}$) of all soils, while Andisols have significantly higher pH and lower concentrations of exchangeable Al. Spodic intergrades have chemical properties similar to Spodosols, but support an assemblage of tree species that is intermediate between those of the Spodosols and Andisols. Spodosols support a higher proportion of tree species indicative of relatively moister and cooler conditions – 87% of site basal area is occupied by western hemlock, western redcedar, Engelmann spruce, and subalpine fir. In contrast, Andisols support a higher proportion of species indicative of relatively drier environments, with 60% of the site basal area occupied by ponderosa pine, Douglas-fir, western larch, and grand fir. Spodosols and Spodic intergrades support greater total basal area than Andisols and contain significantly greater quantities of organic carbon to a depth of 50 cm. Analysis of the relationships between soil chemical properties and forest communities indicates that soils supporting spruce—subalpine fir forest types possess chemical characteristics representative of strongly podzolized Spodosols, while the soils supporting grand fir—Douglas-fir—western larch forest types have chemical properties similar to those of non-podzolized Andisols. In summary, this study illustrates a clear relationship between soil morphology, chemistry, and forest communities in the Northern Rocky Mountains. These results, in combination with the known geospatial distribution of Andisols, Spodic intergrades, and Spodosols, can be used to improve the efficiency and quality of soil mapping and land inventory efforts, which ultimately serve to inform forest management decisions in the Northern Rocky Mountain region.

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DEDICATION

This work is dedicated to my parents. Mom, Dad, thank you for supporting me throughout all of my endeavors. I wouldn’t be who or where I am today without you.

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CHAPTER 1: CHEMICAL PROPERTIES OF ANDIC AND SPODIC SOILS IN THE NORTHERN ROCKY MOUNTAINS

Introduction

Genesis and morphology of forest soils in the Northern Rocky Mountains has been greatly influenced by the presence of volcanic ash (McDaniel et al., 1993). Approximately 7600 years BP, the eruption of Mt. Mazama (now Crater Lake, OR) led to the deposition of up to a meter of volcanic ash in the region (Zdanowicz et al., 1999; McDaniel et al., 2005). Additionally, the 1800 AD eruption of Mount St. Helens (MSH) deposited a relatively thin (approximately 1-cm thick) layer of ash on top of the existing Mazama ash (Smith et al., 1968). The ash-mantled soils of the Northern Rocky Mountains have traditionally been classified as Andisols, however, in recent decades the presence of Spodosols in the region has been documented (McDaniel et al., 2005; McDaniel and Wilson, 2007; Valerio et al., 2016).

Spodosols are typically defined in Soil Taxonomy by the presence of a spodic horizon underlying an albic horizon (Soil Survey Staff, 2014). This horizon sequence develops as a result of podzolization, which is defined by the mobilization and eluviation of Fe and Al from surface horizons, and the subsequent immobilization of these metals in short-range-order complexes with organic matter in an illuvial horizon (Buol et al., 2011). Albic horizons are characterized by relatively light color due to the removal of clay and/or free iron (Soil Survey Staff, 2014). Spodic horizons are relatively darker, often have a reddish hue, and their classification is dependent on a variety of laboratory determinations including pH, organic C, and ammonium oxalate-extractable Al and Fe (Soil Survey Staff, 2014). The Spodosol requirements described here often translate to an E-Bhs sequence for the first two mineral horizons in a soil profile. Non-podzolized Andisols generally exhibit an A-Bw sequence for the first two mineral horizons.

Podzolization in andic soils has been widely documented in literature. Spodic soil characteristics have been found in tephra influenced soils in the Cascade Range of Washington (Dahlgren and Ugolini, 1991) as well as in Alaska (Ping et al., 1989), New Zealand (Parfitt and Saigusa, 1985), and Japan (Shoji et al., 1988). However, in the Northern Rocky Mountains, the unique sequence of the thin, light-colored Mount St. Helens (MSH) ash layer overlying the thicker, darker, reddish Mazama ash layer closely resembles the E-Bs sequence observed in spodic soils. Due to these similarities, differentiation between Andisols and Spodosols in the Northern Rocky Mountain region has proven difficult (Valerio et al., 2011). Additionally, the degree of podzolization is variable among soils in the study area. The likelihood of podzolization increases with increasing elevation and effective precipitation (Valerio et al., 2016). Soils at higher elevations and north-facing slopes are often strongly podzolized and classify as Spodosols, while soils at lower elevations and south-facing slopes are non-podzolized and classify as Andisols. Soils at intermediate elevations and various aspects often exhibit some degree of podzolization, however, either the albic or spodic horizons are not expressed well enough to meet taxonomic criteria for Spodosols. Many of these soils classify as Spodic intergrades of Andisols (Soil Survey Staff, 2014).

Because podzolization has occurred in volcanic ash parent material, there is considerable overlap between the mineralogical properties of Andisols and Spodosols in the Northern Rocky Mountain region (Shoji and Ito, 1990; McDaniel et al., 1993).

Andic soils have unique mineralogy, and as a result have predictable chemical characteristics such as high glass content, oxalate-extractable Al and Fe, and P retention (Soil Survey Staff, 2014). However, simply identifying andic properties is not sufficient in distinguishing Andisols from Spodosols. Instead, it is necessary to identify Spodosols using chemical and morphological properties that are indicative of podzolization.

An initial review of pedon data from recent studies examining the mineralogical and chemical properties of andic and spodic soils in the Northern Rocky Mountains (McDaniel et al., 1993;1995; 2005) indicates several chemical trends coincide with increasing podzolization. Podzolization is driven by water infiltration and the input of low molecular weight organic acids into the system (Schaetzl, 2002). Geospatial modeling of Spodosol distribution in northern Idaho demonstrates that Spodosols are more likely to occur at higher elevations and north-facing slopes where effective precipitation is greater (Valerio, 2011). Due to the greater effective precipitation, it is expected that podzolized soil horizons will exhibit relatively lower pH values (McDaniel et al., 1993). Consequently, exchangeable Al, which is highly soluble in low pH environments, (Sparks, 2003) is expected to be relatively high in these podzolized horizons. Lastly, thick continuous litter layers exist throughout the heavily forested ecosystem of the Northern Rocky Mountains, allowing for a constant input of organic C into the soil system. However, as soils become increasingly podzolized, the vertical distribution of organic C in soil profiles changes, with Spodosols exhibiting relatively higher quantities of organic C in subsurface horizons (Schaetzl, 2002; Alexander et al., 1993). To date, there have been no comprehensive studies comparing the total C densities in Andisols and Spodosols in the Northern Rocky Mountain region.

The overall objective of this study is to analyze soil pH, exchangeable Al, and organic C among Andisols, Spodic intergrades, and Spodosols in the Northern Rocky Mountains. Although many pedology studies conducted in the region in recent decades have included analysis of some of these properties, such studies have been limited to relatively small sample sizes and geographic scales. This study aims to examine numerous pedons throughout the region, representing a wide range of environmental, site, and soil morphological characteristics. Previous chemical analyses of these soil types have demonstrated distinct differences in chemical properties such as ammonium oxalate and Na pyrophosphate-extractable Al and Fe, and pH of surface horizons (McDaniel et al, 1993; Valerio et al., 2016). However, such studies have not examined relationships between these soil types and soil organic C, exchangeable Al, and pH in subsurface horizons. It is hypothesized that these chemical properties of Andisols, Spodic intergrades, and Spodosols will differ greatly. Specifically, it is suspected that Andisol properties will differ significantly from Spodosols, and that Spodic intergrades will have chemical characteristics, and as a result, soil quality and function more similar to Spodosols than non-podzolized Andisols. Results of this study will establish relationships between soil morphological properties, taxonomic classification, and predictable ranges of soil chemical properties. Such information can be used to improve the efficiency and interpretation of soil classification and mapping, as well as provide valuable baseline data to aid in making informed land use management decisions.

Materials and Methods

Study Area

Sites selected for use in this study are located in a 497,000-ha portion of the Idaho panhandle, in a region that is part of the Northern Rocky Mountains Major Land Resource Area (U.S. Dept. of Agriculture, 2006). Due to the vast extent of the study area, sample sites exhibit great variation in topography, elevation, and climate. Study sites range in elevation from 800 m to 1800 m, and precipitation ranges from approximately 46 cm to over 200 cm annually (Idaho Panhandle National Forests – GIS, 2002). Temperature and moisture regimes in the study area vary primarily as a function of elevation, and range from frigid to cryic, and xeric to udic, respectively (Valerio et al., 2016).

Conifers make up the dominant overstory vegetation, with western redcedar (*Thuja plicata* Donn ex D. Don), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), Douglas-fir (*Pseudotsuga menziesii* (Mrb.) Franco), western larch (*Larix occidentalis* Nutt.), grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) being the most abundant tree species present.

Volcanic eruptions of Mount Mazama and Mount St. Helens (MSH) have greatly influenced soil morphology in the region. The eruption of Mount Mazama resulted in the deposition of approximately half a meter of ash across the study area (McDaniel et al., 2005). The weathered Mazama ash is a reddish-brown color with a typical hue of 7.5YR (McDaniel and Hipple, 2010). Circa 1800 AD, an eruption of Mount St. Helens resulted in the deposition of approximately one cm of ash. This relatively young ash layer retains its unweathered light color and has been found to be a useful indicator of stable site conditions (McDaniel et al., 1993, 1994).

A more detailed description of the geology and physiography of the study area can be found in Valerio et al. (2016).

Sampling Design and Site Selection

The sampling sites used in this study are a sub-set of sites used in the Valerio (2011) study, which modeled the distribution of andic and spodic soils in the region. Previous research (e.g., McDaniel et al., 1993) has indicated that the occurrence of podzolized soils in the region is a function of elevation and aspect. Based on this, Valerio (2011) selected 72 sites, representative of the range of these two variables across the study area. As a result of this sampling scheme, a relatively equal number of non-podzolized sites, classified as Andisols; moderately podzolized sites, classified as Spodic intergrades; and highly podzolized sites, classified as Spodosols, were established.

In order to effectively examine the relationships between soil classification, soil chemical properties, and forest communities (see Chapter 2), sample sites were required to exhibit no evidence of substantive soil disturbance by human or natural causes, and forest vegetation was judged to be in a mature stage of succession. Generally, the presence of the MSH ash layer and a stand age of at least 75 years were required to meet site suitability criteria.

Field Methods

Sites in this study were originally sampled and described by Valerio (2011). Following an initial site inspection, Valerio excavated a soil pit (approximately 50 cm-by 50 cm-by 75 cm deep) and described and sampled horizons using standard methods (Schoeneberger et al., 2002). A detailed explanation of the methods and procedures used by Valerio to select and sample sites can be found in Valerio (2011) and Valerio et al., (2016).

For purposes of this study, several small excavations were initially examined at each site to determine the level of disturbance and to assess the variability in soil morphological properties. Five mature trees were randomly selected and increment bored to determine the approximate stand age. The litter layer was sampled at five randomly selected points on the site by cutting and removing 15 cm-by-15 cm squares of the organic layer down to the contact with mineral soil. The thickness of the litter layer was measured at each sampling location in order to obtain the volume of each sample collected. Both mineral and organic samples were originally stored in re-sealable plastic bags and then transported to the University of Idaho Pedology Laboratory where the samples were allowed to air dry before undergoing further laboratory analysis.

Laboratory Analysis

Air-dried samples were gently crushed and sieved through a 2-mm mesh screen. The following methods were used to determine the chemical properties of the sampled pedons: Soil pH for mineral soil samples was measured using a 1:1 soil-to-water ratio.

In order to achieve saturation, pH for the litter layer (O horizon) samples was measured using a 1:3 soil-to-water ratio. All pH measurements were made using an electronic pH meter with a gel electrode. Exchangeable Al was measured using the KCl extraction method (Soil Survey Staff, 2014). Extracts were analyzed using a Thermo Electron Corporation iCAP 6000 Series inductively coupled plasma spectrometer. Total organic C was determined via dry combustion using a Vario MAX CNS analyzer (Elementar Americas, Inc.). In order to determine the amount of C per horizon, bulk density values for volcanic ash horizons were assumed to be 0.9 g/cm^3, and bulk density values for underlying mineral horizons were assumed to be 1.3 g/cm^3. These values were based on laboratory data for similar pedons analyzed in the study area (National Cooperative Soil Survey, 2016). All organic samples were dried at 60 degrees C for 48 hours and then weighed. The dry weights were divided by the sample volume as measured in the field to determine bulk density. The mean of the five organic horizon bulk densities was used to calculate C density of the litter layer. Due to sampling difficulties attributed to high rock fragment contents in the subsoil of many pedons, many soils were not sampled at depths much beyond 50-75 cm. Therefore, to allow for uniform comparisons, total C densities were calculated for the top 50 cm of each pedon.

Statistical Analysis

Statistical analyses were conducted using GraphPad Prism 7.0a software. Analysis of chemical properties consisted of ANOVA to determine whether or not significant differences existed among means. Upon confirmation of significant differences, Fisher LSD multiple comparisons were then conducted. Comparisons were made between like horizons of different soil types, as well as between sequential horizons within each soil type. Due to the inherent variability associated with field-based sampling across a large study area, all analysis was performed at the 0.10 alpha level.

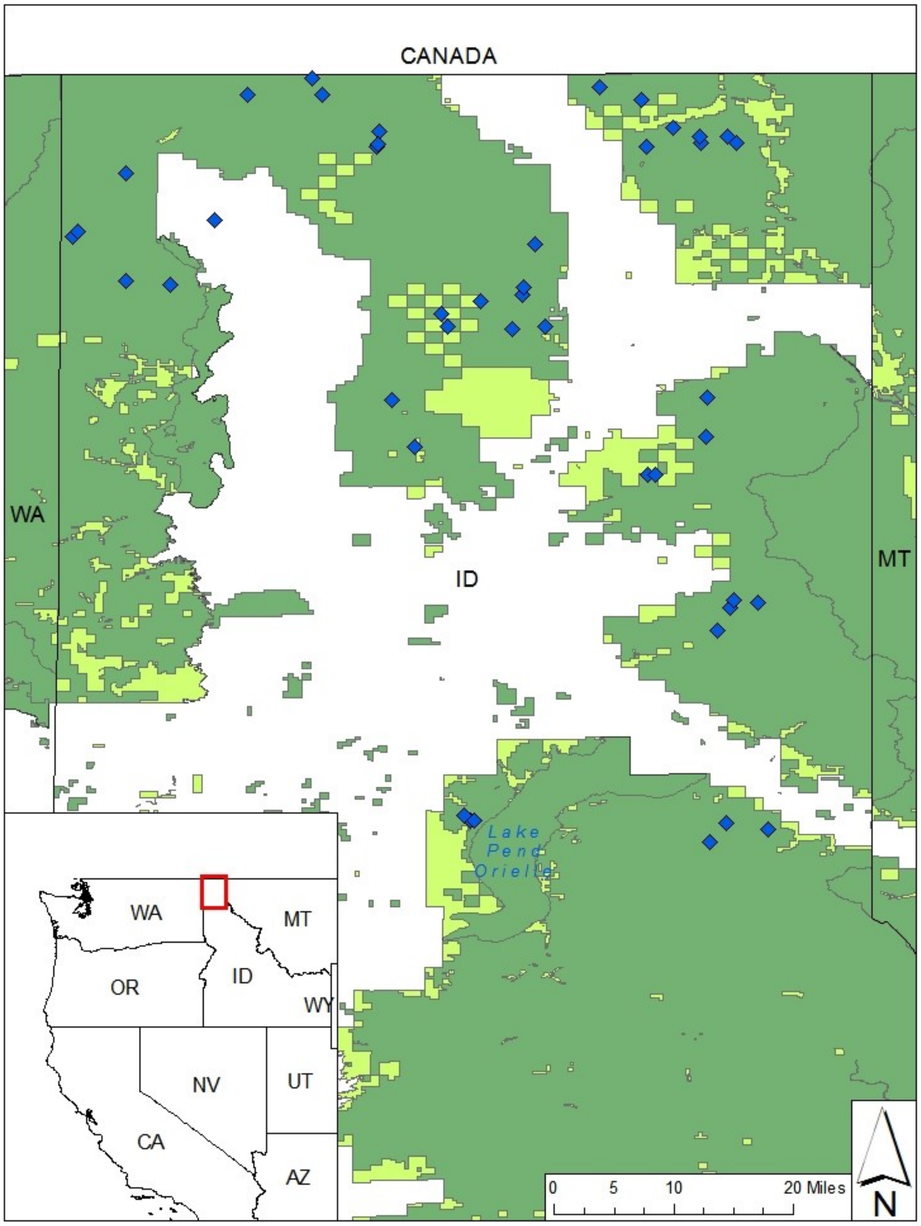

Figure 1.1. Map representing the geographical extent of sampled pedons. Study area consists of National Forest land (dark green) and other forested land (light green). Sample sites are indicated by blue diamonds.

