SOIL ORGANIC CARBON AND SITE CHARACTERISTICS IN ASPEN AND EVALUATION OF THE POTENTIAL EFFECTS OF CONIFER ENCROACHMENT ON SOIL PROPERTIES IN NORTHERN UTAH

by

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ABSTRACT

Soil Organic Carbon and Site Characteristics in Aspen and Evaluation of the Potential Effects of Conifer Encroachment on Soil Properties in Northern Utah

by

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In the Intermountain West, aspen (*Populus tremuloides*) has declined mainly due to a combination of successional processes, fire suppression and long-term use of ungulates which has led to replacement by conifers, sagebrush or other shrub communities. Conifer encroachment is believed to cause critical changes in the ecosystem properties. In order to understand the impacts of conifer encroachment on soil properties such as soil organic carbon (SOC) storage, soil morphology, and soil chemical properties, and the implications of such changes, it is very important to assess the soil properties under the two vegetation types. The objectives of this study were to i) quantify SOC stocks and their variability in pure aspen forests; ii) evaluate the role of various biotic and abiotic site parameters as drivers of this SOC; iii) evaluate the effect of conifer encroachment on SOC storage, soil morphology, soil microclimate and soil chemical properties. The study was conducted in three catchments in Northern Utah in two phases: i) a transect study with 33 sampling points in a pure aspen community; ii) a paired plot study based on comparing six plots in to aspen and nearby conifer plots as representatives of end-member communities. Soils under aspen were mainly Mollisols, whereas the soils associated with conifers were classified as Alfisols, Inceptisols and Entisols. Even under pure aspen there was a significant SOC variability among sampling points and aspects, and SOC was negatively correlated with soil moisture index and average tree diameter and positively correlated with vegetation density. The paired plot comparison showed that SOC in the mineral soil (0-60 cm) was significantly higher under aspen, while O horizon thickness and C content was higher under conifers. The total SOC (O layer + mineral soil) was not significantly different among the vegetation types, suggesting an upward redistribution of SOC in conifer soils. The soil moisture in summer was also higher under aspen compared to conifers. Other chemical properties were not affected by vegetation types. Our study indicates that i) no differences in SOC can be detected in surface soil horizons (<20 cm); ii) SOC is highly variable and greatly influenced by soil moisture and forest characteristics; iii) conifer encroachment is likely to alter soil microclimatic and SOC amount and distribution.

(163 pages)

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CONTENTS

Page

ABSTRACT…………………………………………………………………….......iii

ACKNOWLEDGMENTS…………………………………………………….....v

LIST OF TABLES...………………………………………………………….......viii

LIST OF FIGURES………………………………………………………….....ix

CHAPTER

1. INTRODUCTION……………………………………………………...1

   ASPEN and CONIFER ENCROACHMENT 1
   STUDY OBJECTIVES and HYPOTHESES 7

2. LITERATURE REVIEW 12

   ASPEN in the WEST 12
   CHANGE in the VEGETATION COVER and SOIL PROPERTIES 15
   SOIL ORGANIC CARBON STORAGE 17
   FACTORS CONTROLLING SOC ACCUMULATION 19

3. STUDY AREA 25

   SITE DESCRIPTION 26
   EXPERIMENTAL DESIGN 27

4. SOIL ORGANIC CARBON STORAGE UNDER PURE ASPEN STANDS AND ITS RELATIONSHIP WITH SITE CHARACTERISTICS IN NORTHERN UTAH……………………....36

   INTRODUCTION 36
   METHODS and MATERIALS 39
   RESULTS and DISCUSSION 45
   CONCLUSION 53

5. EVALUATION OF THE POTENTIAL EFFECTS OF CONIFER ENCROACHMENT: A PAIRED PLOT STUDY……………………….69

   INTRODUCTION 69
   MATERIALS and METHODS 72

RESULTS and DISCUSSION 80
CONCLUSION 90

6. SUMMARY AND CONCLUSIONS……………...................................120

REFERENCES……………………………………………………………………125

APPENDIX………………………………………………………………………136

LIST OF TABLES

Table Page

4.1 General characteristics of the sampling site along the four Transects …..……………………………………………………………. 55

4.2 Selected properties of the soil pedons sampled in 2005 along the four transects ....……………………………………... 56

4.3 Winter and summer nutrient availability regime determined from the PRS-probes installed along the four transects ..………………. 57

4.4 Correlation coefficients between SOC to a depth 0-10 cm and 0-40 cm and site characteristics …………………………………………… 58

5.1 Soil morphology, chemical, physical properties of pedons………………... 94

5.2 Estimated winter and summer dynamic nutrient regime of the paired plots………………………………………………………………………… 97

5.3 Exchaengeable cation pools with depth under two vegetation types……………………………………………………………………... 98

5.4 Stand characteristics in the paired plots………………………………..... 101

LIST OF FIGURES

Figure Page

3.1 Relative location of the study sites at DLL………………………………….. 33

3.2 Geological map of the watershed at DLL……………………………………. 34

3.3 Relative location of the study sites at TWDEF………………………………. 35

4.1 Maps of the study area in the Upper Frost Canyon at DLL……………………………………………………………….......... 59

4.2 Soil organic carbon storage in the top 0-10 cm and 0-40 cm mineral soil ……………………………………...…………...………... 60

4.3 Cumulative moisture index for the transect points during summer 2005 and summer 2006 by aspect…………………………………… 61

4.4 Soil moisture index for the transect points during summer 2005 and 2006………………………..…………………………………………………... 62

4.5 Soil temperature along the four transects expressed in degree days………… 63

4.6 Tree density by aspect……………………………………….…………….. 64

4.7 Average tree diameter by aspect ………………..……………….……… 65

4.8 Regression analysis of SOC (0-40 cm) and cumulative moisture index (log transformed)…………………………………………….. 66

4.9 Regression analysis of SOC (0-40 cm) and density (square root transformed) ……………………………………………. 67

4.10 Regression analysis of SOC (0-40 cm) and average tree diameter (log transformed)……………………...……………………………...…… 68

5.1 Location of the paired plots in the watersheds at DLL………………………………………………………………........... 102

5.2 Aerial photo with the delineated watershed and the paired plots at TWDEF……………………………………………………………...... 103

Figure Page

5.3 Schematic presentation of how the plots are setup with corresponding instruments………………………………………………………………… 104

5.4 Soil moisture calibration curves for the aspen (a) and conifer (b) soils in Upper Frost at DLL……………………………………………………….. 105

5.5 Soil moisture calibration curves for the aspen (a) and conifer (b) soils in Bear Canyon at DLL………………………………………………………. 106

5.6 Typical pedon under aspen (A) and conifer (B)…………………………... 107

5.7 Carbon concentration along soil depth in aspen soils. Solid symbols represent pedon samples; open symbols represent soil cores (0-15 cm)…….. 108

5.8 Carbon concentration along soil depth in conifer soils. Solid symbols represent pedon samples; open symbols represent soil cores (0-15 cm)…….. 109

5.9 Soil organic carbon storage in aspen and conifer pedons (0-60 cm)………… 110

5.10 Average SOC distribution in the mineral soil……………………………….. 110

5.11 Total soil organic carbon storage (forest floor + mineral soil) in aspen……... 111

5.12 Total soil organic carbon storage (forest floor + mineral soil) in conifer…………………………………………………………………... 111

5.13 Cumulative moisture index (summer 07) presented by area under the curve in aspen and conifer in Upper Frost Canyon………………………………… 112

5.14 Cumulative moisture index (summer 07) presented by area under the curve in aspen and conifer in Bear Canyon…………... 113

5.15 Cumulative moisture index (summer 07) presented by area under the curve in aspen and conifer in TWDEF……………... 114

5.16 Average daily temperature in aspen and conifer in Upper Frost Canyon (FA1, FA2) and in Bear Canyon (BA)……………………………………… 115

5.17 Average daily temperature in aspen (TA2) and conifer (TC2) at TWDEF…... 116

Figure Page

5.18 Regression analysis of SOC (0-60 cm) and cumulative moisture index………………………………………………………………………….. 117

5.19 Regression analysis of SOC (0-60 cm) and tree density………………………………………………………………………… 118

5.20 Regression analysis of SOC (0-60 cm) and average tree diameter ……………………………………………………………………………... 119

CHAPTER 1

INTRODUCTION

Aspen and Conifer Encroachment

Quaking aspen (*Populus tremuloides* Michx) is the most widely distributed tree species in North America (Baker 1925; Little 1979), exists within a great diversity of ecological settings, and exhibits a similar diversity of ecological roles (DeByle 1985; Romme et al. 2001). In the west, 75 % of the aspen occurs in Colorado (50%) and Utah (25%) (Bartos 2001). Aspen condition in the west is categorized into three types (Bartos and Campbell 1998): a) stable, where aspen is considered properly functioning and self-replacing; b) successional to conifers, where disturbance forces such as fire are altered by humans giving shade tolerant species like conifers a marked advantage; and c) decadent, where aspen clones are generally of a single age and very open and mature trees are not replaced.

Aspen-dominated forests in the west have numerous ecological and economical values such as forage for livestock, habitat for wildlife, landscape diversity, esthetics, and water yield (DeByle and Winokur 1985; Bartos 2001). However, there has been a great concern that aspen has been declining in the west, followed by the replacement by conifers. It has been argued that this recent ecosystem change is outside the range of historical variation and has been deemed as an ‘‘environmental catastrophe’’ (Club 20 1998).

According to Campbell and Bartos (2001) aspen is a keystone species, meaning that it influences the survival and abundance of many other species in the community in which it lives. Its removal or addition results in a relatively significant shift in the composition of the community and sometimes even in the physical structure of the environment (Wilson 1992). In the case where some of the natural disturbance forces (primarily fire) are altered by human intervention, aspen-dominated landscapes convert to mixed-conifer, which is followed by loss of ecosystem functions that modify the sites dramatically. One of these functional alterations can be water depletion as conifers use more water than aspen. This loss of water means that it is not available to produce undergrowth vegetation, recharge soil profiles, or increase streamflow. Our understanding of the impacts of conifer encroachment on soil properties such as soil organic carbon (SOC) storage, soil morphology, and soil chemical properties; and the implications of these changes are still unclear because not many specific studies have been done. However, it is generally known that the succession of communities, which is defined as sequential change in the relative abundance of dominant species in a community following disturbances (Huston and Smith 1987), often alters the chemical, physical, and biological properties of the soil through their occupancy. Such alterations, in turn, can contribute to the relative change in abundance of the dominant species that characterizes succession (Fisher and Binkley 2000).

Effect of Conifer Encroachment on Soil Properties

Soil Organic Carbon Storage

Aspen forests differ from associated vegetation types in amount, distribution, and character of organic matter and nutrients (Jones and DeByle 1985). Hoff (1957) carried out an aspen and conifer paired plot study and found that SOC in the upper A horizon was higher in aspen than in conifers. Tew (1968) also found that the organic matter in the upper 15 cm under aspen in Northern Utah was 4% higher than adjacent stands of shrubs and herbaceous vegetation. However, some studies in Minnesota (Alban 1982) and Canada (Paré and Bergeron 1996), respectively, have shown that the organic matter content was lower in aspen compared to spruce and pine forests, even though nutrient accumulation was greater under aspen than under conifers. The lower SOC under conifers compared to aspen soils can be due to lower input of litter, higher organic matter turnover rates, or a combination of both. If conifer soils are indeed characterized by lower organic carbon, then conifer encroachment can potentially cause a change of SOC storage, and small changes in SOC storage are believed to have a significant effect on atmospheric CO_2 concentrations (Kirschbaum 2000; Amundson 2001). There is a clear need to understand total carbon storage under the two vegetation types and the various controlling factors. C storage is a net result of the processes of primary production and decomposition. Alterations in carbon inputs, losses and their controlling factors influences C storage (Grigal and Ohmann 1992).

The major factors that have been found to control SOC are climate, vegetation, elevation, terrain position and soil texture. The relationship between SOC and site characteristics can be variable depending on the spatial scale, geographic location, and vegetation type. The relationship between SOC and climate has been explicitly studied at large and small scales. SOC generally increases with increasing precipitation and decreasing temperature (Post et al. 1982; Burke et al. 1989; Jobbagỳ and Jackson 2000; Homann, Kapchinske, and Boyce 2007) at large and small scales. SOC increases generally with elevation and decreases linearly as terrain shape shifts from concave to convex (Trumbore, Chadwick, and Amundson 1996; Conant et al. 1998; Bolstad and Vose 2001). Soil texture has also been considered as a major factor controlling SOC

(Burke et al. 1989; Grigal and Ohmann 1992) through its vital role in the physical protection of the organo-mineral complexes (Six et al. 2002).

The presence and distribution of specific vegetation types in a site can affect site micro-climatic conditions such as soil moisture, which in turn can contribute to changes in C storage. Studies in the Intermountain West indicate that the average shallow soil moisture is higher in the aspen plots relative to the adjacent conifer plots (LaMalfa and Ryel 2008), which might be attributed to higher winter snow accumulation in aspen than conifer stands. Similar studies in Montana (Moore and McCaughey 1997) and hydrological modeling based on hydrological process research in Russia and Canada (Gelfan, Pomeroy, and Kuchment 2004) have also reported that snow accumulation is 15-40% lower in conifers relative to deciduous or open stands, which might contribute to the lower soil moisture status of the conifers relative to the aspen stands. The restricted moisture availability affects undergrowth vegetation, which is followed by a substantial decrease in species richness. Moreover the loss of water as a result of conifer encroachment means that it is not available to recharge soil profiles and causes a decrease in streamflow (Bartos 2001).

Amacher et al. (2001) hypothesized that the soil temperature is also affected by succession. Stable aspen stands have relatively cooler soil temperature compared to decadent aspen, even at shallower depths, as a result of relative canopy cover in stable aspen compared to the decadent ones. However, the temperature is not as cool as under the mixed stands because of the shading effect of conifers. According to the Cryer and Murray (1992) ecological succession model, soil temperature is also believed to decrease as conifer invasion occurs. The decrease in temperature as a result of conifer encroachment can affect decomposition by decreasing microbial activity, thus favoring the accumulation of soil organic matter, because microbial activity increases exponentially with increasing temperature (Edwards 1975). The increase in conifer dominated lands can adversely affect many site characteristics that are at the same time controlling factors for carbon storage.

The amount of SOC in soil is also affected by the quality and quantity of litter input. Several studies have shown that aspen litter decomposes much more rapidly than the litter of associated western coniferous forest (Bartos and DeByle 1981; Perala and Alban 1982; Prescott et al. 2000). The difference in the rate of decomposition could be due to the difference in litter quality of the two vegetation types where aspen leaves have higher nutrient concentration and lower lignin and polyphenol concentrations compared to coniferous litter (Perry, Choquette, and Schroeder 1987) together with environmental factors that control the metabolic rate of organisms such as temperature, moisture, pH and aeration (Perala and Alban 1982). The above factors are of a special interest because they are the main controls for the dynamics of the pool of carbon in soils, which according to Schlesinger (1997) can be classified in two stages: 1) process leading to rapid turnover of litter at the surface and 2) process leading to slower production, accumulation and turnover of humus at depth.

Soil Chemical and Physical Properties

Aspen are considered to be efficient nutrient pumps (Lutz and Chandler 1946; Jones and DeByle 1985). Nutrient pumping is the nutrient capture by trees from subsoil, released by weathering of primary minerals and/or nutrients leached from the topsoil that are then recycled by trees and re-deposited near the soil surface. This phenomenon is common in deep rooted trees (Schroth and Lehmann 2003). Aspen is believed to enrich the surface horizons with nutrients not only by the accumulation of humus, but also by its nutrient pumping capability, bringing minerals such as Ca, K and Mg from greater depths, where a network of fine feeder roots is found (Stoeckler 1961). This contributes to the relatively higher pH and base saturation of soils under aspen (Hoff 1957; Morgan 1969; Tew 1968; Alban 1982; Paré, Bergeron, and Camire 1993), which might be related to high Ca requirements of this species (Alban 1982). However, when other vegetation types encroach aspen, soil pH drops to 6.0 or lower, accompanied by a decrease in nutrient level. The lower pH and nutrient levels are postulated to suppress aspen regeneration (Cryer and Murray 1992).

Moreover, conifer encroachment is believed to cause changes in soil forming processes and soil morphology. Cryer and Murray (1992) postulated that stable or permanent stands of aspen are found only on one soil order: Mollisols. In contrast, soils developed under conifers in the Intermountain West are primarily Alfisols characterized by a thick O horizon and relatively thin A horizon (Cryer and Murray 1992). When conifers encroach into aspen stands, the mollic epipedon thins while the albic horizon thickens, which is followed by decreases in soil pH, organic matter, cation exchange capacity (CEC) and nutrients availability.

However, there has been insufficient research done to draw broad conclusions that the occurrence of aspen stand is specifically in one soil order and that conifer encroachment significantly alters the soil morphology. Studies specifically focusing on aspen soil in the Intermountain West have remained limited. To understand contemporary aspen ecosystem condition changes following conifer encroachment, it is vital to understand and investigate the various soil properties that are believed to alter as vegetation type changes.

As much as 25 % of the aspen in the west is located in Utah and many researchers hypothesized that the conifer encroachment can have detrimental effect on these aspen stands. Yet, the hypothesized loss of ecosystem functions and changes in soil properties resulting from conifer encroachment has not been extensively studied. So in this study we will investigate different soil properties associated with aspen and conifers and assess how the differences in soil properties between aspen and conifers can affect ecosystem functions as conifers progressively invade aspen sites.

In this study, the effect of conifer encroachment on soil chemical and physical properties of aspen soils will be studied by focusing on soil organic carbon (SOC), because it influences site quality and productive capacity, and controls many physical, chemical and biological properties of soil, and is believed as an important factor in the persistence of aspen stands (Cryer and Murray 1992). Changes in SOC can also be important to the overall global carbon cycle (Lal et al. 1998). In order to have a better understanding of the effect of conifer encroachment on soil properties, it is essential to look at how SOC and associated chemical and physical properties of the soil vary in aspen forests and change in presence of conifers.

Study Objectives and Hypotheses

In order to understand the effect of conifer encroachment on SOC storage and other inherent soil properties, it is necessary to first understand the total SOC storage dynamics in the stable aspen stands and to investigate what causes variations in SOC.

Moreover, in order to draw conclusions about the effect of conifer encroachment in altering critical aspen ecosystem properties, it is important to compare soil properties between the two vegetation types.

The objectives of this study are to

i. Quantify the amount of SOC under aspen and assess the variability in SOC pool size.
ii. Look at the various biotic and abiotic drivers of SOC variability, including elevation, slope, aspect, soil microclimate and as well as overstory characteristics.
iii. Evaluate the potential effects of conifer encroachment by looking at site characteristics such as SOC storage, soil morphology, soil microclimate and soil chemical properties of aspen and conifer as representatives of end-point communities.

Specific study hypotheses are that:

H1: *SOC will not be constant under stable aspen; SOC is expected to change spatially as a function of multiple site characteristics that affect both carbon input and decomposition***.**

Total SOC storage is specifically expected to be different among the four aspects where northern and eastern facing sites will have higher SOC content than southern and western facing sites. The higher amount of SOC in the northern and eastern facing sites may be due to slower turnover rates as a result of lower temperature, a condition that slows down decomposition. The other important site characteristic that is expected to influence SOC storage is the aboveground vegetation cover as it controls input through litterfall and canopy openness. The latter contributes to changes in soil microclimate such as increase of soil temperature that can hasten decomposition.

H2: *Conifer encroachment is expected to have a significant impact on SOC, nutrients and soil properties.*

H2A. SOC storage is expected to be lower under conifers compared to aspen ecosystem. The lower amount of SOC under conifers might be due to a set of multiple processes such as lower litterfall input, greater decomposability of SOC under conifers, and higher turnover rates due to more favorable microclimate.

H2B. Chemical soil properties such as nutrient availability and pH are expected to be different under conifers compared to the aspen soil. This may be due to the type and concentration of organic acids produced as the result of the decomposition. In addition, it may be due to a higher amount of Ca present in the litter of aspen compared to the conifers, which augments the amount of exchangeable Ca in the soil as a result of decomposition, thus reducing soil acidity and increasing base saturation in the aspen soils.

H2C. The soil morphology is expected to be different under aspen and conifers. Aspen soils are expected to be in the soil order Mollisols and conifer soils are expected to be in the soil order Alfisols. Mollisols under aspen develop as the leaves are rapidly decomposed in the surface, various pedogenic processes such as humification occur at deeper depths where stable humus is formed, which is composed of complex organic compounds synthesized by the soil organisms and resistant polymers of phenolic and aromatic functional groups.

The amount of SOC will be estimated along linear transects established in the four aspects in a small watershed and the various drivers will be measured at the same locations where SOC will be quantified. It is generally expected that SOC will vary with aspect and most of the variability is expected to be explained mainly by changes in vegetation cover and soil microclimate. The results obtained through the paired plot analysis of adjacent aspen and conifer stands will also help to ascertain the extent to which conifer encroachment impacts soil properties.

Thesis Organization

The study is presented as follows:

Chapter 2. *Review of Literature*: this part includes a review of research reports relevant to the factors controlling SOC in general and at different scales, SOC storage under aspen, and the effect of conifer encroachment on soil properties. I look at various approaches and procedures used to estimate SOC storage and relationships with site characteristics, and also to evaluate the effect of conifer encroachment.

Chapter 3. *Study Area*: this part of the study includes description of the study area and also the experimental design of this study.

Chapter 4. *Soil Organic Carbon Storage and Site Characteristics of Aspen Ecosystem*: in this chapter, I present the amount of SOC stored under aspen and the relationship of SOC with the various site characteristics. In addition general inherent soil properties such as microclimate, nutrient regime, pH and CEC of aspen soils will be presented.

Chapter 5. *Site characteristics of aspen and conifer as end point communities*: in this chapter, I present the difference of SOC and other soil properties among the two different vegetation types from data obtained through paired plot analysis.

Chapter 6. *Summary and Conclusions*: this part of the thesis summarizes the results and contributions of this study and discusses the implications for further research.

CHAPTER 2

LITERATURE REVIEW

Aspen in the West

Aspen is the most abundant tree species in Canada's central provinces and the U.S. states of Colorado and Utah (Jones 1985; Lieffers, Landhäusser, and Hogg 2001). In the western U.S., aspen is a shade intolerant species that is unique compared to most western forest trees, because it reproduces primarily by suckering from the parent root system, and disturbance or dieback is necessary to stimulate its regeneration (Bartos and Campbell 1998). Aspen is an important tree species throughout the western United States; it is one of few broad-leaved hardwood trees in many western forests, and it is a valuable ecological component of many landscapes; occurring in pure forest as well as growing in association with many conifer and other hardwood species (Shepperd et al. 2006). It provides many ecological benefits to resource users, including protection of watersheds from erosion, some protection against rapid wildfire advance, increased biological diversity, aesthetic considerations, and wildlife habitat (Amacher et al. 2001). However, there has been substantial popular concern that aspen has been declining during the 20th century in the western landscape (Kulakowski, Veblen, and Drinkwater 2004) and that, in fact, its persistence may be ‘‘doomed’’ (Kay 1997).

The decline of aspen has been associated primarily with a combination of successional processes, reduction (or elimination) of fire, and long-term overuse by ungulates (Bartos and Campbell 1998; Bartos 2001). The replacement of aspen by conifers has been of great concern, and numerous landscapes throughout the West that were once dominated by aspen are in late successional stages dominated by mixed conifer (Bartos and Campbell 1998). It is believed that conifer replacement is gradual and can take from 100 to 200 or more years. However, if an aspen stand is within a mixed conifer forest matrix, conifers can become established within a single decade (Paré, Bergeron, and Longpré 2001). The successional replacement of aspen by conifers is deemed to be an “environmental catastrophe” (Club 20 1998). It is accompanied by ecosystem function losses such as decrease in water yield (Harper, Woodward, and Knight 1981; Gifford, Humphries, and Jaynes 1984), decline in forage production (Mueggler 1985), loss of biodiversity and many other benefits. The soil property changes associated with aspen to conifer succession have not been explicitly studied, even though soil is considered one of the important factors that affect the persistence of aspen stands (Cryer and Murray 1992).

Jones and DeByle (1985) suggested that aspen forests differ from associated vegetation types in amount, distribution, and character of organic matter and nutrients. In the West the soil organic matter under aspen has been postulated to be higher under aspen compared to conifer soil (Hoff 1957; Tew 1968). According to Bartos and DeByle (1981) the annual return of leaf and twig litter to the soil surface is a major contributor to the organic matter and nutrient content of soils under aspen and other deciduous hardwoods. Aspen litter decomposes much more rapidly than the litter of associated western coniferous forest (Bartos and DeByle 1981). As a result of this rapid decay and higher nutrient content in leaves (Daubenmire 1953), aspen are considered to be efficient nutrient pumps (Lutz and Chandler 1946; Jones and DeByle 1985) where they capture nutrients from subsoil and enrich the surface horizons (Stoeckler 1961). This contributes to the relatively higher pH and base saturation of soil under aspen (Hoff 1957; Tew 1968;

Morgan 1969; Alban 1982; Paré, Bergeron, and Camire 1993), which might be related to high Ca requirements of this species (Alban 1982).

Due to this nutrient pumping capability, the presence of aspen stands is believed to hasten nutrient cycling, which could positively affect stand productivity of nearby vegetation (Légaré, Bergeron, and Paré 2005a; Légaré, Paré, and Bergeron 2005b). However, when other vegetation types encroach aspen, soil pH drops to 6.0 or lower, accompanied by a decrease in nutrient levels. Researchers in the west postulated that the lower pH and nutrient levels suppress aspen regeneration (Cryer and Murray 1992). In contrast with the above statement, Bartos and Amacher (1998) in a study at Fishlake National Forest, Utah, found no change in the chemical properties of the surface of the soil as conifer invasion proceeded, except for slightly lower pH and exchangeable K in mixed conifer/aspen soils compared to pure aspen. They also stated that it is unknown to what level soil pH can drop and how much loss of organic matter and nutrients can be tolerated before aspen regeneration is suppressed.

Cryer and Murray (1992) further postulated that stable or permanent stands of aspen in the west are found only on Mollisols, which are characterized by a deep, dark, friable, and relatively fertile A horizon known as a mollic epipedon (Buol et al. 2003). According to Bartos and DeByle (1981), Jones and DeByle (1985), and Cryer and Murray (1992), the mollic epipedon is a result of the addition and rapid turnover of aspen leaves to the soil each year. However, the faster turnover rates are somewhat counterintuitive to higher soil organic matter content in the surface horizon that is characteristic of a mollic epipedon. Instead it can be due to a combination of several processes such as humification (microbial decomposition of organic materials in the soil that produces some relatively stable, dark-colored compounds; and extension of roots into the soil profile) (Buol et al. 2003) and bioturbation (reworking of the soil and organic materials by soil fauna) (Hole and Nielsen 1970). In contrast, soils developed under conifers in the Intermountain West are primarily Alfisols characterized by a thick O horizon and relatively thin A horizon (Cryer and Murray 1992). When conifers encroach aspen stands, the mollic epipedon thins while the albic horizon thickens. This is attributed to the decrease of leaf fall and organic matter of aspen stands, which in turn leads to rapid water infiltration through the horizon forming the albic horizon. According to Cryer and Murray (1992) thinning of the mollic epipedon is followed by decrease in soil pH, organic matter, and lowering of CEC and nutrients. Bartos and Amacher (1998) also found similar morphological changes.

Change in the Vegetation Cover and Soil Properties

Although several researchers have investigated and hypothesized changes in soil properties following conifer encroachment, there is a clear need for a more detailed study of the ecosystem properties of two vegetation types and assess potential impacts associated with conifer encroachment.

Generally, plant communities are dynamic and ever-changing and are also closely linked with soil change (Fisher and Binkley 2000). The succession of communities, which is defined as sequential change in the relative abundance of dominant species in a community following disturbances (Huston and Smith 1987) alters the chemical, physical, and biological properties of the soil through their occupancy, and such alterations contribute to the relative change in abundance of the dominant species that characterizes succession (Fisher and Binkley 2000). Moreover the genesis of soils is governed by five environmental factors known as state factors (Buol et al. 2003): climate, organisms, relief, parent material and time (Jenny 1941). Consequently, changes in vegetation affect the evolution of soils.

Several studies have addressed the changes induced by planting coniferous trees replacing deciduous trees (Paré and Bergeron 1996). Such changes include the change in soil chemical properties such pH, nutrient availability, CEC, base cations (Binkley and Valentine 1991; Paré and Bergeron 1996). Some studies focusing specifically on aspen and conifer soil properties have also pointed out similar differences in soil properties. In a study carried out in Minnesota, Alban (1982) found that organic matter in the forest floor and mineral soil were lower under aspen than spruce and pines, and indicated that this was due to lower organic matter return via litterfall of aspen compared to conifer species. Furthermore, the nutrient accumulation in the forest floor was greatest under aspen or spruce and lowest under pine compared to patterns in the mineral soil. Paré and Bergeron (1996) also found greater accumulation of organic matter and nutrients in the forest floor of spruce than aspen and pointed out that the accumulation of forest floor material under spruce many be due to slower litter decomposition (Pastor et al. 1987). Such trends are different from what the researchers in the west have been hypothesizing and this can be due to different climatic conditions.

In a study conducted out in British Columbia results showed that aspen litter decomposed more rapidly than in spruce (Prescott et al. 2000). The faster rate of decomposition could be due to the higher nutrient concentration and lower lignin and polyphenol concentrations in broadleaves litter than needle litter (Perry, Choquette, and

Schroeder 1987) and/or environmental factors that control the metabolic rate of organisms such as temperature, moisture, pH and aeration (Perala and Alban 1982).

According to Alban (1982) differences in nutrient content under aspen, spruce and pine cover occurred in the surface horizon mineral soil and forest floor. In the forest floor Ca content under aspen and spruce was greater in aspen and spruce compared to the pine trees, and less N and P was accumulated under red pine than under the other two species. In the mineral horizons Ca was highest under pines compared to aspen and spruce, while N, organic matter, and Mg were lowest under aspen and P and K showed no significant differences. However, he pointed out the total amount of Ca of the entire ecosystem was not different, which he further explained as a result of different nutrient distribution pattern among the different species types. Additionally, Alban (1982) pointed out that the pH of the mineral soil surface was lower under aspen compared to pine and this can be due to the lower level of Ca in the mineral horizons of the two species. He found no morphological differences in the mineral soils when compared aspen, spruce and pine.

Soil Organic Carbon Storage

The soil organic carbon (SOC) is a vital constituent of the soil. The nature and quantity affects many physical, chemical and biological properties of forest soils such as soil pH, nutrient supply, water holding capacity, and gas exchange (Fisher and Binkley 2000).

SOC constitutes approximately 2/3 of the terrestrial carbon storage; the relatively large size and long residence time of this pool (of the order of 1,200 yr) makes it a potentially important sink for C released to the atmosphere by fossil fuel combustion (Post et al. 1982). The amount of C in soil represents the balance between inputs of organic material from the biota, which ultimately depend on the type of vegetation and its productivity at a particular site; and losses primarily through decomposition and heterotrophic respiration. Small changes in these processes may have large impact on SOC storage and the global C Cycle.

There has been a lot of work done to estimate the SOC storage in soils on different spatial scales and using different approaches. On a global scale Post et al. (1982) estimated the SOC pool to be about 1,395 Pg based on analysis of 2700 soil profiles categorized by climate using Holdridge life zone classification system. Global surveys based on taxonomic units estimated that the total mass of organic C stored in the upper 100 cm of the soils of the world is 1462-1548 Pg of C (Batjes 1996), which is also similar to the estimate by Eswaran, Vandenberg, and Reich (1993) of about 1576 Pg. The SOC content is generally high in virgin soils under grass or forest vegetation (Bruce et al. 1999). According to Dixon et al. (1994) forest vegetation and forest soils contain 359 Pg and 787 Pg, respectively, for an ecosystem total of 1146 Pg.

The C pool in soil of the 48 contiguous states of the US is estimated to be 80.7 ± 18.6 Pg (Kern 1994). Based on the SOC estimates of the different ecosystem complexes and soil taxonomical units, forest soil carbon content generally ranges from 109-159 Mg C ha^{-1}, which is greater than the SOC in the grasslands with 84-124 Mg C ha^{-1}. Estimates by taxonomical units showed that the lowest SOC is found in Aridisols with a 56 Mg C ha^{-1} and the greatest in Histosols with 843 Mg C ha^{-1}. All the suborders of Mollisols had SOC content greater than 100 Mg C ha^{-1} where the suborders of Alfisols had SOC content ranging from 79-63 Mg C ha^{-1}. These two soil types are of a special interest because aspen has been repeatedly said to occur on the soil order Mollisol, while conifers are associated with Alfisols (Kern 1994).

Grigal and Ohmann (1992) estimated the SOC storage under five vegetation types including balsam fir, jack pine, red pine, aspen and northern hardwoods (maple) and found that the total C storage ranged from 139 Mg C ha^{-1} in the jack pine type to 234 Mg C ha^{-1} in the northern hardwood type, while balsam fir and aspen had 200 Mg C ha^{-1} and 203 Mg C ha^{-1}, respectively. Alban and Perala (1992) in a study conducted to estimate C storage in aspen as succession proceeds concluded that there was no evidence in change of SOC during succession from an aspen-dominated community to a northern hardwood community. In a study conducted to evaluate the carbon budget of a boreal aspen forest, Chen et al. (1999) found that the aspen forest was a strong carbon sink sequestering 200 ± 30 g C m^{-2} y^{-1} and 130 C m^{-2} y^{-1} in 1994 and 1996, respectively. He suggested that if the rates were representative of the Canadian boreal deciduous forests, aspen could sequester up to 0.04 - 0.06 Pg C y^{-1}.