Results and Discussion

pH

Analyses of soil pH between comparable horizons of the three different soil types as well as sequential horizons within each soil type yield noticeable trends (Figure 1.2; Appendix A). Due to the relatively high content of organic acids present in forest litter, as well as the acidic products of organic matter decomposition (Finzi et al., 1998), it was expected that the pH values of the litter layer would be relatively lower than a typical mineral soil horizon. The mean pH of the Andisol organic horizons is 4.8, and is significantly lower than each of the Andisol mineral horizons. The mean pH of the organic horizons of the Spodic intergrades and Spodosols is 4.4 and 4.3, respectively. Both the intergrade and Spodosol organic horizon pH values are significantly lower than that of the Andisols, yet not significantly different from each other. This could be attributed to the increased effective precipitation and leaching associated with the intergrade and Spodosol sites, as well as the variation in litter composition associated with the plant communities unique to each soil type (see Chapter 2).

Andisols in the study area have the highest pH values for all horizons sampled. The three uppermost mineral horizons have mean pH values of 5.1, 5.0 and 5.0, respectively (Figure 1.2). There is no significant difference in mean pH value among these horizons. The relatively consistent pH values throughout the Andisol profiles may be indicative of the lack of eluviation and illuviation, suggesting the non-podzolized nature of these soils.

Mean pH values of comparative mineral horizons between taxonomic Spodosols and Spodic intergrades are very similar, and are both significantly lower than the mean pH values of comparative horizons in Andisols (Figure 1.2). The top three Spodosol mineral horizons have mean pH values of 4.0, 4.5, and 4.8, respectively. Mean pH values of the top three mineral horizons of the Spodic intergrades are 4.2, 4.5, and 4.7, respectively. There are no significant differences in pH between the Spodosol and Spodic intergrade mineral horizons. However, both are significantly lower than the mean pH values of comparable horizons in Andisols (Figure 1.2; Appendix A). This suggests that soil chemistry can be significantly altered by a relatively low degree of podzolization, such as seen in the Spodic intergrades.

Spodosols and Spodic intergrades also exhibit changes in pH within each of their respective profiles. Perhaps the most noticeable characteristic of podzolized soils in this study is the extremely low pH of the surface mineral horizon (usually an E horizon). The mean pH value of the E horizon in Spodosols is significantly lower than the mean pH values of all other mineral horizons within the Spodosol classification. Meanwhile, the mean pH value of the surface mineral horizon of Spodic intergrades is noticeably lower than that of the other mineral horizons within the Spodic intergrade class, but the difference is not statistically significant.

There appears to be a strong relationship between pH of the surface mineral horizon and degree of podzolization in the study area. Podzolization is more likely to occur on sites with greater effective precipitation, which can be attributed to the drop in pH of eluvial horizons (McDaniel et al., 1995). Therefore, soils experiencing a more intense degree of podzolization have relatively lower pH surface mineral horizons. Although summary data support this trend, it is perhaps most evident upon comparing data from a representative pedon of each of the three soil types in this study (Table

2.1). Data for Pedon 8, an Andisol, Pedon 175, a Spodic intergrade, and Pedon 85, a Spodosol, clearly demonstrate the effects podzolization has on soil profile development and chemistry. In addition to the horizon names and taxonomic classification being provided, increasing E horizon lightness and thickness as well as development of spodic horizons in the subsoil indicate increasing podzolization. These trends are also supported by distributions of extractable Al and Fe (Valerio et al., 2016) (Table 2.1). Pedon 8 exhibits no morphological evidence of podzolization, and contains very similar and relatively high pH values of 5.2 and 4.9 for the first two mineral horizons, respectively. Pedon 175 exhibits an intermediate degree of podzolization, possessing a relatively darker E horizon overlying a Bs horizon. The surface mineral horizon pH of this moderately podzolized soil is 4.4, which is much lower than that of the Andisol surface mineral horizon pH but not nearly as low as the E horizon of pedon 85. Pedon 85 exhibits evidence of intense podzolization, possessing a thick light-colored E horizon overlying a well-expressed Bhs horizon, with pH values of the 3.1 and 3.8 for the first two mineral horizons, respectively. Many strongly podzolized pedons sampled in this study possess similar surface mineral horizon characteristics. It is suggested that these mineral horizons have sufficiently low pH to potentially affect microbial community composition, nutrient availability, plant growth, and species composition on these sites.

In contrast to the pedogenic processes affecting surface mineral horizons, it is worth noting that the three soil types do not have significantly different pH values in the third mineral horizon sampled. A likely reason for this is that the depth of these horizons is sufficiently deep to be below that which is affected by podzolization. As a result, the Spodosols and Spodic intergrades have mean pH values in their deeper horizons that are similar to those of the non-podzolized Andisols.

Table 1.1. Horizon data from a representative pedon within each of the three soil types in this study.

Horizon	Depth (cm)	Dry Color	Moist Color	Al + 0.5Fe (%)	pH	KCl Al (cmol$_c$/kg)	Organic C (%)
			Pedon 8 - Andisol - C density: 141 Mg/ha				
Oe	0-3	-	-	-	5.1	0.08	43.0
A	3-6	10YR 4/2	10YR 3/1	1.01	5.2	0.04	11.4
BA	6-15	10YR 5/3	7.5YR 3/2	1.68	4.9	0.15	3.7
Bw1	15-28	10YR 5/4	7.5YR 3/2	2.00	4.9	0.15	2.7
Bw2	28-48	10YR 5/4	7.5YR 3/4	1.51	4.8	0.22	1.6
2BC	48-52+	2.5Y 6/3	2.5Y 5/3	0.16	4.7	0.30	0.3
			Pedon 175 - Spodic intergrade - C density: 195 Mg/ha				
Oe	0-2	-	-	-	4.5	0.39	44.3
E	2-5	10 YR 4/2	10YR 3/1	0.78	4.4	2.01	9.8
Bs	5-20	10YR 4/3	7.5YR 2.5/2	2.11	4.9	1.27	5.2
Bw	20-43	10YR 5/4	10YR 4/4	3.00	5.1	0.45	3.4
2BC	43-61+	10YR 5/4	10YR 4/4	2.18	5.2	0.12	1.2
			Pedon 85 - Spodosol - C density: 205 Mg/ha				
Oe	0-7	-	-	-	4.0	0.57	43.3
E	7-14	10 YR 6/2	10YR 3/1	0.24	3.1	5.27	5.4
Bhs	14-21	10YR 4/3	7.5YR 2.5/2	3.20	3.8	6.10	10.5
Bw1	21-31	10YR 5/3	10YR 3/2	1.51	4.1	1.18	2.3
Bw2	31-42	10YR 5/3	10YR 3/3	1.21	4.2	1.16	1.9
2BC	42-70+	10YR 5/3	10YR 3/2	0.83	4.2	1.10	2.2

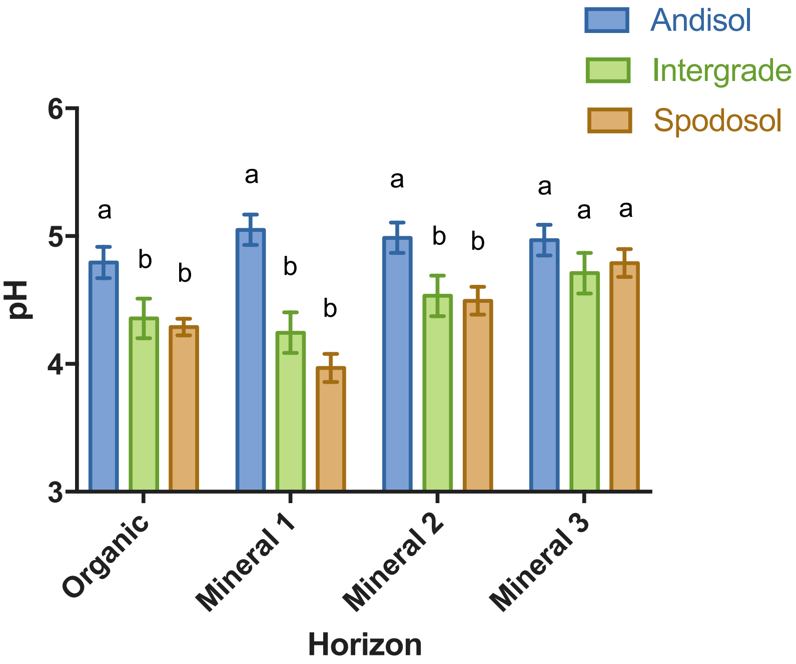

Figure 1.2. Bar graph representing the mean pH for the litter layer (1:3 soil-to-water) and three uppermost mineral horizons (1:1 soil-to-water) of each of the three soil types in this study. Error bars represent standard error. Within each horizon, values with the same letters do not differ significantly at the 0.10 alpha level.

Exchangeable Al

Analysis of exchangeable (KCl-extractable) Al in the organic and three uppermost mineral horizons of Andisols, Spodic intergrades, and Spodosols shows trends similar to those observed with pH (Figure 1.3; Appendix A). Mean KCl Al concentrations in the litter layer progressively increase from 0.21 to 0.53 to 0.67 $cmol_c$/kg in Andisols, Spodic intergrades, and Spodosols, respectively. Although these increases are not significant at the 0.10 alpha level, the trend is apparent (see Appendix A), and suggests that podzolized soils in the Northern Rocky Mountain region may support vegetation communities that take up and cycle relatively larger quantities of Al the soil-plant system. Further discussion of KCl Al in these soils and their associated plant communities can be found in Chapter 2.

Exchangeable Al concentrations of the uppermost three mineral horizons of Spodic intergrades and Spodosols are very similar to each other, and are significantly higher than comparative horizons in Andisols. Andisols exhibit mean KCl Al concentrations of 0.25, 0.32, and 0.32 $cmol_c$/kg in their top three mineral horizons, respectively. The top three Spodosol mineral horizons have mean KCl Al concentrations of 2.5, 1.8, and 1.0 $cmol_c$/kg, respectively, while the mean KCl Al concentrations of the uppermost three Spodic intergrade horizons are 2.6, 1.4, and 0.67 $cmol_c$/kg, respectively. There are no significant differences between the mean KCl Al concentrations of comparative Spodic intergrade and Spodosol mineral horizons. However, the mean KCl Al concentration in the first two mineral horizons of Spodosols and Spodic intergrades is significantly higher than the KCl Al concentration in the first two mineral horizons of Andisols (Figure 1.3). Lastly, the mean KCl Al concentration of the third mineral horizon is also noticeably higher in the two podzolized soil types relative to the Andisols, however, the difference is not statistically significant. The strong resemblance between the mean KCl Al concentrations in the mineral horizons of Spodic intergrades and Spodosols again suggests that soil chemistry can be greatly altered by podzolization, regardless of the intensity.

As with soil pH, Spodosols and Spodic intergrades also exhibit substantial changes in exchangeable Al concentrations with depth (Figure 1.3; Appendix A). Perhaps the most notable aspect of the KCl Al analysis is the spike in exchangeable Al in surface mineral horizons (E horizons) relative to underlying horizons in podzolized soils (Figure 1.3). A plausible explanation for this can be derived from breaking down some of the component processes that together constitute podzolization. When podzolization occurs, secondary Fe and Al complex with organic acids produced by the decomposition of materials from the litter layer. Precipitation and percolation then cause these organo-metallic complexes to eluviate downward in the soil profile, where they eventually accumulate in an illuvial (Bs, or Bhs) horizon (Buol et al., 2011). Organic acids can also leach into subsurface horizons independently, where they then complex with Fe and Al already present in the subsoil (Schaetzl, 2002). The Al in the system that is available to form organo-metallic complexes is considered to be exchangeable Al (Sparks, 2003). In addition, Al complexed with organic matter has been shown to control soil solution Al in organic and surface mineral horizons in forest soils (Bertsch and Bloom, 1996). However, since KCl is ineffective at extracting Al that is bound to organic compounds (Hargrove and Thomas, 1981; Sposito, 1995), the measured KCl-extractable Al in a horizon is representative of only the Al that has not complexed with organic matter. Eluvial E horizons in spodic soils have been shown to contain very low amounts of organically associated Al, but illuvial Bs/Bhs horizons have been shown to contain very high amounts of organically complexed Al (McDaniel et al., 1995; Schaetzl, 2002; Valerio et al., 2016). Because eluvial horizons contain little organically associated Al, a very high proportion of the Al existing in these horizons is KCl extractable, resulting in high total concentrations of exchangeable Al being measured. However, the proportion of organically complexed Al in illuvial Bs/Bhs horizons is very high. Thus, it seems likely that the KCl Al values reported here may underestimate the pool of exchangeable Al present in these soils, especially in illuvial horizons

As with soil pH, there appears to be a strong relationship between the KCl Al of the surface mineral horizon and the degree of podzolization across the study area. Soils experiencing a more intense degree of podzolization have relatively higher concentrations of exchangeable Al in surface mineral horizons. Data from a representative pedon of each of the three soil types in this study further illustrates this trend (Table 2.1). These pedons demonstrate the progressive increase in exchangeable Al coinciding with increasing podzolization. Pedon 8, an Andisol, exhibits no evidence of podzolization and contains negligible KCl-extractable Al concentrations of 0.04 and 0.15 $cmol_c/kg$ in the first two mineral horizons, respectively. Pedon 175, a Spodic intergrade, shows an intermediate degree of podzolization and contains 2.01 and 1.27 $cmol_c/kg$ in the E and Bs horizons. Lastly, Pedon 85, which is one of the most intensely podzolized soils sampled in this study, contains 5.27 and 6.10 $cmol_c/kg$ of KCl-extractable Al in the E and Bs horizons. Although the mean KCl Al concentration of Spodosol Bhs/Bs horizons is significantly lower than that of their E horizons, some individual pedons, such as pedon 85, exhibit extremely high KCl Al values in multiple horizons in the upper part of their profiles. Spodosol surface mineral horizons contain the highest concentrations of KCl Al in this study, with the highest concentration measured being 8.4 $cmol_c$/kg (see Valerio et al., 2016). While Al toxicity has not been extensively studied in north Idaho forest systems, exchangeable Al concentrations ranging from 3.5 to 8.1 $cmol_c$/kg have been shown to be of high risk of Al toxicity in forest systems in Northern Spain (Alvarez et al., 2005). Also, exchangeable Al concentrations of approximately 3 $cmol_c$/kg have proven to significantly inhibit growth in agricultural systems (Farina et al., 1980; Ahlrichs et al., 1990). Therefore, it seems very reasonable that the KCl Al concentrations in these podzolized soils may adversely affect biological activity in the Northern Rocky Mountains.

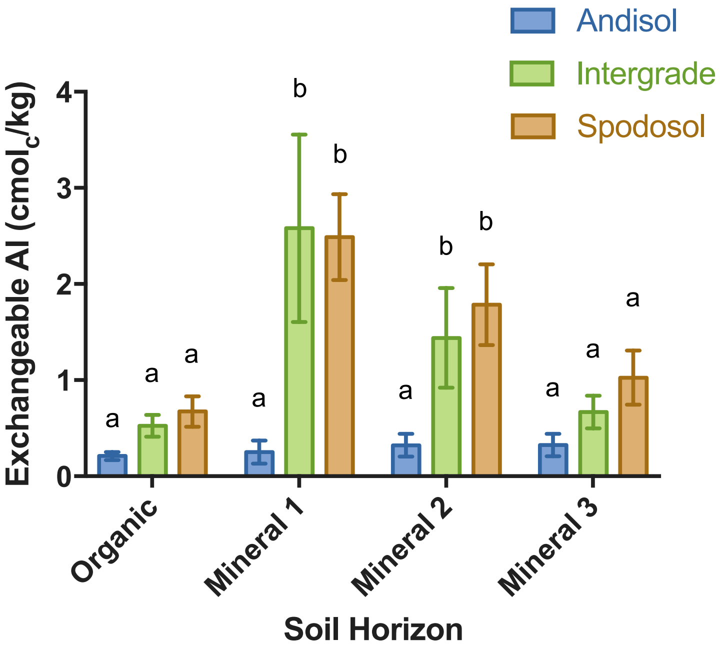

Figure 1.3. Bar graph representing the mean KCl extractable Al concentrations for the organic horizon and three uppermost mineral horizons of each of the three soil types in this study. Error bars represent standard error. Within each horizon, values with the same letters do not differ significantly at the 0.10 alpha level.