Besides estimating SOC under different ecosystem complexes and soil taxonomical units it is crucial to establish the relationships between the geographical distributions of soil carbon and climate, vegetation and other factors as a basis for assessing the influence of changes in any of these factors on the global cycle (Post et al. 1982).

Factors Controlling SOC Accumulation

The major factors that have been found to control SOC are climate, vegetation, elevation, terrain position and soil texture. The relationship between SOC and site characteristics can be variable depending on the spatial scale, location and vegetation type.

The relationships of SOC and climate have been studied at a large and small scales and outcomes appear to be scale-dependent. At a global scale, Post et al. (1982) and Jobbagỳ and Jackson (2000) concluded that SOC generally increases with increasing precipitation and with decreasing temperature for any specific level of precipitation. The same conclusions were drawn from a relatively smaller scale study carried in the grasslands of the US Central Plains (Burke et al. 1989).

Recently, Homann, Kapchinske, and Boyce (2007) conducted a study that encompassed the entire USA and looked at the relationship of mineral soil C and N to climate. They found that the SOC between 0-20 cm soil depth was positively related to mean annual precipitation (MAP) in all the regions, even though the quantitative relation differed among some regions; and negatively correlated with mean annual temperature (MAT). These results were similar to findings by other authors such as Burke et al. (1989), and Jobbagỳ and Jackson (2000). However, Homann, Kapchinske, and Boyce (2007) pointed out that the positive relationship between SOC and MAP was not applicable globally because in some parts of the world, such in the Australian rain forest, SOC was negatively correlated with MAP. They further found that there were also some inconsistency in the trends of the relationships of SOC and MAT.

In a study carried in mountainous forested regions of the western part of Oregon, SOC increased with annual temperature, annual precipitation and actual evapo-transpiration (Homann et al. 1995). Sims and Nielsen (1986) suggested that in cold soils (cryic and frigid) of Montana and Wyoming, SOC increased with precipitation and elevation; and that SOC was higher in colder soils than in warmer soils (McDaniel and Munn 1985). However, in the temperate forests of Minnesota, Wisconsin, and Michigan the patterns of SOC storage were not as strongly influenced by climatic variables as in the west (Grigal and Ohmann 1992). Other researches suggested that the effects of climate on SOC could be explained through the vegetation (Franzmeier, Lemme, and Miles 1985) because SOC storage is controlled by the balance of C inputs from plant production and outputs through decomposition (Schlesinger 1977), which in turn vary as a function of temperature, moisture, and the chemical composition of the litter material (Schlesinger 1997).

Some studies have suggested that SOC was related to both elevation and terrain shape, with SOC increasing with elevation and decreasing linearly as terrain shape shifts from concave to convex in the southern Appalachians (Bolstad and Vose 2001). This pattern might be attributed to lower decomposition rates relative to production at higher elevations or might be due to lower temperature that might slow down the decomposition that could lead to SOC accumulation at higher elevations (Bolstad and Vose 2001). Other studies also indicated that soil C concentrations or stocks increased with altitude in mountainous terrain (Trumbore, Chadwick, and Amundson 1996; Conant et al. 1998; Garten et al. 1999). The differences along elevation gradients reflected a changing balance of soil C inputs and soil C losses that were potentially related to changes in both abiotic factors (e.g., temperature) and biotic factors such as litter quality (Garten and Hanson 2006). More recent studies in the southern Appalachians showed that there was no consistent relationship between total SOC storage in spruce-fir forests and elevation, even though cooler upper-elevation plots were consistently characterized by slower C turnover rates (Tewksbury and Van Miegroet 2007).

Hontoria, Rodriguez-Murillo, and Saa (1999), in a study carried out in Spain, also showed that SOC accumulation was positively correlated with the slope gradient, which contrasts the findings from other studies. However, they explained that the correlation with the slope reflected the influence of land use, where steeper slopes were devoted to land uses such forest and grassland that were characterized by higher SOC, whereas flatter areas were associated with agricultural fields and grazing. They further stated that the correlation with altitude was low although significant.

One of the many factors that affect SOC is soil texture and many researchers have studied the role of soil texture especially the role of clay and silt in SOC storage (Feller and Beare 1997; Hassink 1997; Six et al. 2002). Texture plays a vital role in controlling SOC by chemically and physically protecting the soil organic matter from decomposition. Chemical stabilization of SOC occurs when SOC chemically or physico-chemically bound to the soil minerals such as clay and silt (Six et al. 2002). Physical protection is when the aggregates physically protect soil organic matter (SOM) (Tisdall and Oades 1982; Six et al. 2002) by creating barriers between microbes and enzymes and their substrates and in turn controlling microbial turnover (Elliott and Coleman 1988).

Nichols (1984); Burke et al. (1989); and Grigal and Ohmann (1992) suggested that the percentage of clay is the dominant predictive characteristic for SOC where SOC increased with increasing clay content. Some researchers suggested that SOC is significantly correlated with sand/clay ratio in mesic grassland soils, but that in cold arid and semiarid grasslands, texture had limited value as a predictor of organic carbon levels

(McDaniel and Munn 1985) because in these areas temperature was a limiting factor for organic levels rather than soil moisture and texture. Homann, Kapchinske, and Boyce (2007) also reported a positive relationship with clay content within each region of the US; however clay and silt had small contributions as predictors of SOC across the entire US compared to MAP and MAT.

In addition to the biotic and abiotic factors controlling SOC storage and stability, the role of SOC quality is an important aspect that needs to be considered. SOM is a major terrestrial pool of C. It is a dynamic soil property that is responsive to ecosystem performance (Carter 1996). Soils vary in the amount of organic matter content (Stevenson 1994) but generally the total organic C comprises 48-58% of SOM. SOM consists of a number of pools that are different from each other and can be broadly classified into three: 1) “active/labile” pool which takes several years to turn over, 2) “slow intermediate” pool, which takes years to decades and 3) “passive/refractory” pool which takes years to thousands of years (Parton et al. 1987). Various methods have been used to determine SOC quality including:

i) Chemical fractionation that yields three major fractions: humic acids (HA), fulvic acids (FA) and humin. The method involves extraction with an alkaline reagent following acidification (Stevenson 1994; Collins et al. 1997).

ii) Physical fractionation based on density where SOM can be divided into two broad categories a) light fraction (LF) composed of incompletely decomposed plant and animal debris; b) heavy fraction (HF) consisting of organic matter contained within organomineral microaggregates (Collins et al. 1997).

iii) Radiocarbon dating using naturally occurring ^{14}C (Collins et al. 1997).

iv) Nuclear magnetic resonance that characterizes the molecular structure and functional groups of SOC (Collins et al. 1997).

Even though researchers have postulated the effects of conifer encroachment on ecosystem function, few studies have been carried out to understand changes in key properties that are essential to ecosystem functions such as SOC and other soil properties. In this study carried out in Northern Utah, we will focus on changes in SOC and other soil properties, and investigate the possible associated ecosystem function losses.

CHAPTER 3

STUDY AREA

To address the objectives of this study, the research was conducted at two locations in Northern Utah, one at the Deseret Land and Livestock (DLL), a private holding in Weber County near Randolph; the other at Utah State University’s facility, T.W. Daniel Experimental Forest (TWDEF) in Rich County near Bear Lake. The study was divided into two phases. The first phase of the research was to estimate SOC in pure aspen and assess the drivers of its variability at locations where there were stable aspen stands. Upper Frost watershed, a small sub-catchment about 215 ha at DLL in Northern Utah was chosen for this part of the study. The second phase was to compare and contrast the site characteristics such as SOC, nutrient availability and soil chemical and physical properties of aspen and conifer at locations where both ecosystems co-existed in close proximity under similar site conditions. Sites at Upper Frost and Bear Canyon watersheds at DLL and at Sunset Ridge in TWDEF were chosen for that part of the study. These study sites were chosen because they contained sufficiently large aspen stands; they were ideal sites for aspen-conifer paired plot comparisons as the aspen and conifer stands were adjacent to each other; provided broader spatial applicability to the results; and also capitalized on extensive forest soil, snow and climate data already collected by other researchers (e.g.,Van Miegroet, Hysell, and Johnson 2000; Van Miegroet et al. 2005; Shakespeare 2006; LaMalfa and Ryel 2008).

Site Description

Deseret Land and Livestock is a privately owned ranch in Rich County, Utah, located at 41.10^o N, 111.25^o W (Figure 3.1). It occupies 88,800 ha, including 6,800 ha of Department of Interior Bureau of Land Management (BLM) and Utah state lands. Elevation ranges between 1889 and 2700 m. At around 1920 m elevation on the eastern half of the ranch the vegetation is dominated by sagebrush (*Artemisia tridentata* Nutt.*)*; steppe with an understory of western wheagrass (*Pascopyrum smithii* (Rydb.) A. Löve), needle and thread grass (*Stipa comata* Trin. & Rupr.) and Indian ricegrass (*Oryzopsis hymenoides* Roem. & Schult.). The western half of the ranch, at an elevation of 2652 m, is dominated by mountainous, semi-open brush and grasslands with scattered stands of aspen and conifer mainly Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Mean annual precipitation is 890 mm with 74% as snow accumulation; the wettest months are April, May, June and September. Mean annual air temperature is about 4.5 ^{o}C, mean winter temperature is about -4.9 ^{o}C and mean summer temperature is about 15.1 ^{o}C [as measured by a nearby SNOTEL site (Horseridge) with 10 years of data]. The most common soil orders present are Mollisols, Entisols, Aridisols and Inceptisols (Washington-Allen et al. 2004). The Upper Frost and Bear Canyon catchments are surrounded by the Wasatch formation with loamy texture and by Cambrian age outcroppings of sedimentary rocks (Coogan and King 2001). The parent material of the Upper Frost canyon and the lower portion of Bear Canyon where the plots are established is mainly Wasatch conglomerate (Figure 3.2)

The T.W. Daniel Experimental Forest is Utah State University's facility where many forest soil, snow and climate process studies have been carried out (e.g.,Van

Miegroet, Hysell, and Johnson 2000; Van Miegroet et al. 2005). It is located at 41.86^o N and 111.50^o W, about 30 km North-East from Logan, Utah at an elevation of 2900 m (Figure 3.3). The annual precipitation is 950 mm with an 80% snow accumulation (Van Miegroet, Hysell, and Johnson 2000). Average low temperature is -10^{o}C while highest monthly temperature is 14^{o}C (Schimpf, Henderson, and MacMahon 1980; Skujins and Klubek 1982). The vegetation in the study area ranges from forb meadows and sagebrush to conifer forest, predominantly Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt) and lodgepole pine (*Pinus contorta* ex Louden), and aspen forest. The soil orders present are Mollisols and Alfisols (Skujins and Klubek 1982; Van Miegroet et al. 2005). The parent material of this catchment is Wasatch conglomerate, which is the same as the catchments at DLL. These study sites were chosen because they are suitable for paired plot vegetation study as both aspen and conifer vegetation are present.

Experimental Design

Phase One-Transect Study

To assess the inherent properties of soils under pure aspen, which were used as a reference ecosystem, 33 sampling points that were 32 m apart from each other were located along north (n=11), south (n=8), east (n=7) and west (n=7) facing linear transects in the Upper Frost Canyon drainage at DLL. Transects ran from the top of ridgeline to the bottom, covering an elevation gradient between 2522 m and 2605 m. Such sites could not be established at TWDEF as sufficiently large contiguous areas of pure aspen forests could not be found to allow long linear transects.

Soil Organic Carbon. Along these linear transects we measured total SOC pool to a depth of 40 cm. To estimate the amount of carbon in the soil, mineral soil samples were taken in 10-cm increments to a depth of 40 cm at each of the 33 sampling points. Bulk density of the soil (0-40 cm) was determined at each sampling point using the soil excavation method (Blake and Hartage 1986). Samples were oven-dried at 105^{o}C, sieved (2-mm mesh), and the weight of fine (< 2mm) and coarse fractions (≥ 2mm) were recorded. Sub-samples of <2 mm were analyzed for C concentration using a Leco CHN analyzer (CHN 1000, LecoCorp., St Joseph, MI). Total SOC to a depth of 10 cm and 40 cm was calculated.

Soil Microclimate. To characterize soil moisture, ECH$_2$O probes (Decagon, Pullman, Washington) were installed at each location at a depth of 20 cm. Soil moisture readings (millivolt) were taken in early July, mid July, August, September and October of the 2005 and 2006 using a handheld Decagon reader. Soil temperature was assessed at a depth of about 10-15 cm using Stowaway Tidbits dataloggers (Onset Computer Corporation, Bourne, MA) that were installed along the transects (N, n=4; S, n=4; E, n=3; W, n=3). Tidbits were programmed to record soil temperatures (^{o}C) at 2-hour intervals and were downloaded twice per year, in July and October of 2005 and 2006.

Physical Soil Properties. To characterize the soil morphology, one representative pedon from each aspect was described following standard methods. Horizon description included soil depth, color, structure, texture (hand feel method), consistence and effervescence (Soil Survey Division Staff Soil 1993). In addition, samples from each genetic horizon were collected from the pedons and analyzed in the laboratory for texture by standard hydrometer techniques (Gee and Bauder 1986).

Soil Nutrient Status and Chemical Properties. Soil nutrient availability was assessed using plant root simulator probes (PRS-probes) (Western Ag Innovations Inc., Saskatoon, Canada). We deployed four cation and four anion exchange strips during the summer and winter time of 2005-06 in selected points along the transect (N, n=4; S, n=4; E, n=3; W, n=3). The probes were sent to Western Ag Innovations, Inc. for analysis. In this study total N, K, Ca, Mg and Mn were used. The cation exchange capacity (CEC) and base saturation (BS) were also determined on the < 2mm fraction by extracting exchangeable base cations with 1 M NH_4Cl at pH 7.0 using vacuum extractor (Soil Survey Staff 1996) and analyzing extractant for cations using an inductively coupled plasma spectrometer (ICP) (Iris Advantage, Thermo Electron, Madison, WI); followed by extraction with 2 M KCl and analysis of extractant for NH_4 using flow injection analyzer (Lachat Quickchem 8000, Flow Injection Analyzer). Soil pH was determined by 1:1 deionized water to soil slurry using pH meter.

Stand Characteristics. Overstory vegetation cover was assessed in the reference ecosystem along every point on the transect using a fixed area plot, where the diameter at breast height (DBH) of each individual tree greater than 5 cm was measured within the circular plot of a radius of 10 m.

Statistical Analysis

One-way ANOVA with a Tukey-Kramer adjustment for multiple comparisons was used to test for differences in SOC and other soil properties between the northern, southern, eastern and western facing transects (SAS Insitute 2003). Regressions were performed to asssess the relationship between SOC content and site characteristics.

Phase Two- Paired Plot Study

To compare and contrast the site characteristics of the two vegetation types as representation of end-member communities, six paired plots were established at DLL and TWDEF; two in Upper Frost Canyon and one in Bear Canyon at DLL, and two at TWDEF. Areas were selected based on proximity of the aspen and conifer stands and similarity in elevation and slope. Plots (20 m by 20 m) plots were delineated in adjacent aspen and conifer forests in three locations.

Soil Morphology. In order to compare the morphology and genesis of the soil under aspen and conifer, representative pedons (1 m wide and ≤ 1m depth) were manually excavated in each of the twelve plots, and the soil morphology was described following standard methods (Soil Survey Division Staff 1993). Soil texture was done by hand feel method on site. Soils were classified according to Soil Survey Staff (2003).

SOC Pools and Chemical Properties (Pedon Samples). Soil samples were taken from each genetic horizon using cores (5 cm diameter by 3 cm length). Samples were dried at 105°C, sieved (2-mm sieve) weighed and ground with mortar and pestle prior to analyses. Bulk density and percent gravel was determined using core method (Blake and Hartge 1986). The total C and N concentration of the fine fraction (<2mm) was determined using dry combustion using a CHN analyzer (Leco CHN 1000, Leco Corp., St. Joseph, MI). The total C pool for each pedon was normalized to 60 cm in order to have a consistent depth across all the plots. Chemical properties such as CEC and BS were determined on the fine fraction as described for phase one.

SOC (Split Core Samples). To test for consistency and representativeness of the pedon SOC estimates, additional mineral soil cores were taken in each plot at four random locations using a split core sampler to a depth of 0-15 cm. Samples were composited into two samples per plot and carbon content was estimated from composite soil samples following the same procedure described above. Bulk density determined from pedon samples was used, because samples could not be dried at 105 ^{o}C as they were needed for other soil analysis purposes (incubation).

SOC Pools (Forest Floor). Carbon content of the forest floor in the plots was determined in both aspen and conifer plots in fall 2007 by excavating the O horizon material at one location per plot using a sampling frame that was 12.7 cm by 12.7 cm. Samples were dried at 65^{o}C, weighed and ground and samples were analyzed for C concentration using a CHN analyzer (Leco CHN 1000, Leco Corp., St. Joseph, MI).

Nutrient Availability. To assess the difference in the nutrient availability under the two vegetation types plant root simulators (PRS-probes) (Western Ag Innovations Inc., Saskatoon, Canada), which consisted of ion exchange membranes were installed at 10 cm depth in each plot during summer and winter of 2007. The PRS-probes were shipped to Western Ag Innovations Inc., Canada, for analysis. For the purpose of this study total N, K, Ca, Mg and Mn were used.

Soil Microclimate. Soil moisture regime of aspen and conifer stands was determined by installing twelve ECH$_2$O moisture probes (Decagon, Pullman, Washington) at a depth of 20 cm at the center of each plot. Soil moisture readings (millivolt) were taken using a hand-held device in early June, mid July, August, and October of 2007. The soil temperature of the sites was also assessed using Stowaway Tidbits dataloggers (Onset Computer Corporation, Bourne, MA) installed below the soil surface at a depth of 10-15 cm in each plot. Tidbits were programmed to record soil temperatures (^{o}C) at 2-hour intervals from August 2006-June 2007 and they were downloaded in June 2007.

Stand Characteristics. Overstory vegetation cover of the two vegetation types was measured using a fixed area plot, where the diameter at breast height (DBH) of each individual tree greater than 5 cm (DBH) was measured within the circular plot of a radius of 10 m.

Statistical Analysis

All the data were analyzed using an analysis of variance (ANOVA) of a one way factorial in randomized complete block design with random block effect using PROC Mixed. In addition a paired t-test using PROCTTEST checked the consistency of the test (SAS Institute 2003). Prior to ANOVA, normality tests were done and accordingly data were transformed.

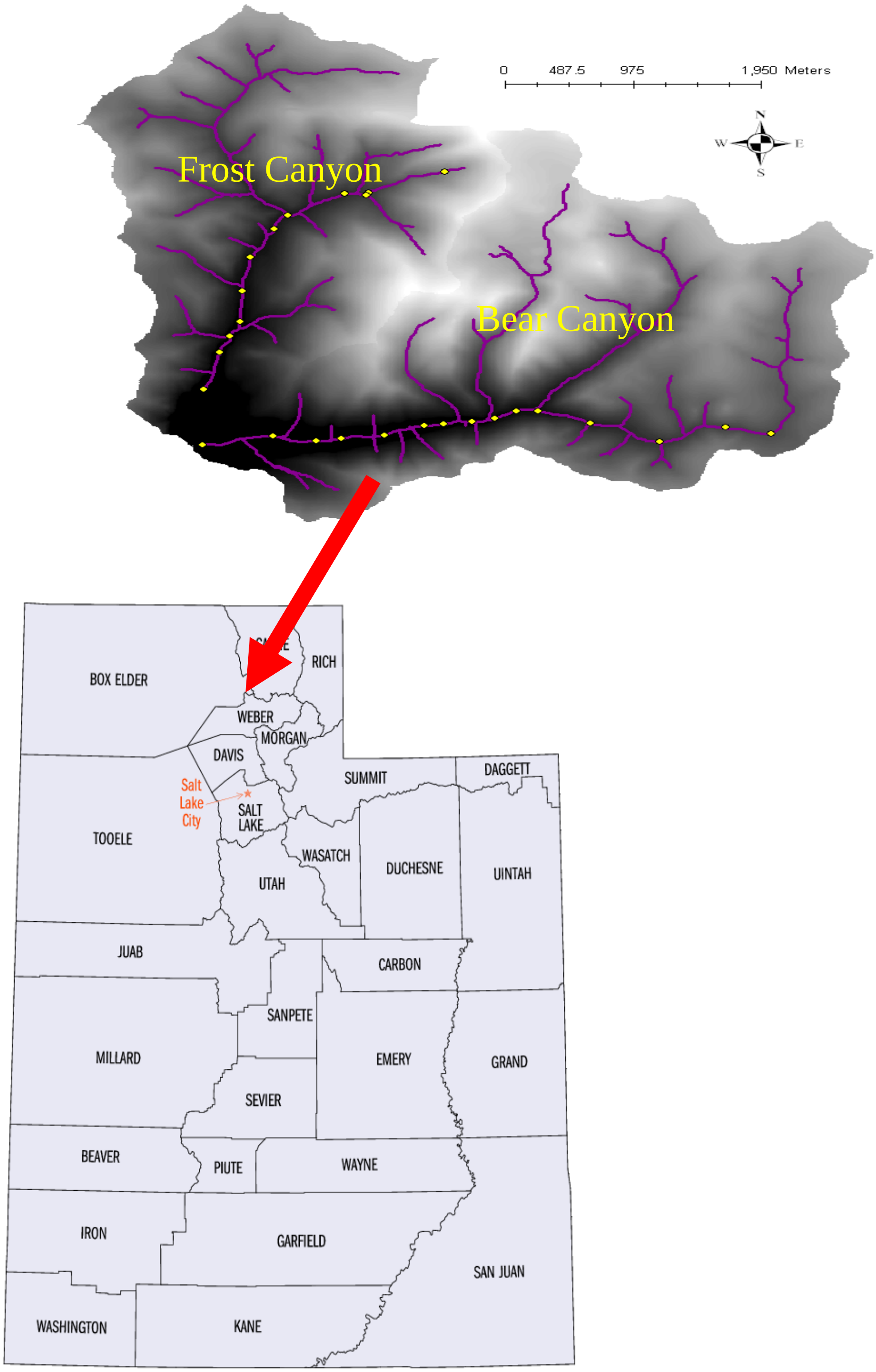

Fig. 3.1 Relative location of the study sites at DLL.

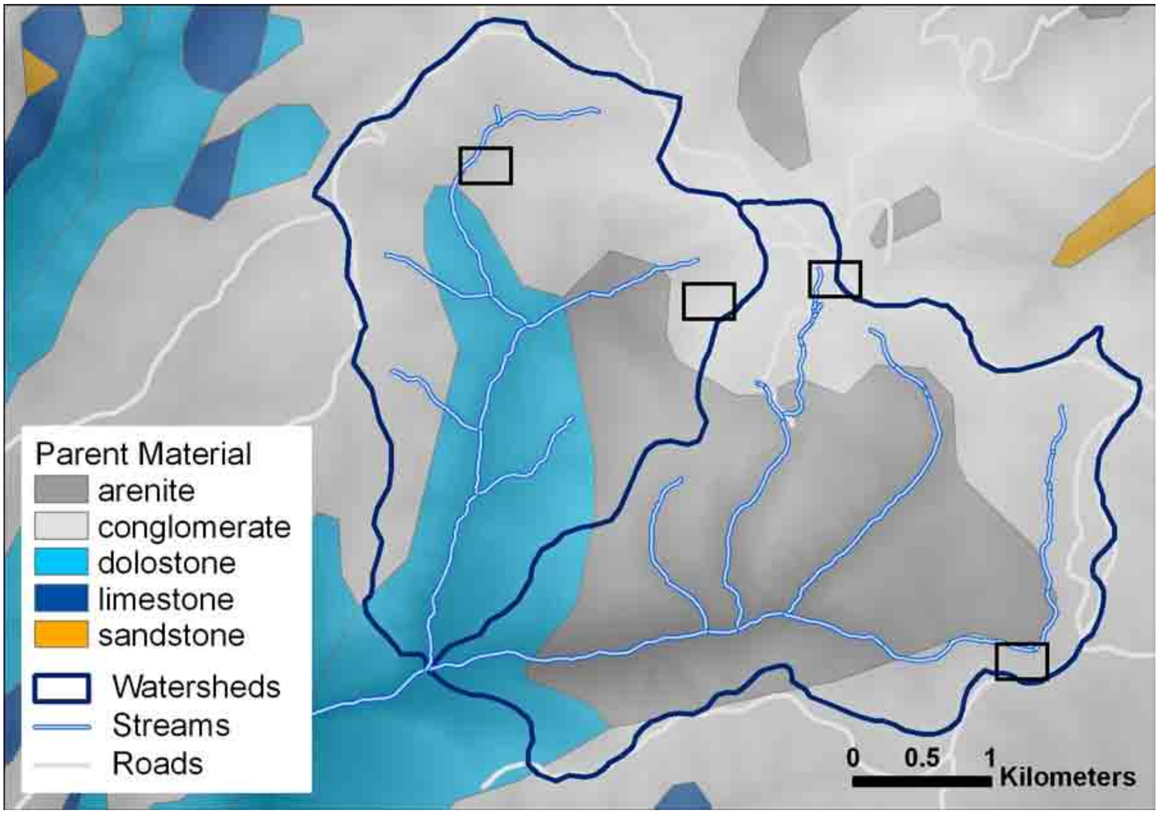

Fig. 3.2 Geological map of the watersheds at DLL.

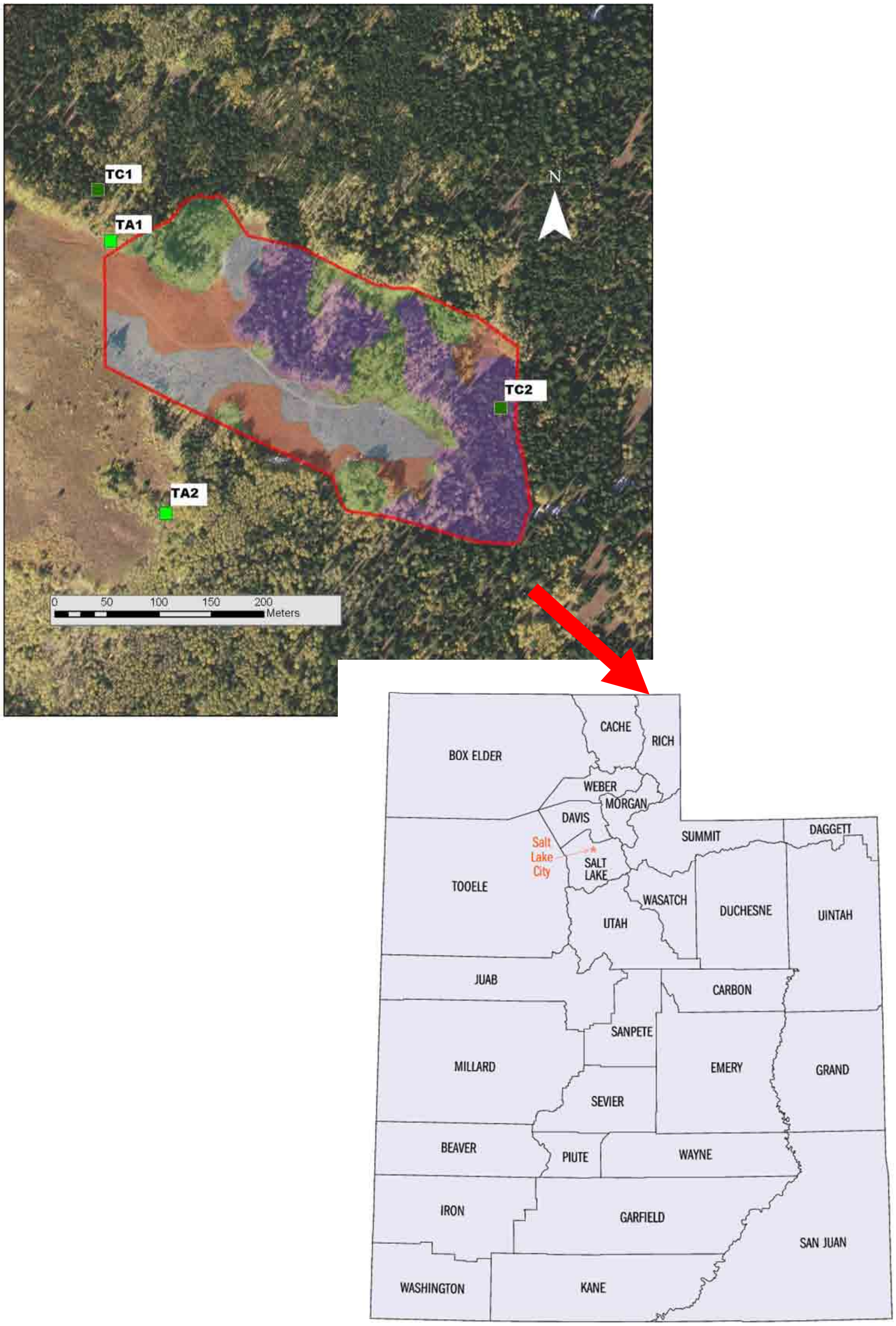

Fig. 3.3 Relative location of the study sites at TWDEF.

CHAPTER 4

SOIL ORGANIC CARBON STORAGE UNDER PURE ASPEN STANDS AND ITS RELATIONSHIP WITH SITE CHARACTERISTICS IN NORTHERN UTAH

Introduction

Aspen is the most abundant tree species in North America mostly in Canada's Central Provinces and the U.S. States of Colorado and Utah (Jones 1985; Lieffers, Landhäusser, and Hogg 2001). In the western U.S., aspen has numerous ecological and economical values such as forage for livestock, habitat for wildlife, landscape diversity, esthetics, and water yield (DeByle and Winokur 1985; Bartos 2001). It occurs in pure forest as well as in association with many conifer and other hardwood species (Shepperd et al. 2006). Aspen has a special value in the west and is considered a keystone species (Campbell and Bartos 2001), meaning that it affects the survival and abundance of many other species in its community. Its removal or addition causes shifts in community composition and sometimes even in the physical environment (Wilson 1992). There is a great concern that aspen has been declining in the west followed by the replacement with conifers.

In addition, aspen forest is believed to be a strong carbon (C) sink (Chen et al. 1999). Soil organic carbon (SOC) is a vital constituent of the soil, considered an important factor in the regeneration of aspen (Cryer and Murray 1992). The nature and quantity of SOC affects many physical, chemical and biological properties of forest soils such as soil pH, nutrient supply, water holding capacity, and gas exchange (Fisher and Binkley 2000).

Concerns related to the increase of atmospheric CO_2 has motivated researchers to estimate the amount, dynamics and controls of SOC at different spatial scales. The major factors controlling SOC are climate, vegetation, elevation, terrain position and soil texture. The factors controlling SOC are often scale-dependent, but on a global (Post et al. 1982), continental (Homann, Kapchinske and Boyce 2007) and regional scale (Burke et al. 1989) climate is considered a major controlling factor. However, Franzmeier, Lemme, and Miles (1985) concluded that the effects of climate on SOC could be explained by vegetation at a regional scale. Generally, on a coarser scale (global and continental scale) SOC is believed to increase with precipitation and decrease with increasing temperatures (Post et al. 1982; Jobbagỳ and Jackson 2000; Homann, Kapchinske and Boyce 2007). Similar conclusions were drawn at a relatively finer scale (regional scale) study in the grasslands of the US Central Plains (Burke et al. 1989).

Another important factor controlling SOC is soil texture, which promotes SOC storage through the role of clay in the protection of soil organic matter (Anderson et al. 1981). Several studies have found that the percentage of clay is the dominant predictive characteristic for SOC with SOC increasing with increasing clay content (Nichols 1984; Burke et al.1989; Grigal and Ohmann 1992). Clays tend to stabilize organic matter, and other environmental factors being equal, a high correlation exists between organic matter and clay contents of soils (Stevenson 1994). However, in cold arid and semiarid grasslands, texture has limited value as a predictor for SOC levels, and this may be because organic matter persists without the influence of clay stabilization. In these areas temperature may be the main controlling factor over other factors (McDaniel and Munn 1985).

SOC is also related to both elevation and terrain shape. The soil C concentrations or stocks increase with altitude in mountainous terrain (Trumbore, Chadwick, and Amundson 1996; Conant et al. 1998; Garten et al. 1999; Bolstad and Vose 2001). The differences along elevation gradients reflect a changing balance of soil C inputs and soil C losses that are potentially related to changes in both abiotic (microclimate) and biotic factors such as litter quality (Garten and Hanson 2006). Slower decomposition rates compared to production at higher elevations characterized by lower temperature, result in greater SOC accumulation (Bolstad and Vose 2001). Recent studies in the southern Appalachians showed that there was no consistent relationship between total SOC storage and elevation, even though cooler upper-elevation spruce-fir forests were consistently characterized by slower C turnover rates (Tewksbury and Van Miegroet 2007). SOC was negatively correlated with terrain shape, where SOC decreases as terrain shape shifts from concave to convex in the southern Appalachians (Bolstad and Vose 2001). Hontoria, Rodriguez-Murillo, and Saa (1999) in a study carried out in Spain, showed that SOC accumulation was positively correlated with the slope gradient, which reflected the influence of land use, where steeper slopes devoted to land uses such forest and grassland were characterized by higher SOC than the flatter terrain dedicated to agriculture. Most regression analyses indicated that only about 50% of the variability in SOC levels could be explained by site characteristics such as climate, elevation, and soil texture (Burke et al. 1989; Grigal and Ohmann 1992; Homann et al. 1995).

Several researchers suggested that SOC under aspen in the Intermountain West was higher than associated vegetation types (Hoff 1957; Tew 1968). However not many studies quantified the amount of SOC stored under aspen or investigated the relationship between SOC and soil characteristics. For this study we focused on Utah, as it contains vast aspen stands that account for 25% of aspen in the west, and chose a small catchment as an example of aspen stand conditions in Northern Utah.

The major objectives of this study are to estimate the amount of SOC stored in pure aspen stands, assess the variability in the SOC pool size, and investigate the various biotic and abiotic factors driving SOC variability. Potential abiotic drivers considered are elevation, slope gradient, aspect and soil microclimate, and biotic drivers include aspen stand characteristics. We hypothesize that SOC will not be constant and it is expected to change spatially as a function of site characteristics, mainly soil microclimate, vegetation and aspect. We expect that stand characteristics such as tree size and density and average tree diameter to influence SOC by affecting litter input and canopy openness. Differences in aspect and soil microclimate are also expected to affect SOC storage by affecting decomposition rates, with greater SOC accumulation expected on drier sites.

Methods and Materials

Study Site

The research was conducted at the Deseret Land and Livestock (DLL), a privately owned ranch located in Northern Utah at 41.10° N, 111.25° W. Vegetation at an average elevation of 1920 m on the eastern half of the ranch is dominated by sagebrush (Artemesia tridentata Nutt.) steppe with an understory of western wheatgrass (Pascopyrum simithi (Rydb.) A. Löve), needle and thread grass (Stipa comata Trin. & Rupr) and Indian rice grass (Oryzopsis hymenoides Roem. & Schult). The western half of the ranch, at an elevation of 2652 m, is dominated by mountainous, semi-open brush and grasslands with scattered stands of aspen and conifer mainly Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco). Mean annual precipitation is 890 mm with 74% as snow accumulation; the wettest months are April, May, June and September. Mean annual air temperature is about 4.5 ^{o}C, mean winter temperature is about - 4.9 ^{o}C and mean summer temperature is about 15.1 ^{o}C [as measured by a nearby SNOTEL site (Horseridge) with 10 years of data]. The most common soil orders present are Mollisols, Entisols, Aridisols and Inceptisols (Washington-Allen et al. 2004). Soil parent material is derived from Wasatch conglomerate. The study site in Upper Frost watershed, a small catchment that is approximately 215 ha, was located between 1889 and 2700 m elevation in the western part of DLL (Figure 4.1).

Experimental Design

Thirty three sampling points that were 32 m apart from each other were located along north (N, n=11), south (S, n=8), east (E, n=7) and west (W, n=7) facing linear transects in the Upper Frost Canyon drainage. Throughout the text the transects will be designated as N, S, E and W. Transects ran from the top of ridgeline to the bottom, covering an elevation gradient between 2522 m and 2605 m (Table 4.1). Sites were chosen because they had a sufficiently large contiguous area of pure aspen forests that allowed long linear transects.

Soil Sampling and Properties. To estimate the amount of SOC in the soil, mineral soil samples were taken in 10-cm increments to a depth of 40 cm at each of the 33 sampling points using sampling pits. Bulk density of the soil was determined at each sampling point by depth using the soil excavation method (Blake and Hartage 1986). Samples were oven-dried at 105^{o}C, sieved (2-mm mesh), and weight of fine and coarse fractions was recorded. Sub-samples of < 2 mm were analyzed for C concentration using a Leco CHN analyzer (CHN 1000, LecoCorp., St Joseph, MI). Total SOC to a depth of 10 cm and 40 cm was calculated as follows:

Mass SOC (Mg ha^{-1}) = OC x BD x D x CF x [(1-(R/100)]

Where OC = Organic Carbon Concentration (g C kg^{-1})

BD = Bulk Density (g cm^{-3})

D = Depth (cm)

CF = Unit Conversion Factor (10^{-1})

R = Percent Rock Fragment

Soil pH was determined on a 1:1 deionized water to soil slurry using pH meter. Texture was determined by standard hydrometer techniques on a subset of sampling points (N, n=4; S, n=4; W, n=4; E, n=3) (Gee and Bauder 1986).

Four soil pedons (1m by 1m), each representative of one transect (N, S, E and W), were exposed and the soil morphology was described following standard methods including soil depth, color, structure, texture (by feel method), consistence, effervescence and field pH (colorometrically) (Soil Survey Division Staff 2003). The soil moisture regime of the area was assumed to be xeric while the soil temperature regime was estimated by calculating mean annual temperature and soil temperature using data obtained from SNOTEL site (Horseridge) located at DLL. Interpretations of the soil properties were made using the field book (Schoeneberger et al. 2002). Soil samples were taken from each genetic horizons in each pedon, dried at 105°C and sieved (<2 mm). Cation exchange capacity (CEC) and base saturation (BS) were determined on the < 2mm fraction by extracting exchangeable base cations with 1 M NH_4Cl at pH 7.0 using vacuum extractor (Soil Survey Staff 1996) and analyzing extractant for cation concentraions using an inductively coupled plasma spectrometer (ICP) (Iris Advantage, Thermo Electron, Madison, WI), followed by extraction with 2 M KCl and analysis of extractant for NH_4 using flow injection analyzer (Lachat Quickchem 8000, Flow Injection Analyzer).

To assess the seasonal nutrient regime of the area, plant simulator probes (PRS-probes) (Western Ag Innovations Inc., Saskatoon, Canada), which are exchange resin membranes, were installed to a depth of 10 cm on selected points along the transects, (N, n=4; S, n=4; E, n=3; W, n=3). Each sample unit consisted of four cation and anion probes. Prior to installation a few probes were also designated as blanks and placed in platic bags during the entire burial time. The first set (winter 2005-06) was installed on October 25, 2005 and removed on June 20, 2006; the second set (summer 2006) was installed on June 20 and removed on July 28, 2006. Once removed from the field, the PRS-probes were cleaned and shipped to Western Ag Innovations Inc. for chemical analysis of a suite of cations including Ca^{+2}, K^+, Na^+, Mg^{+2}, NH_4^+-N; a suite of anions including NO_3^-, $H_2PO_4^-$ -P, $B(OH)^{-4}$-B, SO_4^{-2}-S, Cl^-; and a suite of metals including Cu^{+2}, Zn^{+2}, Mn , Fe^{+3} and Al^{+3} -Al. For the purpose of this study we focused on available Ca^{+2}, Mg^{+2}, K^+ and total N (NO^-_3 -N + NH_4^+-N).

Soil Organic Carbon Drivers. The elevation, aspect and slope of every point along each transect were recorded. To characterize the soil microclimate, soil moisture index (SMI) and temperature were measured along the transects. SMI was determined by installing an ECH_2O moisture probes (Decagon, Pullman, WA) to a depth of 20 at all 33 sampling points along the transects. Using handheld Decagon readers, a total of six readings (millivolts) were taken during summer 2005 (SMI 05), and nine readings during summer 2006 (SMI 06) between the end of June and early October. For the purpose of the study we chose three time periods from each year, where major changes in soil moisture were observed and the dates represented snow melt (June), summer (July, Aug, September) and fall (October).

The field moisture readings (mV) were calibrated for gravimetric (Θm) and volumetric water content (Θv) in the lab using reconstructed soil cores with ECH_2O probes that were subject to several wetting and drying cycles. In order to come up with a relative index of available water for each site, a volumetric moisture threshold (MT) of 10% (Θv) was set, and the available water content (AWC) was calculated by subtracting MT from the calibrated field readings (Θv), which is the residual above permanent wilting point (PWP). The MT threshold corresponded to a soil matric potential of approximately 1500 KPa (PWP) based on the water soil water characteristics equations (Saxton et al. 1986) applied to a tension range >- 1500 to -10 KPa, with volumetric water content (Θv) derived from the following equations:

$$\Psi = A\Theta^{B}$$

$$A = \exp[a + b\,(\%C) + c\,(\%S)^2 + d\,(\%S)^2(\%C)]\ 100.0$$

$$B = e + f(\%C)^2 + g\,(\%S)^2 + g\,(\%S)^2(\%C)$$

Coefficients

a = -4.396, b=-0.0715, c= -4.880x10^{-4}, ^{d}= - 4.285 x 10^{-5}, e= -3.140, f= -2.22 x 10^{-3}

g= -3.484 x 10^{-5}

Where:

Ψ = Matric Potential

Θ = Volumeric water content (m^3/m^3)

C = % Clay

S = % Sand

We calculated the cumulative moisture index (CMI) for the two contrasting summers where summer 2005 was a dry summer and summer 2006 was a relatively wet summer. CMI was estimated for each transect point by the summation of AWC values across the three representative dates of summer 2005 and 2006.

Along selected sites on the four transects (N, n=4; S, n=4; E, n=3; W, n=3) soil temperature regime was measured with Stowaway Tidbits dataloggers (Onset Computer Corporation, Bourne, MA) installed at 10-15 cm below the soil surface and programmed to record soil temperatures at 2-hour intervals. Tidbits were downloaded in July and October of 2005 and 2006. However, we were only able to record the soil temperatures regime of late summer and early fall of 2005 as several tidbits failed. From the available data, which represented each transect over a period of 65 days (Aug 8-Sept 30 of 2005), a soil heat index was expressed as degree days above 5^{o}C.

Overstory vegetation cover was assessed at every transect point using a fixed area plot, where the diameter at breast height (DBH) of individual tree > 5 cm was measured within the circular plot of a radius of 10 m. Using this information live basal area (LBA), average tree diameter (ATD) and tree density (TD) were calculated as follows:

LBA (cm^2) = $(DBH/2)^2 * \pi$

ATD (cm) = (Sum of live basal area/ # of trees) / π

TD (# trees/ ha) = # of trees/ sampling area *10,000

Where: $\pi = 3.14$, sampling area= 314 m^2

Statistical Analysis

One way ANOVA was used to test differences in SOC, nutrient availability, moisture index, temperature and stand characteristics using PROC Mixed followed by pairwise comparisons with a Tukey-Kramer adjustment (SAS Institute 2003). Differences were considered significant at $p \leq 0.1$. The relationship between SOC storage 0-10 cm and 0-40 cm depth (response variable) and the various biotic (stand characteristics) and abiotic factors (elevation, slope, soil-microclimate) (explanatory variables) was tested using linear and multiple regressions. Significance of parameters was examined, model fit was tested; residuals and influence of diagnostics were also examined. To meet normality, some raw data were transformed prior to analysis using log transformations (SMI 2006, CMI and ATD) and square root transformations (tree density).

Results and Discussion

General Site Characteristics

Selected site characteristics are summarized in Table 4.1. The soil texture was mainly loam except for a few sites that had silt loam and sandy loam textures. The southern and eastern facing transects generally had higher rock fragment content compared to the northern and western facing transects (Table 4.1). Based on the pedon descriptions (Table A.1-A.4 in the Appendix), the soils on all but the eastern facing transects were classified as Pachic Argixerolls, which are Mollisols with an argillic subsurface horizon and a thick mollic epipedon (Soil Survey Staff 2003). However, the pedon on the eastern facing transect was classified as Pachic Haploxeroll, with mollic epipedon that is ≥ 50 cm similar to the pedons on the other transects but no subsurface accumulation of clay (Soil Survey Staff 2003). The sites on the eastern facing slopes were steeper than the other sites, which could explain the difference in soil classification. All soils were characterized by a typical mollic epipedon with very dark brown to dark brown and yellowish brown dry colors (Table 4.2). These results are consistent with findings by other researchers (Bartos and DeByle 1981; Jones and DeByle 1985; Cryer and Murray 1992). Cryer and Murray (1992) postulated that stable or permanent stands of aspen are found on Mollisols, and according to Bartos and DeByle (1981), Jones and DeByle (1985) and Cryer and Murray (1992), it was attributed to the addition and rapid turnover of aspen leaves to the soil each year. However, faster turnover rates are somewhat counterintuitive to higher SOC content in the surface horizon. Stabilization due to a series of processes such as humification (microbial decomposition of organic materials in the soil that produces some relatively stable, dark compounds), extension of roots into the soil profile (Buol et al. 2003) and bioturbation (reworking of the soil and organic materials by soil fauna) (Hole and Nielsen 1970) could instead be the reason for higher SOC accumulation leading to the formation of mollic epipedon.

The pH of the soils on the transects (averaged from 0-40 cm) ranged from 5.6-6.8 with most of the sites being above 6.0 (Table 4.1). Results obtained from the analysis of the samples collected from the pedons showed that the CEC of the soils ranged from 10.8-19.0 $\text{cmol}_c\ \text{kg}^{-1}$ in the upper 20 cm and the base saturation in all the sites was greater than 90% (Table 4.2). Generally researchers reported aspen soils characterized by high pH and high base saturation (Hoff 1957; Morgan 1969; Alban 1982; Paré, Bergeron, and

Camire 1993). This might be due to the higher amount of Ca present in aspen soils, which was confirmed by the PRS probe results (Table 4.3). Our results showed that the nutrient availability in winter and summer was not significantly different among aspects (Table 4.3), but in both seasons the amount of Ca captured by the exchange membranes was very high. This might be due to high Ca requirements (Alban 1982), which frequently builds up the Ca concentration in the surface soil as a result of the high annual Ca input via the leaf fall (Chandler 1937; Schroth and Lehmann 2003).

Soil Organic Carbon Storage

The average SOC content of the upper 10 cm in Upper Frost Canyon was 30.9 ± 7.1 Mg C ha^{-1} and to a depth of 40 cm was 111.9 ± 29.1 Mg C ha^{-1}, with a coefficient of variation of 23% (0-10 cm) and 26% (0-40 cm). When the sampling points were categorized by aspect, SOC to a depth of 40 cm ranged from a low of 69 Mg ha^{-1} at one site on the W facing transect to a high of 206 Mg ha^{-1} at a site in the S facing transect. The average SOC content was 94.8 ± 18.8 Mg C ha^{-1} , 140.7 ± 33.9 Mg C ha^{-1} , 125.5 ± 21.7 Mg C ha^{-1}, 102.6 ± 16.1 Mg C ha^{-1} for the N, S, E and W facing transects, respectively. One-way ANOVA indicated that SOC to a depth of 40 cm was significantly different ($p< 0.05$) among aspects with W and N facing transects similar at the lower end and S and E facing transects having the highest values. The SOC content in the upper 10 cm was not significantly different among transects ($p = 0.15$) (Figure 4.2). Our calculated average SOC content of about 111.9 Mg C ha^{-1} is lower than the one reported by O’Neill, Kasischke, and Richter (2002) (151.5 Mg C ha^{-1}) in an aspen study carried on in Interior Alaska to approximately the same soil depth (0-40 cm). The difference in climatic conditions (dry and warm vs. wet and very cold) between the two study sites might have attributed to differences in SOC, with the cold soil temperature possibly slowing down decomposition in Alaska. In contrast, our SOC estimate is considerably higher compared to the values reported by Van Miegroet et al. (2005) in the same climatic region. Moreover, our calculated SOC value is relatively high compared to the SOC estimates for Mollisols reported by Kern (1994) to a depth of 100 cm, which is about 100 Mg C ha^{-1}. Studies have reported that most of the SOC occurs in the upper horizons (30-40 cm) (O'Neill, Kasischke, and Richter 2002; Van Miegroet et al. 2005). So the estimate of the 100 Mg C ha^{-1} reported by Kern (1994) may be concentrated in the upper horizons, making it closer to our SOC estimate.

Site Characteristics and SOC

The variability in SOC among aspects could be explained by site characteristics such as soil microclimate and stand characteristics. Because there were only small differences in elevation and slope among the sites, these site characteristics did not explain SOC variability.

Cumulative moisture index over both summers (2005-2006) was significantly different among the transects ($p < 0.05$). Although only differences between E, N and W facing transects were statistically significant, generally the N and W facing transects were wetter and the S and E facing transects were drier (Figure 4.3). The summer in 2005 was relatively dry compared to the summer in 2006 and aspect differences were most pronounced when the soils were moist (summer 2006) (Figure 4.4). These results suggest that highest SOC accumulation is generally associated with drier site conditions.

Mean degree days over a period of 65 days from August 8th – September 30th 2005 for the N, S, E and W facing transects were 232, 350, 380 and 293, respectively. One-way ANOVA showed that the temperature regime was significantly different with aspect ($p < 0.05$) and the S and E facing transects had higher soil temperatures than the N and W facing transects (Figure 4.5).

The S and E facing transects were more densely vegetated with relatively smaller trees. Tree density differences among aspects were not statistically significant but average tree diameter (13.2 cm and 16.5 cm for S and E vs. 17.2 cm and 20 cm for W and N) was significantly different among the aspects ($p < 0.05$) (Figure 4.6 and 4.7), with the N facing transect supporting the largest trees, and S facing transect the smallest

The combinations of the soil microclimate and stand characteristics could explain the variability in SOC content among aspects. The higher amount of SOC in the S and E facing transects was probably due to lower turnover rates associated with restricted moisture availability. Even though temperature is considered an important controlling factor of decomposition rates (Schlesinger 1997); in arid and semi-arid regions soil moisture often limits the rate of decomposition (Santos et al.1984, Amundson et al. 1989). So in this case, even though the temperature was higher in the S and E facing transects decomposition rates were governed more by moisture limitations than temperature during summer. Moreover, the difference in forest structure might also have influenced SOC content as a result of canopy openness/closeness, which possibly influenced the amount of C input through litterfall and microclimatic conditions affecting decomposition. Even though a general pattern was observed relating SOC to site characteristics from the four aspects, there was a tremendous variability among individual sampling points on the same transects. Therefore, we further analyzed the data at the level of individual sampling points to look for potential relationships between SOC and individual site characteristics, through the use of correlation and regression analysis.

There was not significant correlation between SOC in the upper 10 cm and any of the abiotic and biotic drivers considered (Table 4.4). This was contrary to findings reported by researchers such as Hontoria, Rodriguez-Murillo, and Saa (1999), who found a significant correlation between the surface horizons SOC (0-18 cm) and different soil moisture parameters, temperature, altitude and slope gradient. However, SOC content between 0-40 cm showed a significant negative relationship with soil moisture index expressed as SMI 2005 (r= -0.39 p=0.03), SMI 2006 (r=-0.58, p=0.001) and CMI (r=-0.59, p=0.001). SOC was not influenced by LBA, but generally showed a positive correlation with the tree density and a negative correlation with average tree diameter, meaning that SOC levels were generally higher in sites occupied by a dense forest of smaller trees compared to sites with fewer but larger trees. Other parameters such as elevation and slope did not show any significant correlation and this might be due the ranges small elevation and slope gradient (Table 4.4).

Generally SOC is believed to be positively correlated to mean annual precipitation (MAP) (Post et al. 1982; Jobbagỳ and Jackson 2000; Homann, Kapchinske, and Boyce 2007) so it would be reasonable to expect similar relationship between soil moisture regime and SOC. However, in this study the SOC was negatively correlated with cumulative moisture index. Similar results were reported by Hontoria, Rodriguez-Murillo, and Saa (1999) in a study carried out in Spain where the soil moisture regime is dry in all parts of summer and they attributed SOC pattern to the lack of precipitation accompanied by high temperatures during summer season in the Mediterranean climate. In our case a similar pattern might be occurring where microbial decomposition is slowed down by limited summer soil moisture allowing for greater SOC accumulation. Even though the SOC content in the semiarid and arid regions was not studied extensively, researchers reported that in these ecosystems soil moisture was an important factor controlling many processes including decomposition, soil respiration and nutrient fluxes (Wildung et al. 1975; Parton et al. 1994; Klopatek et al. 1995). Conant, Klopatek, and Klopatek (2000) found that soil respiration rates in semi-arid ecosystems decreased during warm summer months because respiration was water limited during this period. McCulley, Boutton, and Archer (2007) concluded the soil respiration in semi-arid ecosystems was water limited. These findings are relevant to our study as the lower respiration rates are indicative of lower C turnover and could lead to the higher amount of SOC stored in these moisture restricted areas.

Regression analysis showed that the CMI explained only 16% of the variability in SOC (0-40 cm) (R^2=0.16 p=0.03) (Figure 4.8), whereas square root-transformed tree density (R^2=0.33 p=0.02) (Figure 4.9) and the log-transformed average tree diameter (R^2=0.16 p=0.04) (Figure 4.10) accounted for 33 % and 16 % of the variability, respectively. In this study, the influence of stand characteristics, especially tree density, was more important than other factors considered. As was suggested by the transect comparison high SOC occurred in sites characterized many small trees, which could be a surrogate for a more closed canopy, whereas sites that had a more open structure contained less SOC. Even though LBA in this study did not suggest significant differences in litterfall, stand characteristics, especially canopy openness/closeness might have direct effects on the SOC accumulation through differences in the litter fall inputs and differences in canopy shading, causing differences in microclimate that affect microbial activity and decomposition. Moreover, studies have shown that canopy structure of overstory trees can significantly influence understory vegetation (Moeur 1997), which in turn, can significantly contribute to the C input and microclimatic variability. However, in this study we did not assess the understory vegetation, litterfall or litter decomposition rates so further study is required to ascertain exactly how forest structure affects SOC storage.

Multiple regression showed that 46% (R^2=0.46 and p=0.002) of SOC variability could be explained by a combination of tree density, average tree diameter, and cumulative moisture index with most of the variability (33%) explained by tree density. Many researchers have found that site variables were usually able to explain only about 50% of the variability in SOC (e.g. Burke et al. 1989; Grigal and Ohmann 1992). A large proportion of unexplained variations might be due to the effect of uncertainties or the exclusion of important site characteristics, or may be due to the combined effects of errors in variable measurements and natural within-site variability (Hontoria, Rodriguez-Murillo, and Saa 1999).

The regression and ANOVA analyses were consistent; as they showed similar patterns in SOC amount in relation to moisture conditions (higher SOC in sites with drier summer moisture conditions) and stand characteristics (high SOC in sites with high density of small trees).

Conclusion

In this study we estimated the amount of SOC stored under stable aspen and we found that SOC was highly variable even in the small watershed. The SOC content differed significantly with aspect, but differences among aspect were observed to a depth of 40 cm only, and not between 0-10 cm. This indicates the importance of sampling depth as surface sampling (0-10 cm) might not be able to detect important site differences. Among the various drivers that we investigated SOC variability (0-40 cm) was best explained by CMI in summer (2005 and 2006) and selected stand characteristics. No significant correlation was observed between site characteristics and SOC content between 0-10 cm. The relative uniformity of soil texture and small elevation gradient excluded them as important drivers in SOC variability in our study area.

One of the important findings of this study was that SOC variability was influenced by climatic conditions. However, in our study we observed the opposite trend to the general observations by other researchers that SOC increased with precipitation and soil moisture. This is an indication that factors controlling SOC can be dependent on regional climatic conditions. In semiarid and arid ecosystems moisture is considered the main controlling factor for many biogeochemical processes including SOC storage. So in this study the higher SOC could be associated with decreased decomposition, lower soil respiration rates, and decreased microbial activity as a result of restricted soil moisture. Soil temperature might have explained some of the variability in combination with soil moisture, however due to some technical problems we were not able to include soil temperature as a driver variable in our regression analyses. The other important factors, which explained the majority of the variability, were associated with overstory structure expressed by tree density and average tree diameter. These two factors can influence SOC accumulation by causing differences in litterfall input from overstory and understory, or indirectly by causing differences in soil microclimatic conditions that regulate SOC losses through decomposition. We did not measure litterfall input, understory vegetation, or decomposition rates among the aspects and sampling points so we cannot yet clearly indentify the relationship between SOC and stand structure. However, this study is important as a first step in quantifying spatial variability in SOC, more detailed studies of C input and loss rates and the role of understory vegetation in these processes is necessary to better understand SOC storage and dynamics in aspen ecosystems.

Table 4.1 General characteristics of the sampling sites along the four transects (0-40 cm).

ID	Aspect	Elevation m	Slope %	Texture †	BD † g cm^{-3}	RF † %	pH †	LBA m^2 ha^{-1}	Density # trees ha^{-1}
1	North	2594	16	grL	1.02	15	6.3	19.6	955
2	North	2605	9	nd	1.23	18	5.9	30.1	987
3	North	2598	7	nd	1.26	22	6.5	32.6	510
4	North	2595	18	L	1.19	9	6.1	21.6	446
5	North	2594	15	nd	1.09	11	6.2	22.5	605
6	North	2584	11	nd	1.00	14	6.2	23.6	637
7	North	2583	38	grL	1.29	16	6.2	2.8	382
8	North	2557	19	nd	1.33	10	5.8	nd	nd
9	North	2552	13	nd	1.21	8	6.2	2.7	96
10	North	2534	12	nd	1.13	14	6.4	25.6	987
11	North	2531	12	L	1.05	6	6.1	19.6	701
12	South	2571	14	grL	1.35	31	6.2	23.2	1847
13	South	2571	23	nd	1.05	32	6.8	16.7	1624
14	South	2565	24	grL	0.97	30	6.6	13.5	892
15	South	2568	18	nd	1.25	25	6.3	7.9	478
16	South	2583	16	grL	1.56	30	6.3	18.7	1114
17	South	2589	18	nd	1.51	35	5.9	3.8	573
18	South	2597	14	grvSL	1.34	46	6.3	11.2	860
19	South	2575	4	na	na	na	6.1	10.4	510
20	East	2590	9	grvL	1.34	39	6.1	48.9	1847
21	East	2563	34	nd	1.17	26	nd	9.7	860
22	East	2565	46	grL	0.94	18	6.3	5.7	318
23	East	2573	32	nd	1.23	22	nd	17.9	860
24	East	2573	19	grL	1.03	20	5.6	17.9	637
25	East	2526	18	nd	1.25	25	nd	17.4	605
26	West	2583	16	L	0.86	<1	6.3	17.1	669
27	West	2522	14	nd	1.14	<1	nd	11.8	733
28	West	2546	15	L	0.99	<1	nd	nd	nd
29	West	2550	13	nd	0.93	<1	5.9	17.9	733
30	West	2550	10	nd	1.06	2	nd	17.2	669
31	West	2554	11	L	1.10	2	nd	24.3	828
32	West	2552	20	L	1.20	1	5.8	nd	nd
33	West	2544	26	nd	0.92	<1	nd	23.7	1114

† Values are averaged across 4 depths (0-40 cm).

Abbreviations: nd: not determined, v: very, gr: gravelly, L: loam, SL: Sandy loam LBA: Live basal area, BD: bulk density, RF: rock fraction

Table 4.2 Selected properties of the soil pedons sampled in 2005 in each of the four transects.

Horizon	Depth (cm)	Color (Dry)	Field texture	Clay (%)	Rock fraction (%)	Field pH	CEC cmol$_c$ kg^{-1}	BS %
North: Pachic Argixeroll								
A1	0-20	7.5YR 3/2	SL	12	5	5.8	15.4	100
A2	20-40	7.5YR 3/4	L	14	6	6.0	7.2	100
A3	40-53	7.5YR 4/4	L	18	6	6.2	9.6	100
Bt1	53-80	5YR 4/6	L	21	5	6.6	8.2	100
CBt	80-86	5YR 4/4	SL	11	6	6.8	8.3	100
South: Pachic Argixeroll								
A1	0-19	10YR 5/4	GRL	13	16	5.8	15.3	100
A2	19-43	10YR 5/4	GRL	13	16	5.8	11.5	98
Bt1	43-57	10YR 6/4	CBSL	16	30	5.6	4.7	95
Bt2	57-80	10YR 6/4	CBSL	17	22	5.5	2.6	91
C	80-86	nd	nd	nd	65	6.0	2.8	95
East: Typic Haploxeroll								
A1	0-14.5	10YR 3/2	GRSL	9	18	6.2	19.0	100
A2	14.5-33	10YR 3/3	GRSL	8	22	5.9	nav	nav
AC	33-56	10YR 4/3	CBVSL	8	36	5.6	nav	nav
C	56-72	10YR 6/4	CBVSL	3	39	5.4	2.8	95
West: Pachic Argixeroll								
A1	0-40	10YR 5/4	SL	7	5	5.9	10.8	100
A2	40-65	7.5YR 5/4	SL	8	2	6.0	8.8	100
Bt1	65-88	5YR 5/8	SIL	20	3	6.2	2.3	100
Bt2	88-100	5YR 5/8	SIL	21	5	6.0	3.1	100

Abbreviations: nd: not determined, nav: not available V: very, GR: gravelly, CB:cobbly L: loam, SL: sandy loam, SIL: silt loam .

Table 4.3 Winter and summer nutrient availability regime determined from the PRS-probes installed along the four transects (N, n=4; S, n=4; W, n=3; E, n=3).

Aspect	**North**	**South**	**East**	**West**	**P value †**
		-------------μg/10 cm^2/burial period-----			
		Winter 2005-06			
Total N	138	366	434	319	p = 0.15
Ca^{+2}	2839	2970	2747	2761	p = 0.12
Mg^{+2}	169	181	133	172	p = 0.27
K^{+}	46	87	66	51	p = 0.45
P	41	51	54	23	p = 0.67
		Summer 2006			
Total N	38	30	47	32	p = 0.77
Ca^{+2}	1357	1362	1960	1321	p = 0.25
Mg^{+2}	135	115	140	122	p = 0.65
K^{+}	306	235	249	206	p = 0.68
P	13	14	13	7	p = 0.69

† P value indicates significant difference in nutrient regime among the four aspects at $p \leq 0.10$

Table 4.4 Correlation coefficients between SOC at 10 cm and at 40 cm and site characteristics.

Site Characteristics	**SOC 0-10 cm**			**SOC 0-40 cm**		
	r	**p**	**n**	**r**	**p**	**n**
SMI 05	-0.10	0.6	31	-0.39	**0.03 †**	30
SMI 06	-0.13	0.5	31	-0.58	**0.001 †**	30
CMI	-0.16	0.4	31	-0.59	**0.001 †**	30
Elevation (m)	0.11	0.5	31	0.19	0.5	30
Slope (%)	-0.05	0.8	31	-0.00	0.8	30
LBA (cm^2)	-0.02	0.9	28	0.00	0.9	27
Density (# of trees ha^{-1})	0.24	0.2	28	0.43	**0.02 †**	27
ATD (cm)	-0.21	0.3	28	-0.46	**0.02 †**	27

Abbreviations: r: correlation coefficient, n: number of observations. **†** Values in bold are significant values at p≤ 0.10.

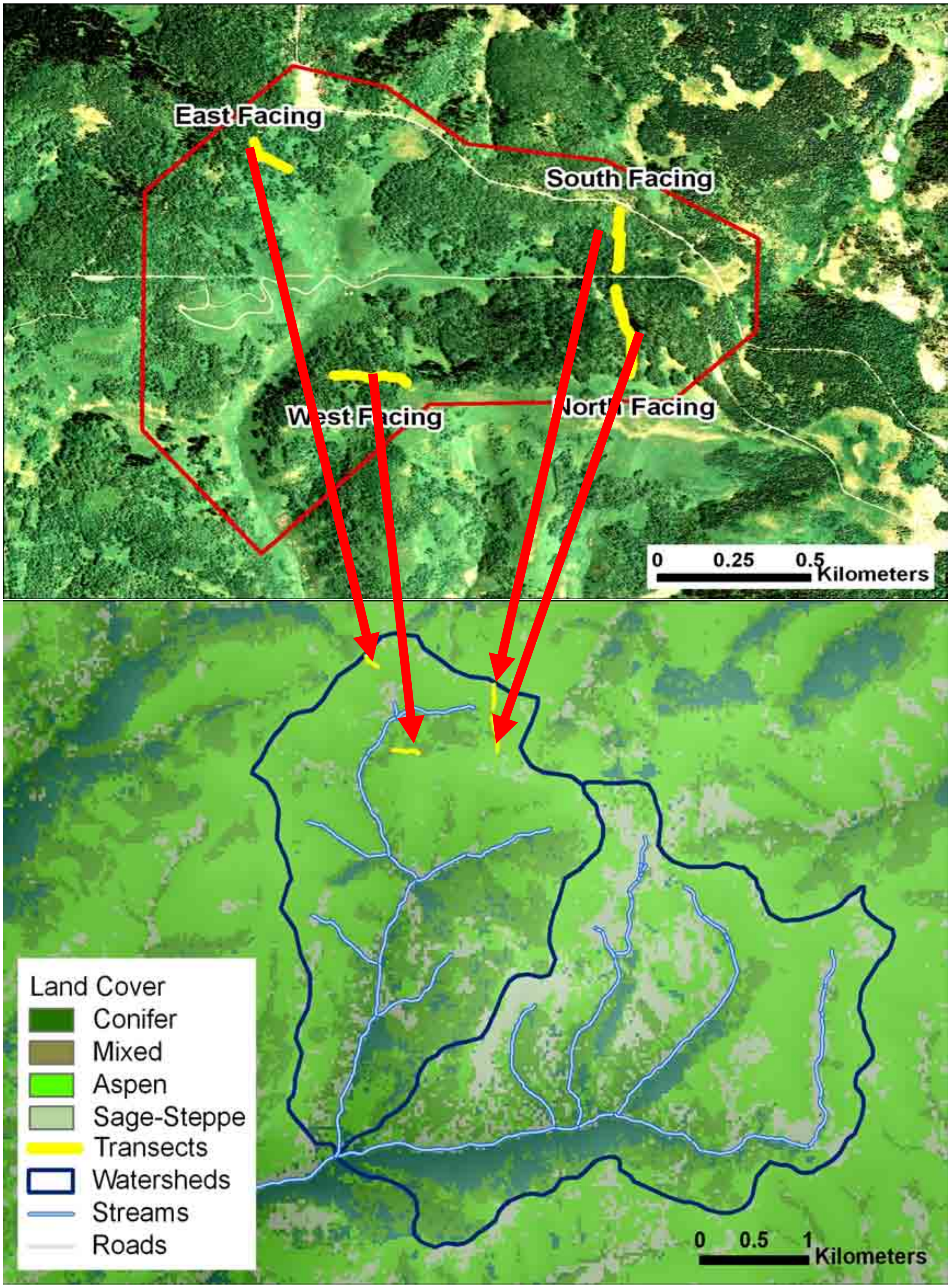

Fig 4.1 Map of the study location in Upper Frost Canyon at DLL. Upper image is an aerial photo where the Upper Frost Canyon watershed is delineated in red and the lower image represents the land cover of the area.