Exchangeable Al and pH Relationships

pH and exchangeable Al appear to follow consistent trends as the degree of podzolization increases. It is extensively reported in literature that soil pH and exchangeable Al have a strong inverse relationship (Ross and Barlett, 1996; Sparks, 2003). Statistical analysis of surface mineral horizon pH and KCl Al confirms a significant negative correlation between these variables in Andisols ($p=0.001$), Spodic intergrades ($p=0.042$), and Spodosols ($p=0.001$) within the study area (Figure 1.4).

Podzolized soils have been shown to have low pH values and high concentrations of exchangeable Al. Although the various physical and chemical processes driving podzolization may affect each of these chemical properties independently, it is likely that they influence each other as well. Exchangeable Al is most prevalent in the form of the monomeric hexa-aqua ion, $[Al(H_2O)_6]^{3+}$ (Sparks, 2003). In the presence of water, this ion can undergo the following hydrolysis reaction (Sparks, 2003):

$$[Al(H_2O)_6]^{3+} + H_2O \leftrightarrow [Al(OH)(H_2O)_5]^{2+} + H_3O^+$$

The result of this reaction is the production of a hydronium ion, which increases soil acidity. This process demonstrates the potential for exchangeable Al to decrease soil pH. Exchangeable Al is also more readily available to the soil solution in low pH environments (Sposito, 1995; 2008; Sparks, 2003).

It is suspected that surface horizons of podzolized soils experience a positive feedback cycle, triggered by the initial effects of podzolization decreasing soil pH, and consequently increasing exchangeable Al in the soil solution. The exchangeable Al ions in solution can then hydrolyze, resulting in the further reduction of soil pH. The perpetual interaction between these two variables would result in a continuous decrease in soil pH and increase in exchangeable Al. It is expected that this reaction would eventually reach a leveling-off point, however, further research would be required to determine what that point is, and what geochemical and environmental factors are responsible. Regardless of whether or not highly podzolized soils in this study have reached such a point, the current pH and exchangeable Al values in these soils prompt concerns of Al toxicity and nutrient deficiencies associated with low pH.

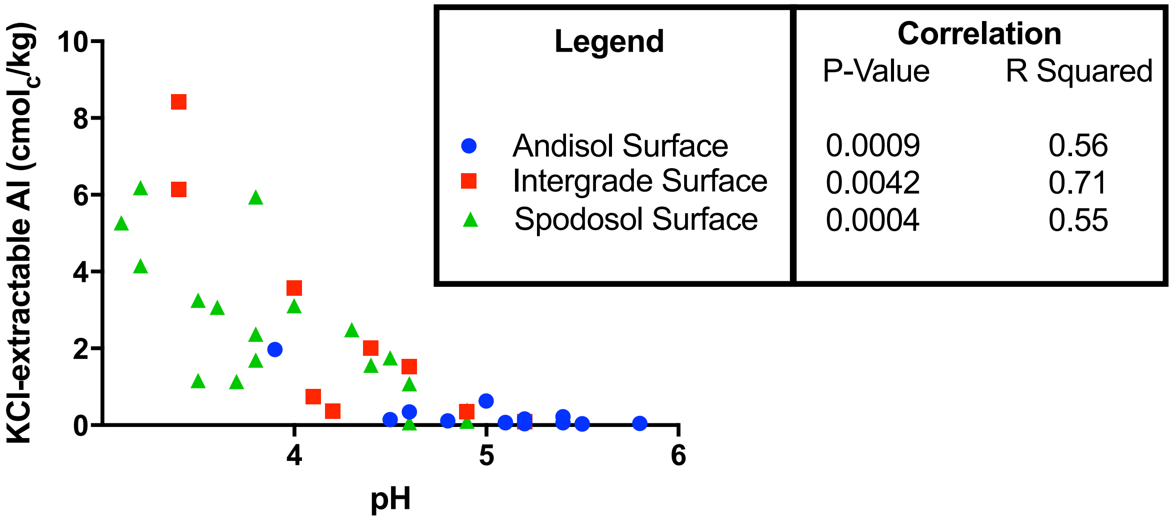

Figure 1.4. Plot of pH vs. KCl Al for the surface mineral horizons of pedons sampled in this study. Statistical correlation was performed using the Pearson correlation coefficient method in Graphpad Prism 7.0a.

Carbon Distribution

The geographical and climatic factors responsible for podzolization are hypothesized to have an effect on the total amount and distribution of organic C in Andisols, Spodic intergrades, and Spodosols in the study area. Numerous pedons from several studies analyzing organic C distributions in Spodosols exhibit significantly less organic C in eluvial horizons relative to both underlying Bs and Bhs horizons as well as horizons of other soil types (Stone et al., 1993; Schaetzl, 2002; Vejre et al., 2002). This trend is largely attributed to the relatively high infiltration, and consequent leaching required for albic horizon development. Because of this, it was predicted that the Spodosol and Spodic intergrade surface horizons in this study would exhibit similar trends.

However, analysis of the organic C content in the surface mineral horizons of the three soil types yielded somewhat unexpected results. Both the Andisols and Spodosols contain the same amount (5.3%) of organic C in their surface mineral horizons, while the mean organic C percentage in the surface mineral horizons of Spodic intergrades is significantly higher (9.7%) (Figure 1.5). The high organic C content found in the surface mineral horizons of the Spodic intergrades may be a result of the increased effective precipitation indicative of podzolized sites, and the relatively warmer temperatures compared to the higher-elevation Spodosol sites. These conditions would increase microbial decomposition rates in these soils (Edmonds, 1991; Prescott et al., 2004) and potentially maximize the incorporation of soluble organic materials derived from the litter layer into the mineral soil. However, further research would be required to substantiate this hypothesis. Although the mean organic C content of Spodosol and

Spodic intergrade surface horizons is higher than expected, the mean organic C content of the Andisol surface horizons is comparable to that of other ash-influenced forest soils in the Pacific Northwest (Totman et al., 2014; National Cooperative Soil Survey, 2016).

Analysis of the organic C content of subsurface mineral horizons yields more expected results. Organic C decreases to 1.8% and 1.1% in the second and third mineral horizons of Andisols, respectively (Figure 1.5; Appendix A). The decrease of organic C in the Andisol subsurface horizons is likely attributed to the lack of illuviation of organo-metallic complexes in these andic soils (Valerio et al, 2016). Statistical analysis of the organic C content in subsurface horizons of the three soil types yields no significant differences. However, the mean organic C content in both the second and third mineral horizons of Spodic intergrades and Spodosols is noticeable higher than that of the second and third mineral horizons of Andisols. This is most likely attributed to the accumulation of organo-metallic complexes in the subsurface (Bs and Bhs) horizons of podzolized soils (Valerio et al., 2016).

Lastly, the mean organic C content of the litter layers is 42.3%, 41.6%, and 40.4% for the Andisols, intergrades, and Spodosols, respectively. These values reflect the organic nature of the litter layers, and do not differ significantly among any of the three soil types (Figure 1.5; Appendix A).

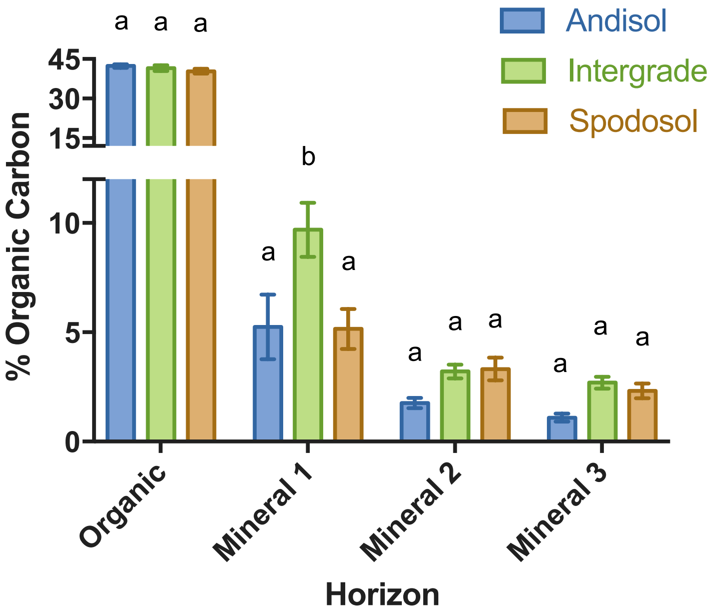

Figure 1.5. Bar graph representing mean percent organic C, as determined via dry combustion, for the organic horizon and three uppermost mineral horizons of Andisols, Spodic intergrades, and Spodosols. Error bars represent standard error. Within each horizon, values with the same letters do not differ significantly at the 0.10 alpha level.

Carbon Density

In addition to analysis of the proportional organic C content by horizon, the mean total C density was also calculated for the top 50 cm of each of the three soil types in this study (Figure 1.6). On average, the top 50 cm of Andisols in the study area contain the least amount of total C per hectare (99.3 Mg/ha), of which 30.7 Mg/ha is contained in the litter layer (Figure 1.6). Andisols have the highest proportion (30.9%) of C stored in the litter layer and the least amount of C stored in the mineral soil. This further suggests that the relatively drier site conditions associated with Andisols may reduce microbial decomposition of organic material and the translocation of soluble organics into the mineral soil.

Spodic intergrades have the highest average C density (145.1 Mg/ha), of which 30.4 Mg/ha is in the litter layer (Figure 1.6). Compared to Andisols, Spodic intergrades have approximately the same total amount of C stored in the litter layer, however, the total amount of C in the top 50 cm is significantly higher. Lastly, the mean C density of the top 50 cm of Spodosols in the study area is 121.2 Mg/ha, of which 35.7 Mg/ha is contained in the litter layer. The total amount of C in the organic layer of Spodosols is approximately the same as the Andisols and the intergrades (no significant difference at the 0.10 alpha level), and the C density of the mineral component is intermediate to that of the other two soil types. Although the difference is not significant, a possible explanation for the lower C density in Spodosols relative to Spodic intergrades is that the more intensive podzolization occurring in Spodosols causes organic C in the form of organo-metallic complexes to be translocated to depths beyond 50 cm. This hypothesis is supported by pedon data which demonstrate that Spodosols have the potential to contain considerable concentrations of organic C (as much as 9.3%) in horizons deeper than 50 cm (Appendix B). However, due to high amounts of large rock fragments in the subsoil of many pedons, sampling depth was often limited to approximately 50-75 cm (Appendix B). In order to objectively compare C densities between soil types, C density was only calculated for the uppermost 50 cm of each pedon. Because any organic C in horizons deeper than 50 cm was not included in the computation of C density, the values reported in this study may underestimate the C densities of these soils.

In recent decades numerous soil C studies have been conducted in the Pacific Northwest as well as in other regions with similar climates and forest vegetation communities. A broad-scale study of coniferous forest soils in the western United States reported soil C density values ranging from 94 to 143 Mg/ha (Turner et al., 1995). Additionally, a Danish study, consisting of 28 Spodosol pedons under coniferous forest, reported a mean C density of 146 Mg/ha (Vejre et al., 2001). The range of C density values reported in these two studies closely resembles the C density values of the Andisols, Spodic intergrades, and Spodosols (99, 145, and 121 Mg/ha, respectively) analyzed in this study. Lastly, a soil carbon study in Mt. Rainier National Park, which included several Andisol and Spodosol pedons, reported an average C density of 163 Mg/ha (Totman et al., 2014). Although this value is somewhat higher than the C densities of the Andisols, Spodic intergrades, and Spodosols in this study, the difference could likely be attributed differences in land use management. Due to the National Park Service's "preservation" style of management, forest stands in the Mt. Rainier study are all 100 to 300+ years old (Totman et al., 2014). The sites used in this study are located on National Forest land, and due to historical logging practices, are typically between

75 and 100 years old. Logging and other land use management practices resulting in the removal of vegetation have been shown to significantly reduce soil C density (Harrison et al., 1995). In addition to the relationships between soil C density, soil classification, and land use management, there appears to be a strong correlation between soil C density and forest vegetation composition as well. These relationships will be discussed further in Chapter 2.

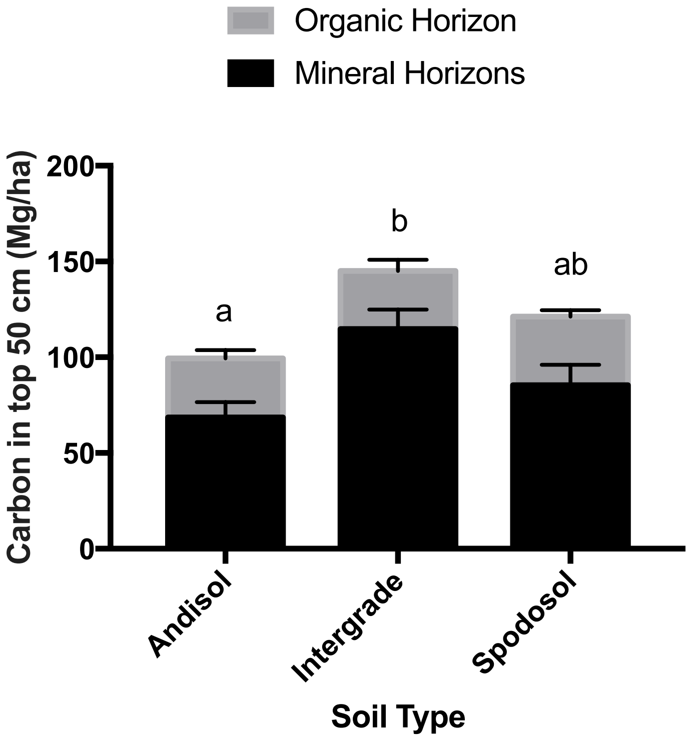

Figure 1.6. Bar graph representing the mean total soil C densities of Andisols, Spodic intergrades, and Spodosols. Different letters indicate significant differences in total C density (alpha=0.10). There are no significant differences between C densities of organic horizons.

Summary

The objective of this study was to analyze soil pH, exchangeable Al, and the distribution of organic C in Andisols, Spodic intergrades, and Spodosols existing on forested landscapes in the Northern Rocky Mountains. Results indicate several trends that coincide with increasing podzolization. Non-podzolized Andisols in the study area exhibit uniform and significantly higher pH values and minimal quantities of exchangeable Al throughout their profiles. Conversely, moderately podzolized Spodic intergrades and highly podzolized Spodosols exhibit significantly lower pH values and possess greater quantities of exchangeable Al, especially in their litter layers and surface mineral horizons. Soil pH and exchangeable Al are shown to have a strong inverse relationship among all soil types analyzed in this study. Soil organic C densities in the top 50 cm are greatest in Spodic intergrades and Spodosols. Podzolized soils also contain greater quantities of organic C in their sub-surface horizons relative to Andisols. Most notably, the exchangeable Al, pH, and organic C characteristics of Spodic intergrades and Spodosols are very similar and, although Spodic intergrades technically are classified as Andisols, it is suggested that they be treated as Spodosols for the purposes of mapping and land use management decisions.

Although the results of this study help expand the knowledge pool about Andic and Spodic forest soils, some topics warrant further research. Future studies targeting the relationships between exchangeable Al in foliage, litter, and mineral soil could yield an explanation for the elevated exchangeable Al concentrations found in podzolized soils. Additionally, a study specifically concerning Al toxicity and tolerance of important tree species in these systems could prove valuable to foresters and silviculturists.

Lastly, a comprehensive C study to include both aboveground biomass and soil C in deep horizons could provide valuable knowledge regarding the C sequestration potential of these soil types and their associated vegetation communities.

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CHAPTER 2: RELATIONSHIPS BETWEEN SOIL MORPHOLOGY, CHEMISTRY, AND VEGETATION COMMUNITIES IN THE NORTHERN ROCKY MOUNTAINS

Introduction

Soil scientists and plant ecologists frequently observe relationships between soils and their associated vegetation communities. Jenny (1941) famously introduced the concept of climate, parent material, topography, biota, and time as being the five factors responsible for soil development. Major (1951), elaborated on this, concluding that climax vegetation communities are also a function of these same five factors. Thus, the development of both soils and climax vegetation communities are functions of the same environmental variables and are thought to be concomitant (Houston, 1988). Considerable efforts have been made to identify and quantify the relationships between soils and vegetation communities in various ecological systems in the western United States (Daubenmire 1970; Hironaka et al., 1983; Cooper et al., 1991, Nesser et al., 1997). In order to effectively investigate these relationships, both forest vegetation communities and soil properties must be characterized in a manner that is applicable to an ecosystem scale.