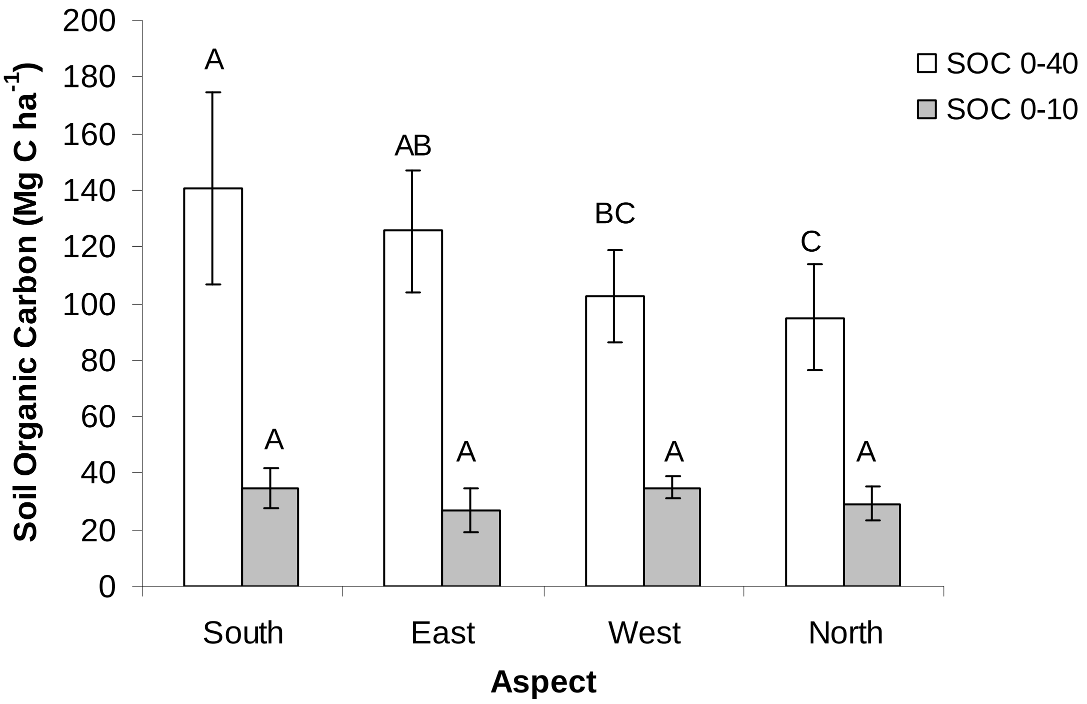

Fig. 4.2 Soil organic carbon storage in the top 0-10 cm and 0-40 cm mineral soil. Means with different letters are significantly different (p= 0.005).

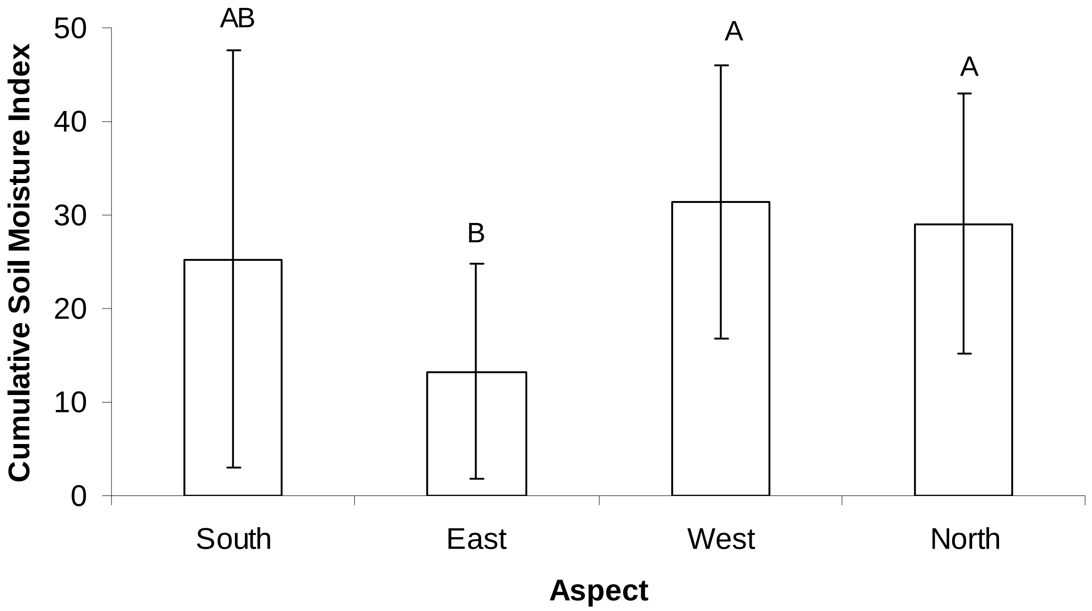

Fig. 4.3 Cumulative moisture index for 2005 and 2006 by aspect. Means with different letters are significantly different (p= 0.03).

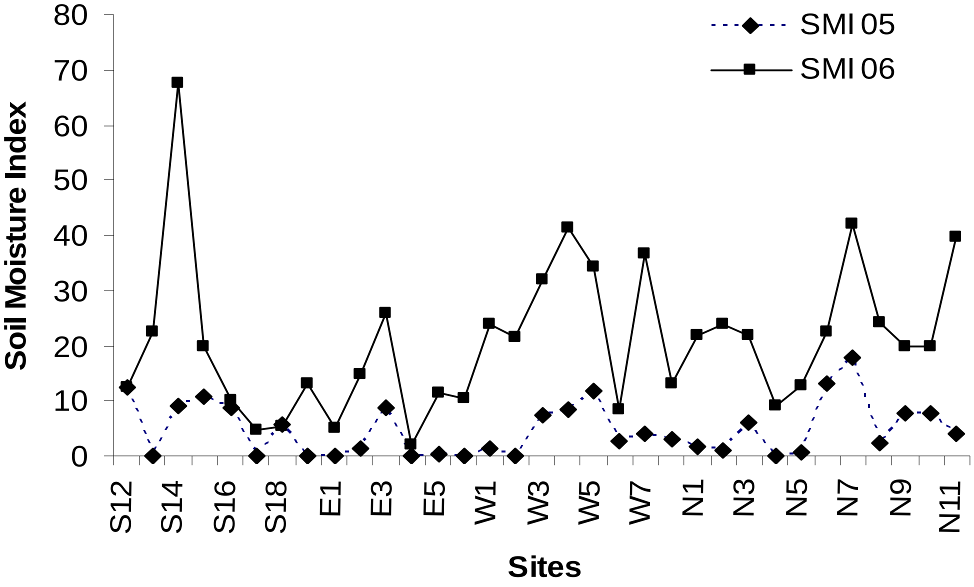

Fig. 4.4 Soil moisture index for the transect points during summer 2005 and summer 2006. S: south, E: east, W: west, N: north.

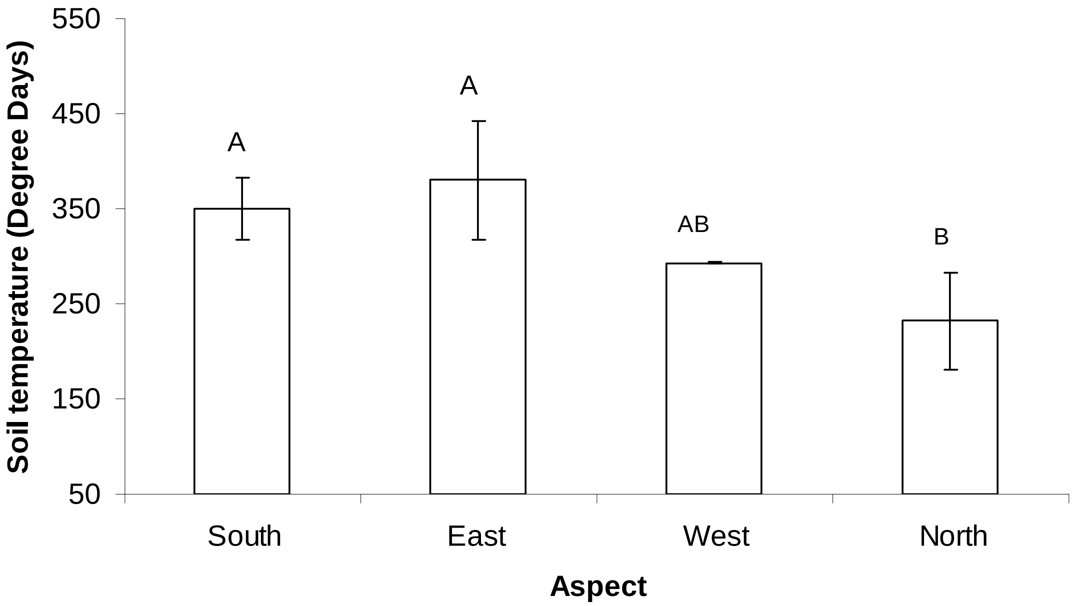

Fig. 4.5 Soil temperature along the four transects expressed in degree days. Means with different letters are significantly different (p=0.04).

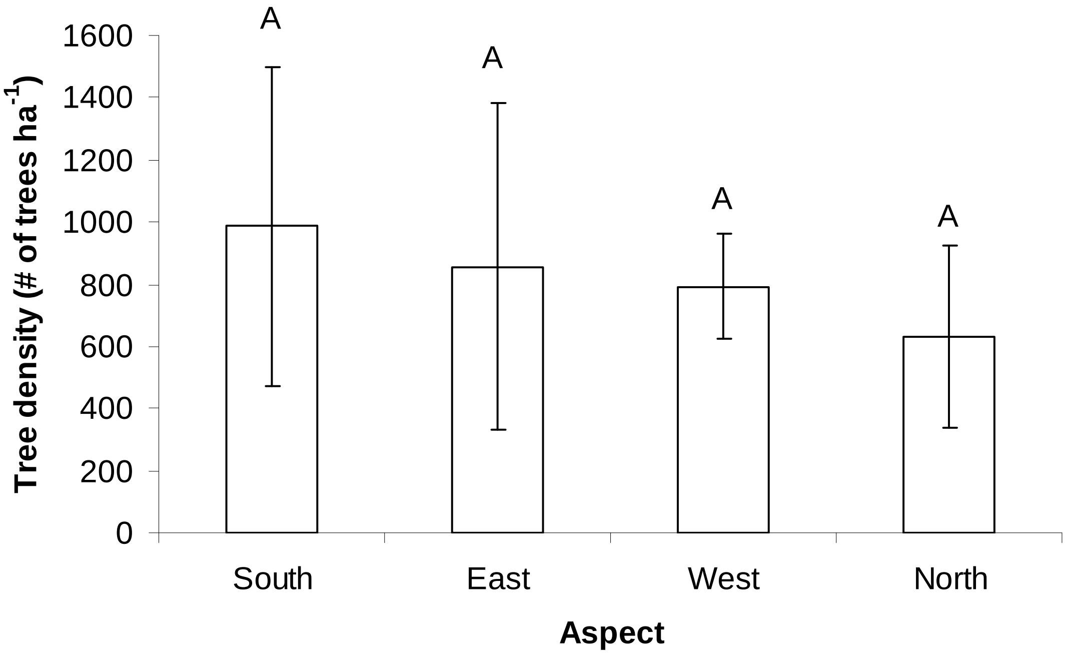

Fig. 4.6 Tree density by aspect. Means with the same letter are not significantly (p=0.3).

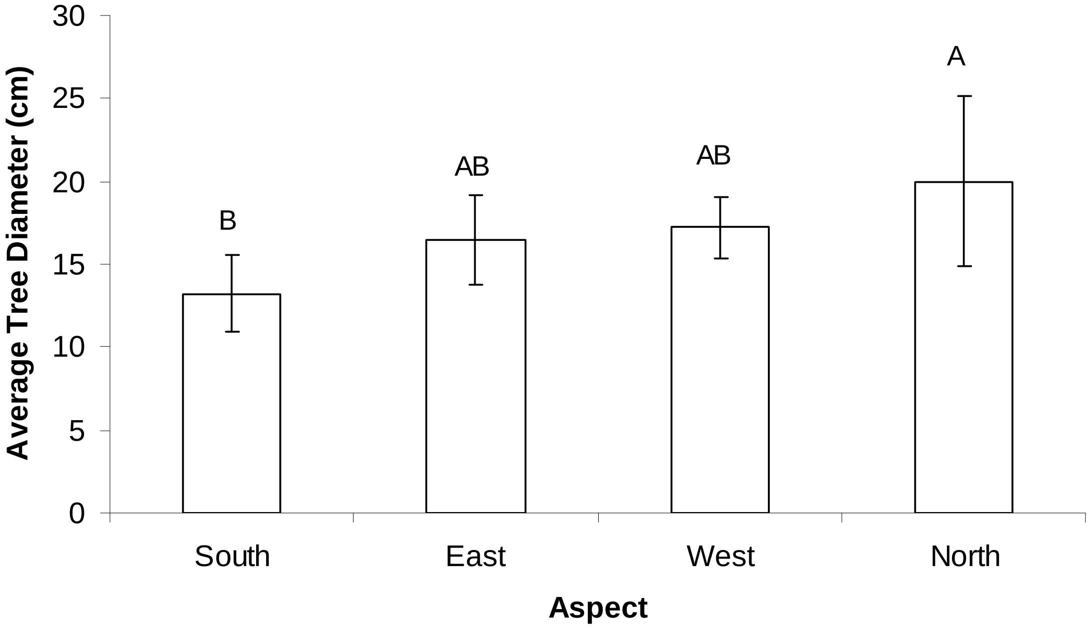

Fig. 4.7 Average tree diameter by aspect. Means with different letters are significantly different (p=0.01).

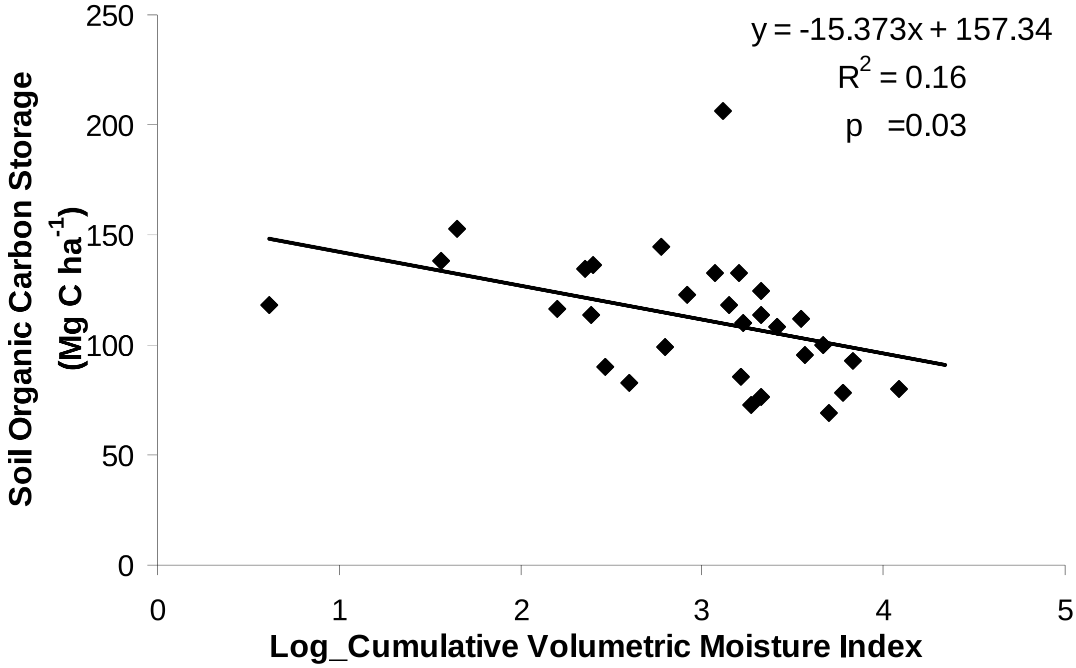

Fig. 4.8 Regression analysis of SOC (0-40 cm) and cumulative moisture index (log transformed).

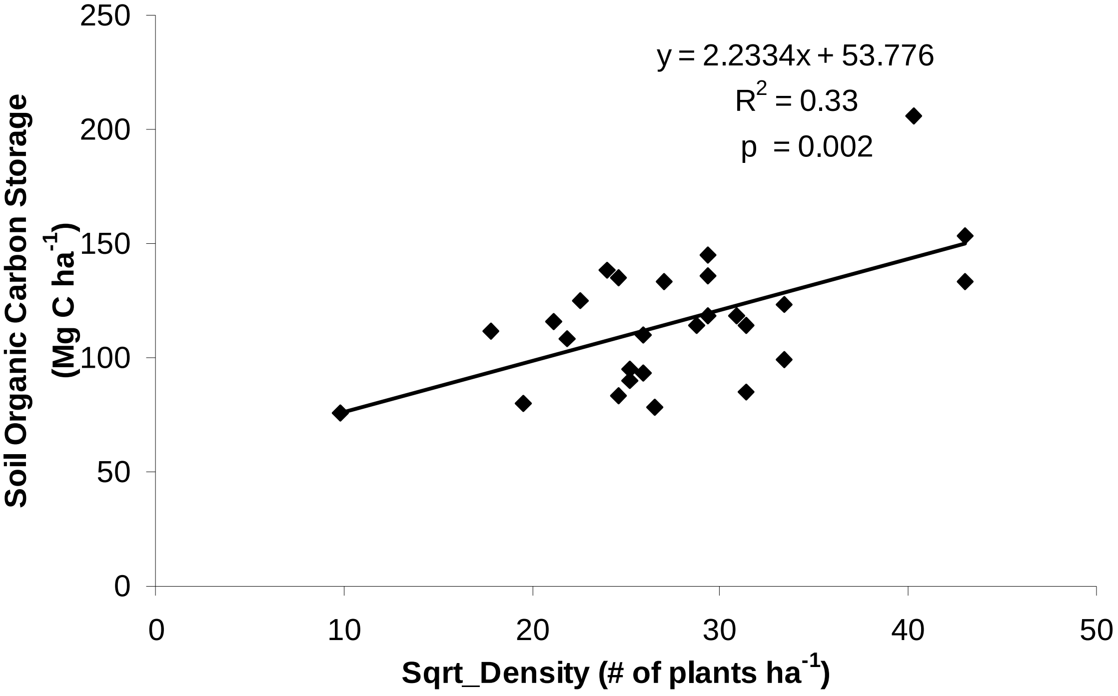

Fig. 4.9 Regression analysis of SOC (0-40 cm) and tree density (square root transformed).

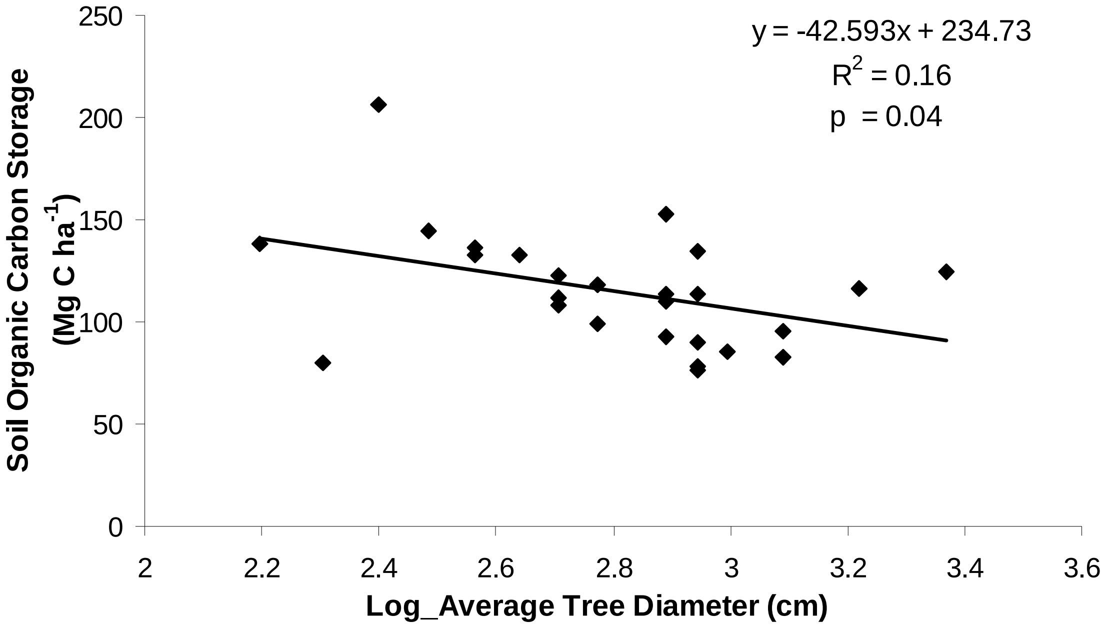

Fig. 4.10 Regression analysis of SOC (0-40 cm) and average tree diameter (log transformed).

CHAPTER 5

EVALUATION OF THE POTENTIAL EFFECTS OF CONIFER ENCROACHMENT: A PAIRED PLOT STUDY

Introduction

Aspen is the most widely distributed tree species in North America (Baker 1925; Little 1979). It is found in the upper Midwest and Lake States, across sub-boreal Canada and Alaska, in the Rocky Mountains from Canada through the US (Preston 1976). It is most abundant in the central provinces of Canada and in the western states of U.S. where 75 % of the aspen occurs in Colorado (50%) and Utah (25%) (Jones 1985; Bartos 2001).

Aspen-dominated forests in the western U.S. provide numerous ecosystem values such as forage for livestock, habitat for wildlife, landscape diversity, esthetics, and high water yield (DeByle and Winokur 1985; Bartos 2001). However, based on historical data, land area covered by aspen in the West has decreased 50% since European settlement (Bartos and Campbell 1998). The decline of aspen is mainly due to a combination of successional processes, fire suppression and long-term use of ungulates (Bartos and Campbell 1998, Bartos 2001). Currently aspen stands are categorized into three condition types (Bartos and Campbell 1998): a) stable, where aspen is considered properly functioning and self-replacing; b) successional to conifers, where disturbance forces such as fire are altered by humans giving shade tolerant species like conifers a marked advantage; c) decadent, where aspen clones are generally of a single age and very open, and mature trees are not replaced.

The decline of aspen in the West is of great concern because it has been argued that the replacement of aspen by conifers is outside of the range of historical variation and has been considered as an ‘‘environmental catastrophe’’(Club 20 1998). This forest transition is followed by loss of ecosystem functions that modify the sites dramatically. Such losses include changes in organic matter, moisture and temperature regime, water storage, etc. Various studies in the West have shown that aspen forests have higher organic matter content compared to adjacent stands containing other vegetation types such as conifers, shrubs and herbaceous vegetation (Hoff 1957; Tew 1968; Jones and DeByle 1985). The implication is that vegetation shifts may potentially change SOC storage, and small changes in SOC are believed to have a significant impact on atmospheric CO_2 concentrations (Kirschbaum 2000; Amundson 2001).

The presence and distribution of specific vegetation types in a site can affect site characteristics such as soil moisture, which in turn can contribute to changes in C storage by affecting SOC dynamics**.** Studies in the West have suggested that conifer encroachment causes a decrease in water yield and streamflow (Gifford, Humphries, and Jaynes 1984; Bartos and Campbell 1998). A decrease in soil water storage can negatively affect understory vegetation (Bartos and Campbell 1998). LaMalfa and Ryel (2008) also indicated that the average shallow soil moisture is higher in aspen plots relative to adjacent conifer plots, especially in winter and spring, due to higher winter snow accumulation in aspen stand. Similar studies in Montana (Moore and McCaughey 1997) and hydrological modeling based on hydrological process research in Russia and Canada (Gelfan, Pomeroy, and Kuchment 2004) have also reported that snow accumulation is 15-40% lower in conifers relative to deciduous or open stands, contributing to a lower soil moisture status of conifer stands.

Some have also postulated that conifer encroachment in aspen stands lowers soil temperature as a result of the shading effect by the conifers (Cryer and Murray 1992; Amacher et al. 2001). As microbial activity increases exponentially with increasing temperature (Edwards 1975), the decrease in temperature as a result of conifer encroachment can decrease microbial activity and decomposition, which would favor the accumulation rather than loss of soil organic matter. So the increase in conifer dominated lands can affect many important site characteristics that control C storage.

As a result of high nutrient content and rapid decay of aspen leaves (Daubenmire 1953), aspen are considered to be efficient nutrient pumps (Lutz and Chandler 1946; Jones and DeByle 1985) that enrich the surface horizons (Stoeckeler 1961). This contributes to the relatively high pH and higher base saturation of surface soils under aspen (Hoff 1957; Tew 1968; Morgan 1969; Alban 1982; Paré, Bergeron, and Camire 1993), which might be related to high Ca requirements of this species (Alban 1982). It is hypothesized that when other vegetation types encroach aspen, a decrease of soil pH to 6.0 or lower takes place accompanied by a decrease in nutrient levels, which are believed to suppress aspen regeneration (Cryer and Murray 1992).

Conifer encroachment may also cause changes in soil forming processes and soil morphology. Cryer and Murray (1992) postulated that stable or permanent stands of aspen are uniquely found on one soil order, Mollisols. In contrast, soils developed under conifers in the Intermountain West are primarily Alfisols. However, there has been insufficient research done to draw broad conclusions that the occurrence of aspen stand is limited to one soil order and that the soil morphology and associated chemical and physical soil properties are always changed by conifer encroachment.

Twenty five percent of the aspen in the West is located in Utah and many researchers hypothesized that the conifer encroachment can have detrimental effect on these aspen stands. Our understanding of the impacts of conifer encroachment on soil properties such soil organic carbon (SOC) storage, soil morphology, and soil chemical properties and the implications of such changes are still unclear because not many specific studies have been done in the Western U.S. However, it is generally known that community shifts alter the chemical, physical, and biological properties of the soil through their occupancy, and that such alterations in turn contribute a change in the abundance of the dominant species that characterizes the succession (Fisher and Binkley 2000).

The main objective of this study is to evaluate the potential effects of conifer encroachment by characterizing the soil properties such as soil morphology, soil microclimate, SOC storage and soil chemical properties of aspen and conifer as representatives of end-point communities in northern Utah using a paired plot design.

Materials and Methods

Study Site

The study was conducted in three small catchments in Northern Utah, namely Upper Frost Canyon and Bear Canyon in Deseret Land and Livestock (DLL) (Figure 5.1) and at Sunset Ridge in T.W. Daniel Experimental Forest (TWDEF) (Figure 5.2). These study sites were chosen because they are suitable for paired plot vegetation study as both aspen and conifer vegetation are present in close proximity to each other. Geology was also similar among all sites.

Deseret Land and Livestock is a privately owned ranch in Rich County, Utah, located at 41.10^o N, 111.25^o W. It occupies 88,800 ha, including 6,800 ha of Department of Interior Bureau of Land Management (BLM) and Utah State Lands (McMurrin 1991). Vegetation on the eastern half of the ranch, at an elevation of 1920 m, is dominated by sagebrush (*Artemisia tridentata* Nutt.*)* steppe with an understory of Western wheagrass (*Pascopyrum smithii* (Rydb.) A. Löve), needle and thread grass (*Stipa comata* Trin. & Rupr.), and Indian ricegrass (*Oryzopsis hymenoides* Roem. & Schult.). The western half of the ranch, at an elevation of 2652 m, is dominated by mountainous, semi-open brush and grasslands with scattered stands of aspen *(Populus tremuloides* Michx*)* and conifer mainly Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Mean annual precipitation is 890 mm with 74% as snow accumulation; the wettest months are April, May, June and September. Mean annual air temperature is about 4.5 ^{o}C, mean winter temperature is about -4.9 ^{o}C and mean summer temperature is about 15.1 ^{o}C [as measured by a nearby SNOTEL site (Horseridge) with 10 years of data]. Even though Frost Canyon and Bear Canyon have contrasting geologies (Shakespeare 2006), the study plots were established on the same geological substate, namely the Wasatch conglomerate. The most common soil orders present are Mollisols, Entisols, Aridisols and Inceptisols (Washington-Allen et al. 2004).

The T.W. Daniel Experimental Forest is Utah State University’s facility, located at about 30 km North-East from Logan, Utah at an elevation of 2900 m (41.86^o N and 111.50^o W). The annual precipitation is 950 mm with an 80% snow accumulation (Van Miegroet, Hysell, and Johnson 2000). Average low temperature is -10^{o}C while highest monthly temperature is 14^{o}C (Schimpf, Henderson, MacMahon 1980; Skujins and

Klubek 1982). The vegetation in the study area ranges from forb meadows and sagebrush to conifer forest, predominantly Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt) and lodgepole pine (*Pinus contorta* ex Louden), and aspen forest. The soil orders present are Mollisols and Alfisols (Skujins and Klubek 1982; Van Miegroet et al. 2005). They were formed in eolian deposits overlying residuum and colluvium from the Wasatch formation (Van Miegroet et al. 2005).

Experimental Design

Six plot pairs were established at DLL and TWDEF, two in Upper Frost Canyon (F1, F2) and two in Bear Canyon (B1 and B2) at DLL, and two at TWDEF (T1, T2) (Figure 5.1 and Figure 5.2). Areas were selected based on the proximity of aspen and conifer stands and similarity in elevation and slope. The plots were 20 m by 20 m (Figure 5.3). To address whether soil properties under the two vegetation types were significantly different, we compared the soil physical and chemical properties, soil microclimate, and also stand characteristics such as tree density and live basal area.

Soil Sampling and Analysis. In order to compare the morphology and genesis of soils under aspen and conifer, representative pedons (1 m wide and ≤ 1m depth) were manually excavated in each vegetation plot. The soil morphology of each pedon was described following standard methods including soil depth, color, structure, consistence and effervescence, pH and texture using the hand feel method (Soil Survey Division Staff 1993). Interpretation of the soil properties was made using the field book (Schoeneberger et al. 2002). Master horizons with appropriate suffixes, diagnostic epipedons and subsurface diagnostic horizons were assigned and the soil taxonomical sub-group was identified using the Keys to Soil Taxonomy (Soil Survey Staff 2003). Soil moisture regime was designated as xeric in all sites, whereas the soil temperature regime was estimated to be cryic in TWDEF and frigid in DLL. A full pedon description can be found in the Appendix (Tables A.5-A.16).

Soil Organic Carbon Pools and Chemical Properties. Soil samples were taken from each genetic horizon using cores (5 cm diameter, 3 cm length). Samples were dried at 105°C, sieved (2-mm mesh), weighed and ground with mortar and pestle prior to analyses. Bulk density and percent gravel was determined using core method (Blake and Hartge 1986). The total C and N concentration of the fine fraction (<2mm) was determined using dry combustion using a CHN analyzer (Leco CHN 1000, Leco Corp., St. Joseph, MI). Because the soil pits were of variable depth, the total C content was normalized to the shallowest depth of 60 cm in order to have a consistent depth for comparison across all the plots. The total C content in the pedon was calculated as follows:

$$\text{Mass SOC (Mg/ha)} = OC \times BD \times CF \times D \times [(1-(R/100)]$$

Where

OC = Organic Carbon Concentration (g C kg $^{-1}$)

BD = Bulk Density (g cm^{-3});

CF = unit conversion factor, 10^{-1};

D = Depth (cm);

R = Rock Fragment Ratio by Mass (%)

Cation exchange capacity (CEC) and base saturation (BS) were also determined on the < 2mm fraction by extracting exchangeable base cations with 1 M NH_4Cl at pH 7.0 using vacuum extractor (Soil Survey Staff 1996) and analyzing extractant for cations using an inductively coupled plasma spectrometer (ICP) (Iris Advantage, Thermo Electron, Madison, WI); followed by extraction with 2 M KCl and analysis of extractant for NH_4 using flow injection analyzer (Lachat Quickchem 8000, Flow Injection Analyzer).

To evaluate the representativeness of C concentrations in the upper horizons of the pedon compared to the entire plot, additional mineral soil cores to a depth of 0-15 cm were taken from each plot at four random locations using a split core sampler. Sub-samples were dried at 105^{o}C, sieved (<2 mm) and C concentrations were determined by dry combustion using a CHN analyzer (Leco CHN 1000, Leco Corp., St. Joseph, MI) as described above. No separate bulk density was determined on these core samples, as they were used for other analysis such as SOC quality, which required fresh soils. In our calculation of SOC pools, we applied estimated bulk density obtained from the pedons.

Soil Organic Pools (Forest Floor). Carbon content of the forest floor in the aspen and conifer plots was determined in fall 2007 by excavating one O horizon sample per plot using a 12.7-cm by 12.7-cm sampling frame. Samples were dried at 65^{o}C, weighed, ground and samples and analyzed for C concentration using a CHN analyzer (Leco CHN 1000, Leco Corp., St. Joseph, MI).

Nutrient Availability. To assess the difference in the nutrient availability under the two vegetation types plant root simulators (PRS-probes; Western Ag Innovations, Inc., Saskatoon, Canada), which consist of ion exchange membranes, were installed at 10 cm depth at the four corners of each sub-plot (Figure 5.3). The nutrient regime of each plot was assessed by deploying four cation and four anion exchange strips during the summer (25 August 2006 - 27 October 2006) and winter time (27 October 2006 – 8 July 2007). The PRS-probes were removed from the field, cleaned and shipped to Western Ag Innovations for analysis of a suite of cations including Ca^{+2}, K^+, Na^+, Mg^{+2}, NH_4^+-N; a suite of anions including NO^-_3-N, $H_2PO_4^-$-P, $B(OH)_4^-$, SO_4^{-2}-S, Cl^-, and a suite of metals including Cu^{+2}, Zn^{+2}, Mn^+, Fe^{+3} and Al^{+3}-Al. For our purpose we focused on available Ca^{+2}, K^+, Mg^{+2} and inorganic N (NH_4^+-N and NO^-_3-N).

Soil Microclimate. Soil moisture index of aspen and conifer stands was determined by installing twelve ECH_2O moisture probes (Decagon, Pullman, Washington) at a depth of 20 cm at the center of each plot (Figure 5.3). Readings (millivolt) were taken using a hand-held device (ECH_2O5 Check, Decagon Devices, Inc., Pullman, WA) in early June, mid July, August, and October of 2007. Field moisture readings (millivolt) were calibrated for gravimetric (Θm) and volumetric soil moisture (Θv) content in the lab using reconstructed soil cores where a known quantity of soil representative for each plot was subjected to drying and wetting cycles. The gravimetric soil moisture content based on core weight and the ECH_2O readings were taken periodically. From this data, calibration curves relating ECH_2O probe readings (mV) to Θv were constructed for each vegetation type and location in DLL (e.g., Figure 5.4 and Figure 5.5). For TWDEF, previously obtained calibration curves for aspen and conifers in the research areas were used (Van Miegroet unpublished data). In order to come up with a relative index of available water content (AWC) for the two vegetation types, a moisture threshold (MT) of 10% was set, which roughly corresponded to wilting point, based on soil texture and tension-moisture relationships applied to a tension range of >1500 -10 KPa (Saxton et al. 1986) using the following equations:

$\Psi = A\theta^{B}$

$A = \exp\,[a + b\,(\%C) + c\,(\%S)^{2} + d\,(\%S)^{2}(\%C)]\ 100.0$

$B = e + f(\%C)^{2} + g\,(\%S)^{2} + g\,(\%S)^{2}(\%C)$

Coefficients

$a = -4.396$, $b = -0.0715$, $c = -4.880\text{x}10^{-4}$, $d = -\ 4.285 \text{ x } 10^{-5}$, $e = -3.140$,

$f = -2.22 \text{ x } 10^{-3}$ $g = -3.484 \text{ x } 10^{-5}$

Where:

Ψ = Matric Potential

θ = Volumetric water content (m^3/m^3)

%C = Percent Clay

%S = Percent Sand

For each measurement date, available water content (AWC) was calculated by subtracting MT from the calibrated field readings. The cumulative soil moisture index (CMI) for the entire summer and early fall of 2007 (June - October) was calculated as the area under the curve representing periodic AWC values using the trapezoidal rule.

The soil temperature of the sites was also measured using Stowaway Tidbits dataloggers (Onset Computer Corporation, Bourne, MA) installed in the center of the plot (Figure 5.3) below the soil surface at a depth of 10-15 cm. Tidbits were programmed to record soil temperatures at 2-hour intervals**.** Due to the malfunction of several tidbits, we were able to record temperature data only in FA1, BA1, BA2, TA2 and TC2 for the period 8 August 2006 through 13 June 2007, limiting our ability to compare soil temperature regime between forest types (except for one plot pair at TWDEF)**.** We divided the temperature data into four periods: late summer (8 August – 21 September 2006), fall (21 September – 16 October 2006), winter (17 October 2006 – 3 May 2007) and spring-early summer (14 May – 13 June 2007), and we calculated the daily average temperature and standard deviation for the specified period.

Stand Characteristics. Overstory vegetation cover of the two vegetation types was measured using a fixed area plot, where the diameter at breast height (DBH) of each individual tree > 5 cm was measured within the circular plot of a radius of 10 m. This information was used to calculate live basal area and tree density. The live basal area was divided by the number of trees in the fixed plot to derive average tree diameter, which we thought to be a better vegetation parameter in predicting the SOC patterns based on the findings on Chapter 4.

Statistical Analysis

All the data were analyzed using a one way analysis of variance (ANOVA) with a randomized complete block design using PROC MIXED, followed by pair-wise comparisons using Tukey-Kramer adjustment; and paired t-tests using PROC TTEST in SAS Release 9.1 (SAS Institute 2003). Differences were considered significant at $p \leq 0.1$. Since both the ANOVA and paired t-tests yielded similar p-values, only one p-value is reported here.

Prior to the ANOVA, normality tests were done and where needed, data were log and square root transformed to meet the normality criteria. In addition, regression analysis was used to determine the role of biotic and abiotic site characteristics on SOC (0-60 cm) under the two vegetation types.

Results and Discussion

Soil Morphology

All soils under aspen were classified as Mollisols except one soil at TWDEF (TA1) that was classified as an Alfisols, whereas the soils under the conifers were classified as Alfisols (BC1, TC1, TC2), Entisols (BC2), and Inceptisols (FC1, FC3) (Figure 5. 6) (Table A.5 through Table A.16 in the Appendix). The soil classifications at DLL and TWDEF were consistent with the previously published results for the sites (Skujins and Klubek 1982; Washington-Allen et al. 2004; Van Miegroet et al. 2005). The one soil under aspen classified as an Alfisol at TWDEF had many similar characteristics to Mollisols, such as a thick A horizon, a mollic epipedon, and color values. However, the soil was characterized by a low pH (4.9) and a base saturation decreasing from 100% in the A horizon to about 39% in the deeper horizons and could therefore not be classified as a Mollisols. Basically in this case a few changes in the soil characteristics caused a shift in classification from Mollisols to Alfisols even though most of the characteristics were similar to Mollisols. The particular site also was not densely vegetated by aspen trees, which could attribute in small changes in the soil characteristics.

The O horizon thickness under conifers ranged from 0.5-10 cm, with O horizons under conifers generally thinner in DLL than in the TWDEF sites. This might be due to the difference in soil temperature regime between the two sites where soils at DLL are characterized by frigid soil temperature regime (warmer soil temperatures) while soils at TWDEF have cryic soil temperature regime. The differences in soil temperature can cause differential decomposition rates (Schlesinger 1997). The O horizon in aspen soils was almost non-existent, likely reflecting the fact that aspen litter decomposes much more rapidly than the litter of western coniferous forest (Bartos and DeByle 1981). Similar results were also obtained in a study carried out in British Columbia where aspen litter decomposed more rapidly than in spruce (Prescott et al. 2000). Alban and Pastor (1993) also concluded that the soil organic matter decomposition rates were higher in aspen stands than in coniferous stands because of a relatively easily decomposable litter (Flanagan and Van Cleve 1983). However, in North Central Minnesota, Perala and Alban (1982) found that the half lives of organic matter and C under aspen were generally longer compared to jack pine and red pine and about the same when compared to spruce.

The A horizon varied greatly in thickness among the two vegetation types; aspen soils had a pronounced A horizon which ranged from 38-53 cm in thickness while the A horizon under the conifers ranged from 5.5-34 cm (Figure 5.6). Across all sites thickness of the A horizon in aspen soils (43.3 ± 6.6 cm) was significantly greater than in conifer soils (16.2 ± 12.4 cm) (p=0.01). The deep A horizon under aspen soils together with other soil characteristics, such as color and high base saturation, qualifies the soils to be classified as Mollisols, which are characterized by a deep, dark, friable and relatively fertile surface horizon known as mollic epipedon (Buol et al. 2003). The conifer soils at TWDEF were further characterized by an accumulation of clay in subsoil with a characteristic Bt horizon, consistent with the observations by Van Miegroet et al. (2005). The soils in both sites were generally characterized by high base saturation (Table 5.1) an indication of limited moisture and restricted cation leaching (Van Miegroet et al. 2005).

Cryer and Murray (1992) had earlier postulated that stable or permanent stands of aspen were found only on Mollisols, while soil developed under conifers in the

Intermountain West were primarily Alfisols characterized by a thick O horizon and relatively thin A horizon. Results from this study are largely in agreement with this conclusion in that almost all aspen soils were classified as Mollisols. However, only half of the pedons under conifers in our study were classified as Alfisols, with the others classified as Inceptisols and Entisols, which are basically less developed soils. The Inceptisols under conifer had an ochric epipedon and cambic subsurface diagnostic horizons while the Entisol had an ochric epipedon with no subsurface diagnostic horizon. Inceptisols and Entisol might in time develop into other soil orders depending on the factors controlling pedogenic processes (Buol et al. 2003).

Soil Organic Carbon Pool and Distribution

The soil organic C concentration decreased with depth in all aspen and conifer plots (Figure 5.7 and Figure 5.8), which was also consistent with findings from other studies at TWDEF, such as Schimpf, Henderson, and MacMahon(1980); and Van Miegroet et al. (2005). The C concentration in the upper mineral soil obtained from pedon (0-20 cm) and soil core (0-15 cm) samples from the plot was not significantly different in aspen (p=0.93) and in conifers (p=0.55 p=0.57); with an overall average of 2.89 % ± 0.82% (CV=28.4 %) in aspen and 2.96% ± 1.13 (CV=38 %) in conifer. It can thus be concluded that C data obtained from the upper horizon in the pedons were indeed representative plot values. The soil C concentration under aspen was higher compared to the results obtained by Schimpf, Henderson, and MacMahon (1980), but it was within the range of values [3.46 % (1-4 cm) and 1.38 % (4-6 cm)] reported by Van Miegroet et al. (2005). Our aspen SOC concentrations were low compared to the values reported by

O'Neill, Kasischke, and Richter (2002) in Interior Alaska which were about 5.85 % in the upper soil surface. It might be associated with the colder temperature regime and thus slower decomposition leading to higher C concentration. Generally, the SOC concentration in conifers was higher than those reported in other studies (e.g., O'Neill, Kasischke, and Richter 2002; Van Miegroet et al. 2005).

Results from the 0-15 cm cores show that SOC content in the upper soil was not significantly different among vegetation types (p=0.52) with an average of 49.5 ± 7.9 Mg C ha^{-1} (CV=16%) in aspen vs. 54.8 ± 20.3 Mg C ha^{-1} (CV=37 %) in conifers . Our results were within the range of published values for the upper 20 cm of many forest soils in the U.S (Franzmeier, Lemme, and Miles 1985, Grigal and Ohmann 1992). However, as hypothesized, the SOC content in the mineral soil to a depth of 60 cm was significantly higher (p=0.001) under aspen with an average of 96.2 ± 26.7 Mg C ha^{-1} (CV=27.7 %) for aspen vs. 66.9 ± 18.6 Mg C ha^{-1} (CV=27.8%) for conifers (Figure 5.9 and Figure 5.10). Differences in SOC content between aspen and conifer soils ranged from a high of 54.4 Mg ha^{-1} in B1 to a low of 7.5 Mg ha^{-1} in T2 (Figure 5.9) This high variability in SOC content could reflect differences in potential SOC drivers such as soil microclimate and stand characteristics, as suggested by results from Chapter 4 that showed that much of the SOC variability was explained by stand characteristics and soil microclimate. The fact that these sites had similar parent material excluded this factor as a source of potential difference in SOC storage. The lack of significant differences in SOC content of the upper surface (0-15 cm) among the two vegetation types emphasized the importance of soil sampling depth, as was also observed in Chapter 4. The consistency of the results indicates that the surface sampling may not always yield very informative results. Most of the time researchers consider the A horizon and the forest floor “dynamic” constituents of the soil and they routinely sample only at shallow depth (Hammer et al. 1995); and many studies estimate forest soil C stocks from shallow samples (e.g., Brady and Weil 2002). However, several researchers (e.g., Fernandez, Rustad, and Lawrence 1993; Hammer et al. 1995; Cromack et al. 1999; Harrison et al. 2003) found that most of the variability in SOC in their study occurred at deeper depths and recommended sampling at greater depth for unbiased results.

The C estimates for aspen stands in the paired plots were lower compared to SOC estimates to a depth of 40 cm obtained from the stable aspen stands at Upper Frost in DLL (111.9 ± 29.1 Mg C ha^{-1}) (Chapter 4). This may reflect the incipient effect of conifer encroachment, leading to a slight decrease in SOC, as many of aspen stands were not pure and already had some conifer saplings in them. Our total SOC under aspen (0-60 cm) was higher compared to published values of 53 Mg C ha^{-1} at 0-130 cm (Van Miegroet et al. 2005) in Northern Utah, which they described as “somewhat” of an outlier, as the site had lower aspen and conifer tree density compared to our study areas. SOC in our study area was lower than values reported by Grigal and Ohmann (1992) in the Lake States (123 Mg C ha^{-1}) and O’Neill, Kasischke, and Richter (2002) in Interior Alaska (163 Mg C ha^{-1}), which might be attributed to the very cold temperatures that slow down decomposition causing greater SOC accumulation. However, Alban and Perala (1992) in a study conducted in the Lake States reported SOC values that range from 52.1- 68.1 Mg C ha^{-1} to a depth of 50 cm, which was low compared to our values. Van Miegroet et al. (2005) reported a value for conifer (90 Mg C ha^{-1} at 0-150 cm) which was lower compared to our SOC estimates.

The SOC in the forest floor was significantly different (p=0.01) between the two vegetation types with an average of 7.7 ± 3.8 Mg C ha^{-1} (CV=50%) under aspen (Figure 5.11) and 58.6 ± 31.7 Mg C ha^{-1} (CV= 50%) under conifers (Figure 5.12). As a consequence, the total SOC (O layer + mineral soil) under the two vegetation types was not significantly different (p=0.19). The average total SOC (mineral + O-layer) under aspen was estimated to be 103.9 ± 24.5 Mg C ha^{-1} (CV= 23.6 %) vs. 125.5 ± 24.8 Mg C ha^{-1} (CV= 19.78%) under conifers. About 92.5 % of the SOC under aspen was stored in the mineral soil, consistent with a study in the Interior Alaska where 93 % of the total SOC under aspen was stored in the mineral soil (O'Neill, Kasischke, and Richter 2002). In contrast only 53 % of the total SOC was located in the mineral soil under the conifers. Total SOC under conifers was within the range of reported values under white spruce in the Interior Alaska (129.2 Mg C ha^{-1}) (O'Neill, Kasischke, and Richter 2002), low compared to published values in the Lake States (181 Mg C ha^{-1}) under balsam fir (Grigal and Ohmann 1982) and somewhat,-higher compared to an earlier study at TWDEF (Van Miegroet et al. 2005). The lack of significant difference in the total SOC content (mineral + O-layer) among aspen and conifer soils could be an indication of the possible redistribution of SOC throughout the profile rather than a true difference in SOC content, in aspen soils most of the SOC is stored in the mineral horizon, while in conifers most of the SOC is stored in the O-layer. However, it should be noted that O horizon estimates were deduced from a few small samples, and more extensive sampling of the O horizon is needed to verify these findings.

As microclimate and stand characteristics proved important in determining SOC content in pure aspen stands (see Chapter 4), these biotic and abiotic site factors were also compared among the vegetation types and as potential drivers for differences in SOC accumulation.

Soil Microclimate

Statistical analysis of the CMI showed that aspen soils had greater moisture content than adjacent conifer soils in summer 2007 (p=0.09) (Figure 5.13- 5.15). In another study at DLL, LaMalfa and Ryel (2008) similarly observed that the average shallow soil moisture content was higher in the aspen plots relative to the adjacent conifer plots. This was attributed to the soil column characteristics such as porosity and depth where aspen soils had higher porosity and higher water holding capacity relative to conifers (LaMalfa and Ryel 2008). Similar studies in Montana (Moore and McCaughey 1997) and hydrological modeling based on hydrological process research in Russia and Canada (Gelfan, Pomeroy, and Kuchment 2004) also reported that snow accumulation was 15-40% lower in conifers relative to deciduous or open stands, contributing to the lower soil moisture status of the conifers relative to the aspen stands, especially following snowmelt in late spring. In contrast, Olsen and Van Miegroet (unpublished data) observed that conifers were less dry in summer compared to the other vegetation types including aspen; this indicates that moisture can be site specific, and as result can be hard to use it as a good explanatory metric.

We tried to assess the soil temperature regime of the area but unfortunately due to failure of the equipment a complete temperature data set for all the plots could not be obtained. However, salvaged data from four aspen and one conifer stand showed that the average daily soil temperature under aspen was 11.8^{o}C in late summer, 3.9^{o} C in fall,

-0.46 ^{o}C in winter, and 8.1 ^{o}C in spring-early summer (Figure 5.16 and Figure 5.17) while corresponding average soil temperatures in the conifer stand were 9.7^{o} C, 3.7^{o} C, 0.1^{o}C and 5.72^{0} C in late summer, fall, winter and spring-early summer, respectively. This limited soil temperature data suggest that aspen soils might be slightly warmer, especially in spring and summer. This is consistent with the Olsen and Van Miegroet (unpublished data), where conifers had lower and less variable temperature.

Soil Nutrient Regime

Results obtained from the PRS-probes represented the dynamic nutrient availability index during summer and winter and are summarized in Table 5.2. There was no significant difference in nutrient availability between the two vegetations during either season, except for manganese (p=0.01) and sulfur (p=0.09), which were somewhat higher in conifer soils in summer. Total N availability was marginally significantly higher in aspen soils in winter (p=0.14) (Table 5.2). The average C/N ratio of soils in aspen and conifer plots was 13 and 11 respectively. Across all soil depths and vegetation types the average BS in DLL was 94% ± 13.5 % (CV=14.1%), while in TWDEF the average BS was 72 % ± 18.5 % (CV=25.7%). All the plots in DLL and TWDEF had fairly low CEC values that decreased with depth, but showed no significant difference among the two vegetation types (Table 5.1). Our BS and CEC results fell within the range of published values by Schimpf, Henderson, and MacMahon (1980). None of these soil characteristics showed significant differences among vegetation type.

Alban (1982) in a research carried out in Minnesota found large nutrient differences in the surface horizons of aspen and conifers. Especially Ca was higher in the forest floor and upper horizons of aspen than under conifers, but total ecosystem Ca did not differ among species. This might reflect the redistribution of Ca (cation pumping) associated with the higher Ca requirements of hardwoods. Our data also showed cation redistribution where most of the cations were in the upper surface and decreased with depth (Table 5.3) However, Bartos and Amacher (1998) in a Utah study did not report any significant differences in nutrient regime between aspen and mixed aspen/conifer stands (except for a slight difference in exchangeable K), and they explained the pattern as due to moisture restrictions which lead to decreased rates of eluvation (Bartos and Amacher 1998). Our results were consistent with these findings.

Stand Characteristics

The stand characteristics of the two vegetation types are summarized in Table 5.4. The LBA of the aspen and conifer was not significantly different (p=0.48). In contrast number of trees per hectare (density) was significantly higher (p=0.05), and the average tree diameter significantly lower (p=0.02) in the aspen plots. These indicated an important difference in forest structure between aspen and conifers, with the latter composed of fewer larger trees, while the aspen stands were densely vegetated with smaller trees. We found that stand structure, rather than LBA was an important driver of SOC content under pure aspen (see Chapter 4).

Site characteristics and SOC in the Paired Plots

To see whether the same biotic and abiotic factors that controlled SOC in pure aspen (see Chapter 4) were the drivers for SOC variability in the paired plots, we performed several regression analyses. SOC content across locations and vegetation types increased with CMI, explaining 25% of the variability in SOC content (R^2=0.25 p=0.09) (Figure 5.18). This was the opposite trend from the one observed in the transect study (Figure 4.8). The SOC content increased with tree density (R^2=0.18, p=0.16) and decreased with average tree diameter (R^2=14, p=0.23), but these correlations were not statistically significant (Figure 5.19 and Figure 5.20). Both the transect (Chapter 4) and the paired plots study suggested similar abioitic and biotic drivers for SOC with SOC changing mainly as a function of stand characteristics and soil moisture. The relationship between SOC and stand characteristics was consistent in both studies; however, in the paired plot study, the relationship between SOC and CMI followed an opposite trend, where higher SOC in the mineral soil was associated with higher soil moisture conditions in aspen, opposite to findings in the transect study. However, in the paired plot we had different vegetation types that influenced soil microclimate in a different ways. Another reason for the apparent inconsistency could lie in the data set. Moreover, in an unpublished study (Olsen and Van Miegroet) observed that conifers had higher soil moisture content and suggested that soil moisture content under conifer is not a limiting factor for soil respiration rates (could be used as for the inverse of SOC storage) compared to other characteristics. The apparently contradictory relationship between SOC and CMI in transect and paired plots studies could be an alternative indication of the strong effect of the different vegetation types. In the first study we dealt only with one vegetation type and CMI had more power explaining the variability, while in the paired plots CMI was not the only factor changing as the study involved different vegetation types. CMI vary with vegetation type, location, and other site characteristics, and in this study CMI could function more as a proxy for vegetation type

Generally, the differences in SOC under aspen and conifer in the mineral soil could be explained by three different case scenarios:

i) Higher input (litterfall) of aspen ecosystems compared to conifers. We did not assess the annual litterfall input under the two vegetation types directly, but probably the deciduous nature of aspen might have contributed to larger annual C inputs.

ii) There might be a difference in SOC quality. Even though researchers reported that conifer forest produce litter that decomposes slowly compared to aspen (Prescott et al. 2000), other studies such as those by Hongve, Van Hees, and Lundström (2000) showed that conifers tend to produce more soluble organic acids, which could lead to greater mobility and loss of soluble OC while aspen litterfall generated more stable humus and recalcitrant SOC. This is confirmed by the occurrence of mollic epipedon under aspen, which was as a result of the formation of stable humus during the melanization process, characteristic for Mollisols. In addition, Olsen and Van Miegroet (unpublished data) found in a laboratory study that conifer soil respired more CO_2 per unit soil C relative to aspen soils, indicative of lower decomposability of SOC under aspen relative to conifers, possibly associated with the stabilization of SOC in the mollic epipedon under aspen.

iii) Differences in vegetation cover can also affect soil microclimate (soil moisture and soil temperature), which in turn affects decomposition rates (Schlesinger 1997).

iv) The different vegetation types result in a change of understory vegetation that can also potentially also contribute to differences in C inputs in and soil microclimate.

Conclusion

The results from this comparison of end-member communities indicate that there are differences in the morphology, microclimate, and some chemical properties of soils under aspen vs. conifer cover. This can be used as an indication that as conifer encroaches aspen stands changes in pedogenesis can occur, possibly associated with the changes in microclimate and amount and nature of C inputs. However, it is not clear how thinning of the A horizon and loss of mollic epipedon take place. Results indicate there is no significant difference in the nutrient regime under the two vegetation types except for Mg and S. Based on this and other studies (e.g., Bartos and Amacher 1998) it is likely that the nutrient regime will not directly be affected by conifer encroachment in areas that are moisture-restricted; however this trajectory may be greatly different under prevailing climatic conditions.

The amount of SOC in the mineral soil is different among the two vegetation types, however differences are not observed in the top soils, which is consistent with the transect study (Chapter 4). Differences between vegetation types become statistically significant only if deeper soil columns are considered, which shows the importance of sampling depth as many researchers focus on the surface layers and sample accordingly. With conifer encroachment there will be a buildup of the O horizon as a result of the less decomposable litter and a possible upward redistribution of SOC in the soil. The total SOC including O-layer is not significantly different. Changes in vegetation from aspen to conifers may thus influence mineral soil SOC and/or the distribution of SOC in the profile, changing the morphology from Mollisols to Alfisols. However, in this study we had one representative sample of forest floor for each plot, so more extensive sampling of O layer will substantiate that redistribution of SOC is indeed occurring.

Most of the SOC under conifer is in the forest floor, which is considered as “unprotected” (Garten et al. 1999) and has the greatest potential to respond to changes in land use, affect the global C cycle (Harrison, Broecker, and Bonani 1993), and can also be susceptible to loss by fire (Van Miegroet et al. 2005). However, the SOC under aspen is allocated mainly in the mineral soil where it is considered “protected” through the organo-mineral complexes. In this case conifer encroachment can cause SOC to become more vulnerable by accumulating most of the SOC in the forest floor and producing more easily decomposable C in the mineral soil.

The soil moisture index is another important ecosystem property that can be greatly influenced by conifer encroachment, as indicated by greater CMI under aspen relative to conifers. So it is likely that following conifer encroachment change in soil moisture may occur, which could adversely affect many biogeochemical processes. In addition, researchers have reported that the decrease in water following conifer encroachment can affect understory vegetation, stream flow, many terrestrial ecosystem processes, fire disturbances, forage, and wildlife habitat. Based on the data that we have available it is hard to draw concrete conclusions about drivers of differences in SOC among the two vegetation types. This study suggests that stand characteristics, soil moisture and possibly soil temperature may play a role in changing SOC content in mineral soil with conifer encroachment. The strong influence of forest characteristics (composition and structure) on SOC is evident from both studies. It is important to note that vegetation may have a direct or indirect influence on SOC, as it influences both the amount and quality of C inputs and greatly affects soil microclimate, which in turn controls SOC dynamics. To fully understand and explain the reasons behind the lower amount of SOC under conifers it is important to closely look at the amount of annual litterfall input, decomposition rates and mechanisms of SOC stabilization. In addition more complete temperature data for both stands together with the available moisture is needed to more fully explore the role of microclimate in SOC variability. There is no doubt that SOC changes as a function of multiple factors; consequently, a detailed characterization of each ecosystem type is important to gain insight in the various relationships between SOC and the so called drivers.

Moreover, there are many unknowns that need further study to increase our understanding of how and in what characteristics the two vegetation types (end-point communities) differ and how ecosystem functions will change as the conifer encroaches aspen and occupies the site. Despite these challenges, this study fills some of the gaps in aspen/conifer encroachment studies and offers insights into the potential impacts of conifer encroachment, such as the changes in distribution of SOC, change in soil moisture content and other properties.

Table 5.1 Soil morphology, chemical and physical properties of the pedons

Horizon	Depth (cm)	Color (Dry)	Field texture	RF VL (%)	Clay (%)	Mass >2 mm (%)	Bulk Density (g/cm^3)	Field pH	C/N	CEC cmol$_c$/kg	BS %
FA1 (Aspen in Upper Frost Canyon) Typic Haploxeroll											
A1	0-14	10YR 5/4	L	6	12	0.4	1.14	6.0	14	6.8	92
A2	14-38.5	10YR 5/4	L	11	13	2.8	1.23	5.8	12	4.8	100
Bw1	38.5-58.5	10YR 5/4	SIL	13	15	1.1	1.47	5.8	13	3.6	98
Bw2	58.5-83	10YR 6/4	SIL	8	16	0.9	1.26	5.6	7	2.2	96
BC	83-100	10YR 6/4	SIL	12	11	2.0	NA	5.5	NA	NA	NA
FC1 (Conifer in Upper Frost Canyon) Humic Haploxerepts											
Oi	0-1	NA	NA	NA	NA	NA	NA	NA		NA	NA
A	1-12.5	7.5YR 2/2	SIL	9	12	2.0	0.80	5.9	9	14.8	100
Bw1	12.5-46.5	10YR 6/4	SIL	8	9	1.7	1.32	5.8	12	5.7	83
Bw2	46.5-67	10YR 6/4	SIL	7	13	0.6	1.16	5.6	10	1.6	100
Bw3	67-95	10YR 6/4	SIL	7	14	0.4	1.23	5.3	9	1.2	63
FA2 (Aspen in Upper Frost Canyon) Pachic Haploxerolls											
A1	0-16.5	10YR 2/2	LS	15	5	3.7	0.84	5.3	16	15.9	92
A2	16.5-38	10YR 5/3	SL	13	7	2.9	1.16	4.9	13	10.1	100
A3	38-60	10YR 5/3	GRSL	18	8	5.5	1.10	4.6	11	6.2	100
C	60-90	7.5YR 6/4	GRSL	30	7	18.9	1.47	5.7	8	1.8	100
FC2 (Conifer in Upper Frost Canyon) Humic Haploxerepts											
Oi	0-2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A	2-7.5	7.5YR 5/4	L	25	14	15.4	1.26	5.8	17	6.8	100
Bw1	7.5-36	7.5YR 5/6	GRL	20	15	4.3	1.10	5.5	15	4.5	98
Bw2	36-66	7.5YR 5/4	SIL	15	10	7.9	1.28	5.6	15	2.8	100
C	66-100	5YR 6/6	L	20	12	ND	ND	5.8	ND	1.6	100

Table 5.1. Cont'd

Horizon	Depth (cm)	Color (Dry)	Field texture	RF VL (%)	Clay (%)	Mass >2 mm (%)	Bulk Density (g/cm^3)	Field pH	C/N	CEC cmol$_c$/kg	BS %
BA1 (Aspen in Bear Canyon) Pachic Haploxerolls											
A1	0-25.5	10YR 5/4	L	4	8	0.8	0.91	6.2	17	12.4	100
A2	25.5-50.5	10YR 5/4	L	3	10	0.7	1.00	6.1	13	6.2	100
Bw1	50.5-70	7.5YR 4/6	L	2	16	0.6	1.13	5.7	12	4.4	100
BC	70-100	7.5YR 4/6	L	1	14	0.3	1.30	5.8	10	3.1	100
BC1 (Conifer in Bear Canyon) Typic Haploxeralfs											
Oi	0-0.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A	0.5-7.5	10YR 4/3	L	7	12	0.6	0.84	6.3	18	18.2	100
AB	7.5-32	7.5YR 4/4	L	6	14	0.3	1.08	5.9	15	7.2	100
Bw1	35-52	7.5YR 5/6	SL	4	19	1.9	1.16	6.2	11	3.2	100
Bt	52-81	5YR 6/6	SCL	3	25	1.3	1.33	6.0	8	3.2	100
BA2 (Aspen in Bear Canyon) Typic Haploxerolls											
A	0-40	10YR 5/3	SL	13	10	1.0	1.05	5.2	13	6.5	100
Bw1	40-50	10YR 7/3	SL	9	8	0.1	1.40	5.5	9	1.7	100
Bw2	50-80	10YR 7/3	LS	15	13	4.2	1.46	5.8	12	1.5	100
C	80-100	10YR 6/3	GRLS	14	14	0.3	1.42	5.4	9	1.7	94
BC2 (Conifers in Bear Canyon) Typic Xerorthents											
Oi	0-1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A1	1-7.5	10YR 6/4	SIL	7	10	3.3	1.16	5.5	14	7.7	94
A2	7.5-35	7.5YR 6/4	SIL	8	8	0.3	1.18	5.4	10	4.4	76
C1	35-42.5	7.5YR 6/4	SIL	9	13	0.2	0.87	5.3	10	1.8	82
C2	42.5-60	2.5YR 7/8	GRSIL	3	14	25.8	1.73	5.4	10	4.8	41

Table 5.1. Cont'd

Horizon	Depth (cm)	Color (Dry)	Field texture	RF VL (%)	Clay (%)	Mass >2 mm (%)	Bulk Density (g/cm^3)	Field pH	C/N	CEC cmol$_c$/kg	BS %
TA1 (Aspen in T.W. Daniel Experimental Forest) Mollic Haplocryalf											
A	0-40	10YR 4/4	GRSCL	18	21	22.6	1.05	4.9	8	11.3	100
Bt1	40-68	7.5YR 4/6	GRSICL	15	30	6.6	1.11	4.9	9	19.0	39
Bt2	68-80	5YR 4/6	GRVSICL	35	27	4.2	1.19	4.7	8	18.4	40
TC1 (Conifer in T.W.Daniel Experimental Forest) Typic Haplocryalfs											
Oi	0-10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A	10-40	10YR 5/4	GRSL	20	17	19.5	0.86	5.2	16	8.7	84
Bt1	40-73	10YR 4/4	GRSCL	18	25	14.4	1.01	5.6	7	8.3	82
Bt2	73-100	5YR 5/6	GRSCL	38	21	44.2	1.21	5.4	9	9.3	83
TA2 (Aspen in T.W.Daniel Experimental Forest) Pachic Haplocryolls											
A1	0-8	10YR 5/3	GRSL	18	10	34.8	0.76	5.3	19	13.8	88
A2	8-53	10YR 5/3	GRSL	20	9	12.2	1.14	5.4	10	6.8	70
C	53-95	7.5 YR 6/4	CBXLS	65	7	29.0	1.17	5.5	9	4.2	67
TC2 (Aspen in T.W. Daniel Experimental Forest) Typic Haplocryalfs											
Oi	0-4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A	4-13.5	10YR 5/4	GRSIL	19	18	19.5	0.86	5.4	18	21.4	73
Bt1	13.5-35	10YR 6/3	GRSIL	15	22	14.4	1.01	6	15	19.2	77
Bt2	35-90	7.5YR 4/6	VGRCL	37	57	44.2	1.21	5.5	9	5.23	52

Abbreviations: NA= not applicable, ND= not determined L= loam, SIL= silt loam, SL= sandy loam, LS= loamy sandy, SCL= sandy clay loam, SICL= silty clay loam, C= Clay, GR= gravelly, GRV= very gravelly, CB= cobbly, CBX= extremely cobbly , VL= volume CEC= cation exchange capacity, BS= base saturation

Table 5.2 Estimated winter and summer dynamic nutrient regime of the paired plots.

Nutrient	Aspen	Conifer	P value
	---------------- µg/10cm^2/burial----------------		
	Winter 07		
Total N	205.77	62	0.14
Ca^{+2}	2279.47	2364.97	0.69
Mg^{+2}	173.75	195.12	0.36
Log(K^+)	3.88	3.72	0.70
P	21.06	17.92	0.48
Log(Mn)	1.34	1.70	0.19
Log(S)	3.12	2.90	0.77
	Summer 07		
Total N	154.6	123.75	0.54
Ca^{+2}	1796.0	1634.97	0.58
Mg^{+2}	166.87	154.60	0.43
K^+	141.43	187.77	0.41
P	8.1	12.5	0.28
Log(Mn)	0.04	1.13	**0.01†**
S	9.08	31.67	**0.09†**

Total N corresponds to the summation of ammonium- and nitrate-N. † Values in bold are significant values at $p \leq 0.10$.

Table 5.3 Exchangeable cation pools with depth under the two vegetation types. Abbreviations: NA= Not available, VL= Very low.