Forest vegetation communities in the western United States are most commonly characterized using a habitat typing system (Cooper et al., 1991). The concept of habitat types was first developed by Daubenmire (1952), and numerous habitat type keys have since been developed for various ecosystems in the western United States. The habitat typing system relevant to this study was developed by Cooper et al. (1991).

A habitat type is defined as a land area potentially capable of supporting a particular plant community at successional climax (Daubenmire, 1968; Cooper et al., 1991). Habitat types are determined by the presence of “indicator species”- species that if present, will ultimately succeed pending no change in environmental conditions and given infinite time for forest succession to occur (Cooper et al, 1991). Mature overstory indicator species are used to designate the habitat series, while understory indicator species are used to identify the type and/or phase. For purposes of this study, only the habitat series are discussed. Indicator species are organized in a hierarchical manner that is representative of increasing succession and moisture. In the forested systems of northern Idaho, the overstory indicator species are (in hierarchical order): western hemlock (TSHE) (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (THPL) (*Thuja plicata* Donn ex D. Don), subalpine fir (ABLA) (*Abies lasiocarpa* (Hook.) Nutt.), grand fir (ABGR) (*Abies grandis* (Douglas ex D. Don) Lindl.), Douglas-fir (PSME) (*Pseudotsuga menziesii* (Mrb.) Franco), and ponderosa Pine (PIPO) (*Pinus ponderosa* Douglas ex C. Lawson) (Cooper et al., 1991). Habitat type designation is dependent on the presence of the species that are considered to be representative of the latest stage of succession. For example, if western hemlock is present, the site is designated as a western hemlock habitat type. If western hemlock is not present and western redcedar is present, then the site is designated as a western redcedar habitat type, and so forth.

Although a popular and often useful tool, habitat typing can sometimes be misleading when characterizing site vegetation (Cooper et al., 1991). Because of the hierarchical classification scheme, habitat type designations are representative of what a site is theoretically capable of supporting and not necessarily representative of the vegetation currently occupying a site. In reality, natural systems periodically experience disturbances such as logging, fire, disease, and drought. Such events reset succession and do not allow for the theoretical climax community, of which habitat type designations are designed to represent, to be present. Additionally, the habitat typing system does include series designations for all species present in an ecosystem, such as western larch (LAOC) (*Larix occidentalis* Nutt.) and Engelmann spruce (PIEN) (*Picea engelmannii* Parry ex Engelm.), which are abundantly present in Northern Rocky Mountain forests.

Soil-vegetation studies in the Northern Rocky Mountains have traditionally characterized forest habitat types and soil morphology as a function of elevation gradients (Houston 1988; McDaniel et al., 1994). Although these studies have established notable trends in the shifting of forest vegetation and soil morphology with increasing elevation, only generalizations have been made in regard to the direct relationships between soil properties and vegetation communities. Houston (1988) examined the relationships between soil morphological characteristics and forest habitat types along an elevational gradient in the Selkirk Mountains of north Idaho. A shift in habitat types from Douglas-fir (PSME) to western hemlock (TSHE) to subalpine fir (ABLA), corresponds to a shift in soil classification from Inceptisols to Andisols to Spodosols, along the increasing elevation gradient (Houston 1988; McDaniel et al., 1994). The relationships between forest habitat types, elevation, and soil morphology provided a significant contribution to the understanding of soil-vegetation relationships in the region. However, since the completion of the Houston study, numerous pedologic studies have been conducted in the region, and have greatly increased the knowledge of Andisol, Spodosol, and Spodic intergrade properties as well as their geographical distribution (McDaniel et al., 1993; Valerio, 2011; Valerio et al., 2016). However, no comprehensive analysis of soil-vegetation relationships has been conducted across the broader Northern Rocky Mountain region.

Andisols, Spodosols, and Spodic intergrades have been shown to exist along a gradient of increasing effective precipitation, which is an important driver of podzolization (McDaniel et al., 1993; Valerio et al., 2016). As soils become increasingly podzolized, significant differences in soil pH, exchangeable Al, and organic C distribution are observed (see Chapter 1). Due to the distinct geospatial distribution of these three soil types as well as their differing chemical properties, it is suspected that Andisols, Spodosols, and Spodic intergrades will support distinctly different forest communities. Therefore, the overall objectives of this study are to: 1) characterize the composition of forest vegetation communities, and; 2) investigate the relationships between forest communities, and the morphological and chemical properties of Andisols, Spodosols, and Spodic intergrades in the Northern Rocky Mountains. Specifically, this study will analyze the relationships between forest vegetation and soil types; and their relationships to soil pH, exchangeable Al, organic C distribution and density, and total basal area. Establishing these relationships can improve the efficiency and interpretation of soil classification and mapping, as well as provide valuable baseline data to aid in the making of informed land use management decisions.

Materials and Methods

Study Area and Site Selection

Forest vegetation was analyzed on the same sites used to describe and sample the soils referenced in Chapter 1 of this thesis. See this chapter for a complete description of the study area, sampling design, and original site selection.

Each of the 72 sites established by Valerio (2011) was visited and evaluated for suitability. For a site to be included in this study, there must have been no evidence of substantive soil disturbance by human or natural causes and forest vegetation was judged to be in a mature stage of succession. Generally, the presence of the MSH ash layer and a stand age of at least 75 years were required to meet site suitability criteria. Five mature trees on each site were randomly selected and increment bored in order to determine the approximate stand age. In total, 44 sites met the necessary criteria, of which 16 sites classified as Andisols, 9 as Spodic intergrades, and 19 as Spodosols.

Field Methods and Analysis

Nested circular fixed-area plots were used to analyze the vegetation present at each site. The pit used to describe and sample the soil (Valerio, 2011) generally served as plot center, however, plot center was sometimes moved slightly in order to ensure representative conditions throughout the sampling area. A 1/10th-acre (0.04 ha) plot was used for analysis of mature overstory species (trees with diameter at breast height > 5”), a 1/20th-acre (0.02 ha) plot was used to quantify juvenile tree species (DBH < 5”), and three 4-m^2 plots were placed randomly within the 1/10th acre (0.04 ha) boundary to survey understory vegetation. Understory vegetation included grasses, forbs, shrubs, and ferns. Juvenile trees and understory vegetation were used for habitat typing purposes only, and not for any type of proportional coverage analysis.

To analyze the mature overstory vegetation, each tree (with DBH > 5”) within the 1/10th-acre plot was identified, and its DBH measured. DBH was then converted to basal area using a conversion equation (Elledge and Barlow, 2012):

$$BA = DBH^2 \times 0.005454$$

Ultimately, the proportional basal area coverage by species and total basal area was analyzed for each soil type and forest type. Juvenile tree species within the 1/20th acre plot were identified and a count was recorded. The percent coverage of each understory species present was ocularly estimated within each of the three 4-m^2 plots. Habitat types were identified using the methods outlined in Cooper et al. (1991).

Forest vegetation was analyzed as a function of both soil morphology and chemistry. Chapter 1 provides a complete description of the methods used to describe, sample, and analyze the soil component of these forest systems.

Results and Discussion

Habitat Type

Characterization of forest vegetation using the habitat typing method does not illustrate clear relationships between habitat types and soil types (Figure 2.1). Within both the Andisol and Spodosol soil classes, western hemlock is the most prevalent series, with 8 of 16 Andisol sites, and 14 of 19 Spodosol sites classifying as the western hemlock habitat type. The most prevalent series within the Spodic intergrade class is western redcedar, although the Spodic intergrade sites exhibit a relatively even distribution of grand fir, subalpine fir, western redcedar, and western hemlock series. In total, 34 of the 44 sites sampled in this study classify as either western redcedar (THPL) or western hemlock (TSHE) series.

The dominance of the western redcedar and western hemlock series can largely be attributed to the method in which habit types are classified. Habitat type indicator species are organized in a hierarchical manner along a gradient that is representative of increasing moisture and progressive succession (Cooper et al., 1991) (Figure 2.1). The series designation for each site is the same as the presence of the species that is furthest along this gradient. As a result, the presence of a single western hemlock or western redcedar, which are both commonly occurring species in the region, results in that site classifying as a western redcedar or western hemlock habitat series. Because of this, habitat series designations should be recognized primarily as bio-indicators of macro- and microsite climatic conditions, and these designations may or may not always represent the dominant basal area overstory composition present on a site.

The subalpine fir series serves as an exception to the moisture-plant successional gradient. Although subalpine fir is placed among the other indicator species on the moisture and successional gradient used for habitat series classification, the occurrence of subalpine fir is primarily a function of temperature and elevation (Alexander, 1987). Although only six sites sampled in this study classify as the subalpine fir habitat series, it is worth noting that four of them classify as Spodosols and one as a Spodic intergrade. This supports the concept first introduced by Houston (1988) and McDaniel et al. (1994) that podzolized soils and subalpine fir coexist in high elevation environments in the Northern Rocky Mountains. This relationship will be discussed further in subsequent sections.

Although there appears to be an association between the subalpine fir habitat series and podzolized soil types, there are no discernible relationships between the other habitat series and soil classification. This is likely because habitat series designations are representative of the vegetation that a site is theoretically capable of supporting, and not necessarily representative of the present-day vegetation communities on a site. Additionally, the habitat typing system's reliance on the use of indicator species prevents other important species, such as western larch (LAOC) and Engelmann spruce (PIEN), from being included in the inventory of forest vegetation.

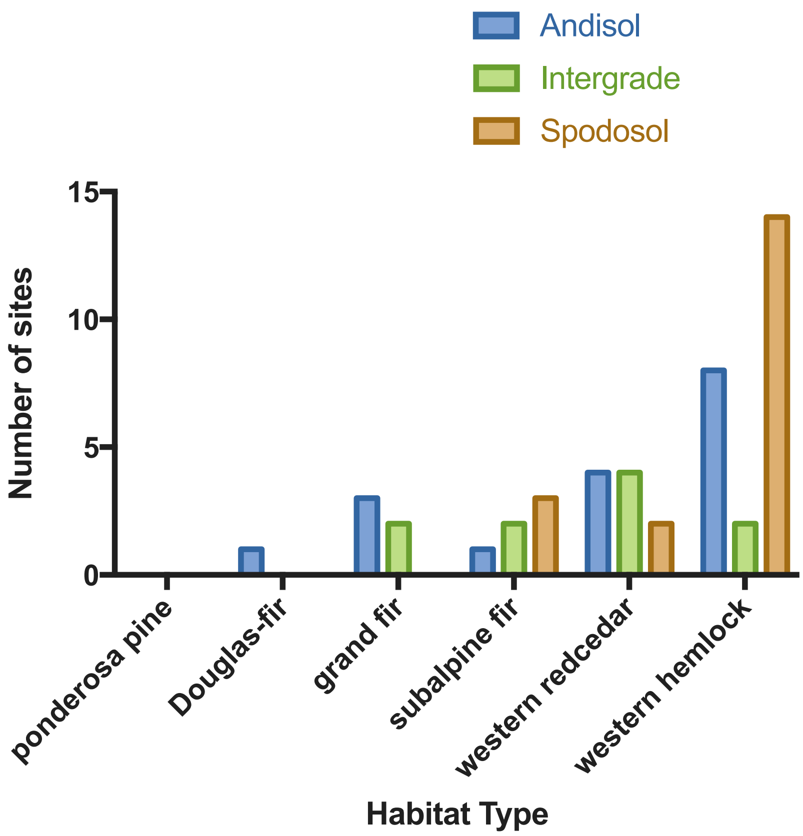


Figure 2.1. Bar graph representing the number of sites in this study as a function of both habitat type and soil type. Habitat types are displayed in the hierarchical order used for classification, which is representative of increasing moisture and advanced forest succession.

Proportional Basal Area of Dominant Overstory Species

In order to further investigate the relationships between soil properties and forest vegetation, the proportional basal area of dominant overstory species was used to analyze the vegetation communities supported by Andisols, Spodic intergrades, and Spodosols across the study area.

Analyses of the proportional basal area coverage of the eight dominant overstory species in the study area as a function of soil type yield several notable trends (Figure 2.2). For this analysis, western larch and Engelmann spruce have been included, as they occupy a substantial proportion of the total basal on many on the sampled sites. Also, for this analysis, the species are presented in a similar sequence to that of the habitat type gradient, but more of an emphasis is placed on temperature, elevation, and effective precipitation rather than successional stage. As a result, subalpine fir has been placed after western redcedar and western hemlock. Western larch and Engelmann spruce are placed adjacent to species that they are commonly associated with (Cooper et al., 1991; Smith and Fischer, 1997).

The eight species are generalized into two groups. The relatively cooler, moister species consist of subalpine fir, Engelmann spruce, western hemlock, and western redcedar; and the warmer, drier species consist of ponderosa pine, Douglas-fir, grand fir, and western larch. The four cooler, moister species account for 87% of the total basal on Spodosol sites and 61% of Spodic intergrade sites. In contrast, the four warmer, drier species account for 60% of the total basal area on Andisol sites. The proportional basal area of “cold species” – subalpine fir and Engelmann spruce, increases from 4% to 17% to 32% in Andisols, Spodic intergrades, and Spodosols, respectively. Conversely, the proportional basal of the two warmest, driest species - ponderosa pine (PIPO) and Douglas-fir (PSME) - decreases from 33% to 21% to 4% in Andisols, Spodic intergrades, and Spodosols, respectively.

Results indicate a substantial shift in the proportional basal area of the dominant overstory species that corresponds to the degree of podzolization in the study area. Non-podzolized soils support a relatively higher proportion of species indicative of warmer, drier conditions while strongly podzolized soils support a relatively higher proportion of species adapted to cooler, moister environments. The proportional basal area on Spodic intergrade sites is relatively evenly distributed among warmer, drier and cooler, moister species. However, the species composition is slightly more similar to that of Spodosols than Andisols.

The trends exhibited by the relative changes in the proportional basal area of dominant overstory species among the three soil types demonstrate the importance of quantifying the actual composition of present-day vegetation for the purpose of forest community classification. By doing so, clear relationships are observed between soil types and forest vegetation. These relationships validate the development and use of a vegetation characterization system based on the proportional basal area of the mature trees in forest communities.

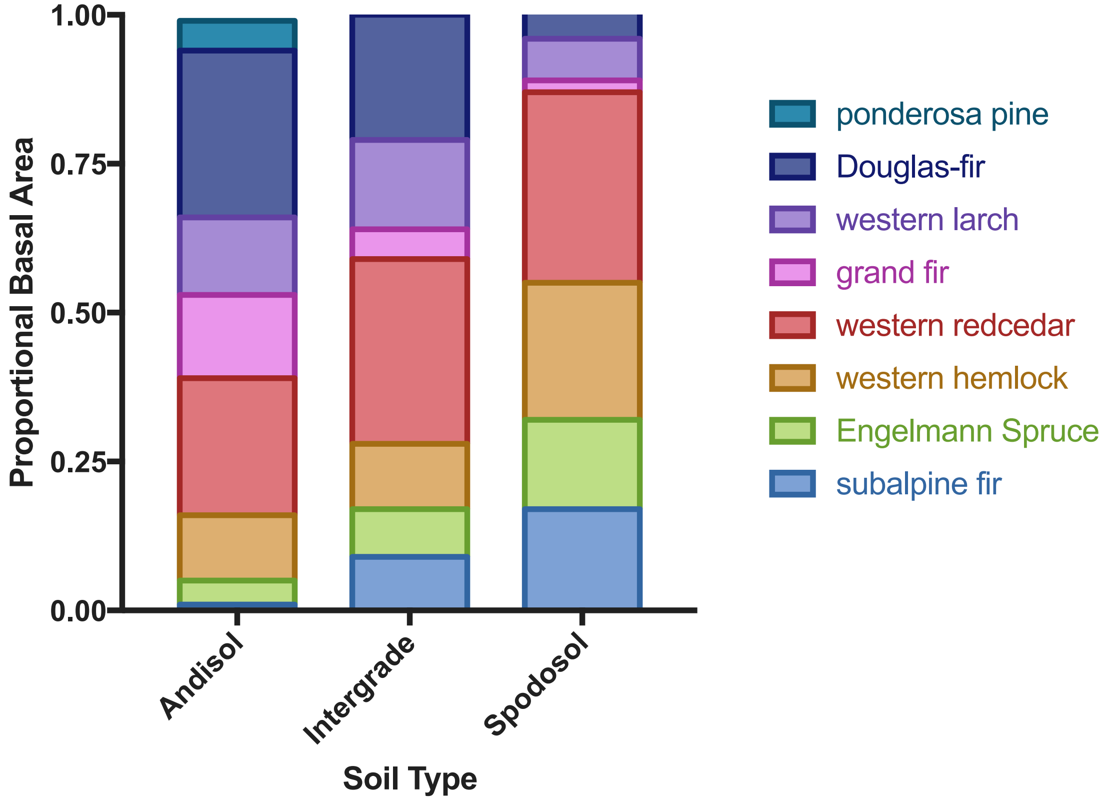


Figure 2.2. Stacked bar graph representing the mean proportional basal area coverage by tree species for each of the three soil types in this study.

Development of Forest Types

In order to account for some of the shortcomings associated with the habitat typing system, this study implements the concept of "*forest types*" as a method of characterizing forest communities in the Northern Rocky Mountain region. Forest types are developed in order to characterize forest vegetation in a manner that is representative of the present-day composition and heterogeneous nature of forest communities.

The concept of forest types involves the grouping of commonly associated species in order to create unique categories of plant communities that can then be related to other variables of interest. Sometimes also referred to as "timber types", or "forest groups", this concept has been used to categorize vegetation communities in numerous studies within the fields of forestry and natural resource sciences (Alexander, 1987; Smith and Fischer, 1997; Sardans and Peñuelas, 2013). Although the concept has been widely used, it is important to note that the forest types established in this study are unique to the vegetation communities, climate variations, and soil properties in the Northern Rocky Mountain region.

Forest types were determined by totaling the basal area of the following three groupings of tree species for each site: grand fir-Douglas-fir-western larch (ABGR-PSME-LAOC), western hemlock-western redcedar (TSHE-THPL), and Engelmann spruce-subalpine fir (PIEN-ABLA). The grouping with the greatest total basal area was designated the forest type for each corresponding site. Due to its minimal presence throughout the study area, ponderosa pine (PIPO) was not factored into the development of forest types.

The associations of the species comprising these forest types have been extensively reported in literature and corroborated through observation. Cooper et al. (1991) report that all species within each respective forest type are considered either minor climax or major seral species when another associated species in the forest type is the designated habitat series. Additionally, a USFS publication characterizing the fire ecology of north Idaho forests establishes nine "fire groups". Each fire group is comprised of species based on their likelihood of occurring together in a forest stand, as well as those species occupying similar roles in forest succession, and having similar response and susceptibility to fire (Smith and Fischer, 1997). The groupings of species comprising each of the three forest types proposed in this study are the same as the groupings of species comprising three different fire groups. In addition to the associations of the species comprising each forest type being substantiated by other studies, personal observation of numerous forest stands and communication with industry professionals lends validation to this approach to vegetation characterization.

Characterization of forest vegetation using the forest type method illustrates clear relationships between forest types and soil types that are not observed when vegetation is characterized using the habitat typing method (Figures 2.1 and 2.3). Additionally, the relationships between forest type and soil type are representative of the trends observed between the proportional basal area of mature overstory species and soil type (Figure 2.2 and 2.3).

The relatively warmer, drier (ABGR-PSME-LAOC) forest type typically occurs at lower elevations and southerly aspects within the study area, and is primarily associated with Andisols (Figure 2.3). Conversely, the cold, moist (ABLA-PIEN) forest type typically occurs at higher elevations and northerly aspects, where snowpack and effective precipitation are greatest (Alexander, 1987). This forest type is predominantly associated with Spodosols (Figure 2.3). The (THPL-TSHE) forest type is the most extensive in the study area, occurring across a broad range of intermediate elevations and aspects. Although this forest type has the potential to be associated with all soil types, it is most commonly associated with Spodic intergrades and Spodosols (Figure 2.3).

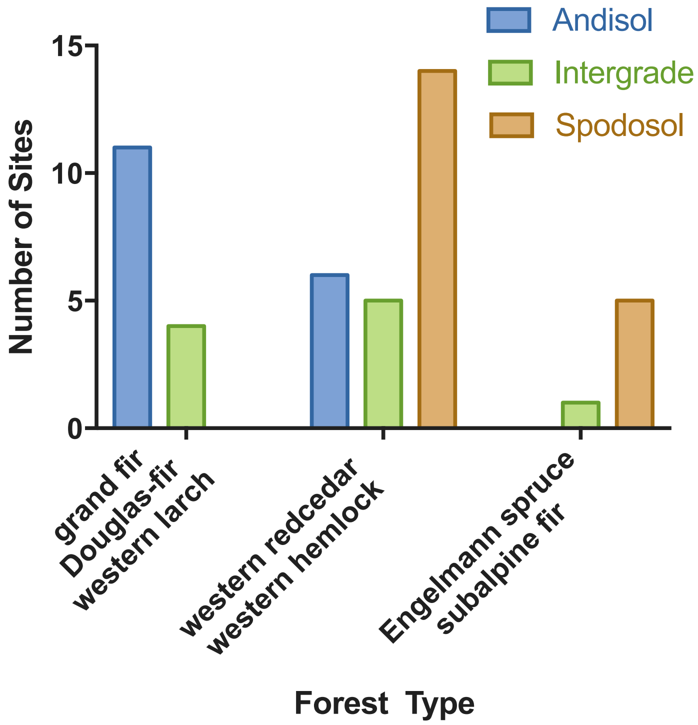


Figure 2.3. Bar graph representing the number of sites in this study as a function of both forest type and soil type. Forest types are displayed in order of increasing podzolization.

Forest Type-Soil Chemical Property Relationships

Given the apparent associations between forest types and soil types, soil chemical properties - pH and exchangeable (KCl-extractable) Al - were examined for the soils supporting each forest type. The pH and KCl Al trends exhibited in Andisols, Spodic intergrades, and Spodosols, as previously determined (see Chapter 1), are very similar to the trends exhibited in soils of corresponding grand fir-Douglas-fir-western larch (ABGR-PSME-LAOC), western redcedar-western hemlock (THPL-TSHE), and subalpine fir-Engelmann spruce (ABLA-PIEN) forest types (Figures 2.4 and 2.5).

Andisols and soils supporting the ABGR-PSME-LAOC forest type both possess relatively high pH values and relatively low exchangeable Al concentrations throughout their respective profiles. Soils supporting the THPL-TSHE forest type exhibit relatively lower pH and higher exchangeable Al values intermediate to those of comparative horizons of the other two forest types, and are most representative of the moderately podzolized Spodic intergrades. Soils associated with the cooler, moister ABLA-PIEN forest type exhibit substantial decreases in soil pH and increased concentrations of exchangeable Al, that are representative of highly podzolized Spodosol properties. Although the pH and exchangeable Al characteristics of Spodosols and the ABLA-PIEN forest type soils are similar, the trend is better illustrated when stratified by forest type. This suggests that the presence of the ABLA-PIEN forest type strongly indicates the presence of podzolized soils. This relationship, in combination with the ability to identify vegetation types using remote sensing technology (Culvenor, 2002), offers great potential to effectively map large areas of podzolized soils in the Northern Rocky Mountain region.

The relationships between forest types and these associated soil chemical properties also provide insight into possible parameters controlling the distribution of forest species that extend beyond physical environmental and climatic variables. Of particular interest is species' tolerance to high Al environments and their role in Al cycling. The surface mineral horizons of soils supporting the ABLA-PIEN forest type contain exchangeable Al concentrations of 4.4 cmol_c/kg, which is nearly three times higher than that of the THPL-TSHE forest type soils (1.6 cmol_c/kg). Due to the prevalence of subalpine fir and Engelmann spruce on sites with high soil Al, it is apparent that these species have adapted to such environments. However, the tolerance of subalpine fir and Engelmann spruce to exchangeable Al, and the role these species play in the cycling of Al in the Northern Rocky Mountains is relatively unknown.

Exchangeable Al concentrations ranging from 3.5 to 8.1 cmol_c/kg were shown to be of high risk of Al toxicity in forest systems located in northern Spain (Alvarez et al., 2005); however, exchangeable Al concentrations within that range in the study area do not appear to detrimentally affect subalpine fir and Engelmann spruce communities. Additionally, multiple studies analyzing the components of Fraser fir (*Abies fraseri* (Pursh) Poir), balsam fir (*Abies balsamea* (L. Mill)), and red spruce (*Picea rubens* (Sarg.)) forest communities in the eastern United States have demonstrated these species' ability to uptake and accumulate substantial amounts of Al in their foliage (Wilson and Butcher, 2012; Boyce et al., 2013). In a controlled study Engelmann spruce seedlings were tolerant to low soil pH (pH 2.5 and 3.5), and demonstrated the ability to accumulate large quantities of Al when subjected to low pH and high Al soil environments (Pan et al., 1991). However, the direct effects of low pH and high Al on growth and reproduction of subalpine fir and Engelmann spruce in natural forested systems in the Northern Rocky Mountains are not well understood.

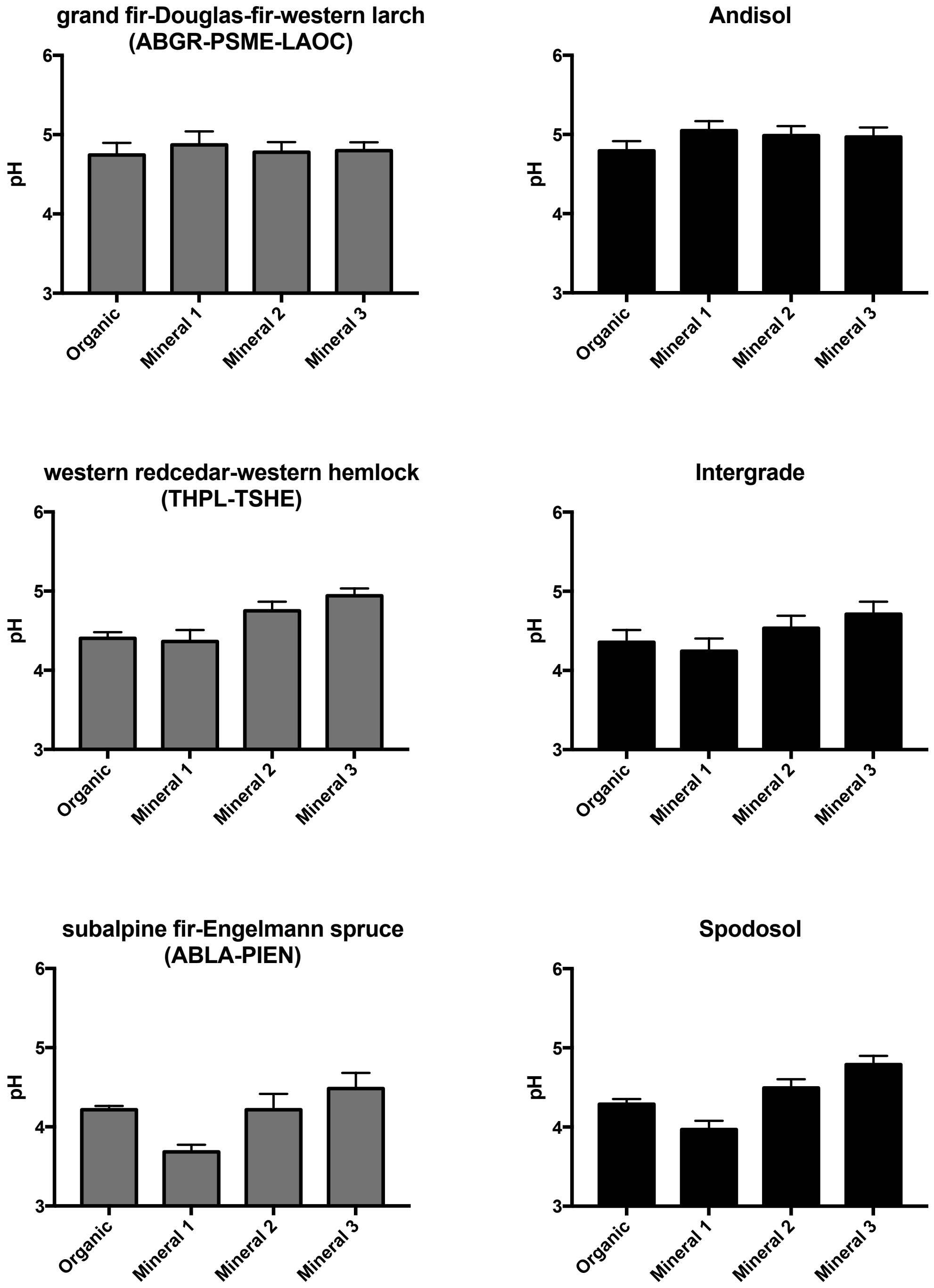


Figure 2.4. pH for the organic and uppermost three mineral horizons each forest type and associated soil type. Error bars represent standard error.

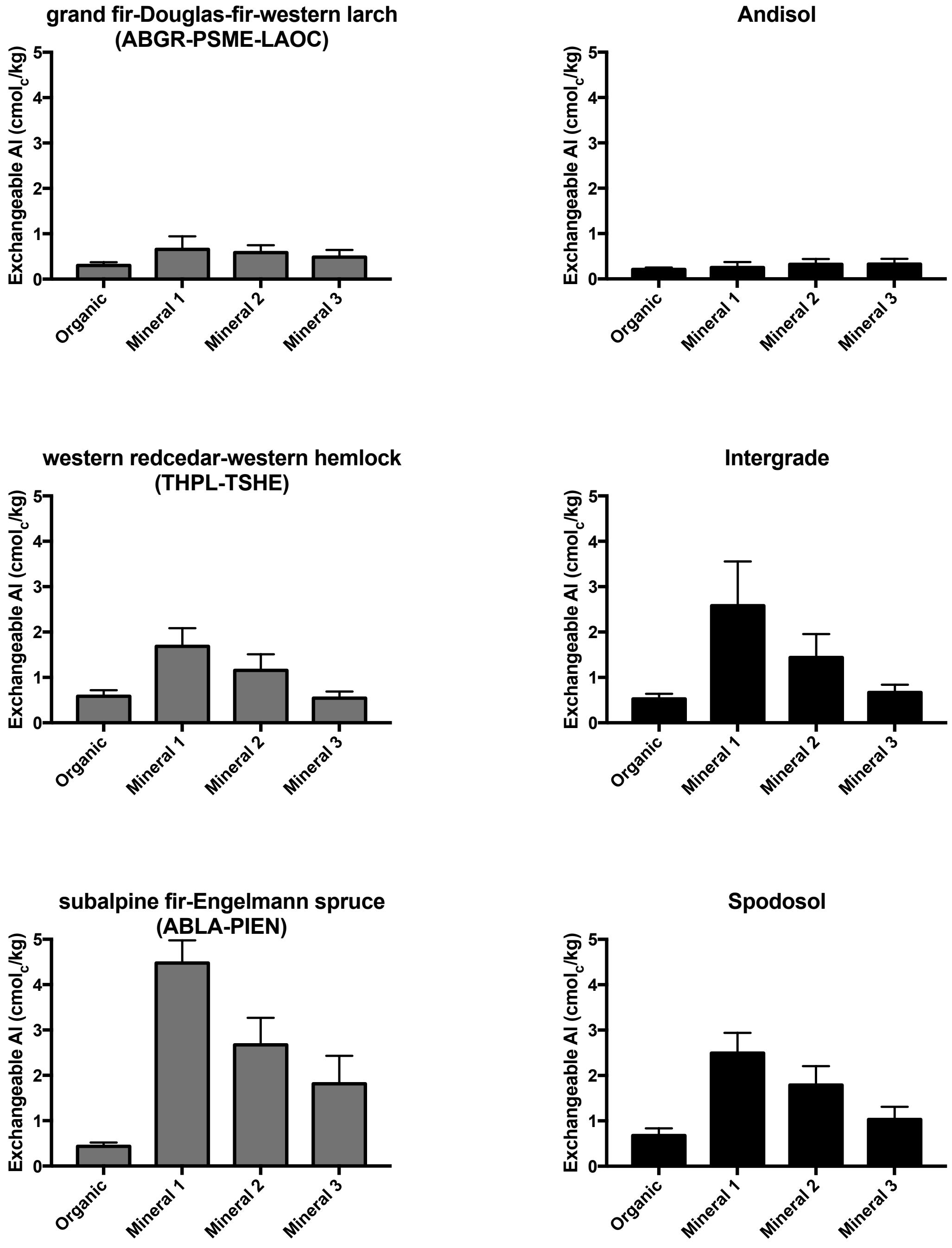


Figure 2.5. KCl-extractable Al for the organic and uppermost three mineral horizons each forest type and associated soil type. Error bars represent standard error.

Ecosystem Carbon Dynamics

Due to the similarity of trends exhibited between soil types and their associated forest types with soil pH and exchangeable Al, the same was expected for the distribution and density of organic C. However, analysis of the relationship between soil organic C as a function of forest type and soil classification did not bear this out (Figures 2.6 and 2.7).

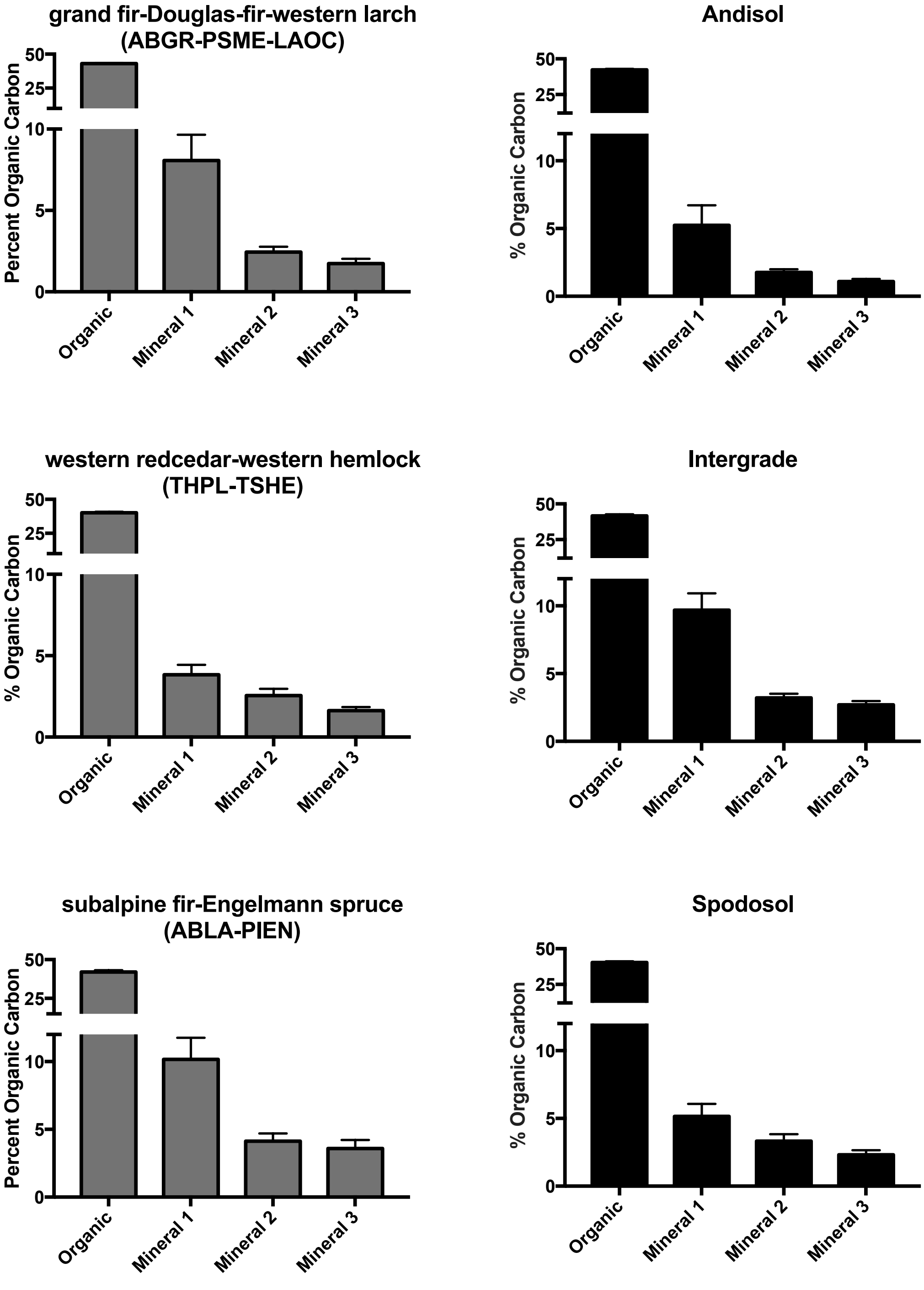
The vertical C distribution patterns exhibited by each of the soil and forest types are typical of a temperate coniferous forest (Jobaggy and Jackson, 2000); however, there are noticeable differences in percent C between like horizons of associated soil and forest types (Figure 2.6). Of the three soil classes, the Spodic intergrades possess the highest percentage (10%) of organic C in the surface mineral horizon. However, the associated THPL-TSHE forest type contains the lowest percentage (3.5%) of organic C in the surface mineral horizon. Conversely, both ABGR-PSME-LAOC and ABLA-PIEN forest types have higher organic C percentages in their surface mineral horizons than the respective Andisol and Spodosol soil types that they are associated with (Figure 2.6).

Similarly, C densities of the forest types do not closely mirror the C density trends exhibited by the associated soil types (Figure 2.7). The Spodic intergrades have a mean C density of 145 Mg/ha, which is highest among the three soil types. However, the THPL-TSHE forest type sites have mean C density of 108 Mg/ha, which is the lowest among the three forest types. The ABLA-PIEN forest type exhibits a C density of 167 Mg/ha, which is significantly higher than the C densities of the other two forest types and is the highest mean C density observed among any of the soil or forest types analyzed.

Several studies analyzing soil C density under different forest communities report similar results. A study conducted in the Colorado Rocky Mountains quantified soil C density in soils located in lower elevation lodgepole pine- (*Pinus contorta*) dominated forests, and higher elevation subalpine fir (ABLA) and Engelmann spruce (PIEN) dominated forests. Results demonstrate significantly higher soil C densities in the subalpine fir and Engelmann spruce forest communities, ranging from approximately 150 to 200 Mg/ha (Kueppers and Harte, 2005). Additionally, a study consisting of several old growth subalpine fir and hybrid white spruce timber stands in British Columbia reported mean a C density of 163 Mg/ha (Fredeen et al., 2005). Lastly, soil C densities of 171 Mg/ha for soils supporting fir- and spruce-dominated forest communities were reported along an elevation gradient in China (Zhang et al., 2011). These spruce and fir forest communities were the two highest along the elevation gradient, and the soil C densities of these forests were higher than all but one other forest type in the study (Zhang et al., 2011).

Although the mechanisms controlling ecosystem C characteristics are incredibly complex, a possible explanation for the increased soil C densities observed in ABLA-PIEN forest types is the inherent cold temperature associated with the higher elevations at which these species occur. Cold temperatures are likely to reduce microbial decomposition rates, causing the rate of organic C inputs (litterfall) to exceed the rate of decomposition, ultimately allowing for a relatively greater accumulation of organic C in the system (Martinez et al., 2013). ABLA-PIEN forest types are also often associated with highly acidic Spodosols, creating an environment that can further reduce microbial decomposition rates (Robson and Abbot, 1989). Lastly, podzolization causes organic C, in the form of organometallic complexes, to be sequestered in the subsoil of Spodosols, further increasing the potential C density of these soils (Schulp et al., 2008).

Although this study was not designed to assess the total aboveground biomass component of these forest systems, total basal area was calculated in order to characterize the composition of forest communities. The mean total basal of each forest type and soil type can be used as a general indicator of the relative production of these groupings (Figure 2.8). Although no significant differences are observed for the mean total basal area among the soil types, the difference among the forest types is notable. The THPL-TSHE forest type has a significantly higher mean total basal area than the other two forest types; however, the THPL-TSHE forest type also has the lowest C density of the three forest types. Conversely, the ABLA-PIEN forest type has the lowest mean total basal area and the highest C density. The contrast between basal area and C density of the forest types suggests that the total aboveground biomass does not influence soil C dynamics as much as other variables within the forest system.



grand fir-Douglas-fir-western larch (ABGR-PSME-LAOC)

Andisol

western redcedar-western hemlock (THPL-TSHE)

Intergrade

subalpine fir-Engelmann spruce (ABLA-PIEN)

Spodosol

Figure 2.6. Organic C distribution for the organic and uppermost three mineral horizons of each forest type and associated soil type. Error bars represent standard error.

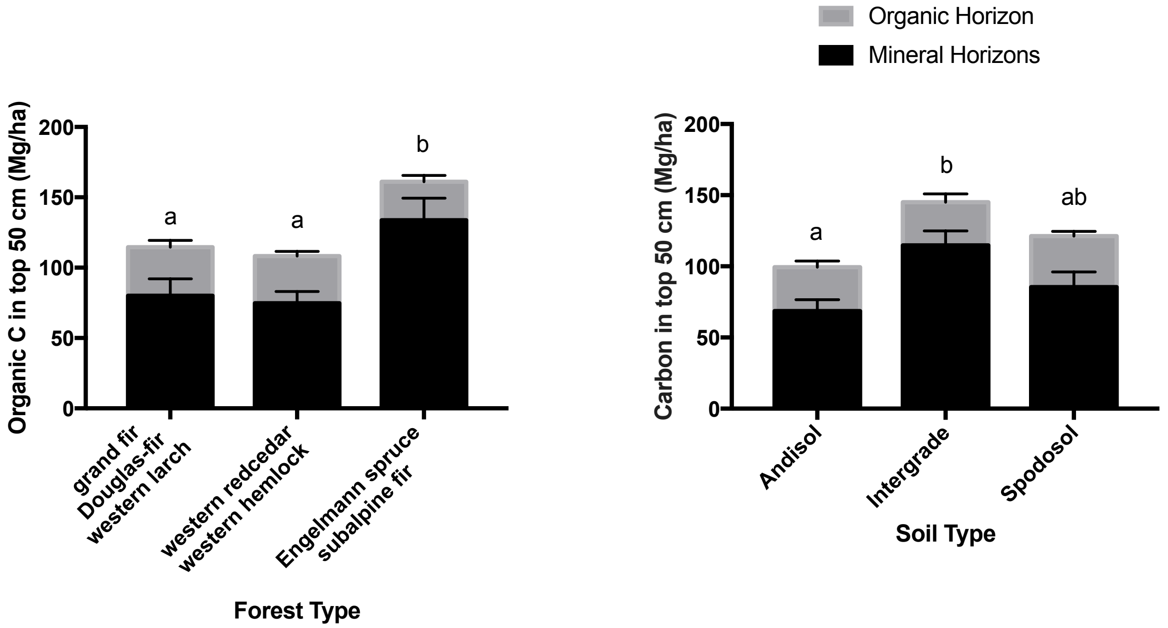


Figure 2.7. Organic C densities for the top 50 cm of soils within each soil class and forest type. Different letters indicate significant differences (Alpha = 0.10) in C density among soil types and among forest types, respectively. Error bars represent standard error.

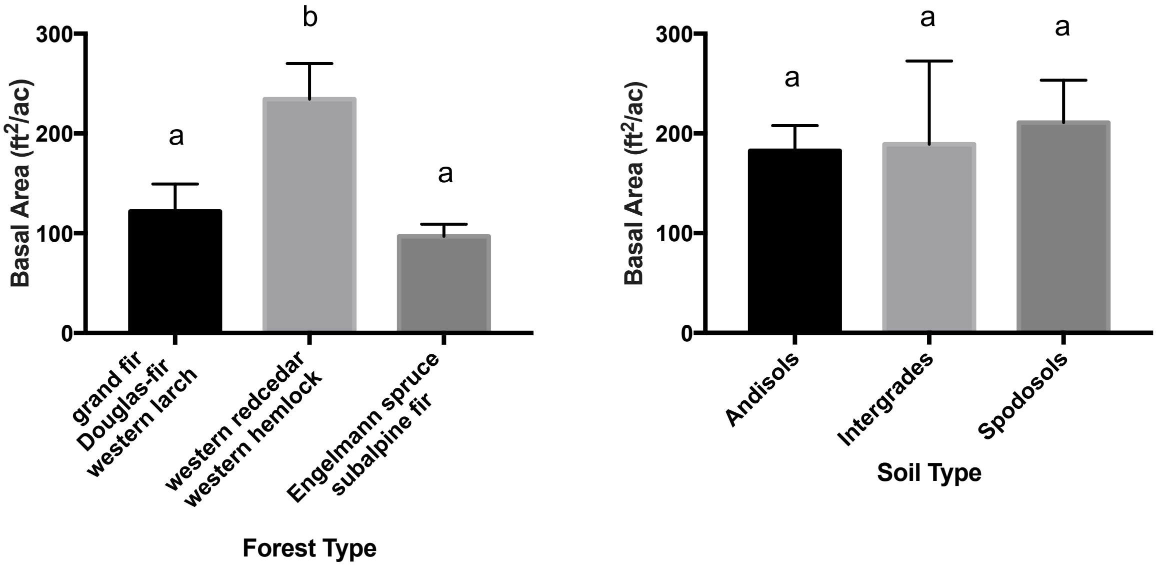


Figure 2.8. Mean total basal area measured on sites for each forest and soil type. Different letters indicate significant differences (Alpha = 0.10) in C density among soil types and among forest types, respectively. Error bars represent standard error.

Summary

Results of this study demonstrate clear relationships between soil morphology, soil chemistry, and forest vegetation communities in the Northern Rocky Mountains. Soils of the relatively warmer, drier grand fir-Douglas-fir-western larch (ABGR-PSME-LAOC) forest types exhibit little evidence of podzolization and are most commonly associated with Andisols. These systems also possess the highest pH values and lowest exchangeable Al concentrations of the three forest types examined. Conversely, soils of the subalpine fir-Engelmann spruce (ABLA-PIEN) forest type exhibit the lowest pH values and highest exchangeable Al concentrations. These forest systems are typically found at higher elevations and are closely associated with Spodosols. The western redcedar-western hemlock (THPL-TSHE) forest type is associated with elevational, climatic, and soil chemical properties intermediate to those of the other forest types, and is supported by both podzolized and non-podzolized soils.

This study also emphasizes the importance of classifying and analyzing vegetation in a manner that is representative of present-day ecological communities. The use of forest types to characterize vegetation results in forest vegetation classes that exhibit clear relationships to soil morphology, chemistry, and organic C distribution and density. These soil-vegetation relationships can be used to improve the efficiency and quality of land inventory efforts, aid in informing land use management decisions, and serve as a foundation for future research and ecological site development.

Although the results of this study increase the knowledge pool about soil-vegetation relationships in the Northern Rocky Mountains, the complex nature of these forest systems allows for numerous potential future research opportunities. Further investigation into the cycling of Al between the mineral soil, vegetation, and the litter layer could yield an explanation for the elevated exchangeable Al concentrations found in soils of different forest types. Additionally, a comprehensive C study that quantifies aboveground biomass, soil C in deep horizons, and mechanisms affecting decomposition of organic matter could provide valuable knowledge regarding the C dynamics and sequestration potential of these soil types and their associated vegetation communities.

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APPENDIX A: SUMMARY STATISTICS

Summary table indicating mean values and statistical significance (alpha = 0.10) of chemical properties for each soil type and horizon. Statistical analysis was conducted using GraphPad Prism 7.0a. Analysis consisted of ANOVA followed by Fisher LSD multiple comparisons. Different capital letters indicate significant differences between sequential horizons of the same soil type. Different lower case letters represent significant differences among like horizons of differing soil types.

Soil Type-Horizon	pH	KCl Al ($cmol_C/kg$)	% Carbon
Andisol Organic	4.8 A,a	0.21 A,a	42.3 A,a
Andisol Mineral 1	5.1 B,a	0.25 A,a	5.3 B,a
Andisol Mineral 2	5.0 AB,a	0.32 A,a	1.8 C,a
Andisol Mineral 3	5.0 AB,a	0.32 A,a	1.1 C,a
Intergrade Organic	4.4 AB,b	0.53 A,a	41.6 A,a
Intergrade Mineral 1	4.2 A,b	2.58 B,b	9.7 B,b
Intergrade Mineral 2	4.5 AB,b	1.44 A,b	3.2 C,a
Intergrade Mineral 3	4.7 B,a	0.67 A,a	2.7 C,a
Spodosol Organic	4.3 A,b	0.67 A,a	40.4 A,a
Spodosol Mineral1	4.0 B,b	2.49 B,b	5.3 B,a
Spodosol Mineral2	4.5 A,b	1.78 C,b	3.3 BC,a
Spodosol Mineral3	4.8 C,a	1.03 A,a	2.3 C,a

APPENDIX B: SELECTED LABORATORY AND MORPHOLOGICAL DATA

Horizon	Depth (cm)	Dry Color	Moist Color	pH	KCl Al ($cmol_c/kg$)	Organic C (%)
Pedon 4 - Andisol						
O	0-4	-	-	4.0	0.71	41.54
Bw1	4-9	10YR 4/3	7.5YR 3/2	4.8	0.11	1.98
Bw2	9-24	10YR 5/4	7.5YR 4/4	5.0	0.07	2.06
Bw3	24-33	10YR 5/4	7.5YR 4/4	4.8	0.03	1.29
Bw4	33-44	10YR 5/4	10YR 4/4	4.8	0.07	0.41
Bw5	44-56	10YR 5/4	10YR 4/3	4.6	0.20	0.22
2BC	56-72+	2.5Y 6/3	2.5Y 4/3	4.7	0.09	0.09
Pedon 8 - Andisol						
Oe	0-3	-	-	5.1	0.08	43.0
A	3-6	10YR 4/2	10YR 3/1	5.2	0.04	11.4
BA	6-15	10YR 5/3	7.5YR 3/2	4.9	0.15	3.7
Bw1	15-28	10YR 5/4	7.5YR 3/2	4.9	0.15	2.7
Bw2	28-48	10YR 5/4	7.5YR 3/4	4.8	0.22	1.6
2BC	48-52+	2.5Y 6/3	2.5Y 5/3	4.7	0.30	0.3
Pedon 12 - Andisol						
Oe	0-5	-	-	4.4	0.22	44.63
Bw1	5-20	10YR 5/3	10YR 3/4	5.2	0.06	1.63
Bw2	20-39	10YR 5/4	10YR 3/3	5.3	0.03	1.16
Bw3	39-51	10YR 5/4	10YR 3/4	5.5	0.14	1.10
Bw4	51-70	10YR 5/4	10YR 4/4	5.4	0.03	0.58
2BC	70-80+	2.5Y 6/3	2.5Y 4/3	5.0	0.14	0.51
Pedon 23 - Spodosol						
O	0-8	-	-	4.3	0.20	44.13
E	8-15	10YR 5/2	10YR 3/1	3.8	2.37	2.64
Bhs	15-23	10YR 4/3	7.5YR 3/2	4.2	2.40	2.44
Bs	23-30	10YR 4/4	7.5YR 3/2	4.3	2.29	3.15
Bw1	30-50	10YR 4/4	7.5 YR 3/3	4.3	1.39	1.91
Bw2	50-71	10YR 5/4	10YR 3/4	4.3	0.86	1.45
2BC	71-75+	10YR 6/4	10YR 4/4	4.4	0.79	1.75
Pedon 25 - Andisol						
O	0-5	-	-	4.4	0.37	33.96
Bw1	5-25	10YR 5/4	7.5 YR 3/4	4.6	0.35	2.22
Bw2	25-45	10YR 5/4	7.5 YR 3/3	4.8	0.11	1.18
2Bw3	45-51+	10YR 5/4	10YR 3/4	4.5	0.68	0.56

Horizon	Depth (cm)	Dry Color	Moist Color	pH	KCl Al (cmol$_c$/kg)	Organic C (%)
Pedon 32 - Spodosol						
O	0-4	-	-	4.5	0.54	45.94
E	4-8	7.5YR 5/2	7.5YR 3/2	3.2	6.18	2.85
Bs	8-19	10YR 4/4	7.5YR 3/4	4.5	0.35	2.72
Bw1	19-31	10YR 4/4	7.5YR 3/3	4.6	0.12	1.90
Bw2	31-52	10YR 5/4	7.5YR 3/4	4.5	0.16	1.30
BC	52-58+	2.5YR 6/4	2.5YR 4/4	4.1	0.83	0.42
Pedon 37 - Spodosol						
O	0-4	-	-	4.2	0.34	42.76
E	4-5	10YR 5/1	10YR 3/1	3.6	3.07	8.51
Bhs	5-6	10YR 4/3	7.5YR 3/2	3.7	4.02	4.00
Bs	6-21	10YR 4/4	7.5YR 3/3	4.5	1.08	3.58
Bw1	21-34	10YR 5/4	7.5YR 3/4	4.6	0.45	3.10
Bw2	34-62	10YR 5/4	10YR 3/4	4.3	1.09	1.83
2BC	62-70	10YR 6/4	10YR 4/4	4.1	1.10	0.58
Pedon 41 - Andisol						
O	0-3	-	-	4.3	0.23	45.44
E	3-8	10YR 4/2	10YR 3/2	3.9	1.97	5.66
Bs	8-19	10YR 4/3	7.5YR 3/2	4.2	1.35	3.37
Bw1	19-32	10YR 5/4	7.5YR 3/3	4.6	0.45	1.90
Bw2	32-47	10YR 5/4	7.5YR 4/4	4.5	0.51	1.46
BC	47-57+	2.5Y 6/4	10YR 4/4	4.2	0.49	0.20
Pedon 43 - Spodosol						
O	0-3	-	-	4.1	0.54	41.10
E	3-5	10YR 5/1	10YR 3/1	3.5	3.26	8.80
Bhs	5-9	10YR 4/3	7.5YR 3/2	3.6	4.66	6.26
Bs	9-22	10YR 4/4	7.5YR 3/2	4.0	2.45	6.05
Bw	22-42+	10YR 5/4	10YR 4/3	4.3	0.90	1.45
Pedon 48 - Spodosol						
O	0-4	-	-	3.8	2.79	34.84
E	4-6	10YR 5/2	10YR 4/2	3.2	4.15	2.79
Bs1	6-11	10YR 4/3	7.5YR 3/2	3.5	4.42	3.72
Bs2	11-17	10YR 5/4	7.5 YR 3/3	4.1	2.75	3.61
Bw1	17-32	10YR 5/4	7.5YR 4/4	4.0	0.97	2.00
2Bw2	32-48	10YR 6/4	10YR 4/3	4.1	0.75	0.45
2Bw3	48-65	10YR 6/4	10YR 4/3	4.1	0.78	0.47
2BC	65-74+	2.5Y 6/4	10YR 4/4	4.0	0.62	0.39

Horizon	Depth (cm)	Dry Color	Moist Color	pH	KCl Al (cmol$_c$/kg)	Organic C (%)
Pedon 52 - Andisol						
O	0-3	-	-	5.6	0.14	39.86
A	3-9	10YR 4/2	10YR 2/1	5.5	0.03	8.42
Bw	9-17	10YR 5/3	10YR 3/2	4.8	0.10	2.27
BC1	17-30	10YR 6/3	10YR 4/3	4.7	0.13	0.66
BC2	30-52+	10YR 6/4	10YR 4/4	4.6	0.19	1.01
Pedon 53 - Spodosol						
O	0-6	-	-	4.9	0.15	39.79
E	6-8	10YR 6/3	10YR 4/1	3.7	1.14	0.94
Bhs	8-13	10YR 5/4	7.5YR 3/2	3.9	0.78	0.75
Bw1	13-24	10YR 5/4	7.5 YR 3/4	5.1	0.03	0.44
Bw2	24-39	10YR 5/4	10YR 3/4	5.1	0.05	0.27
BC	39-69+	2.5Y 6/3	10YR 4/3	5.0	0.02	0.07
Pedon 55 - Spodic intergrade						
O	0-8	-	-	4.0	1.13	33.97
E	8-10	10YR 4/2	10YR 3/1	3.4	6.15	5.05
Bhs	10-17	10YR 4/3	7.5YR 3/2	3.7	5.35	4.03
Bw1	17-26	10YR 5/4	10YR 3/2	4.2	1.13	2.26
Bw2	26-37	10YR 5/4	10YR 3/3	4.1	0.89	2.65
Bw3	37-59	10YR 5/4	10YR 3/3	4.3	0.81	2.18
Bw4	59-70	10YR 5/4	10YR 3/4	4.4	0.29	1.53
2BC	70-81+	10YR 5/4	10YR 3/4	4.1	0.58	0.33
Pedon 56 - Andisol						
O	0-4	-	-	5.1	0.22	42.86
A	4-6	10YR 5/4	7.5 YR 3/4	5.1	0.07	16.89
Bw1	6-13	10YR 5/4	7.5YR 4/4	4.9	0.14	2.39
Bw2	13-26	10YR 5/4	7.5YR 3/4	5.0	0.24	2.07
Bw3	26-48+	10YR 5/4	7.5YR 4/4	5.0	0.14	1.53
Pedon 57 - Spodic intergrade						
O	0-3	-	-	5.5	0.03	43.84
A	3-6	10YR 4/1	10YR 2/1	5.2	0.10	12.00
Bw1	6-20	10YR 5/4	7.5YR 3/2	5.2	0.03	2.72
Bw2	20-53	10YR 5/4	7.5YR 4/3	5.0	0.07	1.84
Bw3	53-75	10YR 6/4	10YR 4/4	4.6	0.16	1.04
BC	75-80+	10YR 6/4	10YR 4/4	4.4	0.30	0.33

Horizon	Depth (cm)	Dry Color	Moist Color	pH	KCl Al (cmol$_c$/kg)	Organic C (%)
Pedon 61 - Spodosol						
O	0-7	-	-	3.9	0.75	40.69
E	7-10	10YR 5/2	10YR 3/1	4.5	1.75	7.45
Bs	10-15	10YR 4/4	7.5YR 3/2	5.0	0.19	3.65
Bw1	15-27	10YR 4/4	7.5YR 3/4	5.3	0.06	2.02
Bw2	27-36	10YR 5/4	7.5YR 3/4	5.1	0.15	1.81
Bw3	36-66	10YR 6/4	2.5Y 4/4	5.0	0.27	0.65
Bw4	66-73+	10YR 6/4	2.5Y 4/4	4.7	0.42	0.71
Pedon 63 - Andisol						
O	0-4	-	-	5.5	0.35	43.92
BA	4-7	10YR 4/2	10YR 3/1	5.4	0.06	17.73
Bw	7-31	10YR 5/4	10YR 3/3	4.4	1.16	2.63
2BC	31-47+	10YR 6/4	10YR 4/3	4.1	1.88	0.91
Pedon 66 - Andisol						
O	0-4	-	-	4.7	0.14	41.88
A	4-7	10YR 4/2	10YR 2/1	5.2	0.05	2.84
Bw1	7-20	10YR 4/4	10YR 3/3	5.0	0.11	2.29
Bw2	20-41	10YR 5/4	10YR 3/4	5.0	0.11	1.38
2BC	41-51+	2.5Y 6/3	10YR 4/3	4.8	0.18	0.31
Pedon 70 - Spodosol						
O	0-4	-	-	4.2	0.16	42.89
E	4-7	10YR 5/1	10YR 3/1	4.9	0.11	9.11
Bs	7-13	7.5YR 6/4	7.5YR 4/3	5.0	0.07	0.97
Bw1	13-26	10YR 6/4	7.5YR 4/4	5.0	0.15	0.72
Bw2	26-37	10YR 6/4	7.5YR 4/4	4.8	0.25	0.68
2BC	37-50+	2.5Y 6/4	2.5Y 4/4	4.6	0.09	0.18
Pedon 72 - Spodic intergrade						
O	0-4	-	-	4.0	0.17	43.40
E	4-7	10YR 4/1	10YR 3/1	4.2	0.36	14.71
Bhs	7-13	7.5YR 4/2	7.5YR 2.5/2	4.0	0.88	2.74
Bs	13-27	10YR 4/4	7.5YR 3/2	4.2	1.75	3.99
Bw1	27-39	10YR 5/4	10YR 3/3	4.2	0.44	2.48
Bw2	39-53	10YR 5/4	10YR 3/4	4.3	0.40	2.14
2BC	53-56+	10YR 5/4	10YR 3/4	4.3	0.39	1.71
Pedon 73 - Spodic intergrade						
O	0-3	-	-	4.2	0.74	44.67
A	3-5	10YR 3/1	10YR 2/1	4.1	0.74	8.25
Bw1	5-15	10YR 4/4	7.5YR 3/2	4.3	0.93	2.47
Bw2	15-38	10YR 5/4	10YR 3/3	4.4	0.44	2.08
Bw3	38-60	10YR 5/4	10YR 3/3	4.3	0.37	1.86
2BC	60-76+	10YR 6/4	10YR 3/4	4.2	0.36	0.77

Horizon	Depth (cm)	Dry Color	Moist Color	pH	KCl Al ($cmol_c/kg$)	Organic C (%)
Pedon 78 - Spodosol						
O	0-8	-	-	4.4	0.10	47.36
E	8-10	10YR 5/1	10YR 3/1	3.8	1.69	5.63
Bs	10-24	10YR 4/3	7.5YR 3/2	4.3	2.46	3.86
Bw	24-39	10YR 4/4	10YR 3/2	4.2	2.66	3.65
BC1	39-70	10YR 5/4	10YR 2/2	4.1	0.15	4.17
BC2	70-100+	10YR 5/4	10YR 2/2	4.0	0.04	5.96
Pedon 85 - Spodosol						
Oe	0-7	-	-	4.0	0.57	43.3
E	7-14	10 YR 6/2	10YR 3/1	3.1	5.27	5.362511
Bhs	14-21	10YR 4/3	7.5YR 2.5/2	3.8	6.10	10.547078
Bw1	21-31	10YR 5/3	10YR 3/2	4.1	1.18	2.3
Bw2	31-42	10YR 5/3	10YR 3/3	4.2	1.16	1.89
2BC	42-70+	10YR 5/3	10YR 3/2	4.2	1.10	2.22
Pedon 99 - Andisol						
O	0-4	-	-	5.1	0.09	42.33
Bw1	4-20	10YR 5/4	7.5YR 3/4	5.1	0.06	0.87
Bw2	20-34	10YR 5/4	7.5YR 3/4	4.8	0.18	0.76
2BC	34-55+	10 YR 6/3	10YR 4/3	4.8	0.04	0.14
Pedon 118 - Spodosol						
O	0-16	-	-	4.1	1.82	36.42
E	16-24	10YR 5/1	10YR 4/1	3.5	1.16	1.74
Bhs	24-30	10YR 4/4	7.5YR 3/4	5.2	0.58	3.70
Bs	30-44	10YR 5/4	10YR 3/4	5.4	0.16	0.73
2BC	44-69+	10YR 6/4	10YR 4/4	5.5	0.11	0.33
Pedon 127 - Spodosol						
O	0-6	-	-	4.6	0.19	40.84
E	6-9	10YR 5/2	10YR 3/1	4.6	0.06	2.77
Bs1	9-16	10YR 4/4	7.5YR 3/2	4.7	0.52	2.05
Bs2	16-31	10YR 5/4	10YR 3/4	4.6	0.77	0.96
2BC	31-59+	10YR 6/4	10YR 5/4	4.5	0.61	0.29
Pedon 147 - Andisol						
O	0-2	-	-	5.5	0.07	43.72
Bw1	2-8	10YR 5/2	10YR 3/1	5.5	0.04	1.71
Bw2	8-23	10YR 5/3	10YR 3/2	5.5	0.04	0.87
Bw3	23-36	10YR 5/3	10YR 3/3	5.3	0.10	0.77
2BC	36-45+	2.5Y 6/3	2.5Y 4/3	5.7	0.01	0.49

Horizon	Depth (cm)	Dry Color	Moist Color	pH	KCl Al (cmol$_c$/kg)	Organic C (%)
Pedon 151 - Spodosol						
O	0-4	-	-	4.2	1.69	35.62
E	4-6	10YR 5/2	10YR 3/1	4.4	1.56	2.72
Bs	6-15	10YR 4/3	7.5YR 3/2	4.6	1.35	1.52
Bw1	15-30	10YR 5/3	7.5YR 3/3	5.3	0.21	1.19
Bw2	30-58	10YR 5/4	7.5YR 3/3	5.3	0.12	0.64
2BC	58-81+	2.5Y 6/4	2.5Y 4/4	5.2	0.19	0.14
Pedon 166 - Spodosol						
O	0-7	-	-	4.3	0.40	41.95
E	7-8	10YR 5/1	10YR 3/1	4.0	-	15.93
Bs	8-16	10YR 4/3	7.5YR 3/2	4.9	1.36	3.28
Bw1	16-31	10YR 5/4	10YR 3/4	5.4	0.23	1.89
2Bw2	31-42	10YR 5/3	10YR 3/3	4.9	0.85	1.01
2BC	42-57+	2.5Y 6/3	2.5Y 4/4	5.1	0.64	0.24
Pedon 167 - Spodosol						
O	0-7	-	-	4.2	0.58	38.39
E	7-10	10YR 5/1	10YR 3/1	3.8	5.94	8.19
Bhs	10-14	10YR 4/3	7.5YR 2.5/2	4.4	2.62	5.10
Bs1	14-26	10YR 4/3	7.5YR 2.5/2	4.3	4.09	4.33
Bs2	26-40	10YR 4/3	7.5YR 2.5/2	4.4	3.37	3.71
Bw1	40-57	10YR 4/4	7.5YR 3/3	4.7	1.47	3.08
Bw2	57-70	10YR 5/4	7.5YR 3/3	4.7	1.11	2.82
2BC	70-78	2.5Y 5/4	10YR 4/4	4.7	1.31	0.63
Pedon 175 - Spodic intergrade						
O	0-2	-	-	4.5	0.40	42.26
E	2-5	10YR 4/2	10YR 3/1	4.4	2.06	9.83
Bs	5-20	10YR 4/3	7.5YR 2.5/2	4.9	1.27	5.15
Bw	20-43	10YR 5/4	10YR 3/4	5.1	0.45	3.41
2BC	43-61+	10YR 5/4	10YR 4/4	5.2	0.12	1.24
Pedon 177 - Spodic intergrade						
O	0-3	-	-	4.2	0.80	41.16
E	3-6	10YR 4/1	10YR 3/1	4.0	3.57	11.95
Bs	6-9	10YR 5/4	7.5YR 3/3	4.5	1.75	2.84
Bw1	9-31	10YR 5/4	10YR 3/3	4.9	0.78	2.27
2BC	31-51+	2.5Y 6/4	2.5Y 4/4	4.9	0.44	0.41

Horizon	Depth (cm)	Dry Color	Moist Color	pH	KCl Al (cmol$_c$/kg)	Organic C (%)
Pedon 179 - Spodic intergrade						
O	0-6	-	-	4.1	0.65	40.29
E	6-7	10YR 3/2	10YR 3/1	3.4	8.41	13.91
Bhs	7-12	7.5YR 5/4	7.5YR 3/2	4.4	0.91	2.24
Bw1	12-27	10YR 4/6	7.5YR 3/3	4.5	0.35	2.04
Bw2	27-50	10YR 4/6	7.5YR 3/4	4.9	0.09	1.84
2BC	50-84+	10YR 5/4	10YR 3/6	4.4	0.79	0.44
Pedon 187 - Andisol						
O	0-4	-	-	4.6	0.09	45.41
Bw1	4-13	10YR 5/4	10YR 3/3	5.8	0.04	0.71
Bw2	13-37	10YR 5/4	10YR 3/4	5.7	0.07	0.70
BC	37-63+	10YR 5/4	10YR 3/4	5.5	0.16	0.73
Pedon 199 - Andisol						
O	0-3	-	-	5.0	0.20	44.97
Bw1	3-9	7.5YR 5/4	7.5YR 3/3	5.2	0.16	1.72
Bw2	9-25	7.5YR 5/4	7.5YR 3/4	5.1	0.18	1.56
2BC	25-49+	10YR 6/3	10YR 4/3	5.0	0.04	0.50
Pedon 207 - Andisol						
O	0-8	-	-	4.4	0.26	41.10
Bw1	8-23	10YR 4/3	10YR 3/2	5.0	0.63	2.42
Bw2	23-38	10YR 4/3	10YR 3/2	5.3	0.18	1.39
Bw3	38-54	10YR 5/4	10YR 3/3	5.5	0.04	1.13
2BC	54-70+	10YR 5/4	10YR 3/3	5.1	0.48	2.76
Pedon 208 - Spodosol						
O	0-4	-	-	4.4	0.50	42.39
E	4-6	10YR 6/2	10YR 4/2	4.0	3.11	1.08
Bs	6-12	10YR 5/4	7.5YR 3/4	5.1	0.21	1.56
Bw1	12-21	10YR 5/4	10YR 3/4	5.1	0.27	1.43
Bw2	21-34	10YR 5/4	10YR 3/4	5.1	0.12	1.30
2Bw3	34-47	10YR 6/4	10YR 4/4	5.0	0.35	0.48
2Bw4	47-53+	10YR 6/4	10YR 4/4	4.8	0.46	0.54
Pedon 222 - Spodic intergrade						
O	0-6	-	-	4.2	0.49	40.63
E	6-9	10YR 4/2	10YR 3/1	4.9	0.35	6.54
Bs1	9-20	10YR 4/3	7.5YR 3/2	4.5	1.40	2.81
Bs2	20-30	10YR 5/4	10YR 3/3	4.8	0.75	2.61
Bw	30-45	10YR 5/4	10YR 3/4	4.8	0.54	1.64
2BC	45-70+	2.5Y 6/3	2.5Y 5/4	4.7	0.40	0.17

Horizon	Depth (cm)	Dry Color	Moist Color	pH	KCl Al (cmol$_c$/kg)	Organic C (%)
Pedon 224 - Andisol						
O	0-6	-	-	4.3	0.00	42.96
Bw1	6-17	10YR 4/3	10YR 3/2	4.5	0.14	1.71
Bw2	17-33	10YR 5/4	10YR 3/3	4.8	1.27	1.03
Bw3	33-46	10YR 5/4	10YR 3/4	5.1	0.73	0.76
2BC	46-66+	10YR 6/3	2.5Y 5/3	4.9	0.40	0.08
Pedon 228 - Andisol						
O	0-6	-	-	4.7	0.20	39.83
Bw1	6-21	7.5YR 4/4	7.5YR 3/3	5.4	0.22	2.80
Bw2	21-43	10YR 5/4	7.5YR 3/4	5.5	0.02	1.01
Bw3	43-51+	2.5Y 6/4	2.5Y 4/4	5.1	0.25	0.17
Pedon 232 - Spodic intergrade						
O	0-5	-	-	4.5	0.31	41.99
E	5-8	10YR 5/3	10YR 3/1	4.6	1.52	4.95
Bs	8-17	10YR 5/4	7.5YR 3/3	5.3	0.42	3.86
Bw1	17-28	10YR 4/4	7.5YR 3/3	5.3	0.28	3.77
Bw2	28-41	10YR 5/4	7.5YR 3/4	5.3	0.05	1.47
2BC	41-51+	10YR 4/4	10YR 3/6	5.2	0.30	0.52
Pedon 245 - Spodosol						
O	0-3	-	-	4.1	0.76	36.80
E	3-7	10YR 5/2	10YR 3/1	4.3	2.49	2.25
Bhs	7-8	10YR 4/4	7.5YR 3/3	5.0	0.23	2.24
Bs	8-16	10YR 5/4	10YR 3/4	5.3	0.02	2.15
Bw1	16-32	10YR 5/4	10YR 4/4	5.2	0.03	1.89
Bw2	32-51	10YR 6/4	10YR 4/4	5.0	0.11	0.41
2BC	51-59+	2.5Y 6/4	2.5Y 5/4	4.8	0.14	0.13
Pedon 253 - Spodosol						
O	0-5	-	-	4.5	0.55	33.91
E	5-7	10YR 6/2	10YR 4/2	4.9	0.39	0.50
Bs	7-15	10YR 5/4	7.5YR 3/4	5.3	0.13	1.24
Bw1	15-32	10YR 5/4	10YR 3/4	5.5	0.02	0.96
Bw2	32-51	10YR 5/4	10YR 3/4	5.4	0.03	1.00
2BC	51-59+	2.5Y 6/3	2.5Y 5/4	5.3	0.13	0.12
Pedon 260 - Spodosol						
O	0-10	-	-	4.8	0.16	38.12
E	10-13	10YR 5/2	10YR 3/1	4.6	1.08	8.65
Bs1	13-25	10YR 4/3	7.5YR 2.5/2	4.7	1.43	3.45
Bs2	25-45	10YR 4/4	7.5YR 3/2	4.9	0.93	2.89
Bw	45-60	10YR 4/4	7.5YR 3/2	4.8	1.07	3.28
2BC	60-70+	10YR 6/4	10YR 4/4	4.8	0.42	9.31

APPENDIX C: BASAL AREA OF DOMINANT OVERSTORY SPECIES

Site ID	Soil Type	Basal Area per Acre								
		TSHE	THPL	PIEN	ABLA	ABGR	LAOC	PSME	PIPO	Total
4	And	0.0	0.0	0.0	0.0	19.2	30.4	0.0	0.0	49.6
8	And	0.0	90.0	0.0	0.0	0.0	3.9	221.6	0.0	315.5
12	And	0.0	25.3	1.4	0.0	0.0	16.0	4.9	0.0	47.6
23	Spod	188.3	547.6	3.8	4.4	0.0	0.0	0.0	0.0	744.1
25	And	49.0	127.4	0.0	0.0	0.0	22.7	13.8	0.0	213.0
32	Spod	186.5	221.9	38.9	146.4	0.0	36.7	0.0	0.0	630.4
37	Spod	29.3	0.0	93.1	65.8	0.0	71.3	0.0	0.0	259.5
41	And	0.0	2.9	77.7	26.8	0.0	120.8	0.0	0.0	228.2
43	Spod	0.0	0.0	153.4	96.5	0.0	0.0	0.0	0.0	249.9
48	Spod	185.7	217.2	0.0	0.0	0.0	0.0	0.0	0.0	402.9
52	And	0.0	0.0	0.0	0.0	0.0	0.0	126.3	35.6	161.9
53	Spod	2.3	28.2	0.0	0.0	9.8	0.0	0.0	0.0	40.3
55	Int	248.5	218.0	0.0	0.0	0.0	0.0	0.0	0.0	466.5
56	And	64.5	30.6	0.0	0.0	156.0	0.0	159.8	0.0	410.9
57	Int	0.0	114.8	0.0	0.0	0.0	22.7	53.1	0.0	190.6
61	Spod	47.5	25.4	0.0	0.0	0.0	12.1	39.7	0.0	124.7
63	And	0.0	1.5	0.0	23.0	185.8	0.0	0.0	0.0	210.2
66	And	0.0	0.0	0.0	0.0	9.7	12.6	85.5	13.3	121.2
70	Spod	51.4	95.9	0.0	0.0	21.6	44.4	30.8	0.0	244.1
72	Int	0.0	0.0	59.0	0.0	4.3	144.7	0.0	0.0	208.0
73	Int	83.6	79.7	0.0	19.0	0.0	0.0	206.3	0.0	388.6
78	Spod	0.0	0.0	121.2	74.0	0.0	0.0	0.0	0.0	195.2
85	Spod	57.9	154.0	99.3	22.6	0.0	0.0	0.0	0.0	333.9
99	And	58.9	66.0	0.0	0.0	1.5	0.0	125.9	0.0	252.3
118	Spod	120.6	158.2	89.3	114.7	0.0	0.0	0.0	0.0	482.8
127	Spod	42.8	324.1	0.0	37.1	0.0	0.0	0.0	0.0	404.0
147	And	0.0	0.0	0.0	0.0	0.0	27.7	45.0	61.0	133.7
151	Spod	125.6	55.7	0.0	0.0	0.0	0.0	0.0	0.0	181.2
166	Spod	0.0	7.8	42.1	45.5	0.0	47.0	5.8	0.0	148.1
167	Spod	0.0	0.0	36.4	108.5	0.0	0.0	0.0	0.0	144.9
175	Int	0.0	0.0	0.0	23.8	0.0	22.8	297.9	0.0	344.5
177	Int	0.0	0.0	0.0	5.7	13.0	3.0	5.4	0.0	27.0
179	Int	0.0	0.0	31.4	103.2	0.0	32.2	44.3	0.0	211.1
187	And	0.0	0.0	0.0	0.0	29.8	12.1	87.9	0.0	129.8
199	And	6.8	139.5	1.5	0.0	0.0	2.7	105.8	0.0	256.3
207	And	156.2	281.8	0.0	0.0	15.0	0.0	0.0	0.0	453.0
208	Spod	83.5	38.3	0.0	74.8	0.0	15.8	0.0	0.0	212.5

Appendix C continued

Site ID	Soil Type	Basal Area per Acre								
		TSHE	THPL	PIEN	ABLA	ABGR	LAOC	PSME	PIPO	Total
224	And	0.0	121.2	105.0	4.5	0.0	65.9	24.9	0.0	321.5
228	And	182.5	77.2	0.0	0.0	0.0	0.0	0.0	0.0	259.7
232	Int	70.5	134.4	6.6	0.0	0.0	93.4	0.0	0.0	304.9
245	Spod	56.4	15.2	0.0	4.2	0.0	48.3	13.3	0.0	137.4
253	Spod	27.8	10.3	7.7	7.1	0.0	0.0	18.7	0.0	71.5
260	Spod	78.8	447.3	14.3	8.9	0.0	0.0	0.0	0.0	549.4

APPENDIX D: SUMMARY SITE AND VEGETATION DATA

Site ID	Soil Type	Habitat Type	Forest Type	C top 50 cm (Mg/ha)
4	Andisol	TSHE/CLUN	ABGR/PSME/LAOC	86.9
8	Andisol	THPL/CLUN	ABGR/PSME/LAOC	141.2
12	Andisol	THPL/CLUN	THPL/TSHE	100.6
23	Spodosol	TSHE/GYDR	THPL/TSHE	138.2
25	Andisol	TSHE/ASCA	THPL/TSHE	112.9
32	Spodosol	TSHE/CLUN	THPL/TSHE	105.2
37	Spodosol	TSHE/CLUN	ABLA/PIEN	146.6
41	Andisol	ABLA/CLUN	ABGR/PSME/LAOC	117.6
43	Spodosol	ABLA/CLUN	ABLA/PIEN	175.3
48	Spodosol	TSHE/GYDR	THPL/TSHE	103.4
52	Andisol	ABGR/VAGL	ABGR/PSME/LAOC	123.9
53	Spodosol	TSHE/CLUN	THPL/TSHE	36.6
55	Intergrade	THPL/ATFI	THPL/TSHE	160.5
56	Andisol	TSHE/CLUN	ABGR/PSME/LAOC	115.4
57	Intergrade	THPL/CLUN	THPL/TSHE	133.8
61	Spodosol	TSHE/CLUN	THPL/TSHE	115.7
63	Andisol	TSHE/ASCA	ABGR/PSME/LAOC	158.4
66	Andisol	ABGR/SPBE	ABGR/PSME/LAOC	109.3
70	Spodosol	THPL/CLUN	THPL/TSHE	65.6
72	Intergrade	ABGR/CLUN	ABGR/PSME/LAOC	174.6
73	Intergrade	TSHE/CLUN	ABGR/PSME/LAOC	117.8
78	Spodosol	ABLA/STAM	ABLA/PIEN	215.2
85	Spodosol	TSHE/CLUN	THPL/TSHE	204.1
99	Andisol	TSHE/CLUN	ABGR/PSME/LAOC	48.7
118	Spodosol	TSHE/CLUN	THPL/TSHE	120.7
127	Spodosol	TSHE/CLUN	THPL/TSHE	75.1
147	Andisol	PSME/PHMA	ABGR/PSME/LAOC	48.6
151	Spodosol	TSHE/ASCA	THPL/TSHE	73.7
166	Spodosol	THPL/CLUN	ABLA/PIEN	112.5
167	Spodosol	ABLA/CLUN	ABLA/PIEN	204.0
175	Intergrade	ABLA/VAGL	ABGR/PSME/LAOC	194.5
177	Intergrade	ABGR/VAGL	ABGR/PSME/LAOC	113.9
179	Intergrade	ABLA/XETE	ABLA/PIEN	149.2
187	Andisol	ABGR/CLUN	ABGR/PSME/LAOC	50.7
199	Andisol	THPL	THPL/TSHE	65.3
207	Andisol	TSHE/CLUN	THPL/TSHE	135.2
208	Spodosol	TSHE/CLUN	THPL/TSHE	76.0
222	Intergrade	THPL/CLUN	THPL/TSHE	128.2
224	Andisol	TSHE/CLUN	THPL/TSHE	79.7

Appendix D continued

Site ID	Soil Type	Habitat Type	Forest Type	C top 50 cm (Mg/ha)
232	Intergrade	TSHE/CLUN	THPL/TSHE	130.0
245	Spodosol	THSE/GYDR	THPL/TSHE	78.2
253	Spodosol	TSHE/CLUN	THPL/TSHE	67.3
260	Spodosol	TSHE/ASCA	THPL/TSHE	192.4