Horizon	**Depth**	**Ca^{+2}**	**K^{+}**	**Mg^{+2}**
	----cm-----	-------------**Kg/ha**-------------		
		FA1		
A1	0-14	1,668	202	130
A2	14-38.5	2,347	270	172
Bw1	38.5-58.5	1,698	279	132
Bw2	58.5-83	1,049	133	94
BC	83-100	NA	NA	NA
Normalized Sum (0-60 cm)		**5,778**	**759**	**440**
		FC1		
Oi	0-1	NA	NA	NA
A	1-12.5	2,494	238	106
Bw1	12.5-46.5	3,593	340	300
Bw2	46.5-67	740	VL	52
Bw3	67-95	419	VL	31
Normalized Sum (0-60 cm)		**6,575**	**638**	**441**
		FA2		
A1	0-16.5	3,570	388	148
A2	16.5-38	4,359	441	158
A3	38-60	3,007	175	116
C	60-90	1,537	29	85
Normalized Sum (0-60 cm)		**10,937**	**1,004**	**422**
		FC2		
Oi	0-2	NA	NA	NA
A	2-7.5	1,060	123	69
Bw1	7.5-36	2,267	147	147
Bw2	36-66	624	14	43
C	66-100	NA	NA	NA
Normalized Sum (0-60 cm)		**3,951**	**284**	**259**
		BA1		
A1	0-25.5	5,041	533	288
A2	25.5-50.5	3,232	200	164
Bw1	50.5-70	1,997	100	126
BC	70-100	2,636	175	178
Normalized Sum (0-60 cm)		**9,246**	**782**	**513**

Table 5.3 Cont'd.

Horizon	Depth	Ca^{+2}	K^{+}	Mg^{+2}
	----cm-----	-------------Kg/ha	------------	
		BC1		
Oi	0-0.5	NA	NA	NA
A	0.5-7.5	1,977	188	7
AB	7.5-32	3,471	476	165
Bw	32-52	1,783	173	120
Bt	52-81	3,160	163	254
Normalized Sum (0-60 cm)		**6,316**	**878**	**358**
		BA2		
A	0-40	4,727	648	287
Bw1	40-50	421	26	32
Bw2	50-80	1,213	155	92
C	80-100	828	7	57
Normalized Sum (0-60 cm)		**5,552**	**725**	**349**
		BC2		
Oi	0-1	NA	NA	NA
A1	1-7.5	912	120	67
A2	7.5-35	1,850	144	154
C1	35-42.5	165	VL	17
C2	42.5-60	798	2	90
Normalized Sum (0-60 cm)		**3,724**	**267**	**328**
		TA1		
A	0-40	6,918	987	1,017
Bt1	40-68	3,273	499	563
Bt2	68-80	1,675	201	281
Normalized Sum (0-60 cm)		**8,512**	**1,344**	**1,419**
		TC1		
Oi	0-10	NA	NA	NA
A	10-40	2,792	2,792	2,792
Bt1	40-73	3,453	3,453	3,453
Bt2	73-100	2,921	2,921	2,921
Normalized Sum (0-60 cm)		**5,931**	**1,083**	**514**
		TA2		
A1		1,087	152	68
A2		3,749	603	331
C		1,770	381	204
Normalized Sum (0-60 cm)		**5,131**	**818**	**434**

Table 5.3 Cont'd.

Horizon	Depth	Ca^{+2}	K^{+}	Mg^{+2}
	----cm-----	-------------Kg/ha		------------
		TC2		
Oi	0-4	NA	NA	NA
A	4-13.5	1,993	74	207
Bt1	13.5-35	4,701	774	547
Bt2	35-90	19,936	1,283	3,088
Normalized Sum (0-60 cm)		**17,206**	**1,525**	**2,382**

Table 5.4 Stand characteristics in the paired plots. † Values in bold are significant values at p≤ 0.10.

Site ID	Vegetation type	LBA (m^2/ha)	Density (# of tress ha^{-1})	Average tree diameter (cm)
F1	Aspen	21.9	478	24.2
	Conifer	46.1	573	32.0
F2	Aspen	18.3	892	16.7
	Conifer	36.4	350	36.4
B1	Aspen	41.5	1561	18.4
	Conifer	37.3	1274	19.3
B2	Aspen	25.8	1242	16.3
	Conifer	34.2	860	22.5
T1	Aspen	53.0	2197	17.5
	Conifer	34.8	637	26.4
T2	Aspen	25.4	1227	17.5
	Conifer	25.2	541	24.3
		p = 0.48	**p = 0.05 †**	**p = 0.02 †**

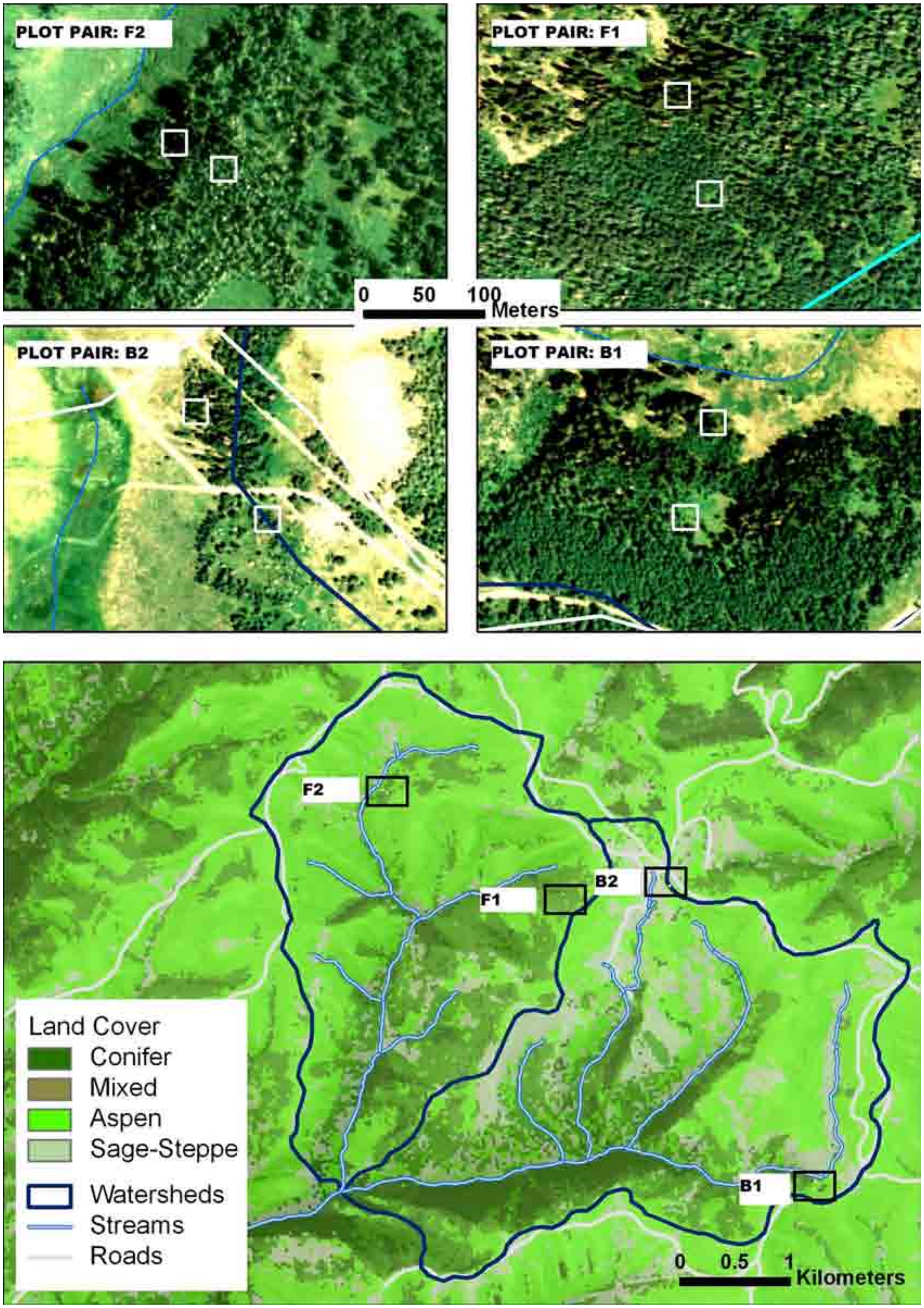

Fig. 5.1 Location of the paired plots in the watersheds at Deseret Land and Livestock.

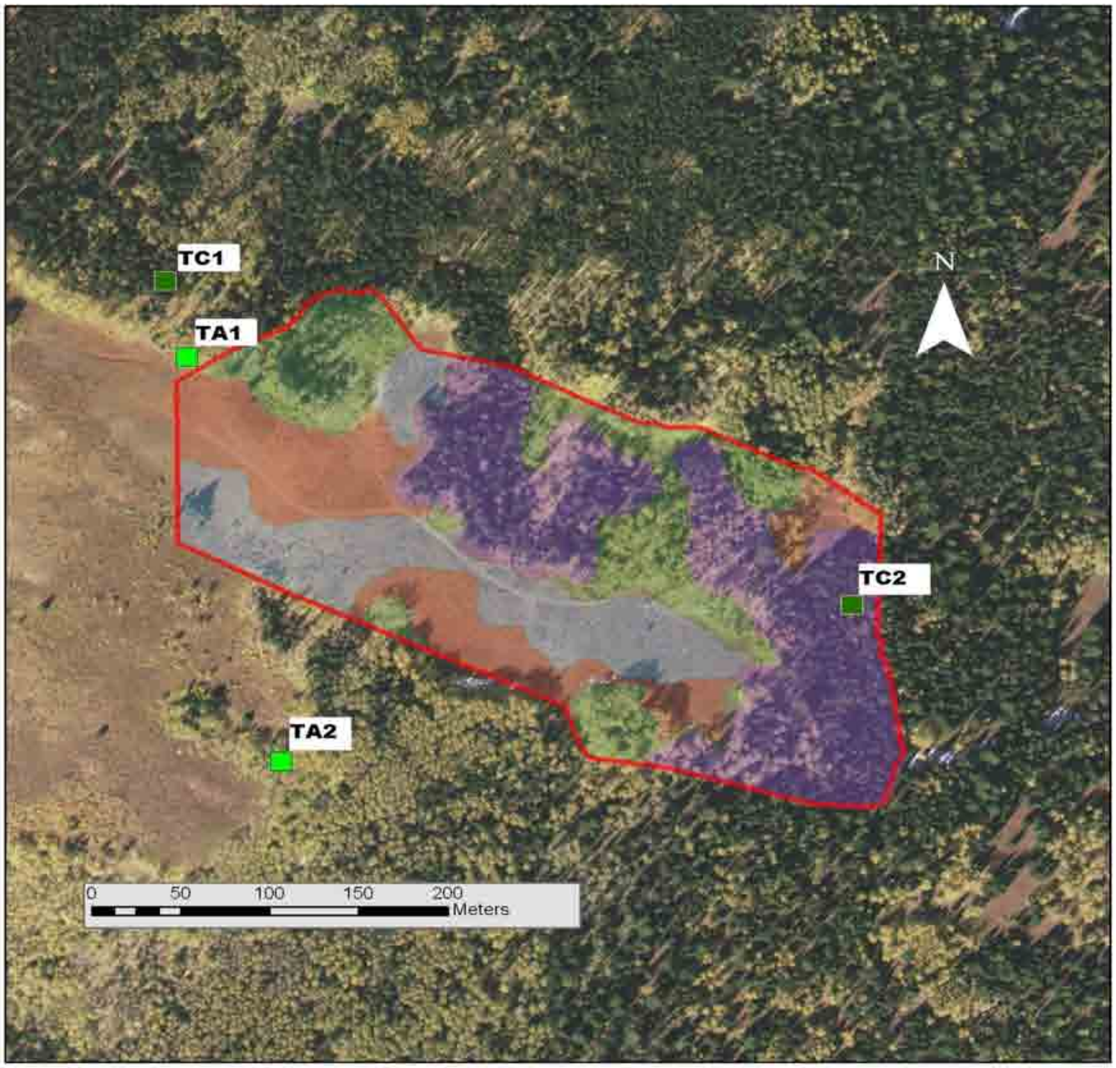

Fig. 5.2 Aerial photo with the delineated watershed and the paired plots at TWDEF.

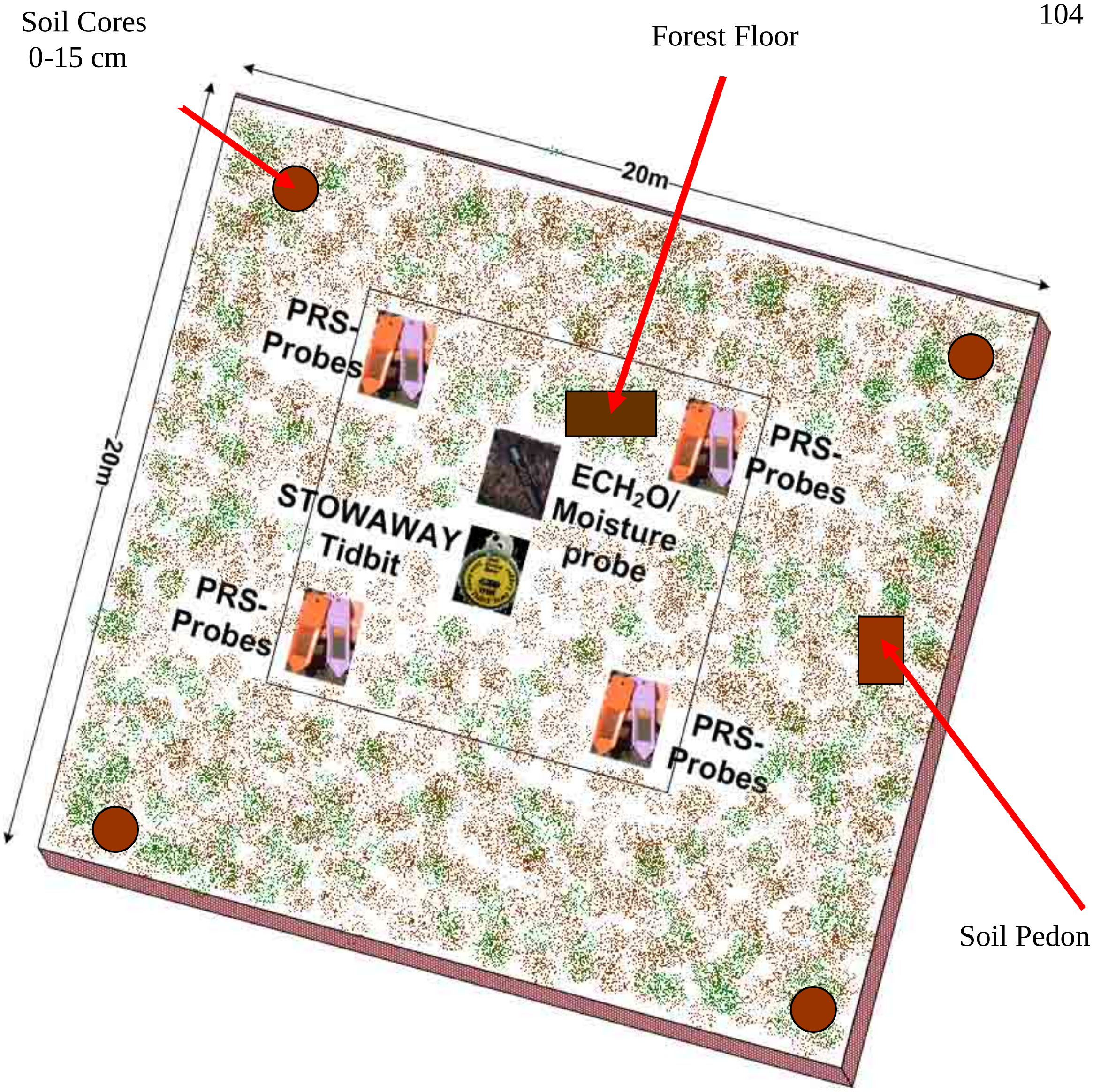

Fig. 5.3 Schematic presentation of how the plots are setup with corresponding instruments.

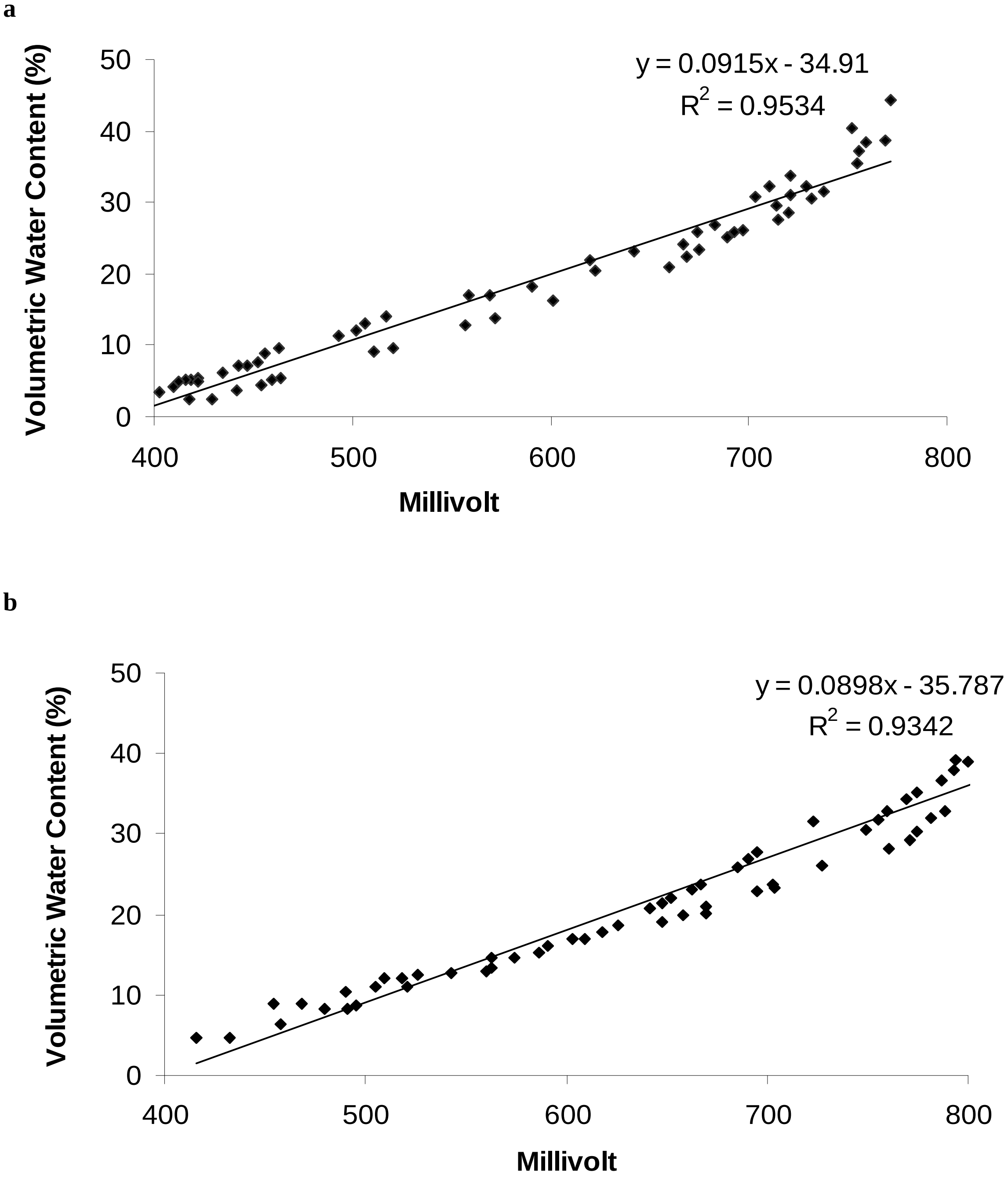

Fig. 5.4 Soil moisture calibration curves for the aspen (a) and conifer (b) soils in Upper Frost at DLL, relating mV reading to Θv (%).

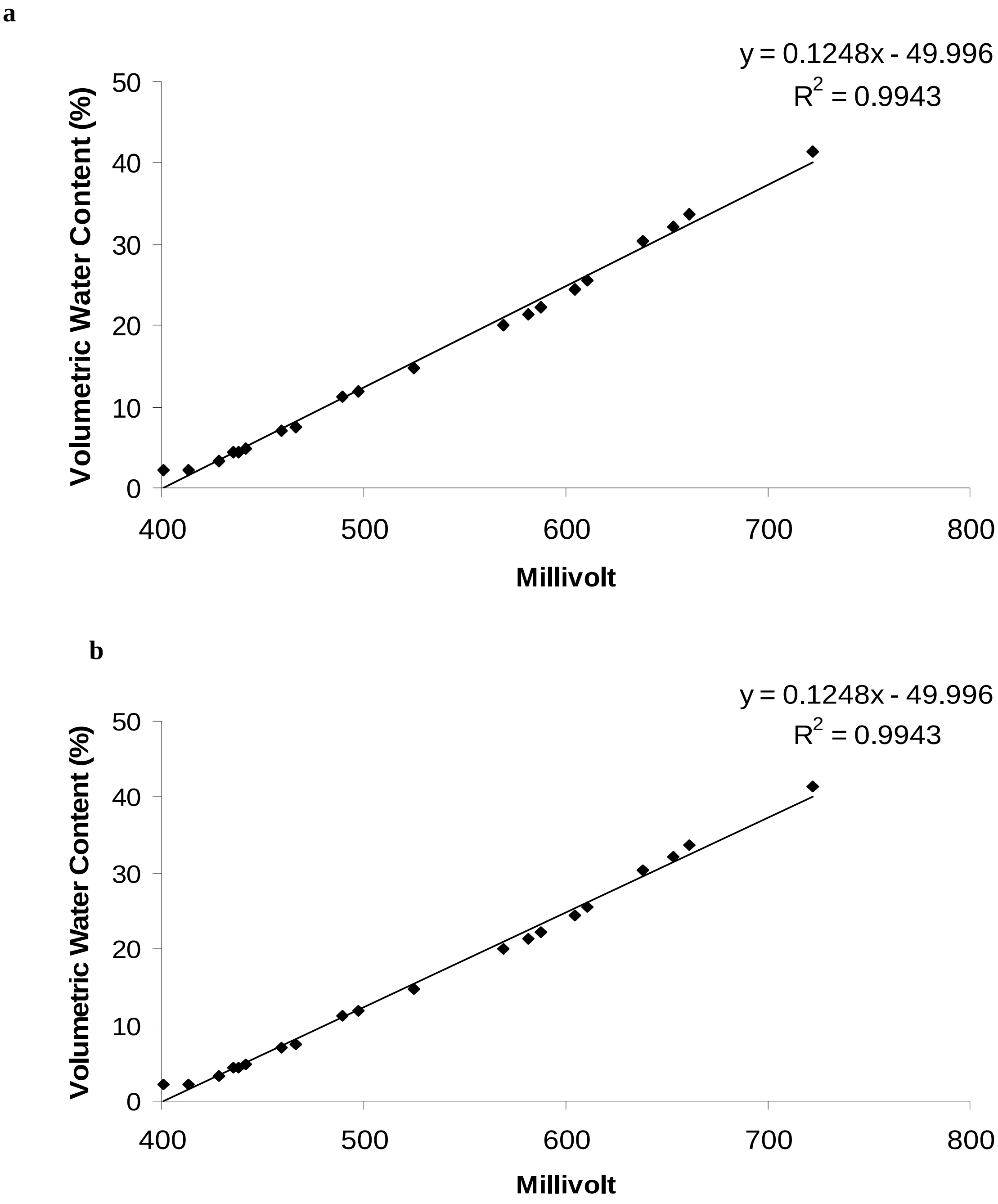

Fig. 5.5 Soil moisture calibration curves for the aspen (a) and conifer (b) soils in Bear Canyon at DLL relating mV to Θv (%).

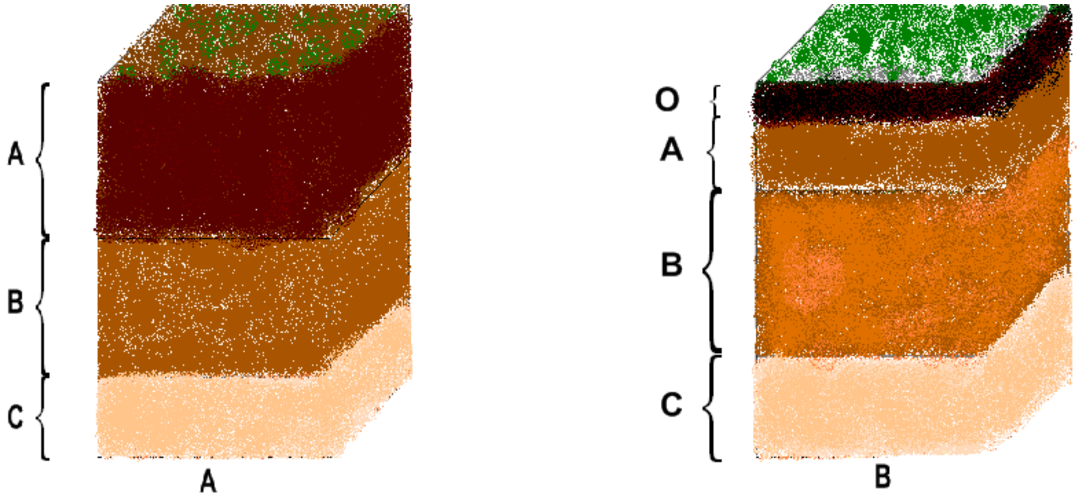

Fig. 5.6 Typical pedon under aspen (A) and conifer (B).

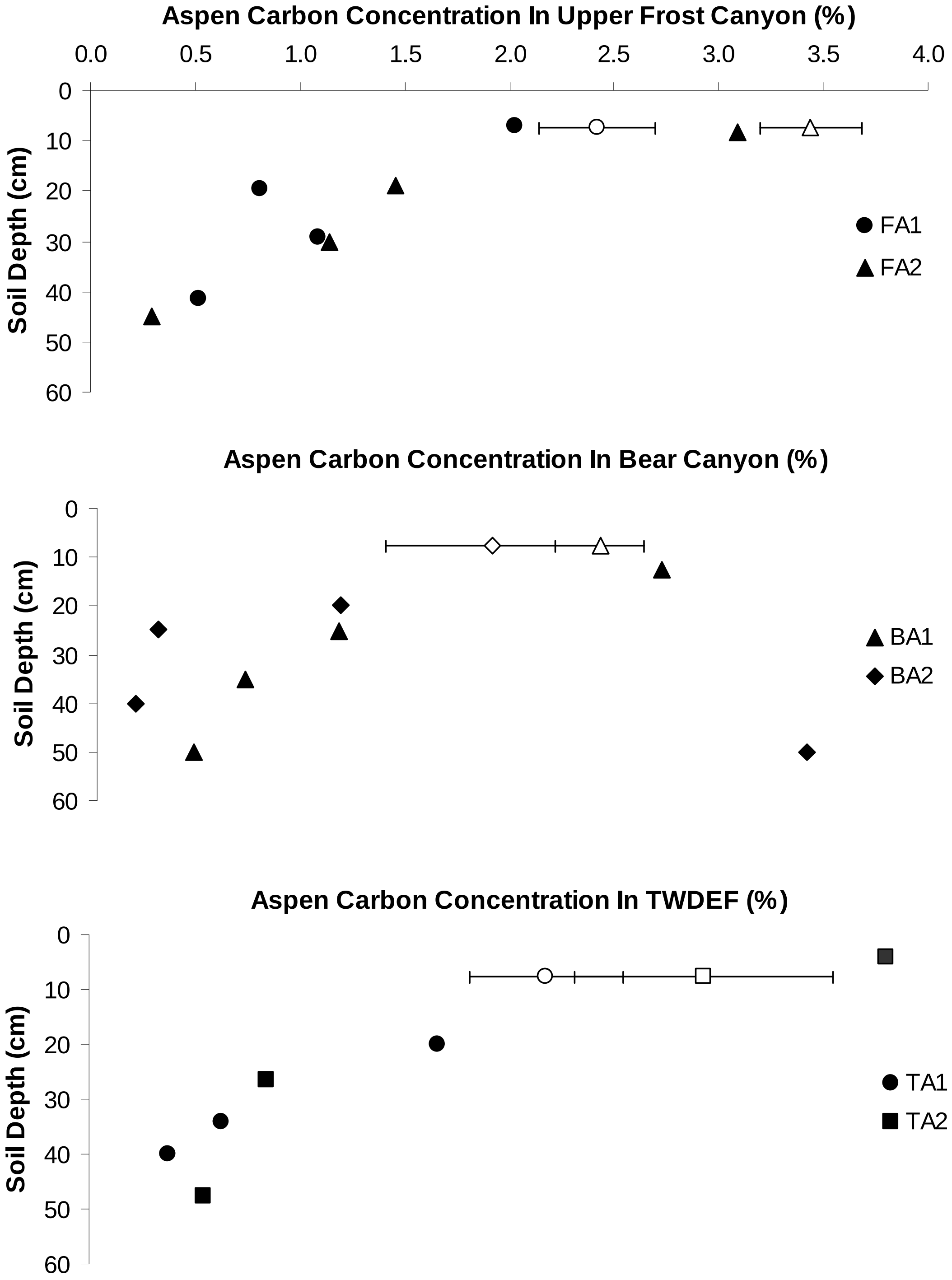

Fig. 5.7 Carbon concentration along soil depth in aspen soils. Solid symbols represent pedon samples; open symbols represent soil cores (0-15 cm). Error bars represent standard deviation among the soil core samples and pedon samples.

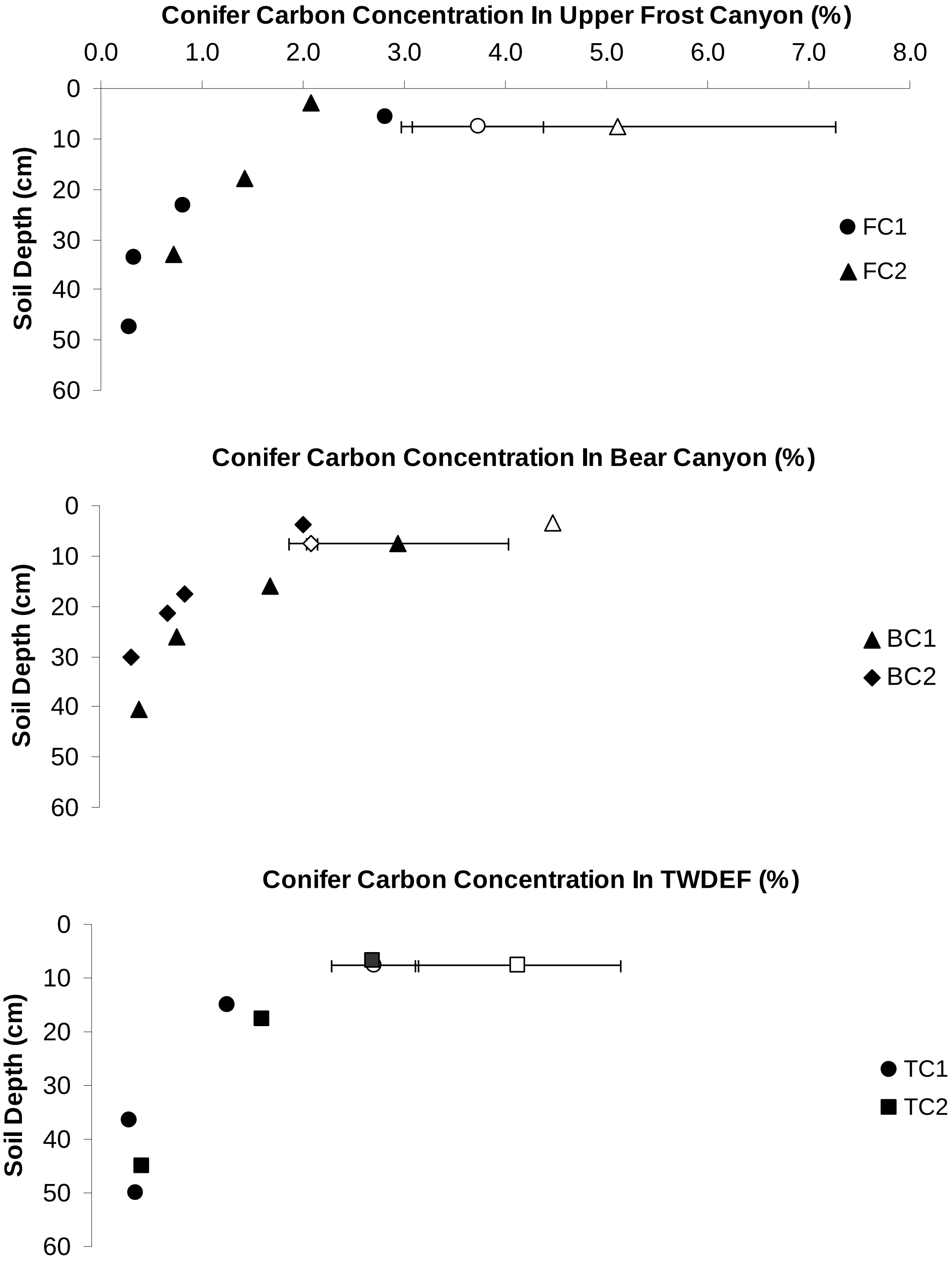

Fig. 5.8 Carbon concentration along soil depth in conifer soils. Solid symbols represent pedon samples; open symbols represent soil cores (0-15 cm). Error bars represent standard deviation among soil core samples and pedon samples.

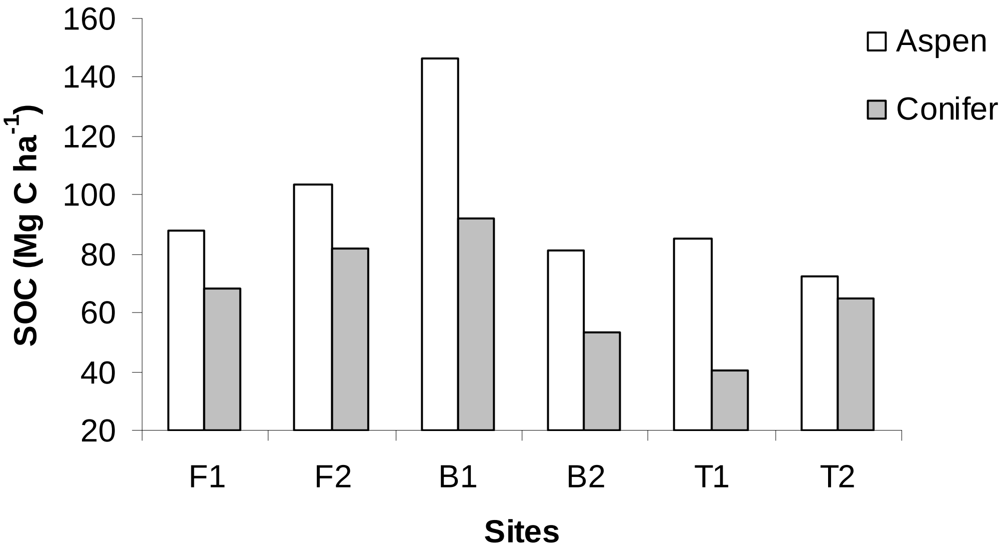

Fig. 5.9 Soil organic carbon storage in mineral soil in aspen and conifer pedons (0- 60 cm).

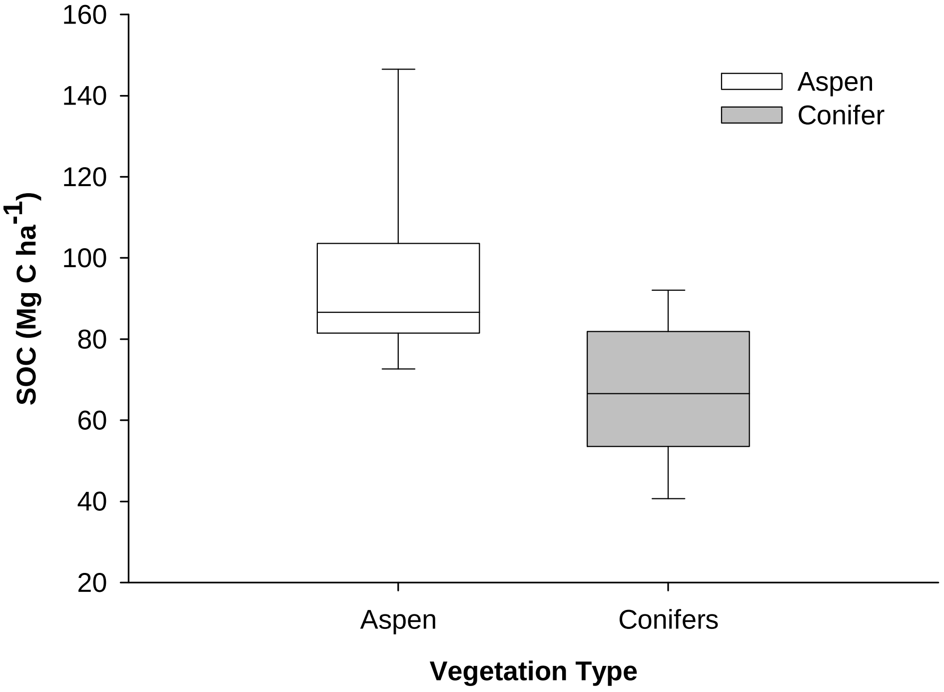

Fig. 5.10 Average SOC content in the mineral soil (0-60 cm) aspen and conifer. The five lines in the box plot represent lowest observation, lower quartile, median, upper quartile and the largest observation.

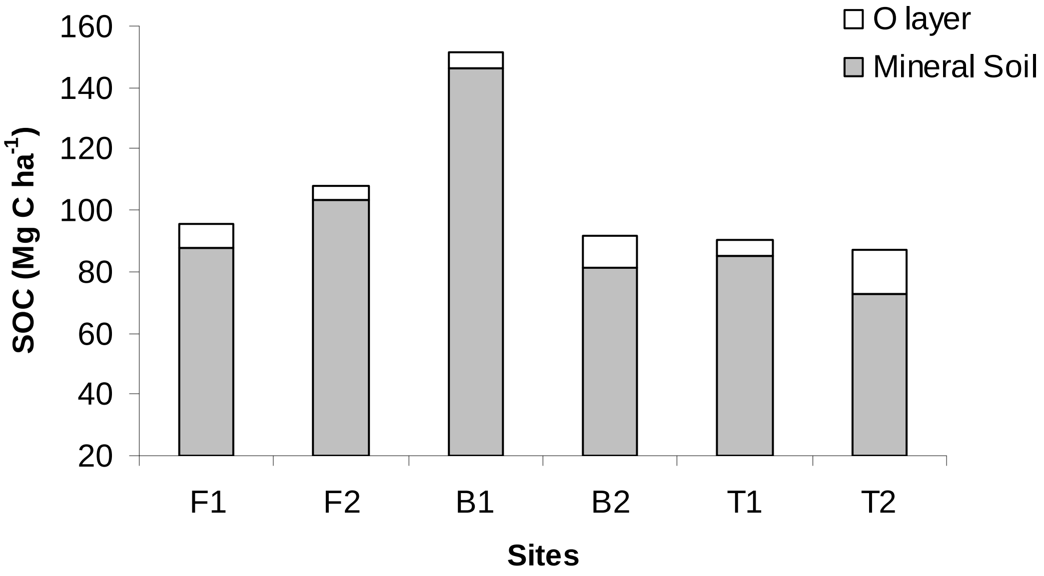

Fig. 5.11 Total soil organic carbon storage (forest floor + mineral soil) in aspen.

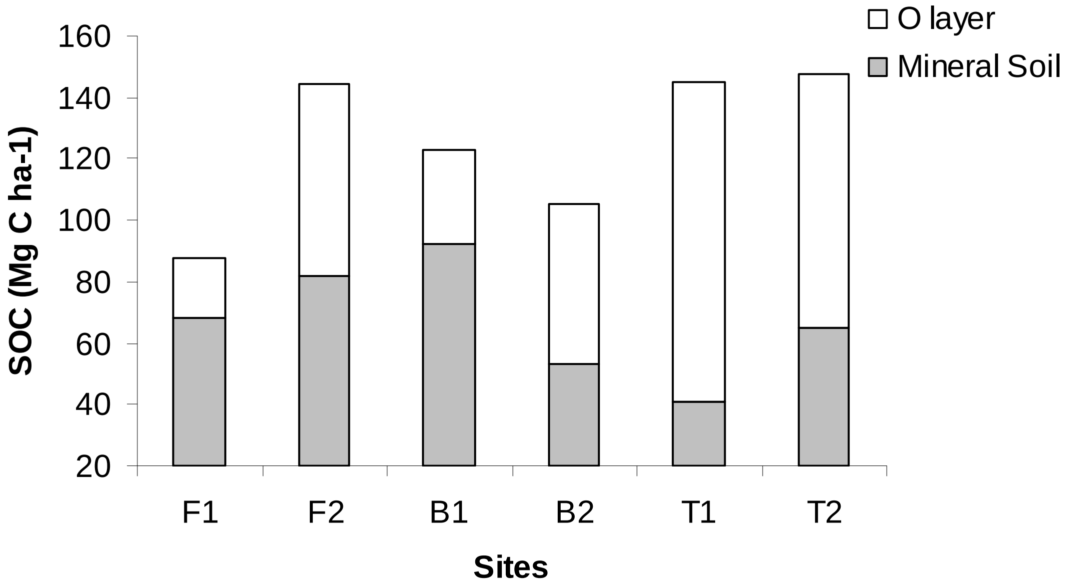

Fig. 5.12 Total soil organic carbon storage (forest floor + mineral soil) in conifer.

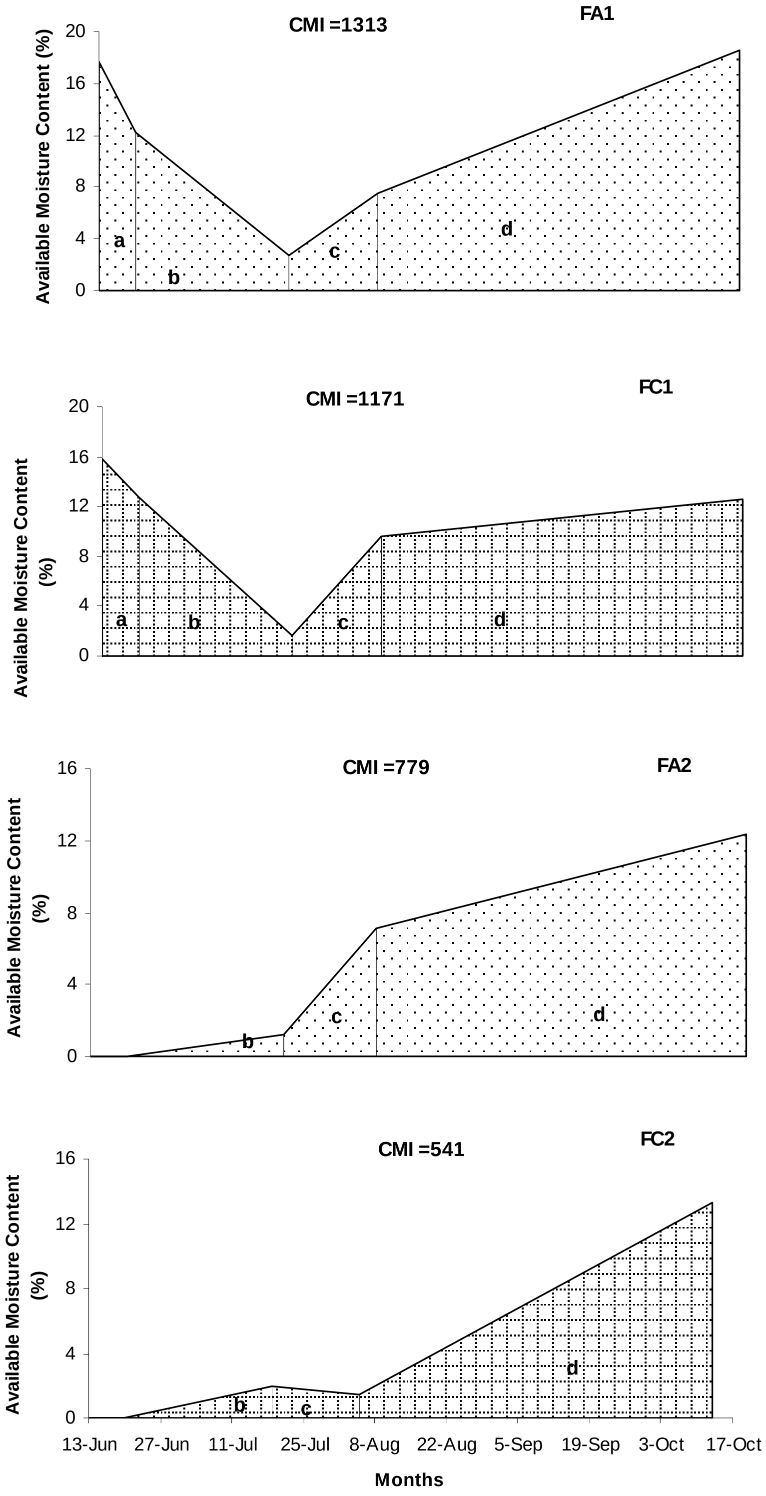

Fig. 5.13 Cumulative moisture index (summer 07) presented by area under the curve in aspen and conifer in Upper Frost Canyon.

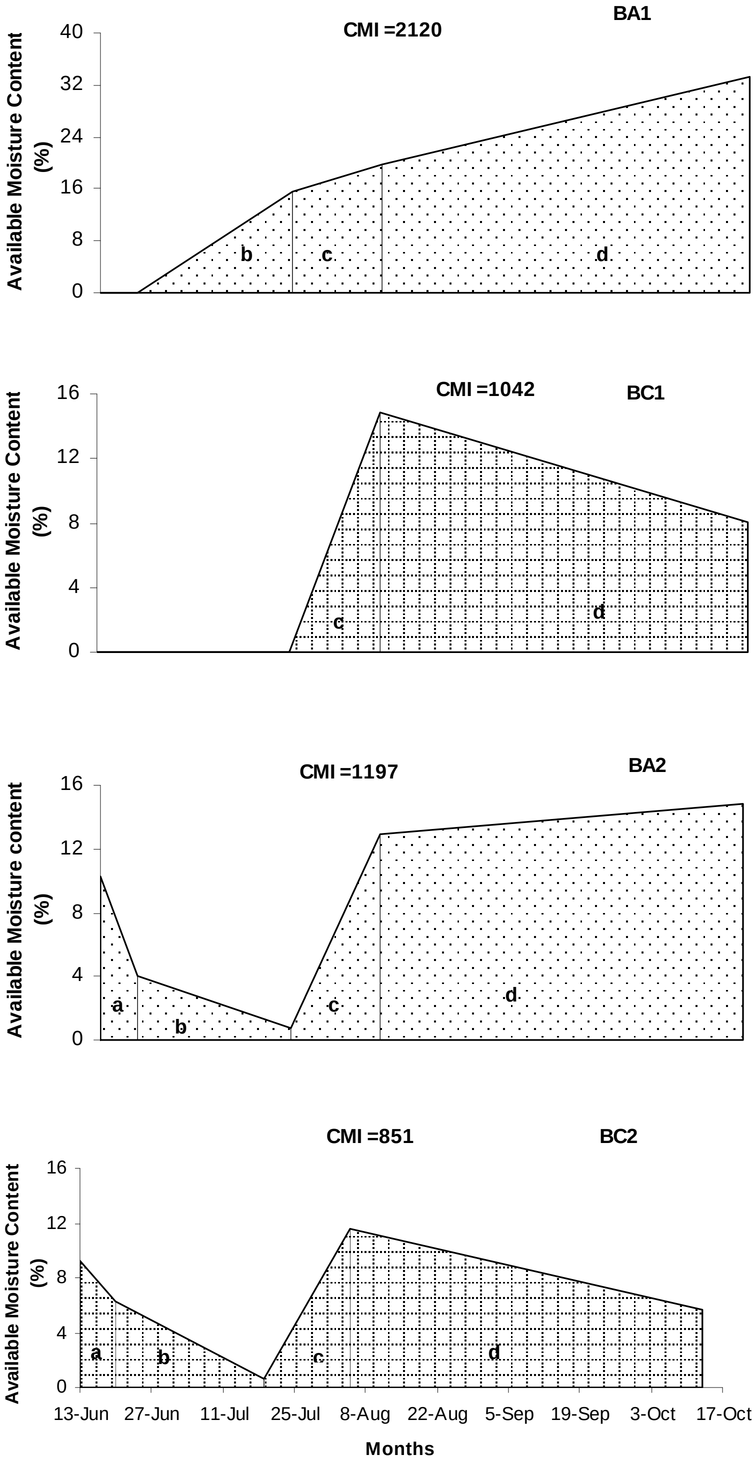

Fig. 5.14 Cumulative moisture index (summer 07) presented by area under the curve in aspen and conifer in Bear Canyon.

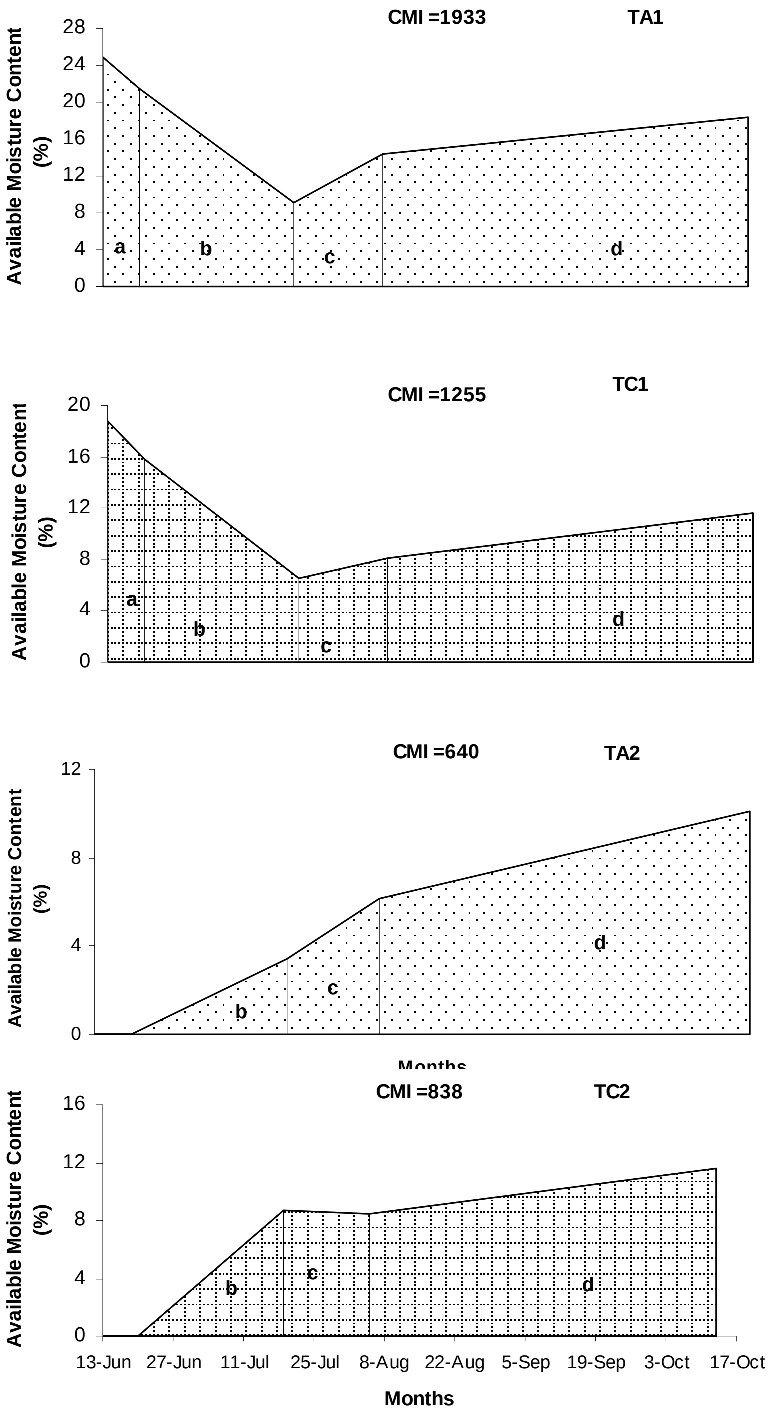

Fig. 5.15 Cumulative moisture index (summer 07) presented by area under the curve in aspen and conifer in TWDEF.

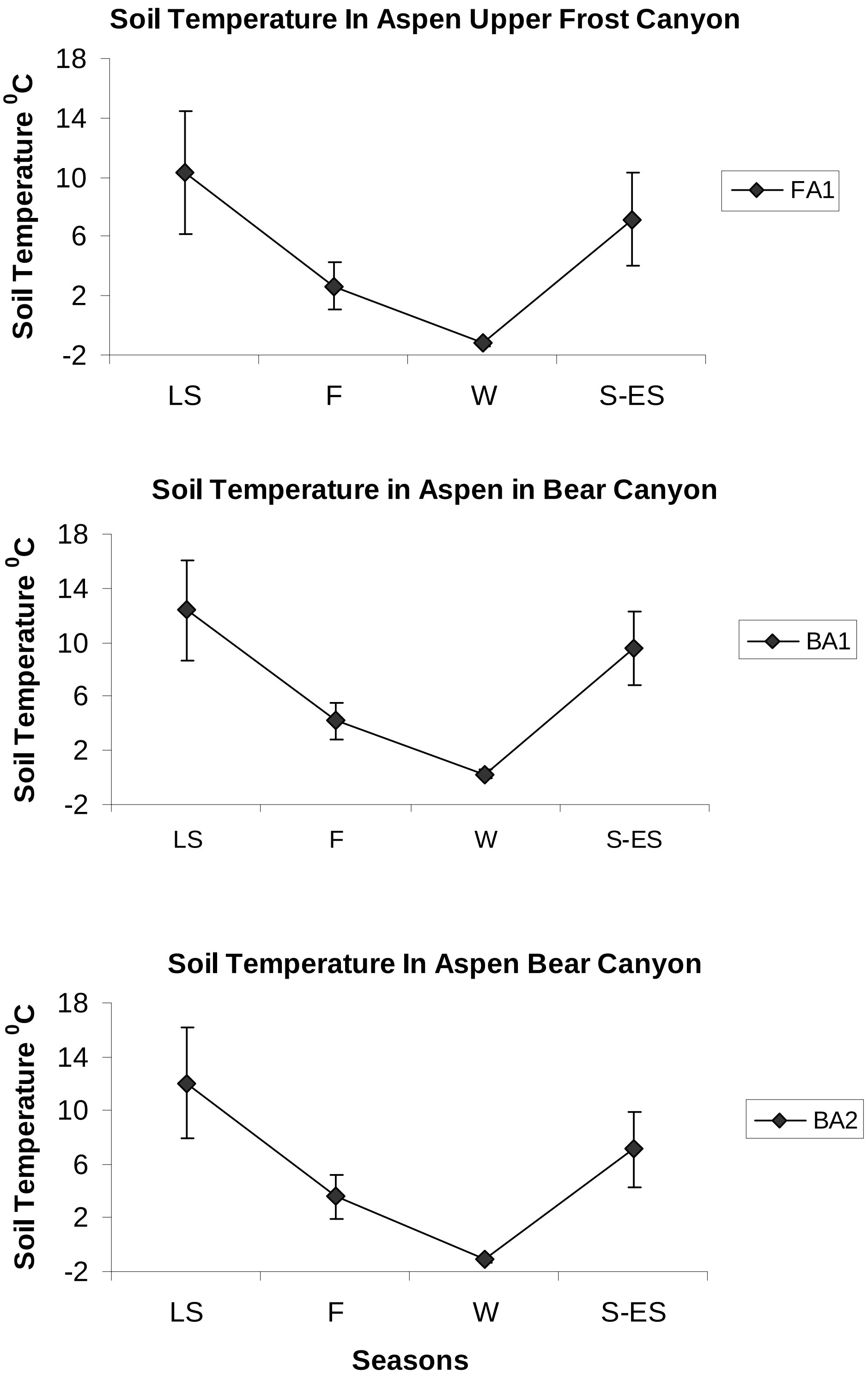

Fig. 5.16 Average daily temperature in aspen (FA1, BA1 and BA2) at DLL. Error bars represent standard deviations about the average daily temperature variability within the seasons LS: Late summer, F: Fall, W: Winter, S-ES: Spring-Early Summer.

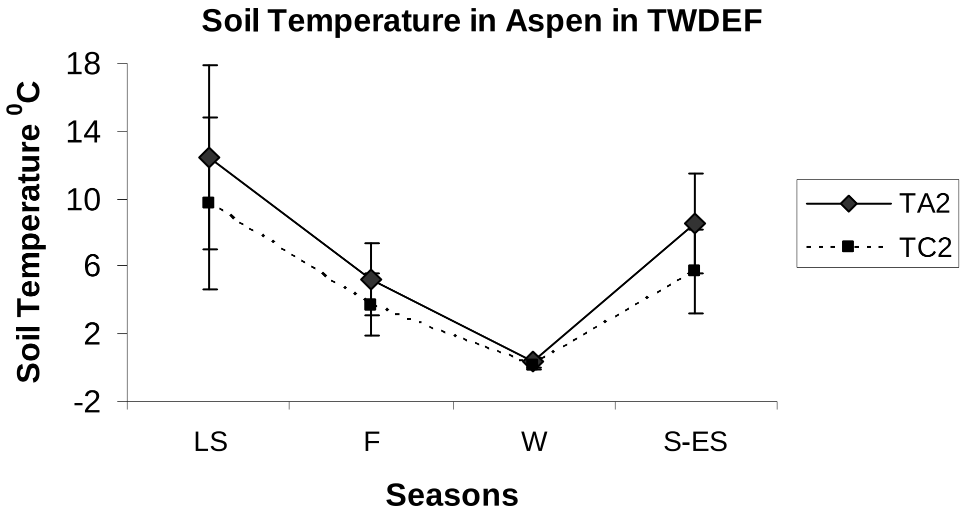

Fig. 5.17 Average daily temperature in aspen (TA2) and conifer (TC2) at TWDEF. Error bars represent standard deviations about the average daily temperature variability within the seasons LS: Late summer, F: Fall, W: Winter, S-ES:Spring-Early Summer.

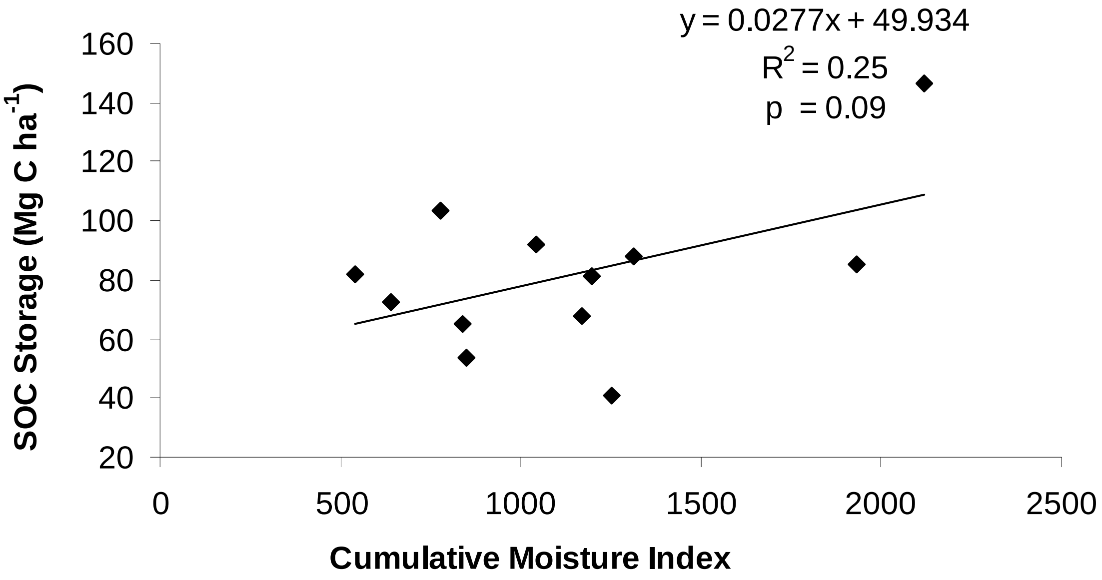

Fig. 5.18 Regression analysis of SOC (0-60 cm) and cumulative moisture index.

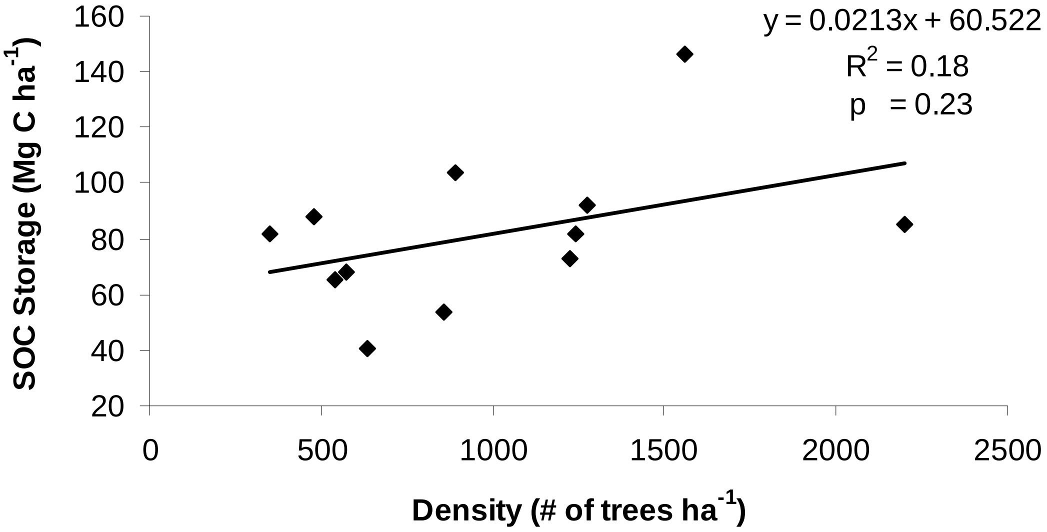

Fig. 5.19 Regression analysis of SOC (0-60 cm) and tree density.

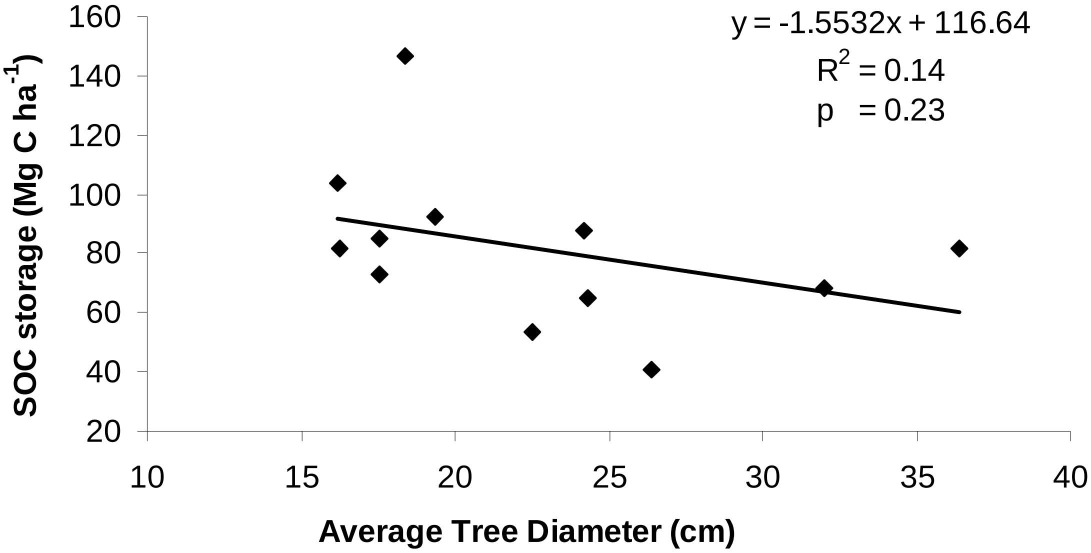

Fig. 5.20 Regression analysis of SOC (0-60 cm) and average tree diameter.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Vegetation has a strong influence on soil biogeochemical processes including SOC. A change of vegetation can cause subsequent changes in SOC storage and dynamics, which is considered as a vital component of soil affecting many other physical, chemical and biological processes in the soil.

In the Intermountain West, aspen has declined due to a combination of successional processes, fire suppression and long-term use of ungulates. However, the decline of aspen related with conifer succession is of great concern in Utah. The potential impacts following conifer encroachment have not been explicitly studied, so it is essential to look at the ecosystem properties of the two vegetation types as representative of end-point communities.

To address this issue we conducted a two-tier study; in phase one we estimated SOC storage under pure aspen stands and its variability, in phase two we compared SOC among aspen and conifer stands as representatives of end-member communities. In both study phases we evaluated the relationship between SOC and site characteristics. To estimate the SOC under pure aspen we established 33 sampling points on linear transects along four aspect in the north, south, east and west facing transects, and various biotic and abiotic characteristics were assessed including stand characteristics, soil moisture, soil temperature, elevation, slope and aspect. In addition, we described the soil morphology of representative pedon at each transect. In the second phase of the study, we established six paired plots composed of aspen and conifer stands in three different watershed characterized various soil properties including SOC, soil morphology, soil microclimate and nutrient regime.

Soils in the pure aspen stands were classified as Mollisols with a characteristic thick A-horizon. As hypothesized aspen stored large amount of SOC (112 ± 29 Mg ha^{-1}, 0-40 cm depth) and it was variable among the transects. Highest values were observed on the south and east-facing sites, and lowest on the north and west-facing transects. However, the average SOC content of upper 10 cm did not vary significantly among aspects.

The difference in SOC could be largely explained by different soil moisture conditions and stand characteristics along the transects. The south and east facing transects were drier and contained more SOC compared to the north and west facing transects. Across the entire Upper Frost Canyon watershed, SOC accumulation was negatively correlated with soil moisture, which was able to explain 16% of the variability of SOC to depth of 40 cm. Even though we did not have enough soil temperature data to perform regression, the temperature regime of the area, expressed as degree days over a period of 65 days in summer, was also significantly different among aspects with higher summer temperatures on the south and east facing slopes compared to the north and west facing slopes. Our results are consistent with other studies that have suggested that the SOC content in arid and semi-arid region is more related to moisture than temperature.

The aspen forest structure was different among transects even though differences were not statistically significant, except for the average tree diameter. South and east facing transects were more densely vegetated and dominated by smaller trees relative to the north and west facing transects. SOC was positively related with vegetation density and explained 33 % of the variability, and negatively related with average tree diameter. These stand characteristics could be a surrogate for higher litterfall input, or differences in understory vegetation and soil microclimate, where the sites characterized by closed canopy could exhibit different soil moisture and temperature. Even though it is hard to make inferences about the various factors and mechanisms controlling SOC the majority of the variability of SOC was explained by soil moisture and stand characteristics.

Results from the paired plots showed a difference in soil morphology where aspen occurred mainly in Mollisols, except for one site at TWDEF that was classified as Alfisols but had a 40 cm thick mollic epipedon. The sites under conifers were classified as Alfisols, Inceptisols and Entisols. In general, morphological differences were expressed in the thickness of the O horizon (conifer > aspen) and of the A horizon conifer [conifer (16.2 cm) < aspen (43.3 cm)]. This partially supports earlier statements of a strong association between aspen and Mollisols, but it may be more meaningful to evaluate the nature of soil profile differences rather than simply focus on classification into soil order.

As hypothesized the SOC content in the mineral soil under aspen (0-60 cm) was higher (96 Mg C ha^{-1}) compared to conifers (66 Mg C ha^{-1}). However the surficial SOC content in the mineral soil (0-15 cm) was not significantly different, which was consistent with the findings from phase one. The SOC content (0-60 cm) under aspen in the paired plot was somewhat lower compared to the SOC content (0-40 cm) under pure aspen stands and this is might be due to the incipient effect of conifer encroachment and/or the wider geographic scope of the study area. The SOC in the forest floor was significantly different under the two vegetation types with an average of 7.7 Mg C ha^{-1} under aspen vs. 58.6 Mg C ha^{-1} under conifers. However, total SOC (O layer + mineral soil) under the two vegetation types was not significantly different, which could be an indication of redistribution of SOC rather than a true difference in SOC content.

Moreover, our paired plot results showed that the moisture content under the two vegetation types was different where aspen had higher moisture content relative to conifers. This finding is consistent with other studies and supports the ideas postulated by other researchers that conifer encroachment can decrease water yield and stream flow. We did not observe any changes in chemical soil properties and nutrient regime.

The regression analysis showed the relationship between SOC and stand characteristics was consistent with the transect study, however CMI and SOC showed an opposite trend from the one observed in the transect study. The apparent contradictory relationship could be indicative of the effect of vegetation type, as soil moisture co-vary with vegetation type.

The higher SOC content in the mineral aspen soil may be the result of:

i) the production of more recalcitrant SOC or stabilization mechanisms that are absent or less pronounced in conifer soils.

ii) relatively higher litterfall input, possibly linked to the understory vegetation, where aspen is believed to support more understory vegetation,

iii) different microclimatic conditions.

The apparent upward redistribution of SOC under conifers could be a concern as the SOC located in the upper surface is considered “sensitive” to changes in climatic conditions and “vulnerable” to disturbances such as fire. So conifer encroachment could possibly influence the distribution of SOC so as to render it more susceptible to losses.

To draw concrete conclusions about the mechanisms responsible for the differences in SOC among aspen and conifer and the potential impacts of conifer encroachment, it would be useful to carry out a detailed study of decomposition rates, litter fall input, understory vegetation and soil microclimate, including temperature and moisture. Even though it is a challenge to characterize exactly how the site characteristics will change following conifer encroachment, this study gives some insights of the general site characteristics’ of the two vegetation types and fills some of the gaps in aspen and conifer encroachment studies.

Overall, the important points from this study are that stand characteristics are important in determining SOC storage and affect multiple site characteristics that affect SOC inputs and dynamics. These are complex systems where many factors play crucial roles in defining the relationship between SOC and other site characteristics. Finally, one important finding from both phases one and phase two studies is the role of sampling depth in detecting change. Most of the significant differences were observed when we considered a greater soil column depth. In assessing forest soil stocks and to evaluate changes due to land use, vegetation type, or disturbance, it is important for researchers to consider sampling at greater depth rather than at the surface only, as the latter could potentially lead to biased results.

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APPENDIX

Table A.1 Field soil description of the pedon in the north facing transect.

USU Soil Description Sheet

Soil ID: **North Aspen**

Date: 7/12/2006

Described by: Mical K, David Eaton

Soil Series (if applicable)**:**

Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed): 12 T 0461066 UTM 4580929

Parent material: Wasatch Conglomerate

Elevation: 8324 ft

Slope: 20%

Aspect: N

Drainage Class: Well drained

Landform, hillslope position: Backslope

Climate: SMR: Xeric STR: Frigid

MAP	**MAT**	**MAST**	**MSST**	**MWST**
890 mm	4.25°C	5.25°C	14 °C	-2.7 °C

Vegetation: **Forest**

Current vs. presumed native Grassland/Woody

Depth to water table:

Surface Stone and Rock: None

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A1	0-20	C	W	D7.5YR3/2 M7.5YR2.5/2	5	GR	SL	12	1	VF	SBK	S	VFR	SO	PO	NE	5.8	M	F	M	F	
A2	20-40	C	W	D7.5YR3/4 M7.5YR3/3	6	GR	L	14	1	CO	SBK	S	VFR	SO	PO	NE	6	M	F	C	F	
A3	40-53	A	S	D7.5YR 4/4 M7.5YR2.5/3	6	GR	L	18	2	CO	ABK	SH	VFR	SO	Po	NE	6.2	C	VF	M	F	Some Mn concentrations
Bt1	53-80	A	W	D5YR4/6 M5YR3/4	5	GR	L	21	3	VC	ABK	SH	FR	SO	Po	NE	6.6	F	C	C	F	Clay films Mn concentrations
CBt	80-86			D5YR4/4 5YR4/6	6	GR	SL		0		MA	MH	FR	SS	SP	NE	6.8	VF	F	C	VF	Clay films and bridges

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments: Mollic epipedon argillic horizon

Diagnostic epipedon, horizons, and other characteristics:

Classification: **Order:** Mollisol **Suborders:** Xeroll **Great Groups: Argixer**olls **Subgroups:** Pachic Argixerolls

Table A.2 Field soil description of the pedon in the south facing transect.

USU Soil Description Sheet	**Soil ID:** **South Aspen**	**Date:** 7/13/2006	**Described by:** Mical K, David Eaton
Soil Series (if applicable):	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 0461066 UTM 4580929		

Parent material: Wasatch Conglomerate	**Elevation:** 8324 ft		**Slope:** 20%	**Aspect:** S	**Drainage Class:** Well drained		
Landform, hillslope position: Backslope	**Climate:** SMR: Xeric	STR: Frigid	**MAP** 890 mm	**MAT** 4.25°C	**MAST** 5.25°C	**MSST** 14 °C	**MWST** -2.7 °C
Vegetation: **Forest** Current vs. presumed native	Grassland/Woody	**Depth to water table:**			**Surface Stone and Rock:** None		

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A1	0-19	C	W	D10YR5/4 M7.5YR3/2	16	GR	GRL	13	1	CO	SBK	S	VFR	SO	PO	NE	5.8	M	F	M	F	
A2	19-43	C	S	D10YR5/4 M7.5YR3/2	16	GR	GRL	13	1	M	SBK	S	VFR	SO	PO	NE	5.8	M	F	M	F	
Bt1	43-57	A	W	D10YR 6/4 M7.5YR2.5/3	30	CB	CBSL	16	1	M	ABK	S	FR	SO	Po	NE	5.6	C	VF	M	F	Clay films
Bt2	57-80	C	W	D10YR6/4 M10YR5/6	22	CB	CBSL	17	1	M	ABK	SH	FR	SO	Po	NE	5.5	C	F	M	F M	Clay films
C	80-86				65	CB			0							NE	6	C	VF	M	VF	

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments:

Diagnostic epipedon, horizons, and other characteristics: Mollic epipedon
Argillic sub surface diagnostic horizons

Classification: **Order:** Mollisol **Suborders:** Xeroll **Great Groups: Argixer**olls **Subgroups:** Pachic Argixerolls

Table A.3 Field soil description of the pedon in the west facing transect.

USU Soil Description Sheet	**Soil ID:** West Aspen	**Date:** 7/15/2006	**Described by:** Mical K, David Eaton		
Soil Series (if applicable):	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 0460153 UTM 4580543				
Parent material: Wasatch Conglomerate	**Elevation:** 8371 ft	**Slope:** 26%	**Aspect:** w	**Drainage Class:** Well drained	
Landform, hillslope position: Backslope	**Climate:** SMR: Xeric STR: Frigid	**MAP** 890 mm	**MAT** 4.25°C	**MAST** 5.25°C	**MSST** 14 °C **MWST** -2.7 °C
Vegetation: Current vs. presumed native Grassland/Woody	**Depth to water table:**	**Surface Stone and Rock:** None			

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**			**STRUCTURE**			**CONSISTENCE**			**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF	Class	%C	Gr	Size	Sh	Dry	Moist	Wet	Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A1	0-40	G	W	D10YR5/4 M7.5YR2.5/3	5 GR	SL	7	1	VC	SBK	Soft	VFR	SO PO	NE	5.9	M	VF	M	VF f	
A2	40-65	C	S	D7.5YR5/4 M7.5YR3/4	3 GR	SL	8	2	VC	SBK	S	VFR	SO PO	NE	6	M	VF m	M	VF f	
Bt1	65-88	C	S	D5YR 5/8 M7.5YR5/6	2 GR	SIL	20	3	VC	SBK	MH	FR	SO PO	NE	6.2	M	VF f	M	VF	Clay fims common
Bt2	88-100			D5YR5/8 M2.5YR4/8	5 Gr	SIL	21	2	VC	ABK	HA	HA	SS SP	NE	6	M	VF	M	VF f	Clay films common

Current landus agricultural field

Weather conditions, soil moisture status at time of description:

Other comments:

Diagnostic epipedon, horizons, and other characteristics: Mollic epipedon

argillic sub-surface diagnostic horizon

Classification: **Order:** Mollisol **Suborders:** Xeroll **Great Groups: Xer**olls **Subgroups:** Pachic Argixerolls

Table A.4 Field soil description of the pedon in the east facing transect.

USU Soil Description Sheet
Soil ID: East Aspen
Date: 7/20/2006
Described by: Mical K, David Eaton
Soil Series (if applicable):
Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed): 12 T 0459855 UTM 4581366
Parent material: Wasatch Conglomerate
Elevation: 8371 ft
Slope: 38%
Aspect: E
Drainage Class: SE or Well drained
Landform, hillslope position: Summit
Climate: SMR: Xeric STR: Frigid

MAP	**MAT**	**MAST**	**MSST**	**MWST**
890 mm	4.25°C	5.25°C	14 °C	-2.7 °C

Vegetation:
Current vs. presumed native Grassland/Woody
Depth to water table:
Surface Stone and Rock: None

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A1	0-14.5	C	S	D10YR3/2 M10YR2/2	18	GR	GRSL	9	1	VF	GR	Soft	VFR	SO	PO	NE	6.2	M	VF	M	VF	
A2	14.5-33	C	W	D10YR3/3 M10YR2/2	22	GR	GRSL	8	2	CO	SBK	S	VFR	SO	PO	NE	5.9	M	VF m	M	VF	
AC	33-56	A	W	D10YR 4/3 M7.5YR2.5/3	36	CB	CBVSL	8	0		SG					NE	5.6	C	F	C	F	
C	56-72			D10YR6/4 M7.5YR5/6	39	CB	CBVSL	3	0		SG					NE	5.4	C	M	C	F	

Current landus agricultural field
Weather conditions, soil moisture status at time of description:
Other comments:
Diagnostic epipedon, horizons, and other characteristics: Mollic epipedon
NO sub-surface diagnostic horizons
Classification: **Order:** Mollisol **Suborders:** Xeroll **Great Groups: Haploxer**olls **Subgroups:** Typic Haplocryolls **Family**: Mixed, Isofrigid Pachic Haploryolls

Table A.5 Field soil description of the pedon in FA1 in Upper Frost Canyon under aspen

USU Soil Description Sheet | **Soil ID:** **FA1 Aspen** | **Date:** 7/19/2006 | **Described by:** Mical K, David Eaton

Soil Series (if applicable)**:**

Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed): 12 T 0461754 UTM 4579488

Parent material: Wasatch Conglomerate

Elevation: 8659 ft

Slope: 17%

Aspect: NW

Drainage Class: Well drained

Landform, hillslope position: Backslope

Climate: SMR: Xeric STR: Frigid

MAP 890 mm **MAT** 4.25^{o}C **MAST** 5.25^{o}C **MSST** 14 ^{o}C **MWST** -2.7 ^{o}C

Vegetation: Forest

Current vs. presumed native Grassland/Woody

Depth to water table:

Surface Stone and Rock:

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	%	RF	Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A1	0-14	C	S	D10YR 5/4 M10YR 3/3	6	GR	L	12	1	M	SBk GR	S	VFR	SO	PO	NE	6	M	VF	M	VF	
A2	14-38.5	G	S	D10YR 5/4 M7.5YR3/3	11	GR	L	13	2	CO	SBK	S	VFR	SO	PO	NE	5.8	M	VF	M	VF	
Bw1	38.5-58.5	G	W	D10YR 5/4 M7.5 YR 3/4	13	GR	SIL	15	2	CO	SBK	S	FR	SO	PO	NE	5.8	M	VF	M	VF	
Bw2	58.5-83	C	W	D10YR 6/4 M7.5 YR 3/4	8	GR	SIL	16	2	CO	SBK	S	VFR	SO	PO	NE	5.6	C	VF	M	F	
BC	83-100			D10YR 6/4 M7.5 YR 4/4	12	GR	SIL	11	1	M	SBK	S	VFR	SO	PO	NE	5.5			M	VF	

Current land d

Weather conditions, soil moisture status at time of description:

Other comments:

Diagnostic epipedon, horizons, and other characteristics: Mollic Mollic epipedon

Cambic subsurface horizon

Classification: **Order:** Mollisol **Suborders:** Xeroll **Great Groups: Haploxeroll** **Subgroups:** Typic Haploxeroll

Table A.6 Field soil description of the pedon in FC1 Upper Frost Canyon under conifer.

USU Soil Description Sheet	**Soil ID:** **FC1 Conifers**	**Date:** 7/19/2006	**Described by:** Mical K, David Eaton
Soil Series (if applicable):	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 0461754 UTM 4579481		

Parent material: Wasatch Conglomerate	**Elevation:** 8536 ft	**Slope:** 35%	**Aspect:** NW	**Drainage Class:** Well drained

Landform, hillslope position: Backslope	**Climate:** SMR: Xeric	STR: Frigid	**MAP** 890 mm	**MAT** 4.25^{o}C	**MAST** 5.25^{o}C	**MSST** 14 ^{o}C	**MWST** -2.7 ^{o}C

Vegetation: **Forest** Current vs. presumed native Grassland/Woody	**Depth to water table:**	**Surface Stone and Rock:**

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
Oi	0-1																					
A	1-12.5	C	S	D7.5YR 2/2 M10YR 4/3	9	GR	SIL	12	1	VF	GR	S	VFR	SO	PO	NE	5.9	M	VF	M	VF	
Bw1	12.5-46.5	G	W	D10YR 6/4 M10YR3/4	8	GR	SIL	9	2	CO	SBK	SH	VFR	SO	PO	NE	5.6	M	VF	M	VF	
Bw2	46.5-67	G	W	D10YR 6/4 M10YR 6/4	7	GR	SIL	13	2	CO	SBK	SH	FR	SO	PO	NE	5.8	M	VF	M	VF	
Bw3	67-95			D10YR 6/4 M10 YR 6/4	7	GR	SIL	14	1	CO	SBK	SH	FR	SO	PO	NE	5.3			M	V	

Current landus agricultural field

Weather conditions, soil moisture status at time of description:

Other comments:

Diagnostic epipedon, horizons, and other characteristics: Ochric epipedon

Cambic horizons

Classification: **Order:** Inceptisols **Suborders:** Xerepts **Great Groups: Haploxer**epts **Subgroups:** Typic Haploxerepts

Table A.7 Field soil description of the pedon in FA2 in Upper Frost Canyon under aspen.

USU Soil Description Sheet	**Soil ID:** **FA2 Aspen**	**Date:** 7/20/2006	**Described by:** Mical K, David Eaton	
Soil Series (if applicable):	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 0463937 UTM 4576883			
Parent material: Wasatch Conglomerate	**Elevation:** 8230 ft	**Slope:** 21%	**Aspect:** NW	**Drainage Class:** Well drained
Landform, hillslope position: Backslope	**Climate:** SMR: Xeric STR: Frigid	**MAP** 890 mm	**MAT** **MAST** 4.25°C 5.25°C	**MSST** **MWST** 14 °C -2.7 °C
Vegetation: **Forest** Current vs. presumed native Grassland/Woody	**Depth to water table:**	**Surface Stone and Rock:** None		

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A1	0-16.5	G	S	D10YR2/2 M7.55YR 3/3	15	GR	GRSL	5	2	F	GR	MH	S	SO	PO	NE	5.3	M	VF	M	VF	
A2	16.5-38	G	S	D10YR5/3 M10YR2/2	13	GR	SL	7	1	CO	SBK	MH	S	SO	PO	NE	4.9	M	VF m	M	VF	
A3	38-60	A	W	D10YR 5/3 M10YR2/2	18	GR	GRSL	8	2	CO	SBK	MH	SH	SO	PO	NE	4.6	M	VF f	M	VF	
C	60-90			D7.5YR6/4 M7.5YR 5/6	30	GR	GRSL	7	0		MA	HA	VH	SO	PO	NE	5.7	F	VF	M	VF	

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments:

Diagnostic epipedon, horizons, and other characteristics: Mollic

NO sub surface diagnostic horizon

Classification: **Order:** Mollisol **Suborders:** Xeroll **Great Groups:** Haploxerolls **Subgroups:** Pachic Haploxerolls

Table A.8 Field soil description of the pedon in FC2 in Upper Frost Canyon under conifer.

USU Soil Description Sheet	**Soil ID:** **FC2 Conifers**	**Date:** 7/20/2006	**Described by:** Mical K, David Eaton
Soil Series (if applicable)**:**	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 0460971 UTM 4576980		

Parent material: Wasatch Conglomerate	**Elevation:** 8187 ft	**Slope:** 26%	**Aspect:** NW	**Drainage Class:** Well drained

Landform, hillslope position:	**Climate:**		**MAP**	**MAT**	**MAST**	**MSST**	**MWST**
Backslope	SMR: Xeric	STR: Frigid	890 mm	4.25^{o}C	5.25^{o}C	14 ^{o}C	-2.7 ^{o}C

Vegetation: **Forest** Current vs. presumed native Grassland/Woody	**Depth to water table:**	**Surface Stone and Rock:** None

HORIZON	DEPTH	BDY		COLOR	TEXTURE				STRUCTURE			CONSISTENCE				REACTION		ROOTS		PORES		Ped&Void Surface Features
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	Concentrations, RMFs, etc.
Oi	0-2																					
A	2-7.5	C	S	D7.5YR5/4 M7.55YR 3/3	25	GR	GRL	14	1	CO	SBK	MH	FR	SO	PO	NE	5.8	M	VF	M	VF	
Bw1	7.5-36	G	W	D7.5YR5/6 M5YR3/4	20	GR	GRL	15	2	CO	SBK	MH	VFR	SO	PO	NE	5.5	M	VF	M	VF	
Bw2	36-66	C	S	D7.5YR 5/4 M5YR 4/4	15	GR	GRSIL	10	2	CO	SBK	MH	FR	SO	PO	NE	5.6	M	VF	M	VF	
C	66-100			D5YR6/6 M2.5YR 4/6	20	GR	GRL	12	0		MA	HA	FI	SO	PO	NE	5.8			M	VF	

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments: Very thhin O horizon

Diagnostic epipedon, horizons, and other characteristics: Ochric

Sub-srurface diagnostic horizon: Cambic

Classification: **Order:** Inceptisols **Suborders:** Xerepts **Great Groups: Haploxer**epts **Subgroups:** Humic Haploxerepts

Table A.9 Field soil description of the pedon in BA1 in Bear Canyon under aspen.

USU Soil Description Sheet	**Soil ID:** **BA1 Aspen**	**Date:** 7/21/2006	**Described by:** Mical K, David Eaton
Soil Series (if applicable):	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 0460074 UTM 4580512		

Parent material: Wasatch Conglomerate	**Elevation:** 8238 ft	**Slope:** 35%	**Aspect:** N	**Drainage Class:** Well drained

Landform, hillslope position:	**Climate:**		**MAP**	**MAT**	**MAST**	**MSST**	**MWST**
Backslope	SMR: Xeric	STR: Frigid	890 mm	4.25°C	5.25°C	14 °C	-2.7 °C

Vegetation: **Forest** Current vs. presumed native Grassland/Woody	**Depth to water table:**	**Surface Stone and Rock:** None

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A1	0-25.5	C	S	D10YR5/4 M10YR 3/2	4	GR	L	8	2	M	GR	Soft	VFR	SO	PO	NE	6.2	M	VF	M	VF	
A2	25.5-50.5	C	S	D10YR5/4 M7.5YR3/4	3	GR	L	10	2	C	SBK	SH	VFR	SO	PO	NE	6.1	M	VFm	M	VF	
Bw1	50.5-70	C	S	D7.5YR 4/6 M5YR3/4	2	GR	L	16	2	C	SBK	SH	FR	SO	PO	NE	5.7	M	VFf	M	VF	
BC	70-100			D7.5YR4/6 M10YR4/6	1	GR	L	14	2	C	SBK	M	HA	SS	SP	NE	5.8	M	VF	M	VF	

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments:

Diagnostic epipedon, horizons, and other characteristics: Mollic epipedon
Cambic

Classification: **Order:** Mollisol **Suborders:** Xeroll **Great Groups: Haploxeroll** **Subgroups:** Pachic Haploxeroll

Table A.10 Field soil description of the pedon in BC1 in Bear Canyon under conifer.

USU Soil Description Sheet	**Soil ID:** **BC1 Conifers**	**Date:** 7/21/2006	**Described by:** Mical K, David Eaton
Soil Series (if applicable):	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 0460026 UTM 4580536		

Parent material: Wasatch Conglomerate	**Elevation:** 8238 ft	**Slope:** 39%	**Aspect:** N	**Drainage Class:** Well drained

Landform, hillslope position:	**Climate:**		**MAP**	**MAT**	**MAST**	**MSST**	**MWST**
Backslope	SMR: Xeric	STR: Frigid	890 mm	4.25°C	5.25°C	14 °C	-2.7 °C

Vegetation: Current vs. presumed native Grassland/Woody	**Depth to water table:**	**Surface Stone and Rock:** None

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
Oi	0-0.5																					
A	0.5-7.5	C	W	D10YR4/3 M10YR 3/3	7	GR	L	12	1	M	SBK	Soft	VFR	SO	PO	NE	6.3	M	VF	M	VF	
AB	7.5-32	C	W	D7.5YR4/4 M7.5YR3/4	6	GR	L	14	2	C	SBK	SH	VFR	SO	PO	NE	5.9	M	VF m	M	VF	
BW1	35-52	C	S	D7.5YR 5/6 M5YR5/6	4	GR	SL	19	2	C	SBK	SH	FR	SO	PO	NE	6.2	M	VF f	M	VF	
Bt	52-81			D5YR6/6 M2.5YR4/8	3	GR	SCL	25	1M	C	SBK	HA	HA	SS	SP	NE	6	F	VF	M	VF	Clay films

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments: Thin O horizon < 1cm Solid Rock @ bottom is effervescent

Diagnostic epipedon, horizons, and other characteristics: Ochric epipedon

Argillic sub-surface diagnostic horizons

Classification: **Order:** Alfisols **Suborders:** Xeralfs **Great Groups: Haploxeralfs** **Subgroups:Typic Haploxeralfs**

Table A.11 Field soil description of the pedon in BA2 in Bear Canyon under aspen.

USU Soil Description Sheet
Soil ID: **BA2 Aspen**
Date: 7/21/2006
Described by: Mical K, David Eaton
Soil Series (if applicable)**:**
Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed): 12 T 0462646 UTM 4579653
Parent material: Wasatch Conclomerate
Elevation: 8536 ft
Slope: 8%
Aspect: SW
Drainage Class: Well drained
Landform, hillslope position: Summit
Climate: SMR: Xeric STR: Frigid
MAP 890 mm
MAT 4.25^{o}C
MAST 5.25^{o}C
MSST 14 ^{o}C
MWST -2.7 ^{o}C
Vegetation: **Forest**
Current vs. presumed native Grassland/Woody
Depth to water table:
Surface Stone and Rock:

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A	0-40	C	S	D10YR 5/3 M10YR 3/2	13	GR	SL	10	2	VF	GR	S	VFR	SO	PO	NE	5.2	M	VF	M	VF	
Bw1	40-50	C	W	D10YR 7/3 M7.5YR5/6	9	GR	SL	8	1	CO	SBK	SH	VFR	SO	PO	NE	5.5	M	VF	M	VF	
Bw2	50-80	C	W	D10YR 7/3 M10YR 6/6	15	GR	GRLS	13	1	CO	SBK	SH	FR	SO	PO	NE	5.8	F	VF	M	VF	
C	80-100			D10YR 6/3 M10 YR 5/4	14	GR	LS	14	1	CO	SBK	SH	VFR	SO	PO	NE	5.4	F	F	M	F	

Current landuse:
Weather conditions, soil moisture status at time of description:
Other comments:
Diagnostic epipedon, horizons, and other characteristics: Mollic
No subsurface diagnostic horizons
Classification: **Order:** Mollisol **Suborders:** Xeroll **Great Groups: Haploxerolls** **Subgroups:** Typic Haploxerolls

Table A.12 Field soil description of the pedon in BC2 Bear Canyon under conifer.

USU Soil Description Sheet	**Soil ID:** BC2 Conifers	**Date:** 7/19/2006	**Described by:** Mical K, David Eaton	
Soil Series (if applicable):	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 0462646 UTM 4579653			
Parent material: Wasatch Conglomerate	**Elevation:** 8598 ft	**Slope:** 5%	**Aspect:** W	**Drainage Class:** Well drained
Landform, hillslope position: Foot slope	**Climate:** SMR: Xeric STR: Frigid	**MAP** 890 mm	**MAT** 4.25°C **MAST** 5.25°C	**MSST** 14 °C **MWST** -2.7 °C
Vegetation: **Forest** Current vs. presumed native Grassland/Woody	**Depth to water table:**	**Surface Stone and Rock:** None		

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
Oi	0-1																					
A1	1-7.5	C	S	D10YR6/4 M5YR 4/4	7	GR	SIL	10	2	M	Pl	S	FR	SS	SP	NE	5.5	M	VF	M	VF	
A2	7.5-35	C	W	D7.5YR6/4 M5YR3/4	8	GR	SIL	8	1	M	Pl	SH	VFR	SS	SP	NE	5.4	M	VF	M	VF	
C1	35-42.5	G	W	D7.5YR 7/4 M10YR 5/4	9	GR	SIL	13	0		MA	SH	FR	SS	SP	NE	5.3	C	VF	M	VF	
C2	42.5-60			D2.5YR7/8 M2.5YR 5/4	13	GR	SIL	14	0		MA	SH	FR	SS	SP	NE	5.4			M	VF	

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments: Very thhin O horizon

Diagnostic epipedon, horizons, and other characteristics: Ochric Epipedon
No subsurface diagnostic horizons

Classification: **Order:** Entisol **Suborders:** Orthents **Great Groups: Xerorthents** **Subgroups:** Typic Xerorthents

Table A.13 Field soil description of the pedon in TA1 in TWDEF under aspen.

USU Soil Description Sheet	**Soil ID:** **TA1 Aspen**	**Date:** 7/12/2006	**Described by:** Mical K, David Eaton
Soil Series (if applicable):	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 0461066 UTM 4580929		
Parent material: Wasatch Conglomerate	**Elevation:** 8637 ft	**Slope:** 5%	**Aspect:**
Drainage Class: Well drained			
Landform, hillslope position: Summit	**Climate:** SMR: Xeric STR: Cryic		
Vegetation: Current vs. presumed native Grassland/Woody	**Depth to water table:**	**Surface Stone and Rock:** None	

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A	0-40	C	W	D10YR4/4 M7.5YR3/3	18	GR	GRSCL	21	2	M	SBK	SH	VFR	SS	SP	NE	4.9	M	VF	M	VF	
Bt1	40-68	C	W	D7.5YR4/6 M7.5YR4/4	15	GR	GRSiCl	30	2	C	SBK	SH	FR	SS	SP	NE	4.9	M	VF	M	VF	Clay films common
Bt2	68-80	A	S	D5YR 4/6 M5YR 4/6	35	VGR	GRVSiCl	27	2	C	ABK	MH	FR	SS	SP	NE	4.7	M	VF	M	VF	Clay films common

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments:

Diagnostic epipedon, horizons, and other characteristics: Arigillic horizon

Classification: **Order: Alfisol Suborders: Cryalf Great Groups: Argi**cryalf **Subgroups:** Mollic Haplocryalf

Table A.14 Field soil description of the pedon in TC1 in TWDEF under conifer

USU Soil Description Sheet

Soil ID: **TC1 conifer**

Date: 25/12/2006

Described by: Mical K, David Eaton

Soil Series (if applicable):

Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed): 12 T 0461066 UTM 4580929

Parent material: Wasatch Conglomerate

Elevation: 8637 ft

Slope: 9%

Aspect:

Drainage Class: Well drained

Landform, hillslope position: Shoulder

Climate: SMR: Xer STR: Cryic

Vegetation: Current vs. presumed native Grassland/Woody

Depth to water table:

Surface Stone and Rock: None

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
Oi	0-10	C	I																			
A	10- 40	G	S	D10YR5/4 M7.5YR4/3	20	GR	GRSL	17	2	C	SBK	HA	FI	SO	PO	NE	5.2	M	VF	M	VF	
Bt1	40-73	C	S	D10YR4/4 M7.5YR3/3	18	GR	GRSL	25	2	C	SBK	HA	FI	SS	SP	NE	5.6	M	VF	M	VF	Clay films
Bt2	73-100			D5YR5/6 M5YR 4/6	38	VGR	GRVSCL	21	2	M	SBK	VH	FR	SS	SP	NE	5.4	M	VF	M	VF	Clay Films

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments:

Diagnostic epipedon, horizons, and other characteristics: Ochric epipedon Argillic sub-surface horizons

Classification: **Order:** Alfisol **Suborders:** Cryalf **Great Groups: Haplo**cryalfs **Subgroups:** Typic Haplocryalfs

Table A.15. Field soil description of the pedon in TA2 in TWDEF under aspen.

USU Soil Description Sheet
Soil ID: **TA2 Aspen**
Date: 25/12/2006
Described by: Mical K, David Eaton
Soil Series (if applicable)**:**
Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed): 12 T 0457649 UTM 463808
Parent material: Wasatch Conglomerate
Elevation: 8781 ft
Slope: 20%
Aspect:
Drainage Class: Well drained
Landform, hillslope position: Shoulder
Climate: SMR: Xeric STR: Cryic
MAP **MAT** **MAST** **MSST** **MWST**
Vegetation: Current vs. presumed native Grassland/Woody
Depth to water table:
Surface Stone and Rock: None

HORIZON	**DEPTH**	**BDY**		**COLOR**	**TEXTURE**				**STRUCTURE**			**CONSISTENCE**				**REACTION**		**ROOTS**		**PORES**		**Ped&Void Surface Features**
	(cm)	Dis	Top	Dry/Moist	% RF		Class	%C	Gr	Size	Sh	Dry	Moist	Wet		Effer	pH	Qty	Size	Qty	Size	**Concentrations, RMFs, etc.**
A1	0-8	C	W	D10YR5/3 M10YR3/2	18	GR	GRSL	10	2	VF	GR	S	VF	SO	PO	NE	5.3	M	VF	M	VF	
A2	8-53	C	W	D10YR5/3 M10YR3/3	20	GR	GRSL	9	2	M	SBK	S	VF	SO	PO	NE	5.4	M	VF	M	VF	
C	53-95	C	S	D7.5YR6/4 7.5YR 4/6	>65	XCB	CBXLS	7	2	F	SBK	MH	Fr	SS	SP	NE	5.5	M	VF	M	VF	

Current landuse:
Weather conditions, soil moisture status at time of description:
Other comments:
Diagnostic epipedon, horizons, and other characteristics: Mollic
No subsurface diagnostic horizons
Classification: **Order:** Mollisol **Suborders:** Cryoll **Great Groups: Haplocryolls** **Subgroups:** Pachic Haplocryolls

Table A.16 Field soil description of the pedon in TC2 in TWDEF under conifer

USU Soil Description Sheet	**Soil ID:** **TC2 conifer**	**Date:** 25/12/2006	**Described by:** Mical K, David Eaton
Soil Series (if applicable):	**Location (UTM; Latitiude & Longitude; Section, Township, Range; USGS Quad; other as needed):** 12 T 045986 UTM 4634591		

Parent material: Wasatch conglomerate	**Elevation:** 8781 ft	**Slope:** 3%	**Aspect:**	**Drainage Class:** Well drained
Landform, hillslope position: Shoulder	**Climate:** SMR: Xeric STR: Cryic			
Vegetation: Current vs. presumed native Grassland/Woody	**Depth to water table:**			**Surface Stone and Rock:** None

HORIZON	**DEPTH** (cm)	**BDY** Dis	Top	**COLOR** Dry/Moist	**TEXTURE** % RF		Class	%C	**STRUCTURE** Gr	Size	Sh	**CONSISTENCE** Dry	Moist	Wet		**REACTION** Effer	pH	**ROOTS** Qty	Size	**PORES** Qty	Size	**Ped&Void Surface Features Concentrations, RMFs, etc.**
Oi	0-4																					
A	4-13.5	G	W	D10YR5/4 M10YR3/3	5	GR	SIL	18	1	m	SBK	HA	VF	SO	PO	NE	5.4	M	VF	M	VF	
	13.5-35	A	W	D10YR6/3 M10YR3/3	6	GR	SIL	22	2	M	SBK	S	VF	SO	PO	NE	6	C	VF	M	VF	
Bt2	35-90			D7.5YR4/6 7.5YR 4/6	4	GR	CL	57	3	VC	ABK	MH	Fr	SS	SP	NE	5.5			M	VF	Clay film

Current landuse:

Weather conditions, soil moisture status at time of description:

Other comments: Ochric epipedon argillic sub-surface horizons

Diagnostic epipedon, horizons, and other characteristics:

Classification: **Order:** Alfisol **Suborders:** Cryalf **Great Groups: Haplo**cryalfs **Subgroups:** Typic Haplocryalfs **Family**: