DISSOLVED ORGANIC CARBON IN NORTHERN BOREAL FOREST SOILS UNDER TWO DIFFERENT AGED FOREST STANDS

BY

PASCAL JOSEPH JEAN CYR

A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfilment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Soil Science
University of Manitoba
Winnipeg, Manitoba

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FACULTY OF GRADUATE STUDIES

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements of the degree

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ABSTRACT

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Dissolved organic carbon (DOC) forms a small yet important part of the carbon cycle. The purpose of this study is to determine if dissolved organic carbon concentrations in Northern Boreal Forest soils vary significantly between different aged forest stands, landscape positions, depths in the soil profile, and with time. Secondary objectives included: i) characterising and quantifying the effect of drainage and forest stand age on surface soil organic carbon content and soil temperatures; ii) examining the influence of soil organic carbon content and soil climate on DOC concentrations; and, iii) estimating DOC fluxes in the two different aged forest stands.

The study area is located in the Northern Boreal Forest between Thompson and Leaf Rapids in north-central Manitoba. In 2001, a small group of collaborating researchers selected seven different aged forest stands (burn sites) between Thompson and Leaf Rapids to represent a forest fire chronosequence developed on clayey glaciolacustrine parent materials. Two of these sites, the 1964 and 1930 burn sites, were selected for detailed study as they represented regenerating and mature forest stands located on clayey glacio-lacustrine parent materials within gently undulating landscapes, and were in relatively close proximity to Thompson with easy access from the highway. Three parallel transects (toposequences) were established at each burn site to provide replication of upper, middle and lower slope positions. Piezometers were installed at multiple depths and were supplemented by suction lysimeters along the central transects in order to permit collection of soil water samples under both saturated and unsaturated conditions.

On average, DOC concentrations were higher on the younger 1964 burn site than the mature 1930 burn site, but near surface DOC concentrations were not significantly different ($p=0.05$) within upper slope positions. Observed DOC concentrations had a positively skewed log-normal distribution, with DOC concentrations and variability decreasing with increasing depth in the soil profile. DOC concentrations decreased from ~20 to 60 mg C L^{-1} in surface organic horizons, to ~ 3 to 4 mg C L^{-1} in mineral horizons at the 244-cm depth, and were positively correlated with % OC content. Peak DOC concentrations occurred in spring, followed by an overall decrease in DOC concentrations until early-fall. From June till September 2003, precipitation DOC fluxes were 1.1 to 1.5 g C m^{-2} and soil surface DOC fluxes were 4.8 to 9.5 g C m^{-2}.

Thickness of surface organic horizons and soil organic carbon stocks were related to drainage, forest stand age, the past history of local fire severity, and the presence of mineral and organic hummocks. Within moderately well drained soils, organic horizon thickness ranged from ~2 cm on recently burnt forest stands to ~17 cm on mature forest stands, and surface soil organic carbon stocks ranged from ~1 to 5 kg C m^{-2}, depending on past fire severity. Organic horizon thickness (~20 to 60 cm) and surface SOC stocks (6 to ~30 kg C m^{-2}) increased in poorly drained soils, but were highly variable.

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    Suzanne Trumbore, Greg Winston

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    Marcy Litvak

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    Ben Bond-Lamberty

FOREWORD

This thesis has been prepared according to the manuscript style as outlined in the University of Manitoba Department of Soil Science thesis preparation guidelines. The Canadian Journal of Soil Science referencing style is used. Publication of various sections of this thesis are planned for the near future in the Canadian Journal of Soil Science.

This thesis forms part of an interdisciplinary study of carbon cycling within a Northern Boreal Forest fire chronosequence near Thompson, Manitoba. Several different aged forest stands developed on clayey glacio-lacustrine parent materials were selected by an international team of researchers. Field observations are presented for the entire forest fire chronosequence, but the primary focus of this thesis is on the 1930 and 1964 burn sites.

Chapter 1 presents a general introduction. Chapter 2 presents a description of the Thompson study area, including information on climate, geology, vegetation, and soil distribution. Chapter 3 presents an overview of DOC related literature. Chapter 4 presents a description of the precipitation, soil moisture, soil temperature, and dissolved organic carbon measurement methodology and results. Chapter 5 presents a summary of soil organic carbon data for the soils at the burn sites. Chapter 6 provides a general discussion and synthesis of material presented in the previous chapters, with Chapter 7 providing a summary and conclusions. The Appendix contains a detailed description of instrument construction and installation methodologies, and additional soil and water analyses, including radiocarbon dating results, particle size analysis, and soil hydraulic properties. Soil, vegetation, and landscape descriptions are provided, and include field and laboratory soils data for the 1930 and 1964 burn sites.

Portions of the soil organic carbon data have been presented in part at various meetings and conferences (Cyr and Veldhuis, 2002a and 2002b) and is supplemented with data from additional soil profiles and laboratory analyses. Sections of the DOC study have been presented at the Manitoba Soil Science Society 2003 annual meeting (Cyr and Veldhuis, 2003), with updates & results presented at the Manitoba Soil Science Society 2004 annual meeting (Cyr et al., 2004).

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LIST OF ABBREVIATIONS

BOREAS	- Boreal Ecosystem Atmosphere study
BOREAS-NSA	- Boreal Ecosystem Atmosphere study, Northern Study Area
DOC	- Dissolved Organic Carbon
DOM	- Dissolved Organic Matter
DON	- Dissolved Organic Nitrogen
DOP	- Dissolved Organic Phosphorus
FIRES-ExB	- FIRe Ecosystem Succession - Experiment Boreal
GHG	- Greenhouse gas
IC	- Inorganic Carbon
NVOC	- Non-Volatile Organic Carbon
OC	- Organic Carbon
OM	- Organic Matter
ppmv	- parts per million by volume
ppbv	- parts per billion by volume
POC	- Particulate Organic Carbon
SOM	- Soil Organic Matter
TC	- Total Carbon
TIC	- Total Inorganic Carbon
TOC	- Total Organic Carbon
VOC	- Volatile Organic Carbon

MEASUREMENT UNITS

Mass	1 Pg	=	1 Gt	=	10^{15} g		
	1 t			=	10^{6} g		
Length	1 m			=	10^{2} cm	=	10^{3} mm
Area	1 ha			=	10^{4} m^{2}		
Volume	1 L			=	10^{3} cm^{3}	=	1 mm x 1 m^{2}
Concentration	1 kg L^{-1}			=	10^{6} mg L^{-1}		
Rate	1 mm yr^{-1}			=	0.1 cm yr^{-1}		
Flux per unit area	1 kg ha^{-1} yr^{-1}			=	10^{-1} g m^{-2} yr^{-1}	=	10^{2} mg m^{-2} yr^{-1}

Prefixes

Peta- (P) = 10^{15}
Tera- (T) = 10^{12}
Giga- (G) = 10^{9}
Mega- (M) = 10^{6}
Kilo- (k) = 10^{3}
Hecto- (h) = 10^{2}
Centi- (c) = 10^{-2}
Milli- (m) = 10^{-3}
Micro- (μ) = 10^{-6}

1. INTRODUCTION

1.1 Background

In an effort to better predict carbon cycling within northern boreal forests, an international team of researchers conducted several research projects near Thompson, Manitoba. Research carried out from 1994 to 1996 in the BOREAS-NSA (BOReal Ecosystem Atmosphere Study, Northern Study Area) indicated that carbon cycling was affected by soil texture, drainage and forest stand age (Sellers et al., 1997). In order to better quantify the effects of forest stand age on the carbon cycle of northern boreal forests, collaborating researchers selected seven different aged forest stands (burn sites) between Thompson and Leaf Rapids in 2001 to represent a forest fire chronosequence developed on clayey glaciolacustrine parent materials. A forest fire occurred in the study area in 2003, permitting the addition of a very recent burn site to the study.

1.2 Objectives

Dissolved organic carbon (DOC) forms a small yet important part of the carbon cycle. The primary objective of this study is to determine if DOC concentrations in northern boreal forest soils vary significantly between different aged forest stands, landscape positions, depths in the soil profile, and with time. Secondary objectives were: i) characterising and quantifying the effect of drainage and forest stand age on surface soil organic carbon content and soil temperatures; and, ii) examining the influence of soil organic carbon content and soil climate (temperature and moisture) on DOC concentrations.

1.2.1 Hypotheses

Dissolved organic carbon (DOC) concentrations:

1) vary significantly between different aged forest stands, landscape positions, and depths within the soil profile;
2) vary significantly with time; and
3) are dependent on soil organic carbon content and soil temperature.

Organic horizon thickness and surface soil organic carbon stocks:

1) are significantly different between different aged forest stands and landscape positions;
2) are significantly greater within older forest stands;
3) increases from upper to lower slope landscape positions;

1.3 Location and Description of Study Sites

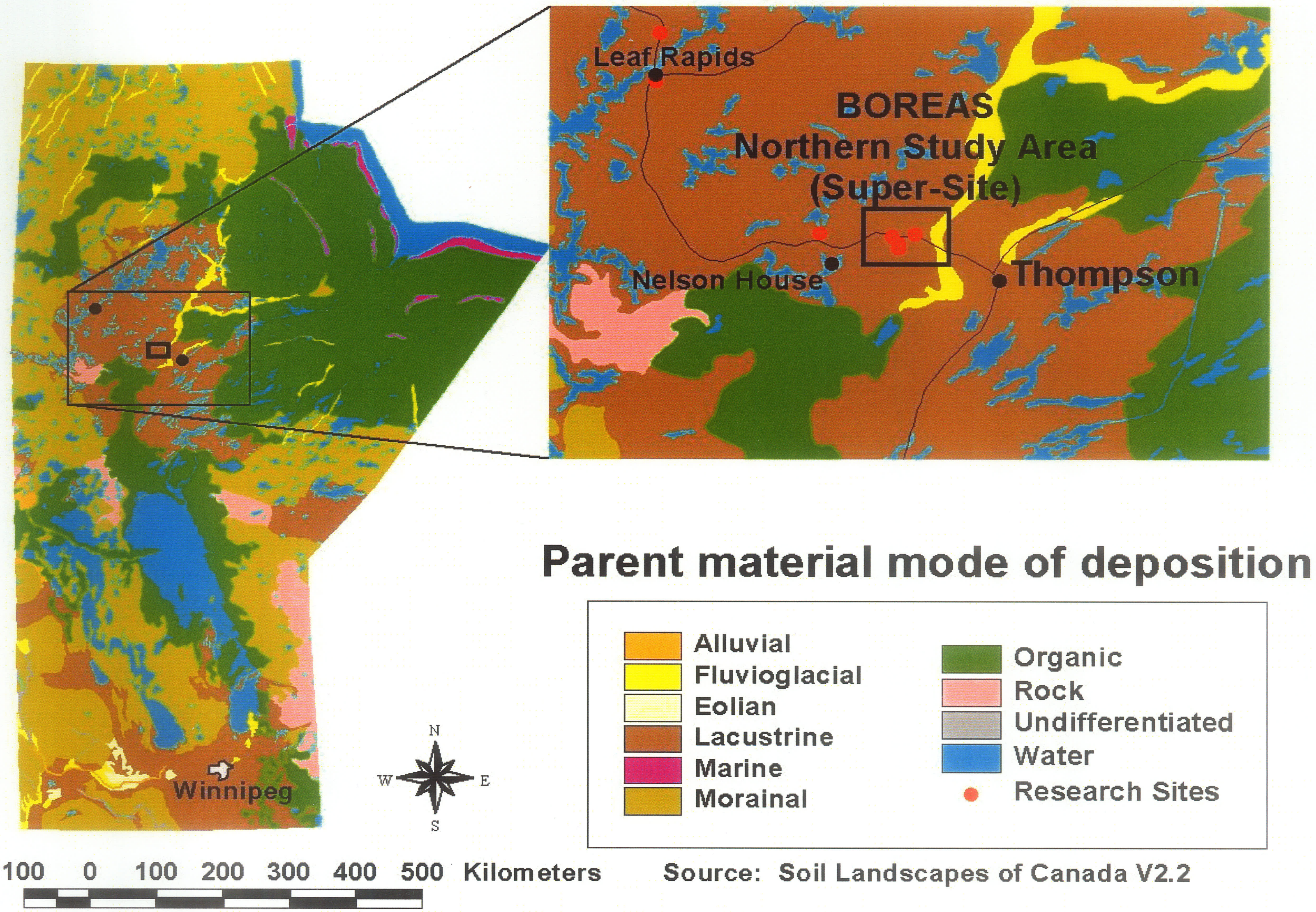
The study area is located in the northern boreal forest between Thompson and Leaf Rapids in north-central Manitoba. The 1964 and 1930 burn sites were selected from among different aged forests stands to represent young and mature forest stands developed on clayey glaciolacustrine parent materials within gently undulating landscapes. Three parallel transects (toposequences) were established in the 1964 and 1930 burn sites to provide replication of upper, middle and lower slope positions. Piezometers and thermistors were permanently installed at multiple depths within each sampling location and were supplemented by suction lysimeters and tensiometers installed along the central transects during the 2002 and 2003 field seasons.

2. DESCRIPTION OF THE STUDY AREA

The study area is located within the Churchill River Upland ecoregion of the Boreal Shield ecozone (Table 2.1). The 1989 burn site is located along the Footprint river just past the Nelson House Indian Reserve, approximately 70 km west of Thompson, whereas, the 1981, 1964, 1930 and 1870 burn sites are located between Thompson and the Nelson House Indian Reserve, and are within the boundaries of the BOREAS Northern Study Area (Figure 2.1). The 1870 burn site is also known as the Old Black Spruce (OBS) site. The 1998 and 1995 burn sites are located in the South Indian Lake ecodistrict (349) and the Leaf Rapids geologic domain near the town of Leaf Rapids, 213 km northwest of Thompson. The remaining burn sites are in the Three Point Lake ecodistrict (356) and the Kisseynew geologic domain. An ecological description of the South Indian Lake and Three Point Lake ecodistricts is provided by Smith et al. (1998) and bedrock geology maps and descriptions are provided by Manitoba Energy and Mines (1986a, 1986b, and 1989). Information bulletins produced by the Land Resource Group of Agriculture and Agri-Food Canada (Land Resource Group - Manitoba, 2002 and 2003) provide biophysical descriptions for the study area, including thematic and interpretive maps produced from digital soils and terrain data derived from ecological land classification and soil survey data collected at scales of 1:50,000 to 1:250,000 as part of the Biophysical Land Inventory of the Churchill - Nelson Rivers Study Area (Beke et al., 1973), the Northern Resource Information Program (NRIP) in the 1970's, and from more recent studies and new photo-interpretation.

Surficial deposits in the Thompson study area were laid down about 8700 to 7700 years ago when Glacial Lake Agassiz extended into north-central Manitoba. Parent materials consist primarily of varved clayey and silty glacio-lacustrine blankets and veneers overlying Precambrian bedrock. The underlying bedrock gives the landscape its undulating to hummocky appearance. Drainage is slow and impeded due to the low hydraulic conductivity of the fine textured parent materials and the discontinuous nature of the relatively young drainage network. Numerous lakes, bogs and fens have formed in lowlands and depressions.

Mature northern boreal forests consist primarily of black spruce (*Picea Mariana*) with a feathermoss-sphagnum moss groundcover on clay textured soils, and jack pine (*Pinus Banksiana*) on sandy textured materials. The cold cryoboreal soil climate and humid to aquic moisture regime is conducive to the accumulation of organic deposits of variable thicknesses, and to the development of discontinuous permafrost in peatlands and, to a lesser extent, on clayey uplands under mature forest. Surface organic materials consist of duff (LFH) layers on upland sites, and Sphagnum and/or forest peat on lower slopes, veneer bogs, and peat plateau bogs. Sedge and brown moss peat usually occur in depressional fens and under peat plateau bogs. Dominant soils consist of Gray Luvisols in well to imperfectly drained upper to mid slope positions, with peaty Luvic Gleysols, Terric Fibrisols, and Organic Cryosols occurring in poorly drained landscape positions.



Source: Soil Landscapes of Canada V2.2

Figure 2.1 Location of forest fire chronosequence (burn sites) between Thompson and Leaf Rapids, Manitoba.

Table 2.1 Ecology, geology, soils and topography of the seven different age burn sites.

Year of burn	**1998**	**1995**	**1989**	**1981**	**~1964**	**1930**	**~1870**
Connotative Name	North of Leaf Rapids	Leaf Rapids	Footprint River	South of OBS	2 ditches	SiC Mound	Old Black Spruce (OBS)
Age since burn (2002 reference year)	4 years	7 years	13 years	21 years	~38 years	72 years	~132 years
Coordinates							
Latitude & Longitude (WGS84)	56.63599 -99.94832	56.46049 -99.97442	55.91689 -98.96432	55.86426 -98.48428	55.91168 -98.38207	55.90614 -98.52463	55.87937 -98.48375
NTS map sheet	Uhlman Lake (64-B)		Nelson House (63-O)				
	64-B12	64-B05	63-O15	63-O16	63-O16	63-O15	63-O16
Ecological stratification (Smith et al., 1998)							
Ecozone	Boreal Shield (6)						
Ecoregion	Churchill River Upland (88)						
Ecodistrict	Southern Indian Lake (349)		Three Point Lake (356)				
Soils Landscapes of Canada (SLC), version 1.0 (Canada Soil Inventory, 1989)							
Map Polygon #	336	262	235				
Dominant soils and landscapes	Clayey Gray Luvisols developed on lacustrine parent materials with a hummocky surface form and 10-15% slopes						
Bedrock Geology (Manitoba Energy and Mines, 1986a, 1986b, and 1989)							
Structural Province	Churchill Structural Province						
Geologic Domain	Leaf Rapids		Kisseynew				
This study							
Dominant Soil Series Code	WBW	WBW WRD	WBW	WBW	WBW	SWK	SWK
Dominant Textures	C	C-SiC L-SiCL	C	C	C	C/SiC	C and C/SiC
Dominant Slopes	c-e (2-15%)	c-e (2-15%)	c-e (2-15%)	a-b (0-2%)	a-c (0-10%)	a-c (0-5%)	a-c (0-5%)

WBW: Wabowden series, Orthic Gray Luvisol with a columnar or coarse-medium blocky Bt horizon.
WRD: Warren Landing series, shallow Orthic Gray Luvisol over bedrock, with a columnar or coarse-medium blocky Bt horizon.
SWK: Sipewesk series, Orthic Gray Luvisol with a granular or fine-medium subangular blocky Bt horizon.
Textures: C = Clay; L = Loam; SiC = Silty Clay; SiCL = Silty Clay Loam.

2.1.1 Climate

The climate in the area is characterized by long, very cold, snowy winters and short, cool to warm summers with approximately one third of annual precipitation occurring as snow. From 1971 to 2000, mean annual precipitation at the Thompson airport was 517.4 mm and mean annual air temperature was −3.2°C (Table 2.2 and 2.3), or 535.6 mm and −3.4°C from 1961 to 1990 (Environment Canada, 1998 and 2004). Soils near Thompson, Manitoba are characterized as having a cold cryoboreal to very cold subarctic soil climate and a humid to aquic moisture regime (Clayton, et al. 1977). This is conducive to the accumulation of organic deposits of variable thickness and to the distribution of discontinuous permafrost in peatlands and, to a lesser extent, in clayey uplands under mature forest (Mills et al., 1987; Veldhuis et al., 2002).

In cold climates, seasonal temperature changes result in alternate freezing and thawing of soils and may cause cryoturbation or mixing of soil due to differential freezing of soil layers and the effects of frost heave. This zone of alternate freezing and thawing is known as the active layer. When mean annual temperatures are near or below zero degrees Celsius, soils may remain frozen for prolonged periods of time. A condition known as permafrost exists when frozen conditions persist throughout the year and from year to year in some part of the soil profile (Clayton et al., 1977).

The study area is within the southern portion of the discontinuous permafrost zone, where permafrost first develops in organic soils and is sporadic within fine textured soils. Permafrost and patterned ground become more widespread in the northern half of the discontinuous permafrost zone (Tarnocai, 1973).

Table 2.2 Thompson temperature climate normals (1971-2000) (Environment Canada, 2004).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)													
Daily Average (°C)	-24.9	-20.4	-12.9	-2.2	6.5	12.6	15.8	14.1	7.2	0.0	-12.0	-22.0	-3.2
Standard Deviation	3.6	3.9	3.2	2.8	2.1	1.6	1.4	1.9	1.6	2.0	3.7	4.0	1.1
Degree Days													
Above 5 ˚C	0.0	0.0	0.2	12.3	95.3	230.2	334.9	282.3	90.7	12.8	0.2	0.0	1058.9
Soil Temperature (a.m. observation) (°C)													
at 5-cm depth (°C)	-4.5	-4.7	-3.9	-1.1	3.8	9.9	14.0	12.8	7.5	2.4	ND	-3.4	ND
at 10-cm depth (°C)	-3.7	-4.0	-3.3	-0.8	ND	ND	14.5	13.6	8.1	2.9	ND	-2.7	ND
at 20-cm depth (°C)	-3.4	-3.9	-3.3	-1.1	3.4	9.7	14.3	13.8	8.8	3.4	-0.1	-2.2	3.3
at 50-cm depth (°C)	-1.7	-2.4	-2.3	-1.2	1.6	7.8	12.8	13.3	9.8	4.8	1.4	-0.4	3.6
at 100-cm depth (°C)	0.2	-0.6	-1.0	-1.0	-0.7	2.1	7.0	9.2	8.6	5.8	2.9	1.2	2.8
at 150-cm depth (°C)	1.5	0.8	0.4	0.2	-0.0	1.5	5.4	8.0	8.4	6.6	4.2	2.5	3.3
at 300-cm depth (°C)	2.9	2.3	1.9	1.4	1.0	0.9	1.7	2.9	4.2	4.9	4.5	3.6	2.7
Soil Temperature (p.m. observation) (˚C)													
at 5-cm depth (°C)	-4.5	-4.7	-3.9	-0.3	7.2	13.7	17.5	16.1	9.9	3.2	ND	-3.4	ND
at 10-cm depth (°C)	-3.7	-4.0	-3.3	-0.4	ND	ND	16.6	15.6	9.5	3.4	ND	-2.7	ND
at 20-cm depth (°C)	-3.5	-3.8	-3.3	-1.0	4.0	10.6	15.1	14.6	9.2	3.5	-0.1	-2.2	3.6

Table 2.3 Thompson precipitation climate normals (1971-2000) (Environment Canada, 2004).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
						Precipitation (mm & cm)							
Rainfall (mm)	0.1	0.2	0.8	6.2	33.0	67.9	86.1	73.7	58.5	19.9	1.6	0.2	348.2
Snowfall (cm)	21.1	18.0	21.6	20.8	12.0	1.4	0.0	0.1	3.9	22.1	35.0	30.2	186.2
Precipitation (mm)	18.2	15.9	20.6	26.0	44.4	69.4	86.1	73.9	62.4	41.4	32.8	26.3	517.4
						Snow Depth (cm)							
Average depth (cm)	41	45	42	15	1	0	0	0	0	2	15	30	16
Median depth (cm)	40	45	42	14	0	0	0	0	0	0	13	31	15

2.1.2 Surficial Geology

The study area is located in the northern portion of the Glacial Lake Agassiz basin, west of the Settee moraine known locally as Spirit Hill. The Settee moraine represents the divide between the Keewatin ice sheet to the west and the Hudson ice sheet to the east (Klassen, 1983). Surficial geology in the study area consists predominantly of varved clayey to silty glaciolacustrine blankets (2-15 m thick) and veneers (1-2 m thick) underlain by morainal till and bedrock (Klassen, 1976 and 1986), which give the landscape its undulating to hummocky appearance. Local areas of granitic bedrock outcrops occur in the western part of the study area near Leaf Rapids. Spirit Hill is the most prominent geologic feature within this area and consists of sandy materials of morainal and glaciofluvial origin.

At its maximum extent, Glacial Lake Agassiz occupied approximately 46 Mha, although the lake never occupied the whole of this area at any one time (Bird, 1972). The formation of Glacial Lake Agassiz started approximately 12,000 to 13,000 years ago during the initial melting and retreat of the Wisconsin ice sheet. Klassen's (1983, 1986) reconstruction of the chronology of ice retreat from the northern-central Manitoba indicates that the Thompson area was still covered by glaciers about 9,000 years ago. By 8,800 to 8,700 BP, Glacial Lake Agassiz basin west of the Settee moraine was covered by water 150 to 200 m deep, resulting in the deposition of glaciolacustrine sediments. The area east of the Settee moraine was covered by stagnant ice. Water levels dropped as the ice sheets retreated to the north, and the basin west of the Settee moraine was no longer submerged by 7,700 BP. Final drainage of Lake Agassiz into the Tyrrell Sea (current day Hudson Bay) occurred about 7,500 BP.

2.1.3 Soils, Drainage and Topography

The 1:10 million scale Soil Landscapes of Canada map for Manitoba (Version 1.0) identifies the dominant soils in the Thompson study area as clayey Gray Luvisols developed on lacustrine parent materials with a hummocky surface form and 10-15% slopes (Canada Soil Inventory, 1989). Digital soils maps developed for the BOREAS-NSA identify the dominant soils as moderately well to imperfectly drained Gray Luvisols in upland sites, and peaty Luvic Gleysols, Terric Mesisols, Mesisols, Fibrisols, and Organic Cryosols in lowland to depressional positions (Veldhuis, 1995; Figure 2.2 and Table 2.4). Thickness of organic horizons in lower slope positions can vary greatly within relatively short distances (Johnston et al., 1963) as Gleysols, peaty Gleysols and Terric Fibrisols are found in close association (Veldhuis and Dutchak, 1978; Velduis, 1995). Low permeability of clay materials, the presence of near surface bedrock, the relatively young age of the topographically complex landscapes, and climatic conditions have resulted in the development of numerous lakes, bogs and fens in lowlands and depressions linked by a discontinuous drainage network (Figures 2.2-2.4).

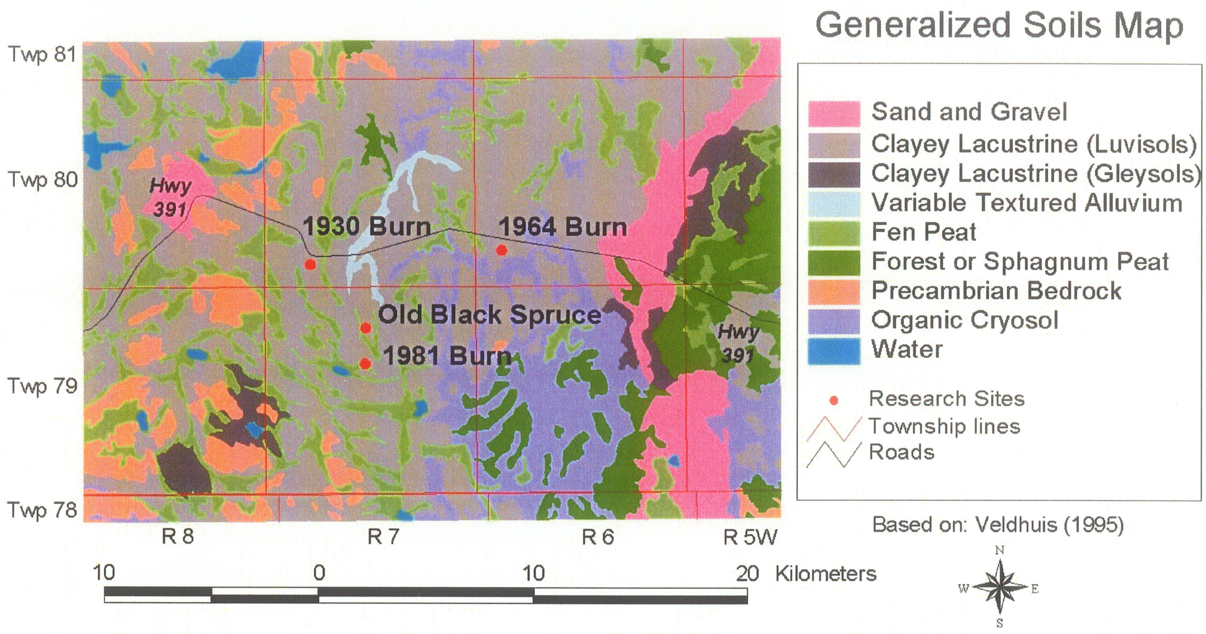


Figure 2.2 Generalized reconnaissance soils map for the BOREAS-NSA (based on Veldhuis, 1995). Location of forest fire chronosequence (burn) sites near Thompson, Manitoba, are shown.

Table 2.4 Percent area of each soil type identified on the generalized reconnaissance soils map. (Based on Veldhuis, 1995)

Generalized Soils	Area (ha)	Area (%)
Sand and Gravel	3476	5%
Sand and Gravel (Gleysols)	36	0%
Sandy Lacustrine	2029	3%
Sandy Lacustrine (Gleysols)	68	0%
Clayey Lacustrine (Luvisols)	23323	33%
Clayey Lacustrine (Gleysols)	2069	3%
Variable textured Alluvium (Regosols)	313	0%
Shallow Organic Fen Peat	5243	7%
Deep Organic Fen Peat	6856	10%
Shallow Organic Forest or Sphagnum Peat	11553	16%
Deep Organic Forest or Sphagnum Peat	699	1%
Permafrost, Organic	10577	15%
Precambrian Bedrock	4807	7%
Water	516	1%
Total	71565	100%

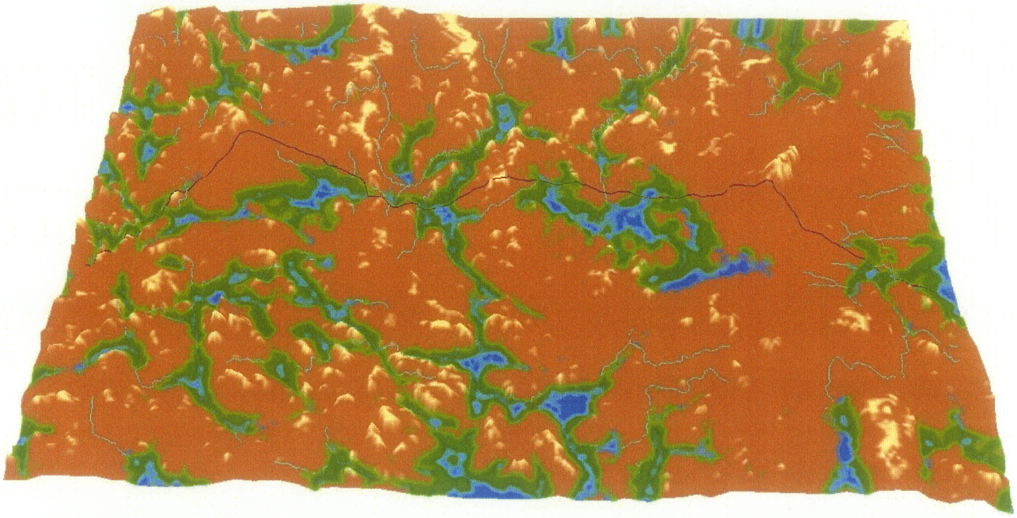


Figure 2.3 Landform classification for BOREAS-NSA draped over DEM data. Based on DEM data (Wang et al., 2000) classified using LSM software (MacMillan and Pettapiece, 1997).

Landforms and Relief

🟨 Upland
🟫 Midslope
🟩 Toeslope
🟦 Depression
~ River

DEM data (Wang et al, 2000) classified with LSM software (MacMillan and Pettapiece, 1997).

Drainage Class

🟩 Rapid
🟩 Well
🟨 Imperfect
🟧 Poor
🟥 Very Poor
▨ Unclassified
🟪 Marsh
🟦 Water

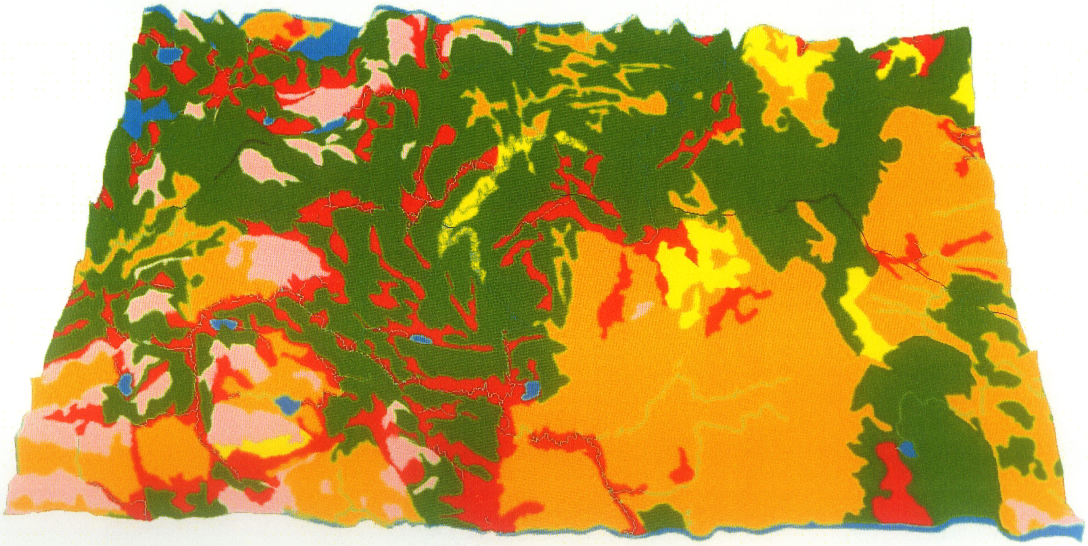


Figure 2.4 BOREAS-NSA soil drainage classification draped over DEM data. Based on soils data from Veldhuis (1995) and DEM data from Wang et al. (2000).

2.1.4 Forest Fire History and Vegetation

Approximately 30 % of the area has been burned in the 30 to 35 years preceding 1992 (Steyaert et al., 1997). Fire frequency is expected to increase as a result of climate change (Stocks et al., 1998), and this may already be occurring. Historical fire data from Manitoba Conservation (2003a) suggests that fire frequency is increasing (Figure 2.5), but limited fire history data exists for Manitoba prior to 1980 (Steyaert et al., 1997). From 1980 to 2002, on average 0.35 x 10^6 ha yr^{-1} were burned by lightning (270 fires yr^{-1}, 1300 ha per fire) and the three years with the greatest area burned by lightning were 1989, 1994 and 1995 (2.9, 1.4, and 0.8 Mha respectively).

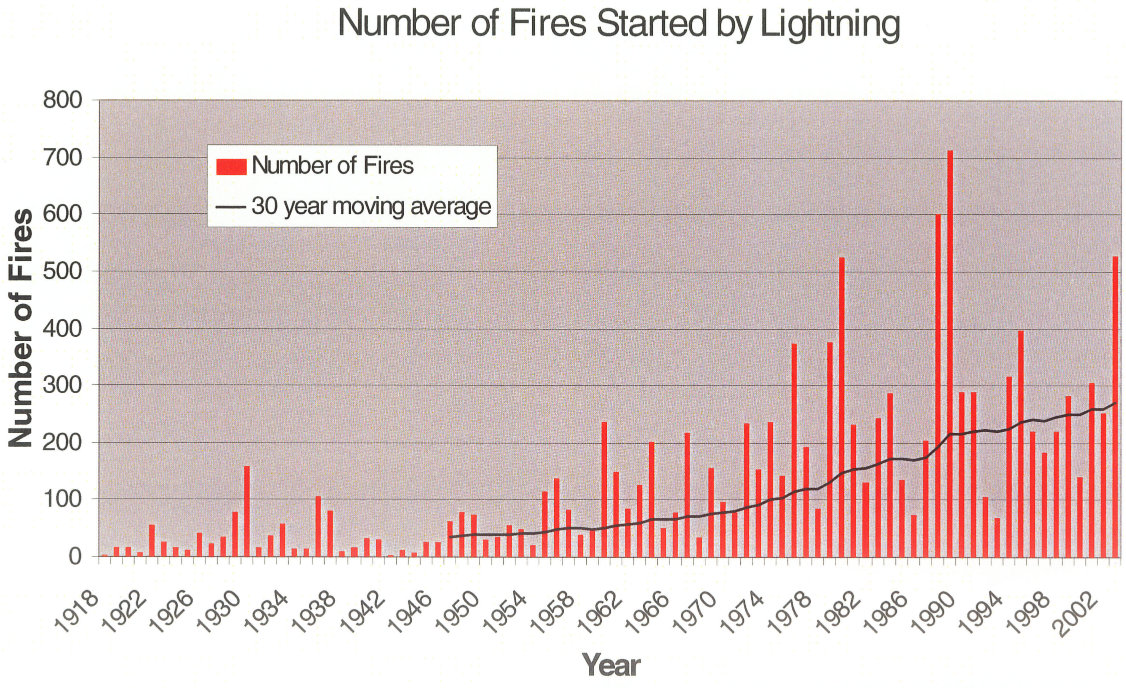


Figure 2.5 Forest fires in Manitoba between 1918 and 2003 caused by lightning. Based on data obtained from Manitoba Conservation (2003a).

Ahlgren (1974) cautions against the rigid adoption and over-application of popular ideas of either fire exclusion to prevent damaging or dangerous fires or the use of fire as a cure-all for forest and grassland regeneration as not all ecological niches within an environment are fire-adapted. Pinus banksiana-Picea mariana ecosystems of the north central United States are adapted to low frequency fire periodicity of only once per tree species rotation (Ahlgren, 1974). Mature trees may be destroyed by intense fires, but some fire adapted species, such as jack pine, require the heat of fire to release seeds from their cones. Aspen quickly regenerates after disturbances such as fire or cutting (Clayton et al. 1977). Fire adapted species may have more flammable litter and needles than non fire-adapted species and in the absence of fire, non fire-adapted species may invade and replace the fire-adapted species (Ahlgren, 1974). Early successional plant species are typically rapid growing and short-lived with high reproductive rates, while late successional plant species are typically slower growing and longer-lived species (Botkin and Keller, 1995). "The factors involved in fire ecology must be identified and carefully considered for each region and species involved" (Ahlgren, 1974). "In the words of Holloway (1954) ... 'For a single forest, the complex actions and interactions of all plants, soil, animals, microorganisms, and man together with all factors of climate, topography, lithology, and history must be studies together and in synthesis.' " (as referenced by Ahlgren, 1974).

Vegetation species, spacing, canopy height and density in northern boreal forests vary according to forest stand age (Bond-Lamberty, et al., 2002a and 2002b), soil fertility, texture, temperature and moisture (Sellers et al., 1997). As the burnt area recovers, ecosystem succession occurs and ecosystem species composition changes over time (Table 2.5).

Table 2.5 Vegetation distribution along a northern boreal forest fire chronosequence (Bond-Lamberty, et al., 2002a and 2002b).

	Overstory	Understory	Ground Cover
Youngest stands (1989 and 1995 burn sites)	Seedlings - Bog birch (*Betula glandulosa*) - paper birch (*Betula papyrifera* var. *papyrifera*) - willow spp. (*Salix* spp.)	- Fireweed (*Epilobium angustifolium* L.) - blueberry (*Vaccinium myrtilloides* Michx.) - Horsetail (*Equisetum* spp.)	
Medium aged stands (1964 and 1981 burn sites)	- Black Spruce saplings <u>Dry stands</u> - Jack pine (*Pinus Banksiana*) - Aspen (*Populus tremuloides*) <u>Wet stands</u> - Tamarack (*Larix lariciana*) - Birch	- Hazel (*Corylus cornuta* Marsh.) - Willow - Labrador tea - serviceberry (*Amerlanchier alnifola* (Nutt.) Nutt.) - Bog birch (*Betula glandulosa*)	<u>Dry stands</u> - bearberry (*Arctostaphylos uva-ursi* (L.) Sprenge.) - reindeer lichen (*Cladina* spp.) - feathermoss <u>Wet stands</u> - sphagnum - Labrador tea
Oldest stands (1870 and 1930 burn sites)	- Black Spruce (*Picea Mariana*)	- Labrador tea (*Ledum groenlandicum* Oeder) - wild rose (*Rosa* spp.) - green alder (*Alnus Crispa* (Ait.) Pursh)	<u>Dry stands</u> - Feathermoss (*Pleurozium* or *Hylocomium*) <u>Wet stands</u> - Sphagnum
Others species mentioned		- Liliaceae Spp.	- Bunchberry (*Cornus canadensis*)

Jack pine (*Pinus Banksiana*) and trembling aspen (*Populus tremuloides*) are the dominant tree species during the early stages of forest regeneration after wildfire. Mature northern boreal forests consist predominantly of black spruce (*Picea Mariana*) with a feathermoss groundcover on clayey uplands, and stunted black spruce and sphagnum moss in poorly drained lower slope positions. Jack pine (*Pinus Banksiana*) and lichen dominate on coarser texture materials. Understory vegetation consist of willow (*Salix* spp.), alder (*Alnus* spp.), low shrubs and herbs. Feathermoss (*Pleurozium* and *Hylocomium*) dominates on more productive clayey upland sites, whereas Sphagnum moss, brown moss and sedges occur within lower slope bogs and depressional fens.

Forest fires reduce the canopy and forest floor cover of a stand, permitting a greater proportion of incoming solar radiation and precipitation to reach the soil surface. Differences in soil moisture, temperature, organic carbon stocks, and decomposition rates are therefore expected to exist between different aged forest stands developed on similar parent materials and in similar landscape positions. France et al. (2000) determined that dissolved organic carbon (DOC) concentrations in Canadian boreal lakes increased in relation to the severity of forest disturbances occurring within the past 4-13 years, with clearcut or burnt watersheds averaging 2 to 3 mg C L^{-1} more DOC than undisturbed reference catchments after removing the landscape effect of catchment drainage ratio (catchment area / lake area).

It is important to note that forest fires and the production of DOC are neither 'good' nor 'bad', they are simply natural ecosystem processes that must be studied and understood so that the effects of human and natural perturbations can be predicted.

3. LITERATURE REVIEW

3.1 Carbon Fractions in Soil and Water

Carbon compounds transported by water in precipitation, soil water and river water can be separated into various components (Thurman, 1985; Clesceri et al., 1998). Total Carbon (TC) represents the sum of both the inorganic and organic carbon (IC and OC). Both IC and OC can be separated into volatile carbon compounds and non-volatile carbon compounds, the latter consisting of particulate and dissolved fractions (Figure 3.1).

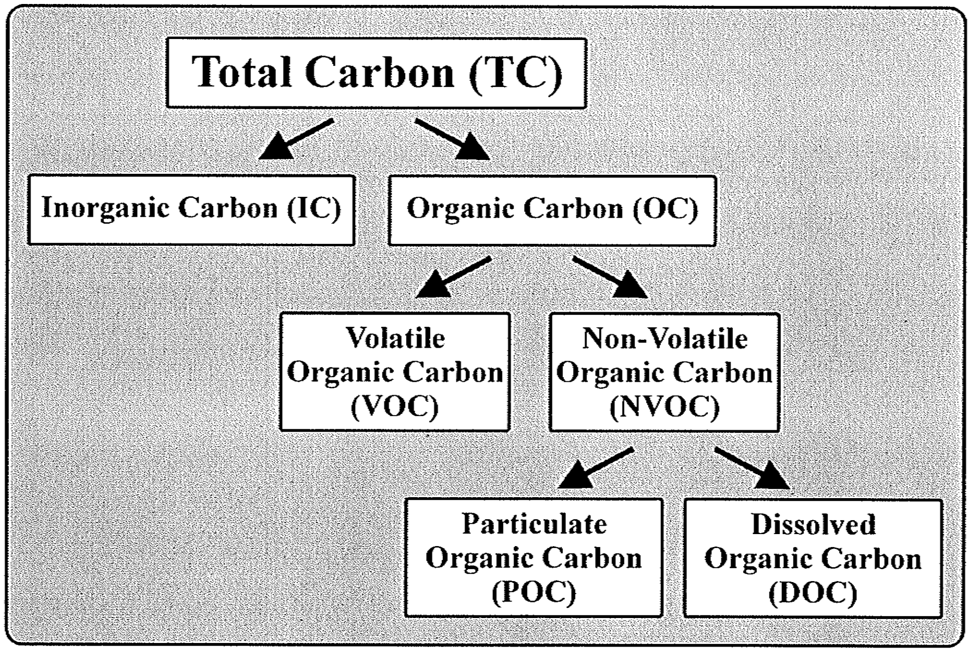


Figure 3.1 Carbon fractions in soil water.

3.1.1 Inorganic Carbon

Non-volatile inorganic carbon (NVIC) includes particulate inorganic carbon (PIC) which may be in the form of suspended carbonate minerals (e.g. calcite and dolomite), and dissolved inorganic carbon (DIC) which is mostly found in the form of bicarbonate ions (HCO_3^-) (Meybeck, 1993). Carbon dioxide (CO_2) is a volatile inorganic carbon (VIC), as it can be removed from water by gas purging.

3.1.2 Organic Carbon

3.1.2.1 Volatile and Non-Volatile Organic Carbon

Volatile organic carbon (VOC) is composed of light hydrocarbons such as methane (CH_4), but concentrations are usually very small (<0.05 mg C L^{-1}). Non-volatile organic carbon (NVOC) is composed of particulate organic carbon (POC) and dissolved organic carbon (DOC), where DOC is defined as the portion of non-volatile organic carbon which passes through a filter with 0.45 µm diameter pores.

3.1.2.2 Particulate Organic Carbon

Particulate organic carbon (POC) is defined as organic carbon retained on a filter with 0.45 µm diameter pores. POC can be further classified into coarse POC (> 1 mm) and fine POC (1 mm to 0.45 µm). POC includes carbon contained within discrete plant and animal organic matter, and organic coatings adsorbed onto sand, silt and clay (Thurman, 1985; McCracken et al., 2002). Density separation techniques can be used to separate POC within particulate organic matter from DOC adsorbed to mineral soil particles.

3.1.2.3 Dissolved Organic Carbon

Dissolved organic carbon (DOC) is defined as the portion of non-volatile organic carbon which passes through a filter with 0.45 µm diameter pores. However, most of the DOC is smaller than 1 nm (Thurman, 1985).

3.1.2.4 Total Organic Carbon

Total organic carbon (TOC) is defined as the sum of POC + DOC + VOC. According to Thurman (1985), TOC is not as useful a measurement as the individual carbon fractions, since DOC is chemically more reactive than POC. Furthermore, POC increases dramatically with increasing river discharge, therefore, measurements of TOC reflect changes in POC more than DOC.

3.2 Carbon Fractionation Techniques

3.2.1.1 Organic Matter Versus Organic Carbon

Organic matter (OM) contains carbon, nitrogen, phosphorus, potassium, sulphur, hydrogen, oxygen, and other elements. The terms organic matter (OM) and organic carbon (OC) are often used interchangeably, but OM refers to the organic compounds, whereas OC only refers to the carbon content of these organic compounds. The terms particulate and dissolved organic matter (POM and DOM) are used to refer to dissolved organic compounds in general, and POC and DOC are used to refer to the measured carbon contents.

3.2.1.2 Filtration of POM and DOM

Physical filtration separates inorganic and organic materials into particulate (≥ 0.45 μm) and dissolved (<0.45 μm) fractions. A variety of filter types and pore sizes are used to separate particulate and dissolved fractions, making it difficult to compare results quantitatively (Kalbitz et al., 2000). Silver filters (0.45 to 0.1 μm) are slow and expensive compared to glass-fibre (GF) filters (2.0 to 0.5 μm) (Thurman, 1985). Thurman (1985) states that silver filters prevent bacterial growth by releasing 50 to 100 μg silver L^{-1}, but he also states that only viruses and ultra-small bacteria can pass through a 0.45 μm filter. Glass fibre

(GF) filter paper is often used as it is low cost and is neither a carbon source, nor should it significantly adsorb organic compounds. Whatman GF/C filter paper with 1.2 μm diameter pores has been used for previous DOC research within the Thompson study area (Moore and Newcomer, 1999; Moore, 2003).

3.2.1.3 Measurement of DOC

After filtration of the water sample to remove POC and PIC, acidification to a pH 2 or lower converts DIC fractions to CO_2, a VOC. VOC and VIC are then purged from the aqueous solutions by gas stripping under controlled laboratory conditions. Oxidation converts remaining DOC fractions to CO_2, which is then measured by infrared spectrometry or colorimetric techniques. Thus, the order and combination of physical and chemical fractionation techniques used determine the measured carbon fraction.

3.2.1.4 Fractionation of DOM

Evans et al. (2001) describe dissolved organic matter (DOM) as "a complex mixture of organic compounds, ranging from simple acids and sugars to complex humic substances". "Most of what is collectively termed 'dissolved organic matter' in soils is complex molecules of high molecular weight, namely, humic substances. Only small portions of DOM, mostly low molecular weight substances such as organic acids, sugars and amino acids can be identified chemically (Herbert and Bertsch, 1995). Similar to soil organic matter, a general chemical definition of DOM is impossible." (Kalbitz et al., 2000). A combination of physical and chemical fractionation techniques can be used to partition organic matter into various fractions based on solubility, acidity, molecular size, and sorption chromatography characteristics. DOM can be classified into hydrophilic and hydrophobic constituents, and as acids, bases or neutrals (Evans et al., 2001). DOM fractionation techniques are discussed in further detail by Leenheer (1981), Thurman (1985), and Herbert and Bertsch (1995).

3.3 Roles of DOC

Although rarely discussed in soil genesis textbooks, dissolved organic matter (DOM) “has a major role to play in soil formation (Dawson et al., 1978; Petersen 1976), mineral weathering (Raulund-Rasmussen et al., 1998), and pollutant transport (Kalbitz et al., 1997; Temminghoff et al., 1997; Marchner, 1999)” (Kalbitz et al., 2000). Decomposition of organic matter contributes to soil formation via accumulation of particulate and dissolved organic matter (POM and DOM) in soils (melanization), mineral weathering via production of carbonic and dissolved organic acids, podzolization (McDowell and Wood, 1984), and chelation of heavy metals via absorption of heavy metals to suspended or soluble organic compounds capable of being transported by water.

There are numerous ecological roles of DOM in freshwater ecosystems, which include the following (Shindler and Curtis, 1997; France et al., 2000; and Quinby, 2000): DOM affects the acid-base chemistry and the cycling of metals (copper, mercury, aluminum); flocculates with suspended sediment, increasing sedimentation rates; is a source of energy and nutrients to the microbial food chain; protects aquatic organisms by attenuating harmful UV-B radiation; restricts the depth of the euphotic zone; and stabilizes the depth of the thermocline in lakes.

3.4 DOC Distribution and Processes

3.4.1 Terrestrial DOC Transport to Surface Waters

Particulate and dissolved organic carbon from terrestrial ecosystems is transported by surface and subsurface flow into rivers, freshwater lakes and, ultimately, into coastal waters and the deep ocean. Terrestrial processes have therefore a significant impact on the measured DOC concentrations and fluxes within downstream components of the hydrologic cycle. Terrestrial, atmospheric, and within-stream processes all contribute to the hydrologic fluxes of DOC to the ocean, and the role of DOC within the carbon cycle.

Opsahl and Benner (1997) detected lignin (a DOM source found only in terrestrial vegetation) in Pacific and Atlantic ocean water, with concentrations 2.6 times higher in the Atlantic, consistent with greater riverine discharge to the Atlantic. Raymond and Bauer (2001) detected young (^{14}C-enriched) biologically labile terrestrial DOC, old (^{14}C-depleted) biologically refractory terrestrial DOC, and predominantly old terrestrial POC in river water discharged to the western North Atlantic. Terrestrial black carbon within marine sediments and the deep ocean is derived from forest fire ash, geologic (radiocabon dead) graphitic rocks, and industrial burning of fossil fuels (Schmidt, 2004). Global riverine DOC fluxes to the oceans have been estimated as 199 x 10^{12} g C yr^{-1} by Meybeck (1993).

3.4.1.1 DOC Concentrations and Fluxes

DOC concentrations range from 6 to 400 mg C L^{-1} in bogs, 2 to 30 mg C L^{-1} in mineral soils, and 0.2 to 15 mg C L^{-1} in groundwater (Thurman, 1985). Groundwater concentrations are log-normally distributed with a median of 0.7 mg C L^{-1} (Leenheer et al., 1974, as referenced by Thurman, 1985). Most DOC concentrations in groundwater are below 2 mg L^{-1}, and increase in oil-shales (2 to 5 mg L^{-1}), coal deposits (5 to 10 mg L^{-1}), and in petroleum and oil field brines (as much as 1000 to 40000 mg L^{-1}) (Thurman, 1985).

Within the Thompson study area, Dalva and Moore (1991) reported that DOC concentrations increase from 2 to 3 mg L^{-1} in precipitation to 10 to 50 mg L^{-1} in water passing through forest canopies and organic soil horizons. Moore and Newcomer (1999) measured dissolved organic carbon in water from precipitation, throughfall, stem flow, soil seepage, ponds and rivers within the BOREAS Northern-Study Area and results were recently published by Moore (2003) (Figure 3.2). However, the reported DOC concentrations for the clay subsoil actually represent shallow seepage water "transmitted across the organic-mineral interface of the clayey soil", and not through deeper parent materials.

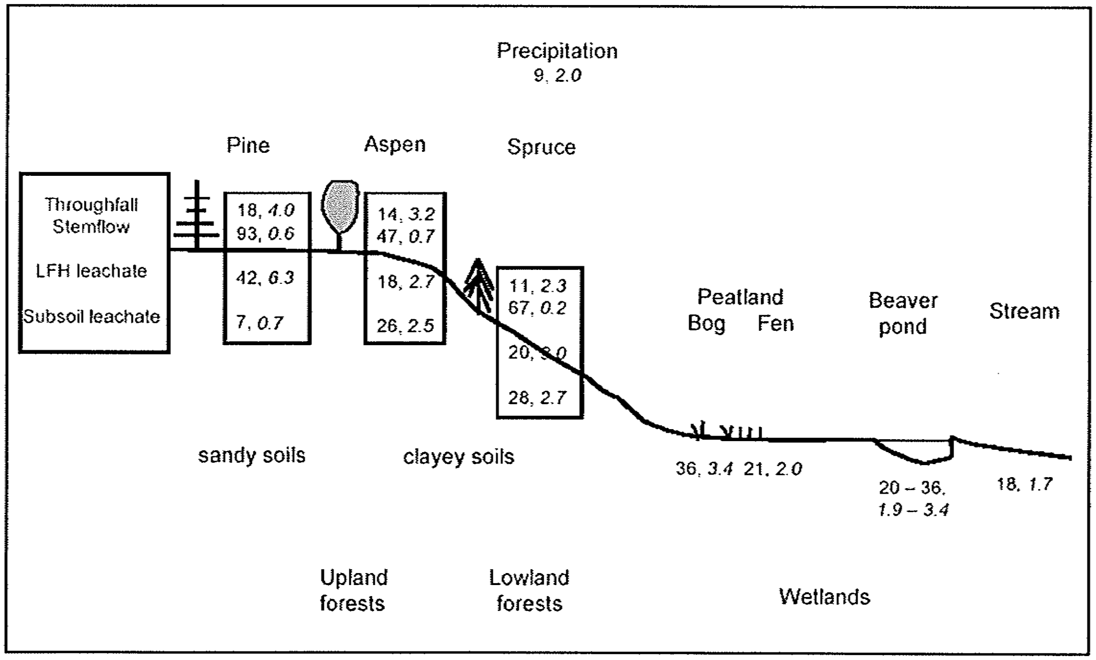


Figure 3.2 Concentration (mg L^{-1}) and flux (g m^{-2}) of DOC in northern boreal landscapes, mid-May to mid-September 1994. (Moore, 2003; reproduced with permission).

Shallow preferential flow paths are important to storm runoff during large storm events, but deep flow paths are important to producing stream base-flow (e.g. Mulholland et al., 1990). Higher DOC concentrations are found in shallow subsurface flow (< 2.5 m deep) than in deeper subsurface flow, and large storm events release significant quantities of hydrophobic DOC during perched water table conditions (Jardine et al., 1990; and Mulholland et al., 1990).

DOC exports of 1.6 g C m^{-2} yr^{-1} were measured from a subarctic catchment with discontinuous permafrost (Granger Basin, Yukon), with 69% of this occurring during the spring snow-melt period, indicating the importance of spring-thaw events on DOC fluxes (Carrey, 2003). Most of the riverine DOC was mobilized from near-surface organic soil and riverine DOC increased rapidly on the rising limb of stream hydrographs indicating the importance of surface organic horizons and shallow preferential flow paths on terrestrial DOC fluxes. DOC peaked prior to maximum flow and then declined exponentially to pre-base flow levels while flows remain high, indicating the depletion of a soil carbon source.

DOC concentrations in watershed outlet streams is positively correlated to % wetland area within watersheds (Quinby, 2000). Fraser et al. (2001) measured a DOC export of 8.3 ± 3.7 g C m^{-2} yr^{-1} from an ombrotrophic bog in Ontario, Canada, and estimated DOC loading via precipitation as 1.5 ± 0.7 g C m^{-2} yr^{-1}. Dawson et al. (2002) measured total annual carbon exports of 19.1 g C m^{-1} yr^{-1} from a north-east Scotland catchment, and 12.1 g C m^{-1} yr^{-1} from a Mid-Wales catchment. DOC fluxes represented 88.4% of the carbon flux at the NE Scotland site, and 69.0% at the Mid-Wales site.

3.4.2 DOC Production and Consumption

DOC production and consumption is controlled by the physical, biological and chemical decay of organic matter. DOC stocks are controlled by the quantity, quality, and biodegradability of above and below ground organic matter stocks, the decomposer type and population, and environmental factors (moisture, temperature, frost) which limit or promote metabolism. Greenhouse gases are the ultimate product of POC and DOC decomposition with CO_2 being produced under oxidizing conditions and CH_4 under reducing conditions. DOC in the hydrosphere and pedosphere is an important part of the carbon cycle and ecosystem based studies of greenhouse gases and global warming.

3.4.2.1 Quantity and Quality of Organic Matter Stocks

Boreal forests cover approximately 9% of Earth's terrestrial biomes, yet contain about 23% of global terrestrial carbon stocks, with approximately 88 petagrams (10^{15} g) carbon in vegetation, 471 Pg C in soils, and a net primary productivity (NPP) of 2.6 to 3.2 Pg C yr^{-1} (Prentice et al., 2001). Boreal forests contains 42 to 64 megagrams (10^6 g) carbon per hectare in vegetation and 247 to 344 Mg C ha^{-1} in the upper one metre of soils, with significant quantities of carbon stored below this depth in peatlands (Prentice et al., 2001).

Apps et al. (1993) estimate that the Canadian boreal forest contains 8 Pg C in plant biomass, 65 Pg C in mineral forest soils (includes plant detritus), and 113 Pg C in peat. The majority of soil organic carbon (SOC) in North America is stored in soils of the Organic and Cryosolic orders within boreal and arctic regions (Tarnocai and Lacelle, 1996; Tarnocai, 1997). Boreal, subarctic and arctic ecoclimatic provinces contain approximately 88% of Canada's total SOC mass (111.8, 75.7 and 43.0 Pg C, respectively) (Tarnocai, 1997). Based on the Canadian soil organic carbon database, average total SOC content varies from 9.3 kg m^{-2} in Brunisols and Luvisols to 133.7 kg m^{-2} in Organic soils, with an average of 20.0 kg m^{-2} in Gleysols and 40.6 kg m^{-2} in Cryosols (Tarnocai, 1997). In comparison, carbon stocks in overstory vegetation within the Thompson study area ranges from 5 to 8 kg m^{-2} for jack pine, 16 to 18 kg m^{-2} for aspen, and 39 to 48 kg m^{-2} for black spruce (Gower et al., 1997).

Soil organic matter (SOM) contains OM in various stages of decomposition including plant residues, microbial biomass, and humic substances (humus). Plant residue consist of detritus (twigs, leaf litter and needles), woody debris (standing dead timber and coarse woody debris), and dead roots which have been partially or entirely incorporated into the soil. Indicators of organic matter quality include degree of decomposition, % organic carbon content, C:N ratio, and lignin:N ratio. Degree of decomposition (Fibric, Mesic, Humic) is determined by the Von Post scale of decomposition (a field test), rubbed and unrubbed fibber content (a laboratory method), or the Pyrophosphate index (Soil Classification Working Group, 1998).

Average decomposition of DOC is fastest in throughfall and "forest floor horizons" (Qualls and Haines, 1992). Using litter samples and undisturbed soil cores in field lysimeters, Hongve (1999) found that rapid decomposition of fresh deciduous leaf litter produced higher DOC peaks in autumn, whereas, coniferous leaf litter and organic soils release DOC more evenly. Within a laboratory study, Moore and Dalva (2001) found in a that DOC production is inversely correlated to degree of decomposition of plant materials, with release of DOC from fresh maple leaves > old maple leaves > Sphagnum moss > fibric peat > hemic peat = sapric peat > Inceptisol A horizon. Litter and humus are the most important DOM sources in soils, but it is not clear how changes in the pool sizes of litter or humus affect DOM release, and the effect of substrate quality on DOC concentrations are often not confirmed in field studies (Kalbitz et al., 2000).

3.4.2.2 Decomposer Community

Soils contain tens of thousands of microbes per gram of soil, and soil biota include bacteria, fungi, and animalia, among other taxonomic categories (Paul and Clark, 1996). Microbial metabolites, incomplete degradation of OM by fungi, and consumption of microbial biomass by soil fauna are important sources of DOM in soils (Kalbitz et al., 2000). "High microbial activity, high fungal abundance, and any condition that enhances mineralization all promote high DOM concentrations." (Kalbitz et al., 2000).

3.4.2.3 Temperature

Soil organisms differ in their thermal tolerance and optimum growth temperature, with most species having a tolerance range of ~ 30 °C (Paul and Clark, 1996). Soil organisms characterised according to their thermal tolerance range (minimum and maximum temperatures) include psychrophiles (-5 to 20 °C), mesophiles (15 to 45 °C), and thermophiles (40 to 70 °C). Within an organism's thermal tolerance range, increasing soil temperature increases enzyme activity until the optimum temperature is reached, but any further temperature increase results in the breakdown of enzymes. Although it is often assumed that soil microbiological activity is negligible at temperatures below 5 °C, psychrophilic snow-mould fungi decompose leaves buried under snow, and mineralization of soil organic matter to ammonium (NH_4) continues at slow rates down to the freezing point (Killham, 1994).

Q_{10} is defined as the change in the rate of a process as a result of increasing the temperature by 10 °C. Reported Q_{10} values typically range from 1 to 5 for DOC production, with most Q_{10} values near 2, indicating a doubling of DOC concentrations per 10 °C increase in temperature. Savage et al. (1997) reported Q_{10} values of 2.6 for CO_2 production, and 1.2 for CH_4 production, whereas Moore and Dalva (2001) reported Q_{10} values of ~1.6 for DOC production. Warming peat soils over a thermal gradient of 2-20 °C in a laboratory experiment increased enzyme activity of peatland phenol oxidase ($Q_{10} = 1.36$), and increased the release of DOC and phenolic compounds ($Q_{10} = 1.33$ and 1.72 respectively) (Freeman et al., 2001). Caution must be used when interpreting these values, as Q_{10} values determined over long incubation/residence times may actually represent net DOC production, as DOC is continuously being produced and decomposed.

3.4.2.4 Moisture and Oxygen

Soil moisture, water table depth, and duration of saturated conditions affect oxygen availability, reduction/oxidation (redox) potential, metabolic pathways and the form and quantity of decomposition products. Oxidizing conditions within upland environments promote decomposition of organic matter and consumption of methane to produce CO_2 (Burke et al., 1997; Savage et al., 1997), whereas lower slope positions subject to prolonged periods of saturation develop reducing conditions which partially inhibit the production of CO_2 (Moore and Knowles, 1989; Roulet et al., 1997).

Moore and Knowles (1989) conducted a laboratory study using peat columns from a subarctic fen, a boreal bog and a temperate wooded swamp in which temperature was regulated between 19 to 23 °C and samples were incubated with 10 mg DOC L^{-1}. Carbon dioxide was the dominant gas emitted from the peat columns under both aerobic and anaerobic conditions. Under inundating conditions (reducing/anaerobic), the molar ratio of CO_2 to CH_4 production was 6:1 for the fen peat and 173:1 for the bog peat, whereas the CO_2:CH_4 ratio was >2500:1 under oxidizing conditions. Roulet et al. (1997) measured a CO_2:CH_4 ratio of 22:1 within a boreal beaver pond.

In a 60 day laboratory incubation study conducted by Moore and Dalva (2001), DOC production from decomposing organic material at 22°C accounted for 14 to 58% (average 24%) of the total carbon released as DOC + CO_2 + CH_4 under oxic conditions, and 63 to 95% (average 82%) of total carbon released under anoxic conditions. Kalbits et al.'s (2000) review of the literature indicated that the most important effects of soil moisture on DOC was that DOC concentrations increased after dry periods and during anaerobic conditions.

3.4.2.5 Time

Residence time is an important factor controlling POC and DOC concentrations (e.g. production, decomposition, adsorption, and sedimentation rates) in soils, groundwater, and surface water bodies. Decomposition is too slow to account for the decline in DOC concentrations with depth in the soil profile (Qualls and Haines, 1992), but over long periods of time, slow biological decomposition decreases DOC concentrations in the soil solution and decomposes adsorbed DOC, renewing adsorption sites (Qualls and Haines, 1992; McCraken et al., 2002).

3.4.3 DOC Adsorption and Desorption

Adsorption has a large role to play in sequestering DOC from soil water and into the soil organic carbon pool. Chemical and physical adsorption processes are responsible for the formation of organic-mineral complexes (aggregates), and the formation of organic matter stains on mineral surfaces (McCraken et al., 2002), especially along preferential flow paths (Bundt et al., 2001). Thus, adsorption of DOC to mineral soil particles is a major factor responsible for the decline in DOC concentrations with depth in the soil profile.

Nodvin et al. (1986) found that the partitioning of DOC between soils and solution was best described using the initial mass isotherm, rather than the Langmuir or Freundlich equations. The initial mass isotherm is given as:

$$\mathrm{RE} = m\mathrm{X}_\mathrm{i} - b$$

Where RE is the addition or removal of DOC from solution, m is a dimensionless partitioning coefficient of DOC between the soil and the solution, X_i is the initial DOC concentration in the solution, and b is the intercept which represents the amount of DOC released from the soil when a solution of zero concentration is added. The slope of the linear regression (m) is defined as the "fraction of total reactive substance in a soil/water system that is retained by the soil" (Nodvin et al., 1986), thus, larger values of m represent greater DOC adsorption to soils. If the measurement units for RE and X_i are the same, m is unitless and within the range of 0 to 1.

Both m and b are affected by soil horizon properties (organic carbon content, extractable iron and aluminum) and the hydrophobic-hydrophilic nature of the DOC in solution (Moore et al., 1992; Moore and Matos, 1999; Kaiser et al., 2001). Jardine et al.

(1989) found that soil organic matter impeded adsorption of DOC, whereas iron oxides and hydroxides increased DOC adsorption. DOC adsorption was highest at a pH of 4.0 to 4.5 and illite (a 2:1 phyllosilicate) adsorbed ~85 % less DOC than kaolinite (a 1:1 phyllosilicate). Hydrophobic DOC is preferentially adsorbed to soil relative to hydrophilic DOC (Jardine et al., 1989 and 1990; Kaiser et al., 2001), thus hydrophilic DOC moves more readily through soils. Using soil samples from the Thompson study area, Moore and Matos (1999) found that clay soils had larger partitioning coefficients (*m*) and intercepts (*b*) than sandy soils. Kaiser et al. (2001) found that the partitioning coefficient (*m*), when determined with *RE* and X_i normalized to soil mass, was weakly affected by temperature, and not affected by soil-to-solution ratio, or prior soil storage conditions. The intercept (*b*) was strongly affected by temperature, soil-to-solution ratio, and prior soil storage conditions, with frozen and air-dried soils releasing 2 to 5 times more DOC than fresh soil samples, whereas, soil samples stored at 3 °C for 28 days released only 1.2 to 1.3 times more DOC than fresh soil samples.

3.5 DOC, Greenhouse Gases, and Climate Warming

3.5.1 Greenhouse Gas Concentrations and Warming Potential

Natural and anthropogenic gases in the atmosphere absorb and emit infrared radiation emitted by the Earth's surface, the atmosphere and clouds, creating the greenhouse gas effect which maintains an average global surface temperature of 14°C (Baede et al., 2001). Greenhouse gases (GHG) such as carbon dioxide (CO_2) and methane (CH_4) have received considerable scientific attention in the past few decades due to their warming potential and increased concentrations within the atmosphere. GHGs have different residence times in the atmosphere and vary in their relative effectiveness in absorbing infrared radiation. Global warming potential is a time-integrated index of the warming effect of a unit mass of a given GHG relative to that of carbon dioxide (Houghton et al., 2001). CO_2 has a reference global warming potential (mass basis) of 1 for 20 to 500 year periods, whereas CH_4 has a global warming potential of 56 for a 20 year period, 21 for a 100 year period, and 6.5 for a 500 year period (Albritton et al., 1996). Data from glacial ice cores (e.g. Vostok, Antarctica) indicate that GHG concentrations over the last 220,000 years have varied from ~190 to 290 ppmv for CO_2 and ~320 to 700 ppbv for CH_4 (Barnola et al., 1987; and Jouzel et al., 1993). Direct measurements of atmospheric CO_2 concentrations made at Mauna Loa Observatory, Hawaii from 1958 to 2004 indicate that CO_2 concentrations have increased from 315 to 378 ppmv (Keeling and Whorf, 2005), greatly surpassing CO_2 concentrations within recent geologic history. The observed increase in atmospheric CO_2 concentrations during the industrial age have been attributed to anthropogenic effects which include cement production, land use change, and burning of fossil fuels (Schimel et al., 2000). Carbon budgets have also indicated that there is a missing carbon sink within northern latitude continental interiors (30 to 60°N) from June till September (Tans et al., 1990; Ciais et al., 1995).

3.5.2 Predicted Climate Change and Potential Impacts

Climate change is expected to be greatest at high latitudes and in continental interiors, with an above average increase in temperature and precipitation in northern boreal forests of Manitoba (Giorgi el al., 2001; Environment Canada, 2005). Climate change is expected to result in more frequent thunderstorms and lightning, increased frequency and intensity of forest fires, and a northward shift in vegetation zones (MCEC and IISD, 2001). Stocks et al. (1998) predict "an earlier start to the fire season, and significant increases in the area experiencing high to extreme fire danger in both Canada and Russia, particularly during June and July". Climate warming is also expected to increase the depth of the active layer (the zone of alternating freezing and thawing), and result in the reduction or disappearance of permafrost from its southern limits (CCIN, 2004).

Periods of drought persisting for at least 3-5 years influenced decomposition rates and the export of dissolved carbon compounds from Glacial Lake Agassiz peatlands in northern Minnesota (Siegel et al., 1995). In the United Kingdom, riverine DOC concentrations increased by 65% over a 12-year period, with significant ($P < 0.05$) differences in DOC concentrations observed in 20 of 22 sites indicating a regionally consistent process, which was attributed to a 0.66 °C increase in mean temperature in the 1990's compared to the three previous decades (Freeman et al., 2001). The processes responsible for this increased DOC flux are, however, still under debate (Tranvik and Jansson, 2002), as hydrologic variability may be more important than temperature dependent biotic controls (Kalbitz et al., 2000; Tranvik and Jansson, 2002; Pastor et al., 2003). Using peat monoliths and intact plant communities from a boreal bog and fen, Pastor et al. (2003) found that "the DOC budget is controlled largely by changes in discharge rather than by any effect of warming or position of the water-table level on DOC concentrations." Fiedler and Kalbitz (2003) also concluded that "large DOM fluxes from anaerobic forest soils are the result of limited DOM retention in the subsoil rather than of large DOM release from the topsoil."

3.5.3 CO_2 Fertilizer Effect

Within modeled terrestrial ecosystems, elevated CO_2 concentrations over three plant generations increased below-ground C, DOC concentrations in top 15 cm of soil, and altered the composition of the soil biotic community (Jones et al., 1998). Schlesinger and Lichter's (2001) study of loblolly pine (*Pinus taeda*) forest plots exposed to elevated CO_2 concentrations indicated that net primary productivity increased by 25 %. Nearly half of carbon uptake was allocated to short-lived tissues, largely foliage, which accumulated in the litter layer and had a fast turnover times (~3 years). After three years, forest floor mass and total mass of carbon and nitrogen in the forest floor were significantly greater within plots with higher CO_2 concentrations than in plots with ambient CO_2 concentrations, but the C:N ratio was not significantly different. Percent carbon increased in the mineral soil (0-30 cm) but was only significantly different in the 0-15 cm depth increment. Carbon-13 ratios (δ^{13} C) indicated that the % carbon content increase from 0-15 cm was associated with an increase in coarse particulate organic matter (POM > 0.5 mm), fine POM (0.5 mm to 53 μm), and mineral-associated (<53 μm) fractions.

3.6 Summary and Knowledge Gaps

Over the last several decades, controlled laboratory studies have advanced our understanding of individual processes (DOC production, adsorption, and decomposition), but interactions under field conditions often mask temperature regulated biotic controls on DOC production (Kalbitz et al., 2000). Abiotic DOC adsorption is the major mechanism responsible for the decline in soil solution DOC concentrations over the short term, but microbial decomposition decreases DOC concentrations over the long term (Qualls and Haines, 1992; McCraken et al., 2002). Much of the field research has focussed on DOC in lakes, rivers, and oceans (Meybeck, 1993; Opsahl and Benner 1997; France et al., 2000), or in temperate forest soils (McDowell and Wood, 1984; Jardine et al., 1990; Qualls and Haines, 1992; Michalzik et al., 2001), despite the fact that a significant quantity of organic carbon is stored in boreal forest soils (Apps et al., 1993; Tarnocai, 1997), and climate change may have a significant impact on boreal forest soils in northern latitude continental interiors (Stocks et al., 1998; MCEC and IISD, 2001; CCIN, 2004). Tans et al. (1990) and Ciais et al. (1995) indicate that there is a missing carbon sink within northern latitude continental interiors. Could this "leak" in the carbon cycle be partially due to surface and subsurface DOC fluxes? Although a recent DOC study has been conducted in this northern boreal forest environment (Moore, 2003), it did not examine in detail the changes in DOC concentrations which are likely to occur with depth in the clay textured soils which predominantly occur in the area. Furthermore, few studies have examined changes in DOC concentrations along a topographic gradient, or the influence of forest stand age after fire.

4. DISSOLVED ORGANIC CARBON

4.1 Abstract

Dissolved organic carbon (DOC) forms a small yet important part of the carbon cycle. The purpose of this study is to determine if dissolved organic carbon (DOC) concentrations in northern boreal forest soils vary significantly between different age forest stands, landscape positions, and depths within the soil profile. Two sites were selected west of Thompson, Manitoba to represent young and mature forest stands developed on clayey glaciolacustrine parent materials typical of the area. Three parallel transects were established at each site to provide replication of upper, middle and lower slope positions. Piezometers were installed at multiple depths and were supplemented by suction lysimeters along the central transects in order to permit collection of soil water samples under both saturated and unsaturated conditions. Observed DOC concentrations had a positively skewed log-normal distribution, with DOC concentrations and variability decreasing proportionally to one another with increasing depth in the soil profile, indicating a multiplicative effect of some factor(s). Precipitation driven leaching events may explain the observed dynamic variations in DOC concentrations and the associated log-normal distribution of DOC concentrations. Peak DOC concentrations occurred in spring, followed by an overall decrease in DOC concentrations until early-fall. On average, DOC concentrations in soil water were higher within the young mixed forest stand, compared to the mature black spruce forest stand, but forest stand age had a smaller influence on DOC concentrations than changes in DOC concentrations with depth and time.

4.2 Introduction

Dissolved organic carbon (DOC) forms a small yet important part of the terrestrial and hydrologic components of the carbon cycle and contributes to the retention and transport of nutrients and pollutants via absorption processes. Most of the field research has focussed on DOC within lakes, rivers, and oceans, or within temperate forest soils, despite the fact that a significant quantity of organic carbon is stored in boreal forest soils and climate change will have a significant impact in northern latitude continental interiors. Boreal forests contain about 23% of global terrestrial carbon stocks with ~88 peta-grams (10^{15} g) carbon in vegetation and 471 Pg C in soils due to the cold and humid climate (Clayton et al., 1977; Prentice et al., 2001). Observed increases in greenhouse gas concentrations within the atmosphere are expected to result in climate warming, drier conditions, and increased frequency of fires within northern latitude continental interiors since increased evaporation will not be offset by increased precipitation (Stocks et al., 1998). This will influence the production and transport of DOC since DOC production is affected by soil temperature and soil organic carbon content (Kalbitz et al., 2000). France et al. (2000) observed higher DOC concentrations in Canadian boreal lakes within clearcut or burnt watersheds, but Schindler et al. (1997) found that "decreased streamflow caused by drought was more important than forest fires in affecting DOC exports from catchments." Moore (2003) examined DOC concentrations in northern boreal forest soils, but did not examine changes in DOC concentrations with depth in the dominant clay textured soils, nor did he examine the influence of forest stand age after fire. Few studies have examined changes in DOC concentrations along a topographic gradient.

4.3 Objectives

The primary objective of this research project was to determine if DOC concentrations in the dominant clay textured northern boreal forest soils near Thompson, Manitoba differ significantly with soil depth, landscape position, and forest stand age after fire. The secondary objective of this project was to examine the effects of environmental factors (precipitation, soil moisture, soil temperature, and carbon stocks) on DOC concentrations.

4.3.1 Hypotheses

Dissolved organic carbon (DOC) concentrations:

1) vary significantly between different aged forest stands, landscape positions, and depths within the soil profile;
2) are significantly greater within older forest stands;
3) increase from upper to lower slope landscape positions;
4) decrease with depth in the soil profile;
5) vary significantly with time; and
6) are dependent on soil organic carbon content and soil temperature.

4.4 Study Area

4.4.1 Selection of Study Sites

The study area is located in the northern boreal forest between Thompson and Leaf Rapids in north-central Manitoba. Two sites were selected west of Thompson, Manitoba, to represent different aged northern boreal forest stands developed on clay textured parent materials. The 1964 and 1930 burn sites represent young and mature stands located on clayey glaciolacustrine parent materials within gently undulating landscapes, and are in relatively close proximity to Thompson with easy access from the highway. Three parallel transects (toposequences) were established at these two sites to provide replication of upper, middle and lower slope positions. Sampling locations within each burn site were labelled according to year of burn (64 or 30), transect (T1 to T3), and slope position (S1 to S3), where S1 represents upland sites, S2 represents mid-slope sites, and S3 represents lowland sites.

4.4.2 Description of Soils and Vegetation

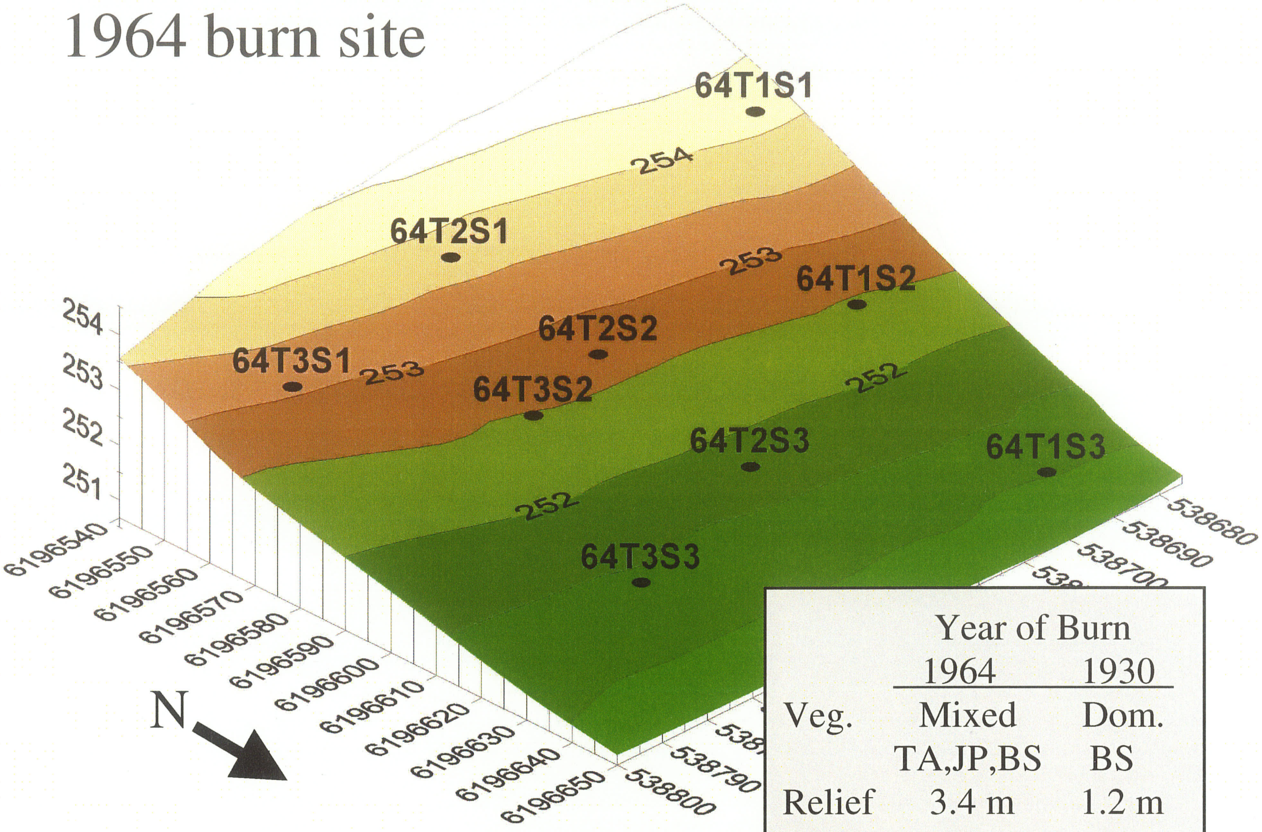
Dominant soils consist of clayey Gray Luvisols on well to imperfectly drained upper to mid slope positions, with peaty Gleysols, Terric Fibrisols, and Organic Cryosols occurring in poorly drained landscape positions. The 1964 burn site faces north with 2 to 6% slopes, whereas the 1930 burn site faces south with 1 to 4% slopes (Figure 4.1). Different aspects exist purely by chance, as this factor was not taken into account during the initial site selection.

The mixed forest stand on the upper slope of the 1964 burn site consists of jack pine (*Pinus Banksiana*), trembling aspen (*Populus tremuloides*), and black spruce (*Picea*

Mariana), with some mature black spruce and trembling aspen spared by the 1964 fire. Forest floor cover consists of lichen, grasses, feathermoss, rose, flowers, and herbaceous plant species underlain by a thin forest duff layer (LFH, 3 to 5 cm thick). Mineral hummocks 10 to 15 cm high occur on the north facing slope of the 1964 burn site. Sporadic permafrost occurs within the lower slope of the 1964 burn site.

Mature vegetation on the upper slope of the 1930 burn site consists of black spruce (*Picea Mariana*) with a feathermoss groundcover, with minor trembling aspen, paper birch (*Betula papyrifera* var. *papyrifera*), and a few jack pine. Most of the mature jack pine have died, probably due to wetter and cooler soil conditions caused by the closed black spruce canopy and the development of thick organic horizons (LFH layers 15 to 20 cm thick) (H. Veldhuis, personal communication, Agriculture and Agri-Food Canada, Winnipeg, MB).

Understory vegetation includes willow (*Salix* spp.) and alder (*Alnus* spp.) on both sites. Lower slopes are dominated by stunted black spruce and local occurrences of tamarack (*Larix lariciana*) and stunted jack pine, with a Labrador tea (*Ledum groenlandicum*) and Sphagnum moss groundcover. Partially burnt very shallow (< 15 cm) forest and Sphagnum peat occur in mid to lower slope transitional positions of the 1930 burn site, whereas, fire scars occur on Sphagnum hummocks in the lower slope of the 1964 burn site. Shallow peat (15-60 cm) occurs on the lower slopes in the form of veneer bogs. Local topographic and hydrologic factors have resulted in imperfect to poorly drained soil conditions and 25 cm thick organic horizons within the mid-slope of the 1930 burn site (site 30T1S2). Moderately deep (80 cm thick) fibric sedge and brown moss peat occur in a water saturated depression southwest of the 1930 burn site, where surface and groundwater accumulate.


1964 burn site

	Year of Burn	
	1964	1930
Veg.	Mixed TA,JP,BS	Dom. BS
Relief	3.4 m	1.2 m
Aspect	N	S
Slope	2-6%	1-4%
LFH	9 cm	16 cm
Organics	45 cm	55 cm

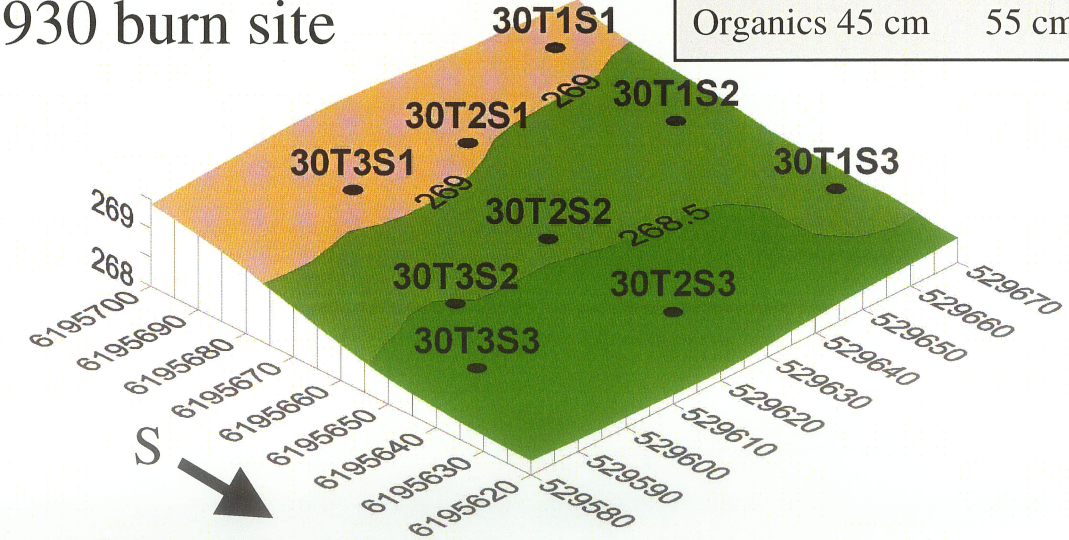

1930 burn site

Figure 4.1 Sampling locations and shaded relief maps for the 1964 and 1930 burn sites. Note: Total relief shown in the table is based on the mineral soil surface. TA= Trembling Aspen, JP = Jack Pine, BS = Black Spruce. 64T3S1 = 1964 burn site, transect 3, upper slope position.

4.5 Materials and Methods

4.5.1 Instrument Installation Methodology

The 1964 and 1930 burn sites were designed as long-term monitoring sites for the study of soil climate, hydrology, and biogeochemistry within clay textured Northen Boreal Forest soils. Sampling platforms, piezometers, thermistors, and frost tubes (Table 4.1) were permanently installed in upper, mid and lower slope positions along each transect. Tensiometers and suction lysimeters were installed in the spring and removed in the fall of each year due to the risk of damage by water freezing within the ceramic tips. Due to cost constraints, tensiometers and suction lysimeters were only installed along the central transect. Soil water samples were collected for DOC analysis from both piezometers and suction lysimeters during saturated conditions, and from suction lysimeters during unsaturated conditions. Further details on instrument installation methodology are provided in Appendix 10.1.

Table 4.1 Field instruments used, and their purpose.

Instrument	Purpose
Piezometer	- to monitor water table depths and hydraulic pressure heads - to sample soil water during saturated conditions
Suction Lysimeter	- to sample soil water during saturated and unsaturated conditions
Tensiometer	- to monitor soil tension and calculate soil moisture content
Thermistor	- to monitor soil temperature
Frost tube	- to monitor frost depths

4.5.1.1 Instrumentation Depths

Surface organic horizon thickness was highly variable, especially in the lower slopes. Piezometers, tensiometers and suction lysimeters were therefore installed in reference to the organic-mineral horizon contact (0-cm depth, i.e. the mineral soil surface) (see Figure 4.2).

Piezometers were installed at 15-cm depth increments up to the 60-cm depth below the mineral soil surface, with additional piezometers installed at the 122-cm and 244-cm depths (Figure 4.2). Suction lysimeters were installed at the 0, 15 and 45-cm depths, with an additional lysimeter installed 15 cm above the organic-mineral horizon contact within peaty lower slope positions. Tensiometers were installed at the 0, 15, 30, 45 and 75-cm depths, and additional tensiometers were installed 30 and 15 cm above the organic-mineral horizon contact in peaty lower slope positions. Tensiometer and suction lysimeter installation depths in 2002 did not exactly match these standardized depths due to differences in the thickness of the moss layer between sites. Longer tensiometers and suction lysimeters were purchased and were installed at standardized depths in 2003.

Soil temperatures were measured at the 5, 10, 20, 50, 100 and 150-cm depths from the top of the duff/peat, and not in reference to the organic-mineral horizon contact. These different reference depths were based on standardized methods used for long-term soil temperature monitoring sites as recommended by the World Meteorological Organization (WMO) (e.g. Environment Canada, 2004), except that temperatures were not measured at the 300-cm depth, and time of measurement was not standardized.

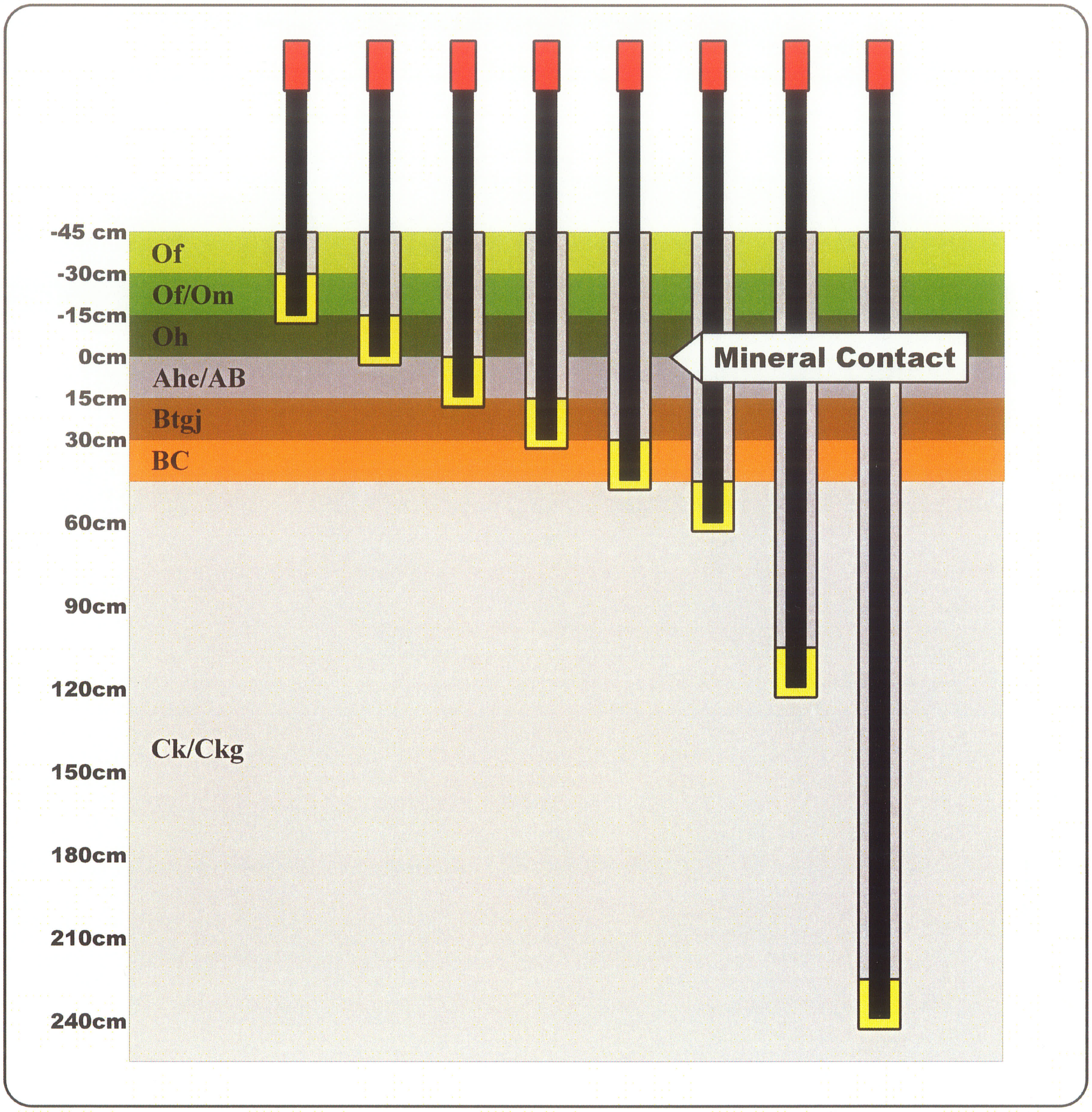


Figure 4.2 Conceptual piezometer nest located in a lower slope sampling location.

4.5.1.2 Date of Installation

Installation of piezometers was completed by the fall of 2002 to the 122-cm depth on the 1964 burn site and on the central transect of the 1930 burn site. Additional 244-cm deep piezometers were also intalled on the upper and mid slopes of the 1964 burn site. The final piezometers were installed by June 19th, 2003. Thermistor installation was completed in late-July of 2002. Tensiometers and suction lysimeters were in the ground by mid-July in 2002 and by late-June in 2003, but tensiometer and suction lysimeter installation was incomplete in 2002 due to the occurrence of prolonged frozen soil conditions. Frost tube installation was completed by mid-July 2003 although reliable frost depth from these instruments were not expected until the following winter, thus requiring the use of 2003 ice depth observations from piezometers as a proxy.

4.5.2 Field Methods

After instrument installation, water elevations and solutes were permitted to equilibrate over a couple weeks or longer, depending on the occurrence of precipitation events and ground water supply. Water was purged from piezometers and lysimeters within a couple weeks after instrument installation and a couple days prior to each measurement and sample collection.

4.5.2.1 Frequency of Measurement and Sample Collection

Field measurements and sample collection were conducted at irregular time intervals from July, 2002 until September, 2002. The 2003 field schedule was adjusted to allow sampling every two weeks from mid-May until late-September, although a complete set of measurements was not acquired until the end of June, 2003. The two week sampling frequency fit the schedule better and provided sufficient data to capture seasonal trends as affected by soil thaw and temperature increases and the longer term effects of precipitation events. Additional sampling and measurements were conducted as the field schedule permitted. Attempts to collect water samples from deeper unfrozen piezometers in the middle of the winter in 2002-2003 failed due to water samples freezing within sampling tube.

Precipitation measurements and samples were usually collected the morning after a precipitation event, but this wasn't always possible. Precipitation samples were collected less frequently during consecutive rainy days, when fieldwork was being conducted at other sites, and during extended periods away from the study area.

4.5.2.2 Water Sampling Methodology

Water sampling instrumentation consisted of tubing connected to a rigid 1000 ml flask via a rubber stopper. A metal screen was used at the bottom end of the tube to prevent organic matter debris or sand from clogging the tubing. A vacuum hand pump was then used to apply suction to the flask to pump water from the piezometers and lysimeters. Water samples were collected into numbered 125 ml amber glass bottles with Teflon TFE fluorocarbon resin-lined caps. Sampling equipment was rinsed out with distilled water between each sample collection. Sample bottles were cleaned with soap and water and rinsed with distilled water prior to reuse.

Duplicate samples, quality control samples, and field blanks were randomly collected throughout the data collection period. Quality control samples consisted of distilled water which had been passed through the rinsed out sampling equipment, whereas field blanks consisted of distilled water which had not passed through the sampling equipment.

4.5.2.3 Pre-Filtration

Water samples were pre-filtered in the field when possible to reduce potential particulate contamination. A homemade in-line filter was tested in 2002, but particles were found in these filtered samples. Subsequent attempts using a commercial inline filter in the spring of 2003 were inefficient as the rate of water flow through the lab quality filter paper was too slow and the filter paper would often clog. Water samples with a high sediment load or significant organic matter contamination required pre-filtration with a larger pore diameter filter than used for the final lab filtration, therefore, Whatman GF/D filter paper (2.7 μm pore diameter) was selected for subsequent pre-filtrations.

4.5.2.4 Maintenance of Piezometers and Lysimeters

Piezometers and suction lysimeters with significant or repeated contamination were cleaned with distilled water and purged. Some piezometers with significant organic matter or soil contamination required repeated flushing with distilled water followed by the purging of the debris and addition of medium sand as a filter.

4.5.2.5 Water Sample Storage and Shipping

Water samples were kept as cool as possible in order to minimize decomposition of particulate and dissolved organic carbon prior to filtration and analysis. Methods used to achieve this objective included transporting samples in a small portable cooler from site to site, keeping the samples in the shade when possible, and transferring the samples to an electric cooler in the vehicle when sufficient samples had been collected. Water samples were then refrigerated and a sample inventory list prepared prior to shipping the samples to the laboratory in a cooler with ice packs overnight by bus.

4.5.3 Laboratory Methods

All water samples were refrigerated and filtered in the lab using Whatman GF/C filter paper (1.2 μm pore diameter). DOC concentrations were measured within one week of sample collection using a Technicon AutoAnalyzer II. According to the Technicon documentation (Technicon, 1978) the detection limit is 20 mg C L^{-1} when the system is set up for the 20-1000 mg C L^{-1} range at 20 samples per hour. Previously reported results (Cyr and Veldhuis, 2003) indicate that the instrument detection limit (IDL) is approximately 2 mg C L^{-1} when using the 2-100 mg C L^{-1} range (i.e. 2 % of the measurement range).

4.6 Results and Discussion

4.6.1 Weather Conditions and Soil Climate

4.6.1.1 Precipitation

Based on field observations and data from rain gauge measurements, precipitation from June until September in 2002 and 2003 was slightly greater on the 1930 burn site than on the 1964 burn site in both years (Table 4.2). Significantly drier soil conditions were observed on the 1964 burn site in 2003 due to lower-than-average precipitation. Elevations for the 1964 and 1930 burn sites are approximately 253 and 269 m, respectively. This elevation difference of about 16 m is relatively minor, thus the observed precipitation trends are likely the result of natural variability in precipitation within space and time. Snow depths were slightly thicker on the 1964 burn site in February and April of 2003 (Table 4.3), but this difference was not statistically significant ($P>0.05$, one tailed t-test).

Table 4.2 Precipitation data for the 1964 and 1930 burn sites, and the Thompson airport.

	June	July	Aug	Sept	June-Sept	Full year
	1971-2000 Long Term Average Precipitation (mm)					
Thompson A	69	86	74	62	292	517
	2002 Precipitation (mm)					
1964 burn site	48	26	74	85	233	ND
1930 burn site	46	55	62	93	256	ND
Thompson A	44	49	127	126	345	570
	2003 Precipitation (mm)					
1964 burn site	32	48	46	57	183	ND
1930 burn site	36	86	43	71	236	ND
Thompson A	46	88	57	53	244	368

NOTE: Measurements are compiled from standard rain gauge measurements supplemented with data from nearby datalogged tipping bucket rain gauges (G. Winston, personal communication, University of California, Irvine).

Table 4.3 Average snow depths (cm) during the winter of 2002-2003.

	2002 Nov	Dec	2003 Jan	Feb	Mar	Apr
			Average snow depth (cm)			
1964 burn site	23	27	28	40	38	24
1930 burn site	23	25	28	35	38	21

4.6.1.2 Soil Moisture

Below average seasonal precipitation resulted in higher near surface tensiometer readings on the 1964 burn site in July 2002, early-August 2003 and early-September 2003 (Figure 4.3). ANOVA conducted in SAS using repeated measures analysis with compound symmetry indicated that soil tension readings were significantly different (p=0.01) between

2002 and 2003, and a highly significantly (p=0.01) interaction effect was observed between landscape position, year of observation and month (Position * Year * Month). Significant (p=0.05) interaction effects were also observed between the different aged forest stands after fire (Burn sites) and year of observation (Year): Burn * Year, Burn * Year * Month, Position * Year, Position * Month, and Depth * Year * Month. Lack of adequate replication due to cost constraints limits the reliability of these results and the ability to detect significant differences in soil tension readings between landscape positions within burn sites.

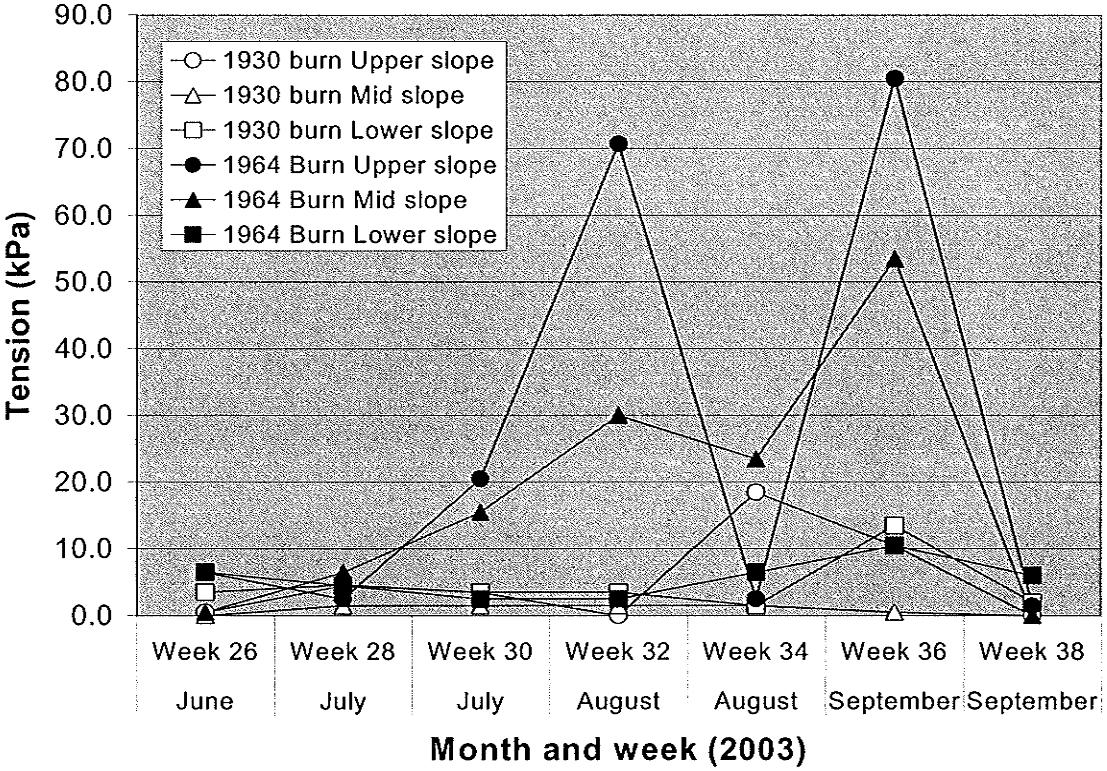


Figure 4.3 2003 biweekly near surface soil tension measurements along central transects of 1964 and 1930 burn sites.

4.6.1.3 Soil Temperatures

Soil temperature data collected at irregular time intervals from July 2002 until October 2003, and at biweekly time intervals from May 2003 until September 2003 were statistically analysed in SAS(version 8.02) using Analyst's ANOVA mixed model and repeat measures procedures. Four covariance structures were tested for use in the repeated measures analysis: compound symmetry (CS), unstructured (US), 1st order autoregressive (AR1), and 1st order ante-dependence (AD1). Wang and Goonewardene (2004) provide an excellent review of these covariance structures and their use in repeated measures analysis using mixed models. Compound symmetry (CS) assumes that correlations remain constant in time, which is likely false since CS provided the worst fit. First order auto-regressive (AR1) covariance requires equally spaced time intervals and assumes that correlations decrease over time, with observations n units apart having a correlation of p^n (Wang and Goonewardene, 2004). AR1 provided the second worst fit, which is likely due to abrupt changes in correlation during precipitation events. The unstructured (US) covariance provided the best fit for the soil temperature data collected at bi-weekly intervals, followed by the 1st order ante-dependence structure (AD1), but US results in less powerful tests (Wang and Goonewardene, 2004). For the 2003 bi-weekly measurement period, measurement depth and month consistently had highly significant effects on soil temperatures ($p<0.01$). Landscape position and forest stand age after fire (Burn) alternated between significance and non-significance depending on the covariance structure used. Several interactions were significant, but only four of these interactions were consistently found to be highly significant ($p<0.01$): Burn * Position, Depth * Month, Position * Month, and Burn * Depth * Month.

Summer (June 03 - August 03) soil temperatures at the 10 cm depth were warmest within the lower slope of the 1930 burn site (Table 4.4) due to the open canopy and south aspect, but coldest within the upper slope of the 1930 burn site, probably due to the greater canopy closure. Upper and mid-slope positions were slightly colder on the 1930 burn site compared to the 1964 burn site, due to greater precipitation (Table 4.1), wetter soil conditions (Figure 4.3), and a closed canopy cover on the 1930 burn site. There was a larger range in seasonal soil temperatures on the 1964 burn site than on the 1930 burn site, with soil temperatures (5 to 50-cm depths) in upper and mid-slope positions of the 1964 burn site being warmer than the 1930 burn site in the summer, and colder in the winter (Figure 4.4). This was attributed to drier soil conditions on the 1964 burn site and the influence of an open tree canopy, which permits greater quantities of solar radiation to reach the soil surface in the summer, and greater quantities of terrestrial thermal energy to escape in the fall.

Soil temperatures at the 50-cm depth warmed up more rapidly in upper and mid-slope positions than in lower slope positions, with colder soil temperatures persisting in the lower slope of the 1964 burn site until late-July of 2002 and 2003 (Figure 4.4). Mean summer soil temperatures (MSST) at the 50-cm depth were coldest in poorly drained lower slope positions (Table 4.4), especially in the lower slope of the 1964 burn site, where poor drainage, thick sphagnum hummocks, and a north aspect contributed to the occurrence of sporadic permafrost. Mean annual soil temperatures (MAST) at the 50-cm depth ranged from 0.0 to 1.1°C. The coldest MAST occurred on the lower slope of the 1964 burn site, due to the north aspect, moderate canopy cover, thick Sphagnum hummocks, and a lower water table than on the lower slope of the 1930 burn site.

Table 4.4 Soil climate on the 1964 and 1930 burn sites.

	1964 burn site			**1930 burn site**		
	Upper	**Mid**	**Lower**	**Upper**	**Mid**	**Lower**
June 03 - August 03	Mean Summer Soil Temperature (°C)					
10 cm depth	7.4	7.1	6.7	6.1	7.1	9.9
20 cm depth	5.6	5.1	3.3	3.8	4.5	5
50 cm depth	3	2.7	0.3	1.6	2	0.7
100 cm depth	0.3	0.6	-0.1	0.2	0.7	0.3
150 cm depth	-0.1	-0.1	-0.1	0.1	0.4	0.4
Oct 02 - Sept 03	Mean Annual Soil Temperature (°C)					
10 cm depth	1.3	1.3	1.2	1.4	1.8	2.3
20 cm depth	1.1	1	0.5	0.9	1.4	1.5
50 cm depth	0.9	0.7	0	0.8	1.1	0.8
100 cm depth	0.6	0.6	0	0.6	1	0.8
150 cm depth	0.7	0.5	0.1	0.7	1	0.9

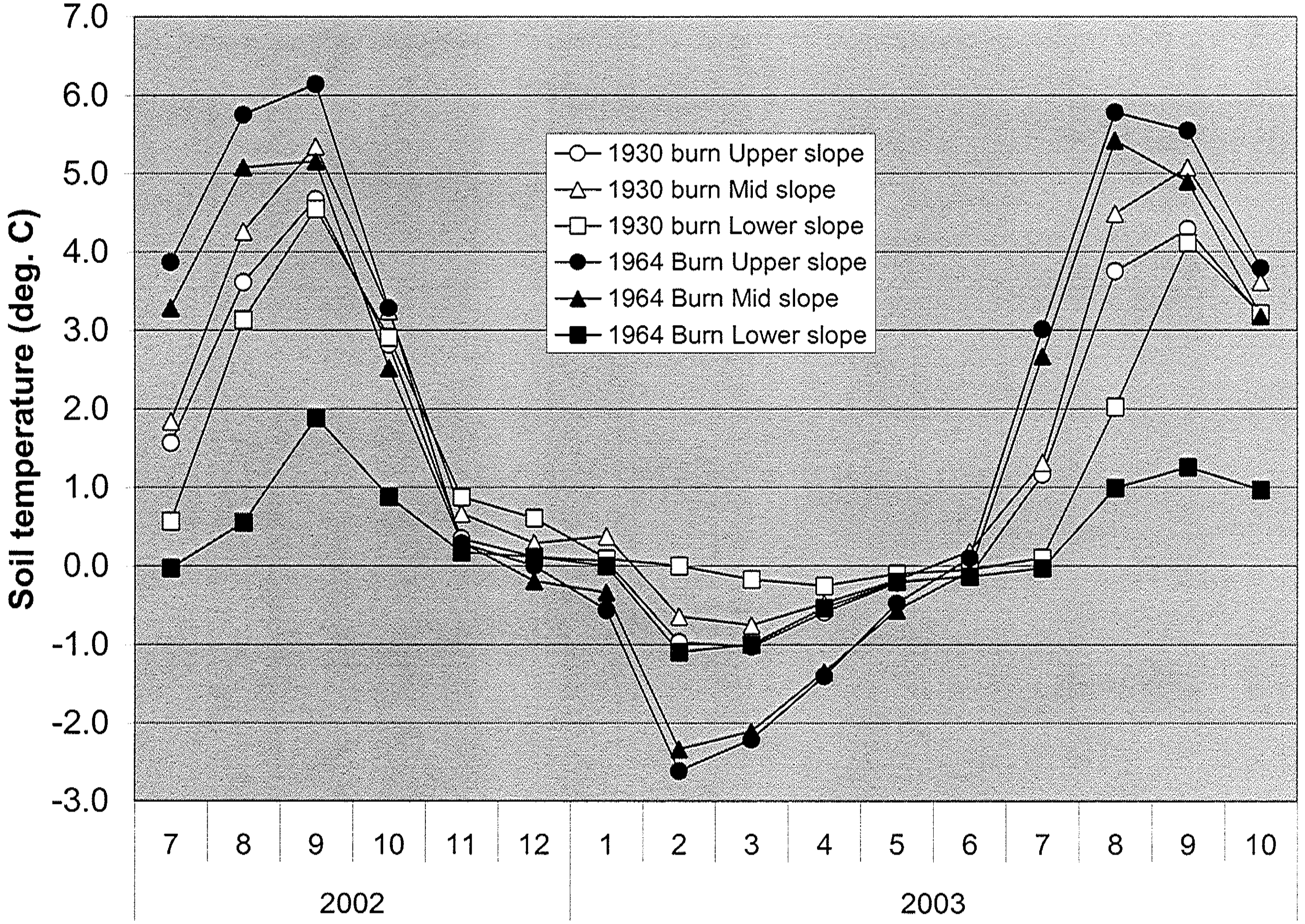


Figure 4.4 Average soil temperature at the 50 cm depth by burn and landscape position.

4.6.2 Dissolved Organic Carbon Concentrations

4.6.2.1 Instrument Detection and Method Detection Limits

The instrument detection limit (IDL) was calculated as five times the signal to noise ratio (SNR), where the SNR was calculated as the mean concentration of blank rinse samples divided by the standard deviation, and the method detection limit (MDL) was the level at which there was a 99% probability that a field sample was different from the blank (Clesceri et al., 1998). IDL for the 2-100 mg C L^{-1} measurement range was 2.5 and 2.6 mg C L^{-1} in 2002 and 2003, respectively. MDL for a 5 mg C L^{-1} quality control sample prepared from stock solution was 4.8 and 5.3 mg C L^{-1} in 2002 and 2003, respectively. A similar method detection limit of 5.1 mg C L^{-1} was obtained for a field sample which was collected in 2001, filtered according to standard methods, split into three replicate sub-samples during filtration and analysed alongside field samples during each of the four sample runs in 2002. Improvements in both the IDL and MDL were achieved by excluding irregular spikes caused by bubbles in the system.

In 2002, 6% of samples were below the instrument detection limit (2 mg C L^{-1}) and 32% of samples were below the method detection limit (5 mg C L^{-1}). Maximum measured DOC concentrations were ~300 mg C L^{-1} for two samples in the spring of 2003. Accuracy of these two measurements was questionable since these values were obtained using samples which had been diluted by up to a factor of 40. Insufficient soil water remained for repeat analysis of the first sample, and there was only enough soil water for one repeat analysis of the second sample, which measured 17.7 mg C L^{-1}.

Review of laboratory results for 2002 and 2003 suggests that establishing a stable baseline is extremely important for accurate measurements. Running out of reagents during the analysis and bubbles within the system are the largest potential sources of error in the analysis. Extremely high errors can occur when bubbles within the system are detected by the instrument, and accuracy of the results is therefore dependent on the operators ability to prevent, detect and exclude these erroneous measurements. Results can be improved by excluding measurements with noticeable spikes and by reducing the amount of carry-over between samples, but achievement of a stable baseline remains a significant issue.

4.6.2.2 Field Blank and Quality Control Results

Field blanks of distilled water and quality control samples collected with the sampling instruments after rinsing typically had measured DOC concentrations below the instrument detection limit of ~2 mg C L^{-1}. Higher DOC measurements were observed on some occasions, such as a field blank from the lower slope of the 1964 burn site where the initial measurement of 2.6 mg C L^{-1} was followed immediately by a duplicate which only measured 1.4 mg C L^{-1}.

4.6.2.3 Log-Normal Distribution

A positively skewed log-normal distribution of DOC concentrations was observed in 2002 and 2003. Review of the data by treatment and individual sites confirmed that DOC concentrations and variability decrease proportionally to one another with increasing depth in the soil profile, indicating a multiplicative effect of some factor(s). The distribution of DOC concentrations was statistically tested in SAS using the Kolmogorov-Smirnov goodness-of-fit test for normal, log-normal and exponential distributions. Attempts to analyse the distribution using repeated measurements from individual instruments at each site failed to produce any statistical output from SAS, possibly due to an insufficient number of replications required for statistically determination of the distribution. Data was therefore grouped first by age of stand, age of stand and landscape position, and then by landscape position and depth. The log-normal distribution was found to have the best match in most cases and was found to be statistically valid for 17 out of 22 groups at the 5% rejection level after taking only landscape position and depth into account. This supported the use of a log transformation of DOC concentrations in the form of log(DOC + 0.1) in order to provide a continuous normally distributed data set for statistical analysis in SAS using analysis of variance (ANOVA) with repeated measures and unequal replication. Temporally and spatially dynamic precipitation events may account for the log-normal distribution of DOC concentrations.

The exponential distribution was found to have the next best match and was statistically valid more frequently at shallow depths than deeper depths. These observations would be consistent with exponential growth and decay rates such as microbial growth and microbial decomposition of organic matter.

4.6.2.4 DOC in Precipitation

DOC concentrations in precipitation ranged from 0.3 to 29.5 mg C L^{-1} (arithmetic mean of 6.8 mg C L^{-1}; geometric mean of 4.7 mg C L^{-1}) and were not statistically different (p=0.05) between study sites, sampling year, or month. In comparison, Moore (2003) reported higher DOC concentrations in precipitation (8.8 to 18.6 mg C L^{-1}; arithmetic mean of 8.0 mg C L^{-1}) for the study area in 1994.

DOC in precipitation water may consist of a combination of aromatic carbon compounds, particulate pollen, and ash from forest fires. Precipitation samples with elevated DOC concentrations may be the result of several factors including ash deposition, canopy throughfall or concentration of DOC by evaporation of the precipitation sample. Cumulative precipitation measured in 2003 using standard rain gauges was 6 % lower on the lower slope of the 1930 burn site (211 mm) compared to the upper slope position (225 mm), which represents a relatively small 7 % increase in DOC concentrations due to greater evaporation under the open canopy of the lower slope.

The four highest DOC concentrations for precipitation (14.7 to 22.4 mg C L^{-1}) were observed between early-June and early-July 2003, with the three highest values occurring on the 1964 burn site. The fifth highest value was observed in late-August 2003 on the 1930 burn site. A large fire occurred east of the 1964 burn site in the summer of 2003 (Fire 292), but it only started on July 12, 2003 and, therefore, was not the cause of the elevated DOC concentrations for the four precipitation samples with the highest DOC concentrations. Manitoba Conservation (2003a) reported 182 fires in northeastern Manitoba between June 4th and July 10th, 2003 with at least four of these occurring within 50 km of the 1964 and 1930 burn sites (Table 4.5). Very fine gray particles were observed in the precipitation water on several occasions throughout the field season, indicating deposition of ash. Timing of forest fire and precipitation events suggests that at least some of the high DOC concentrations in the precipitation samples may be attributed to wet and dry deposition of ash from either nearby forest fires, or from more distant fires.

Table 4.5 Known forest fires in proximity to the 1964 and 1930 burn sites during observed high DOC concentrations in precipitation water samples.

Fire	Latitude	Longitude	Cause	Reported	Extinguished
132	56.12722	-98.55944	Human	2003-Jun-13	2003-Jun-14
248	55.52389	-98.54028	Lightning	2003-Jun-28	2003-Jun-30
259	55.53972	-98.49389	Lightning	2003-Jun-28	2003-Jun-30
274	55.81667	-98.26667	Lightning	2003-Jul-2	2003-Jul-5
292	55.8833	-98.2	Lightning	2003-Jul-12	2003-Oct-14

Note: 1964 burn site: Lat. 55.91294; Long. -98.38116
1930 burn site: Lat. 55.90577; Long. -98.52561

4.6.2.5 DOC in Soil Water

Averaged over all depths, DOC concentrations in soil water were 3 mg C L^{-1} higher in the young 1964 burn site than in the mature 1930 burn site, similar to France et al.'s (2000) observed DOC increase in clear-cut or burnt forest watersheds. Near surface DOC concentrations measured in 2003 ranged from 21 to 36 mg C L^{-1} on the mature 1930 burn site, and 37 to 49 mg C L^{-1} on the younger 1964 burn site, with the largest difference in DOC concentrations (21 to 49 mg C L^{-1}) occurring between the lower slope veneer bogs (Table 4.6). In comparison, Moore (2003) reported DOC concentrations of 42, 18 and 20 mg C L^{-1} in forest floor leachate of pine, aspen and spruce forests, respectively, and 36 mg C L^{-1} in the leachate of a bog.

DOC concentrations in soil water were statistically analysed in SAS(version 8.02) using Analyst's ANOVA MIXED model procedure. Analyses conducted using all available DOC data for 2002 and 2003 without the use of the repeated measures option within SAS indicated that age of forest stand, landscape position and depth in the soil profile all had significant ($p=0.05$) effects on DOC concentrations. Instrument type and year of observation were not found to be significant (p=0.05), based on available data. Significant interaction effects were observed between age of forest stand, landscape position and depth in the soil profile (p=0.05), with some indications of interaction effects between instrument type and sampling depth (p=0.05). No significant interaction effects were observed between year of observation and other factors, except for a weak yet significant interaction between instrument type, sampling depth, and year (p=0.05), possibly due to: piezometer contamination during the year of installation; or due to small differences in the lysimeter sampling locations and depths between the two years.

Analysis using Log(DOC + 0.1 mg C L^{-1}) (Table 4.7, Figures 4.5 and 4.6) produced similar results with the exception that the interaction effects between age of forest stand (Burn site) and landscape position, and the interaction effect between instrument type, sampling depth, and year were no longer significant (p=0.05), and a new significant interaction effect was observed between sampling depth and year of observation (p=0.05). This interactions between sampling depth and year of observation combined with the lack of an interaction between burn site and landscape position for the log-transformed data is of interest since the log-normal distribution of DOC concentrations is thought to be caused by precipitation. Except for small differences in canopy interception, precipitation amounts will not differ substantially between landscape positions within a burn site, but will cause a depth by time interaction as water and dissolved organic carbon are transported down through the soil profile.

Table 4.6 Mean, standard deviation and count of 2002 and 2003 DOC concentrations (mg C L^{-1}).

	1964 burn site			1930 burn site		
	Upper slope	Mid slope	Lower slope	Upper slope	Mid slope	Lower slope
mg C L^{-1}						
2002 Field Season						
Quality Control			1.4 (0.0, 2)			
Precipitation	5.6 (3.5, 8)			3.1 (2.4, 4)		
Soil Depth in Mineral						
-15 cm (-0.5 ft)			44.5 (15.1, 4)			22.0 (3.8, 4)
0 cm (0.0 ft)	42.4 (19.5, 2)	33.2 (ND, 1)	28.8 (19.1, 6)	33.9 (8.1, 4)	22.7 (4.6, 4)	14.3 (2.3, 5)
15 cm (0.5 ft)	17.6 (7.0, 3)	11.5 (3.6, 4)	12.9 (7.8, 9)	19.1 (15.0, 4)	8.4 (1.8, 4)	9.6 (ND, 1)
30 cm (1.0 ft)		9.1 (3.9, 4)	8.7 (4.5, 9)	16.4 (ND, 1)	8.0 (3.2, 2)	4.5 (2.3, 5)
45 cm (1.5 ft)	9.7 (6.2, 2)	9.8 (3.4, 8)	6.8 (2.6, 6)	9.3 (9.0, 5)	3.3 (0.9, 7)	3.2 (ND, 1)
60 cm (2.0 ft)	13.0 (ND, 1)	4.4 (1.0, 7)	2.8 (2.2, 4)	1.4 (0.2, 2)	2.1 (0.1, 2)	6.8 (ND, 1)
122 cm (4.0 ft)	6.4 (4.8, 5)	6.6 (6.5, 9)	4.5 (3.1, 4)	1.6 (ND, 1)	2.8 (ND, 1)	6.4 (ND, 1)
244 cm (8.0 ft)	3.8 (1.4, 2)	3.7 (1.2, 4)				
-15 to 244 cm	14.0 (14.1,15)	8.1 (6.2,37)	14.7 (15.0,42)	16.4 (14.5,17)	8.5 (7.9,20)	11.6 (7.4,18)
mg C L^{-1}						
2003 Field Season						
Field Blank			2.4 (0.3, 2)	1.3 (0.6, 2)		0.6 (0.5, 5)
Quality Control				2.0 (1.3, 3)		1.4 (1.5, 3)
Precipitation	9.2 (7.7,16)			4.9 (3.8,16)		
Soil Depth in Mineral						
-15 cm (-0.5 ft)			49.1 (15.9, 8)			20.7 (3.8, 7)
0 cm (0.0 ft)	37.0 (13.5, 6)	39.8 (12.2, 6)	15.0 (9.7,11)	35.7 (5.6, 9)	31.5 (11.8,10)	17.8 (4.9,19)
15 cm (0.5 ft)	6.2 (3.5, 6)	14.5 (6.8, 6)	13.6 (6.8,18)	16.5 (11.8,11)	15.5 (7.7,18)	14.5 (6.0,34)
30 cm (1.0 ft)	156.0 (208.7, 2)	36.2 (42.3, 3)	14.7 (8.1,11)	14.9 (17.3,17)	9.9 (5.7,19)	8.4 (6.5,18)
45 cm (1.5 ft)	12.5 (18.1,10)	7.3 (3.8,13)	9.1 (4.8,11)	7.5 (4.0,30)	6.2 (3.5,30)	6.8 (4.3,28)
60 cm (2.0 ft)		11.0 (8.4, 8)	3.9 (1.5, 3)	4.7 (2.3,13)	4.6 (1.8,18)	6.1 (4.4,16)
122 cm (4.0 ft)	4.0 (ND, 1)	2.9 (1.2,10)	2.9 (2.4, 5)	2.6 (1.1, 8)	3.2 (1.2,17)	3.4 (1.9,37)
244 cm (8.0 ft)	3.1 (1.7, 5)	2.9 (1.6, 9)	3.5 (2.0,12)	4.6 (2.8, 8)	3.6 (1.8,21)	3.4 (2.6,34)
-15 to 244 cm	23.9 (55.4,30)	12.2 (15.8,55)	14.3 (14.7,79)	11.5 (12.5,96)	8.9 (9.1,133)	8.6 (7.0,193)

NOTE: Mean (Standard deviation, Count)

Table 4.7 Combined 2002 and 2003 DOC concentrations (mg C L^{-1}) and log-transformed DOC concentrations, Log(DOC+0.1).

	1964 burn site			1930 burn site		
	Upper slope	Mid slope	Lower slope	Upper slope	Mid slope	Lower slope
			mg C L^{-1}			
Field Blank			2.4 (0.3, 2)	1.3 (0.6, 2)		0.6 (0.5, 5)
Quality Control			1.4 (0.0, 2)	2.0 (1.3, 3)		1.4 (1.5, 3)
Precipitation	8.0 (6.7,24)			4.5 (3.5,20)		
Soil Depth in Mineral						
-15 cm (-0.5 ft)			47.6 (15.1,12)			21.2 (3.7,11)
0 cm (0.0 ft)	38.4 (13.8, 8)	38.9 (11.4, 7)	19.9 (14.8,17)	35.2 (6.2,13)	29.0 (10.9,14)	17.1 (4.7,24)
15 cm (0.5 ft)	10.0 (7.2, 9)	13.3 (5.7,10)	13.3 (7.0,27)	17.2 (12.2,15)	14.2 (7.5,22)	14.4 (5.9,35)
30 cm (1.0 ft)	156.0 (208.7, 2)	20.7 (28.5, 7)	12.0 (7.2,20)	15.0 (16.7,18)	9.7 (5.5,21)	7.5 (6.0,23)
45 cm (1.5 ft)	12.0 (16.6,12)	8.2 (3.7,21)	8.3 (4.2,17)	7.7 (4.9,35)	5.6 (3.3,37)	6.6 (4.3,29)
60 cm (2.0 ft)	13.0 (ND, 1)	7.9 (6.8,15)	3.3 (1.9, 7)	4.3 (2.4,15)	4.3 (1.9,20)	6.2 (4.3,17)
122 cm (4.0 ft)	6.0 (4.4, 6)	4.6 (4.8,19)	3.6 (2.7, 9)	2.5 (1.1, 9)	3.2 (1.2,18)	3.5 (2.0,38)
244 cm (8.0 ft)	3.3 (1.5, 7)	3.2 (1.5,13)	3.5 (2.0,12)	4.6 (2.8, 8)	3.6 (1.8,21)	3.4 (2.6,34)
-15 to 244 cm	20.6 (45.9,45)	10.5 (13.0,92)	14.4 (14.9,121)	12.2 (12.9,113)	8.8 (8.9,153)	8.9 (7.1,211)
			Log (DOC+0.1)			
Field Blank			0.4 (0.0, 2)	0.1 (0.2, 2)		-0.3 (0.4, 5)
Quality Control			0.2 (0.0, 2)	0.3 (0.2, 3)		-0.1 (0.8, 3)
Precipitation	0.8 (0.3,24)			0.6 (0.3,20)		
Soil Depth in Mineral						
-15 cm (-0.5 ft)			1.7 (0.2,12)			1.3 (0.1,11)
0 cm (0.0 ft)	1.6 (0.2, 8)	1.6 (0.1, 7)	1.2 (0.3,17)	1.5 (0.1,13)	1.4 (0.2,14)	1.2 (0.1,24)
15 cm (0.5 ft)	0.9 (0.3, 9)	1.1 (0.2,10)	1.1 (0.2,27)	1.2 (0.2,15)	1.1 (0.2,22)	1.1 (0.2,35)
30 cm (1.0 ft)	1.7 (1.1, 2)	1.1 (0.4, 7)	1.0 (0.3,20)	1.1 (0.3,18)	0.9 (0.2,21)	0.8 (0.3,23)
45 cm (1.5 ft)	0.9 (0.4,12)	0.9 (0.2,21)	0.9 (0.2,17)	0.8 (0.2,35)	0.7 (0.2,37)	0.8 (0.2,29)
60 cm (2.0 ft)	1.1 (ND, 1)	0.8 (0.3,15)	0.3 (0.6, 7)	0.6 (0.2,15)	0.6 (0.2,20)	0.7 (0.3,17)
122 cm (4.0 ft)	0.7 (0.2, 6)	0.5 (0.3,19)	0.4 (0.6, 9)	0.4 (0.3, 9)	0.5 (0.2,18)	0.5 (0.2,38)
244 cm (8.0 ft)	0.4 (0.4, 7)	0.4 (0.4,13)	0.4 (0.4,12)	0.6 (0.2, 8)	0.5 (0.2,21)	0.5 (0.3,34)
-15 to 244 cm	1.0 (0.5,45)	0.8 (0.4,92)	1.0 (0.5,121)	0.9 (0.4,113)	0.8 (0.4,153)	0.8 (0.4,211)

NOTE: Mean (Standard deviation, Count)

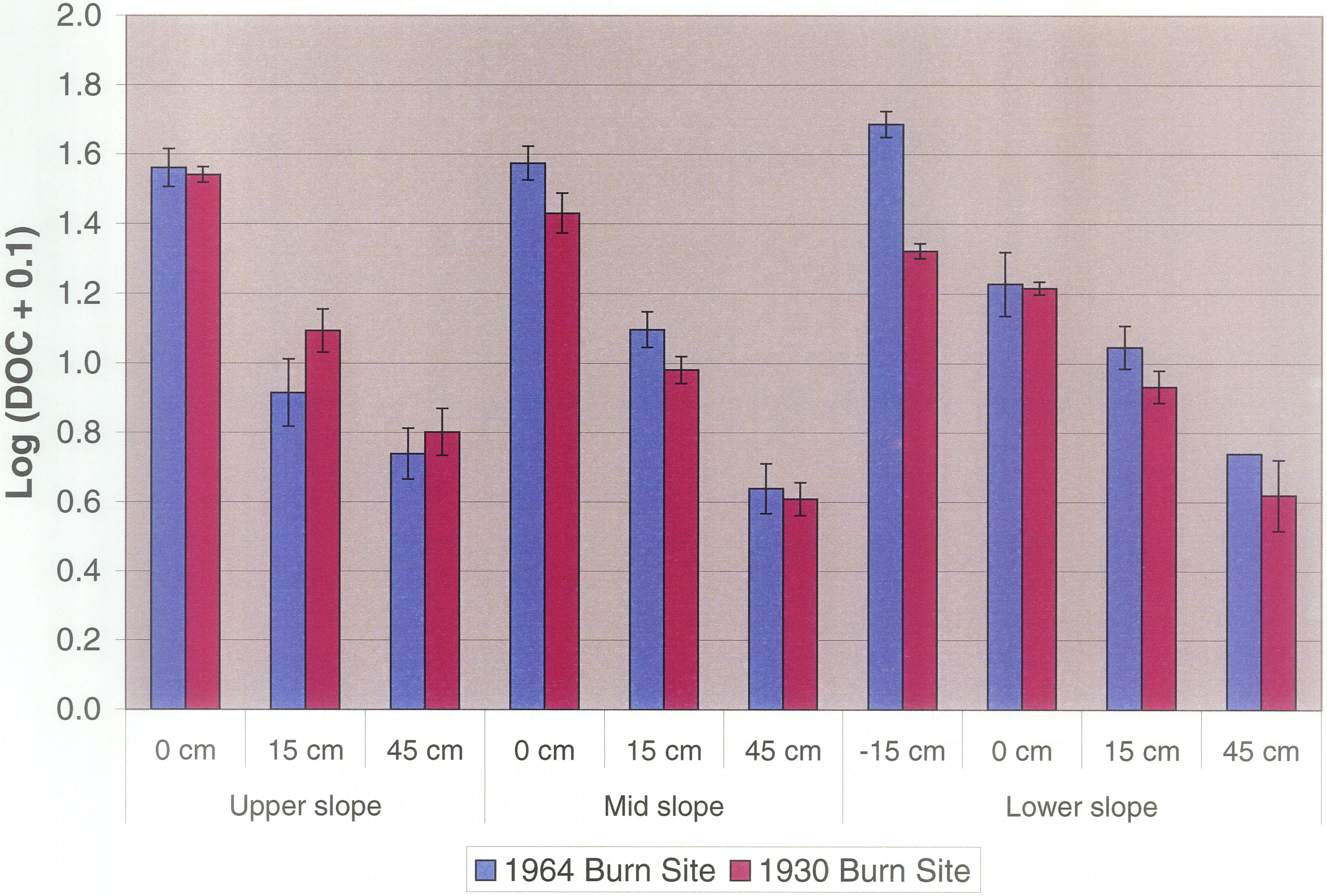


Figure 4.5 Log-transformed DOC concentrations (suction lysimeter water samples) by depth, landscape position and burn site. Error bars are the standard error of the mean.

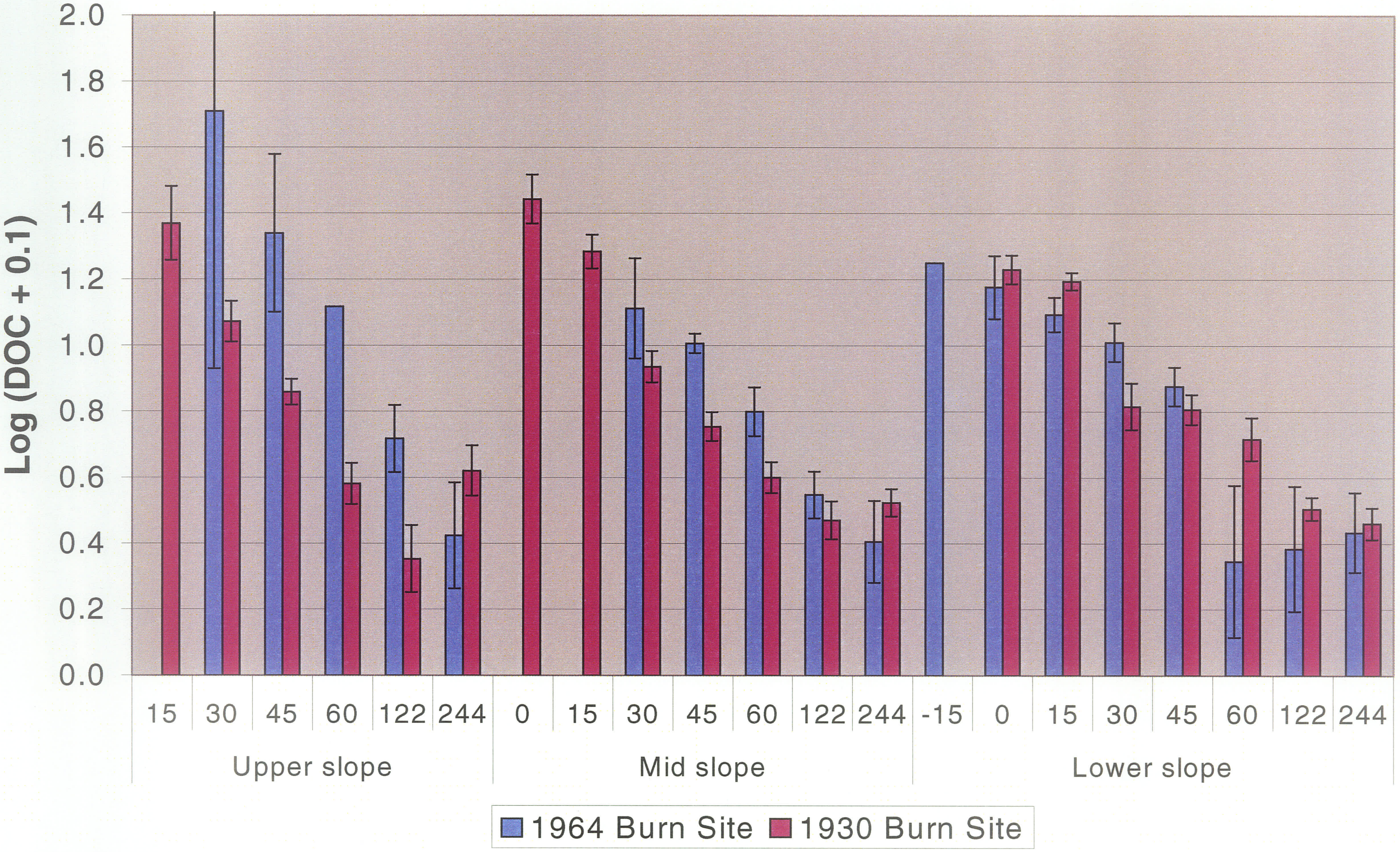


Figure 4.6 Log-transformed DOC concentrations (piezometer soil water samples) by depth, landscape position, and burn site. Depth is measured in centimetres. Error bars are the standard error of the mean. High standard errors and missing error bars indicate insufficient replication due to predominantly unsaturated conditions on the 1964 burn site. Only two observations exist for upper slope piezometers at the 30 cm depth on the 1964 burn site (303.5 and 8.4 mg C L^{-1}, or 2.5 and 0.9 if log-transformed) giving a high standard error of 0.8 .

4.6.2.6 DOC Time Series

Time series graphs (Figures 4.7-4.12) show that DOC concentrations are dynamic, fluctuating over time and with depth. Precipitation data was aggregated into two-week intervals corresponding to DOC biweekly sampling intervals. Snow melt water equivalents for May were estimated using the ten-to-one rule based on the observed decrease in snow depth since mid-April. Measured DOC concentrations for lysimeter and piezometer samples were aggregated into biweekly intervals by burn, landscape position and depth. This masks local variations in the timing and magnitude of water and DOC fluxes within individual sampling locations, but provides an indication of the overall trend in DOC concentrations.

DOC concentrations appeared to vary over two temporal scales: precipitation driven leaching events affected DOC concentrations over shorter time scales (hours to weeks), whereas annual climate driven freeze-thaw, biomass production, and decomposition cycles controlled seasonal fluctuations in soil water DOC concentrations. Extremely high (~300 mg C L^{-1}) to unusually high (40 to 80 mg C L^{-1}) DOC concentrations were observed in mineral horizons $\leq$45 cm deep in May of 2003 on both the 1964 and 1930 burn sites (Figures 4.7, 4.8 and 4.10). Species composition of the tree canopy may explain the higher peak DOC concentrations observed on the 1964 burn site in the spring of 2003, as large DOC inputs are expected from the leaf litter of the trembling aspen which dominate in the mixed deciduous and coniferous forest of the 1964 burn site. Smaller DOC inputs are expected from the mature black spruce forest which dominates on the 1930 burn site. Microbial decomposition of recent leaf litter and mosses may account for some of the higher spring DOC concentrations, but decomposition is thought to increase with soil temperature.

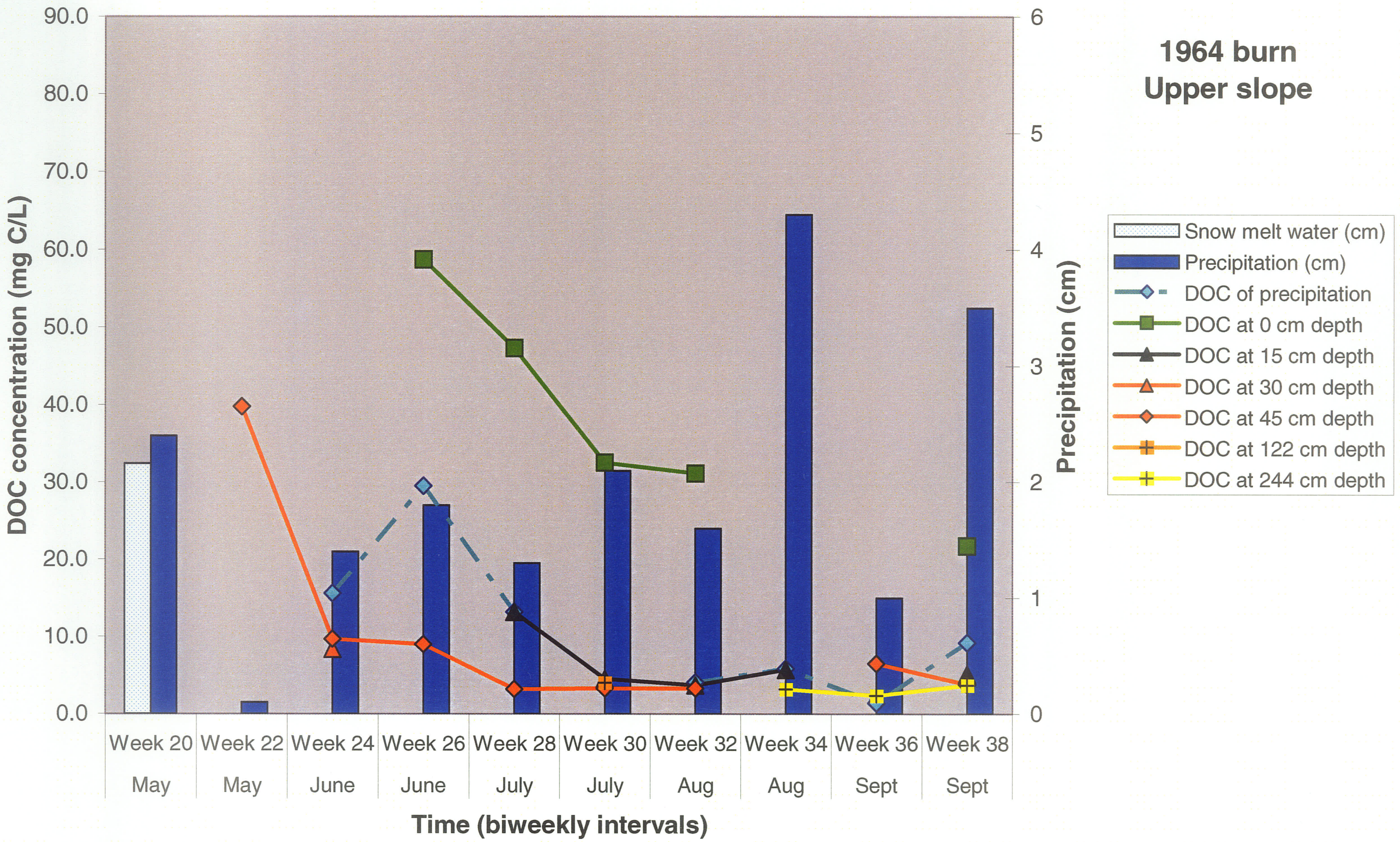


Figure 4.7 Average 2003 biweekly DOC concentrations in upper slope positions of the 1964 burn site.

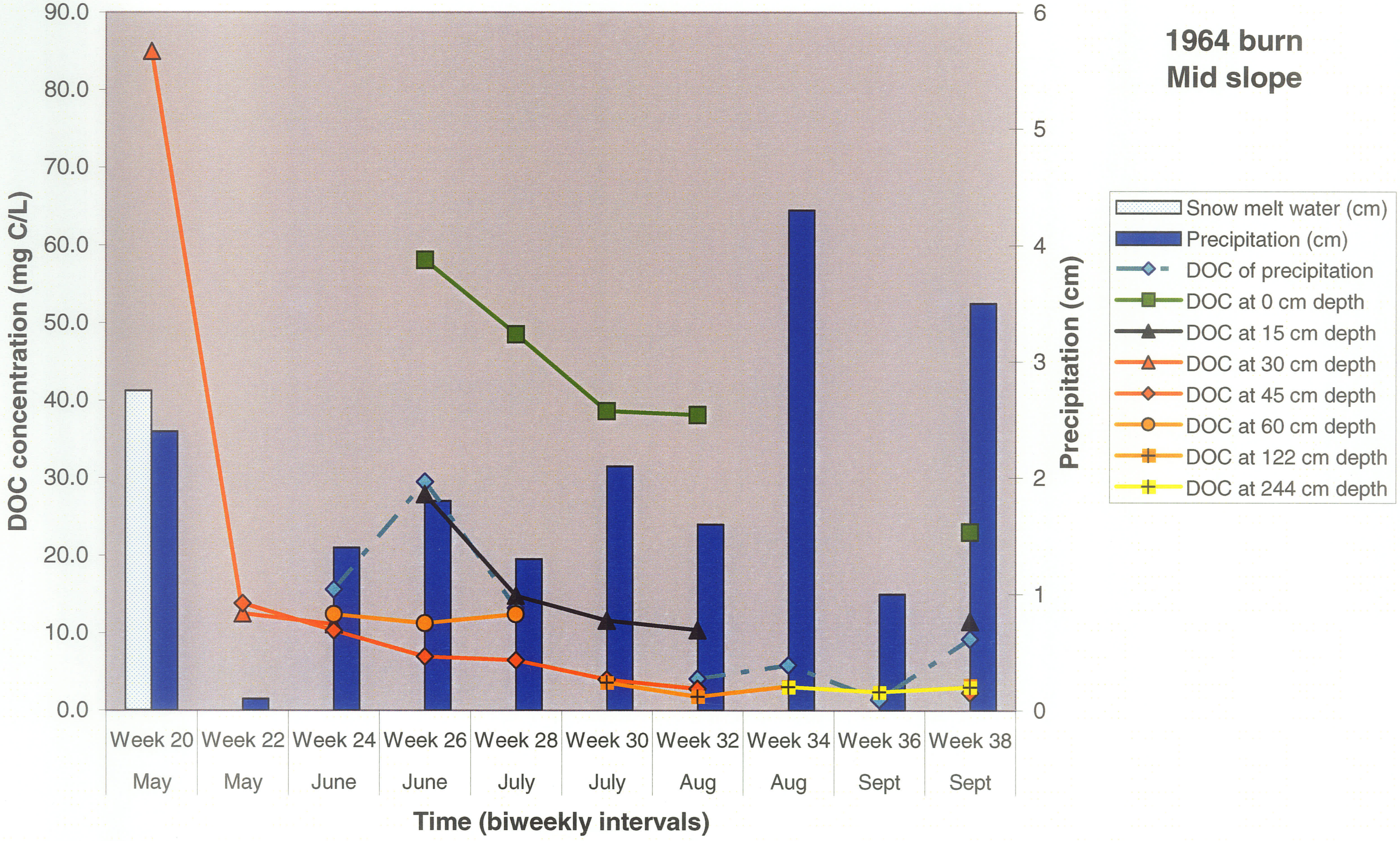


Figure 4.8 Average 2003 biweekly DOC concentrations in mid-slope positions of the 1964 burn site.

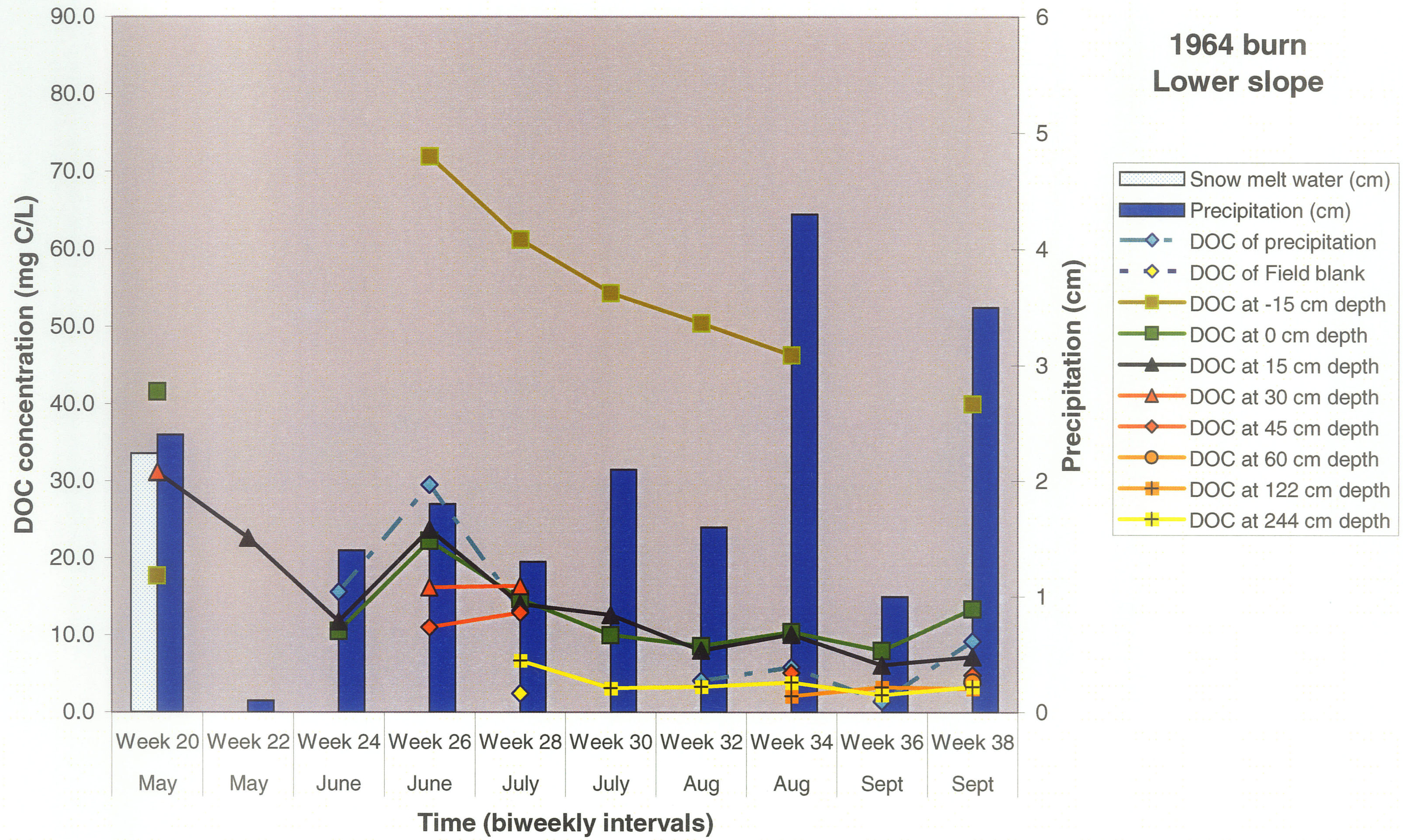


Figure 4.9 Average 2003 biweekly DOC concentrations in lower slope positions of the 1964 burn site.

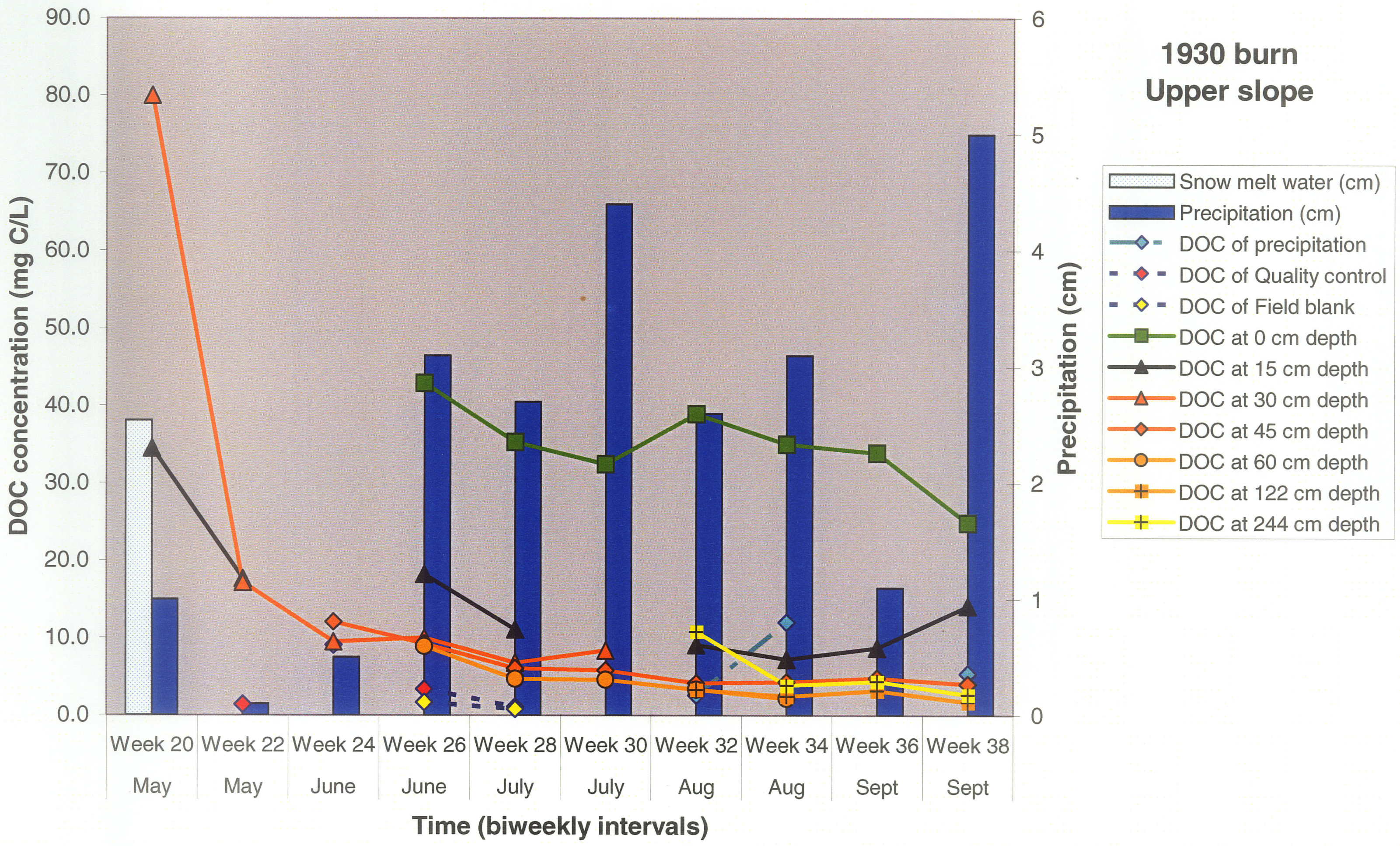


Figure 4.10 Average 2003 biweekly DOC concentrations in upper slope positions of the 1930 burn site.

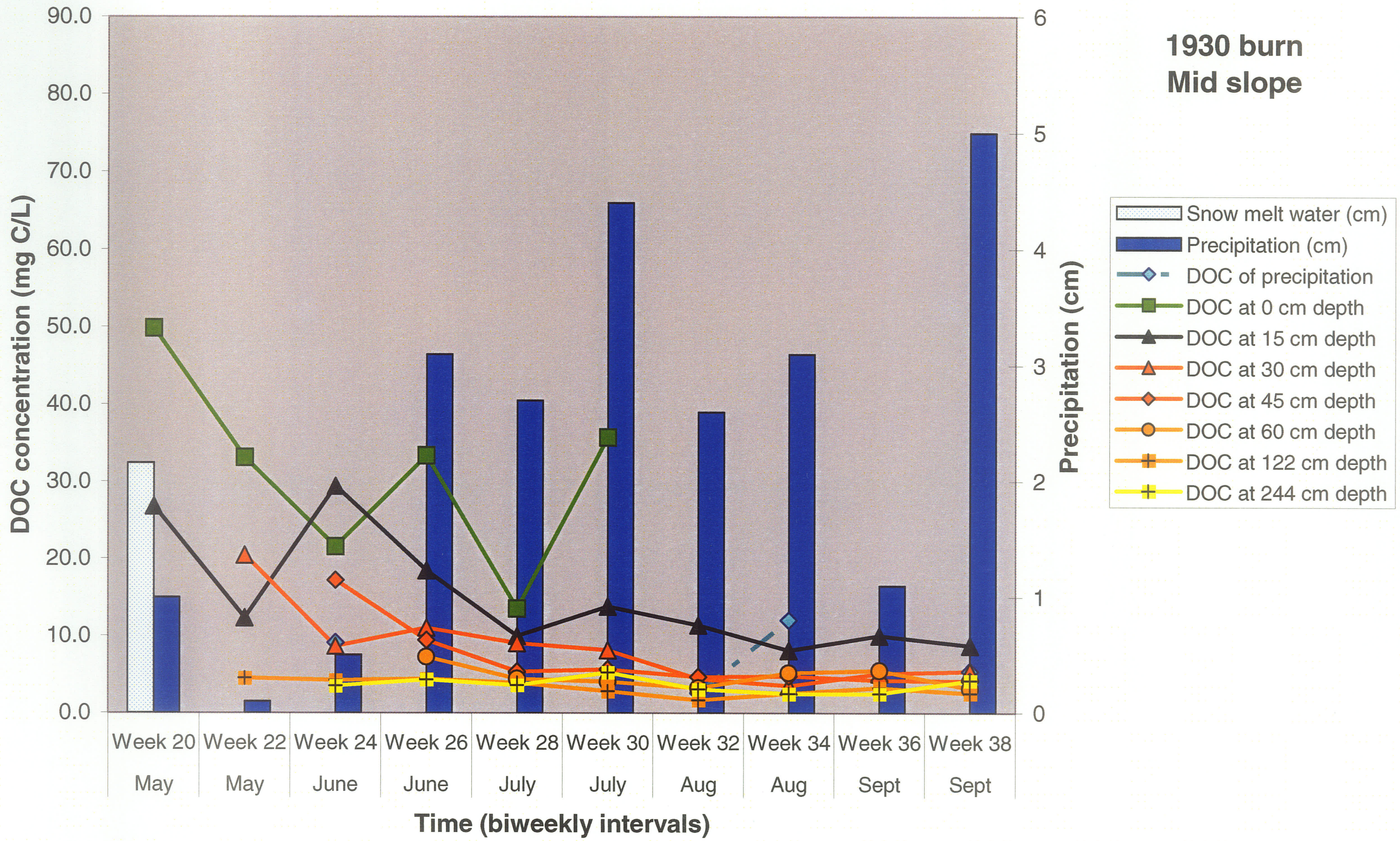


Figure 4.11 Average 2003 biweekly DOC concentrations in mid-slope positions of the 1930 burn site.

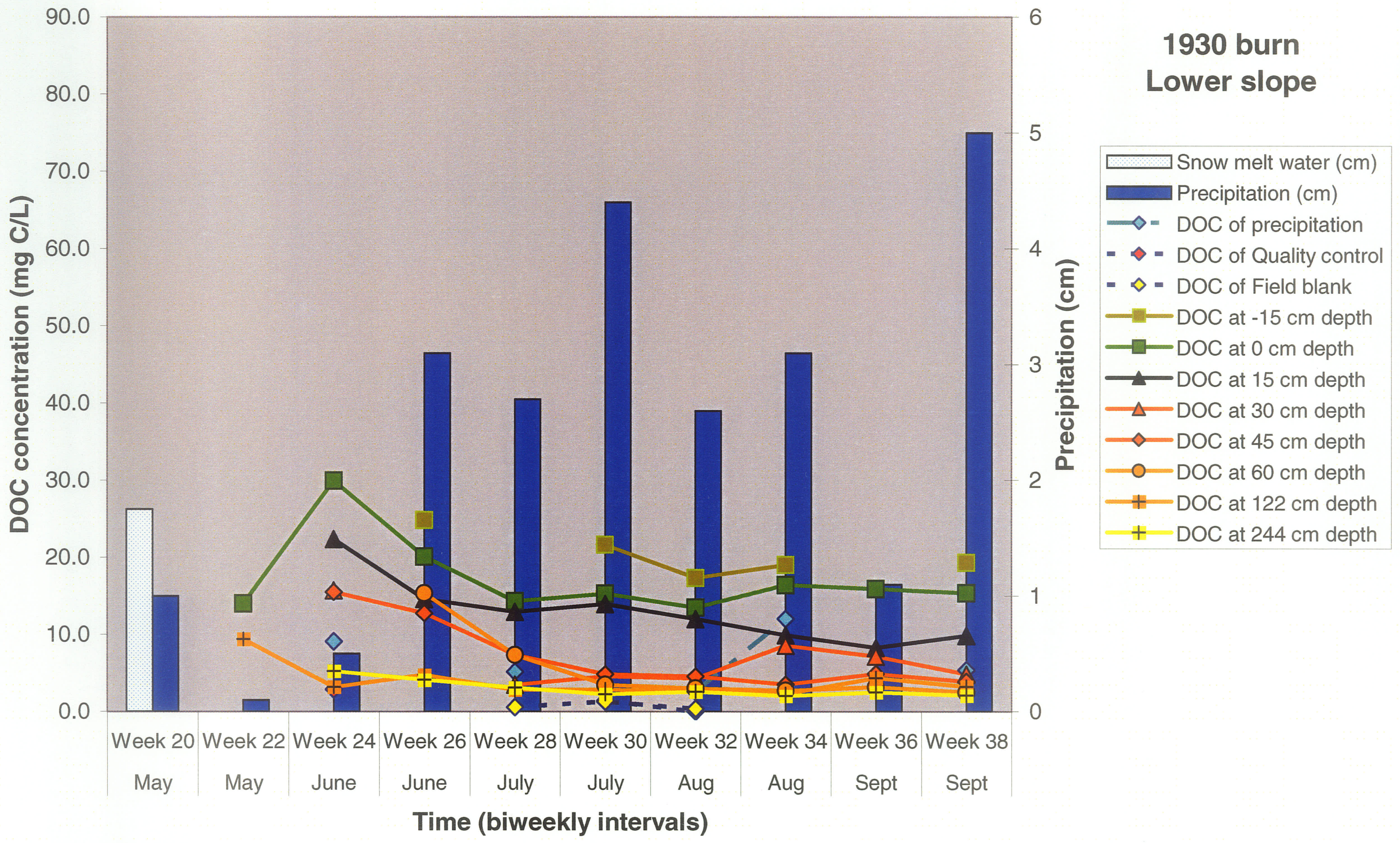


Figure 4.12 Average 2003 biweekly DOC concentrations in lower slope positions of the 1930 burn site.

Unusually high spring DOC concentrations, if valid, may be due to freeze-thaw induced cellular breakdown of recent leaf litter, mosses and microbes, or perhaps root exudate production. Any DOC produced by freeze-thaw induced cellular breakdown or slow microbial decomposition in the fall and spring would either leach into the soil profile or runoff with snow meltwater unless these organic compounds become frozen and remain in the soil profile until after snow melt. Soil water moves laterally downslope over top of the thawing frost table in spring and may transport significant quantities of DOC to rivers as shallow subsurface flow. Laboratory studies are required to verify and quantify freeze-thaw induced release of DOC from recently produced organic materials of different types (leaves, lichen, feathermoss, sphagnum moss, microbes). Additional fall, winter and spring sampling of DOC in soils, and rivers, are required to detect the precise timing and magnitude of freeze-thaw induced DOC fluxes from northern boreal forest ecosystems.

In 2003, DOC concentrations in surface organic horizons steadily declined from late-June until late-September along the central transect of the 1964 burn site (Figures 4.7-4.9). Second order polynomial regressions provided an excellent fit, with R^2 ranging from 0.97 to 0.99, but different regression equations were required for upper, mid and lower slope sites (Figure 4.13).

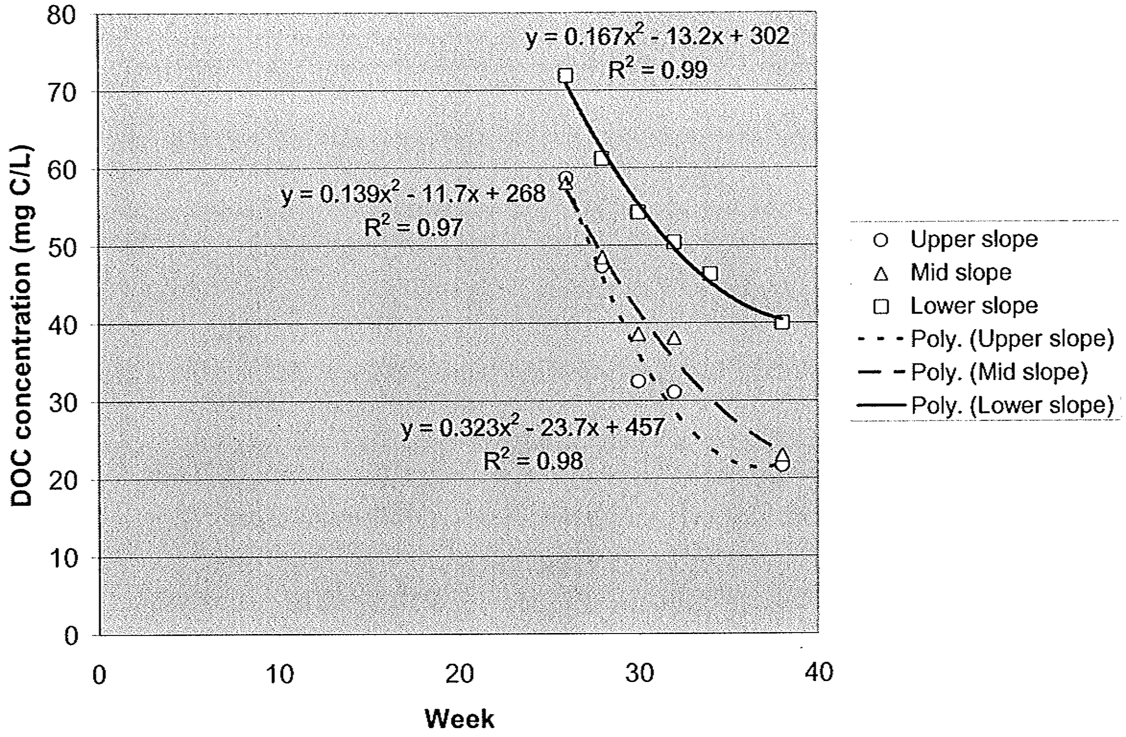


Figure 4.13 DOC concentrations in surface organic horizons of the 1964 burn site.

A matrix table of log(DOC+0.1) values was created in order to decipher the primary factors controlling differences in DOC production within organic horizons near the soil surface (Table 4.8). Only soil water samples collected from shallow suction lysimeters along the central transect were used. Month-of-observation had the greatest influence, followed by burn site. Log transformed DOC values were similar between upper slope positions of the 1964 and 1930 burn sites, but different trends were observed in mid and lower slope positions of the 1964 and 1930 burn sites. Higher than average log transformed DOC values were observed in the cooler, north facing lower slope of the 1964 burn site (MSST 6.7 °C at 10 cm), and lower than average log transformed DOC values were observed in the warmer, south facing lower slope of the 1930 burn site (MSST 9.9 °C at 10 cm). Thus higher log transformed DOC values were associated with cooler months and cooler landscape positions, contrary to published laboratory observations of increased DOC production with increased temperatures.

Table 4.8 Matrix table of log(DOC + 0.1) for soil water samples collected from lysimeters near the soil surface.

	Burn Site		
	1964 Burn Site	**1930 Burn Site**	**Both**
	1.62 (0.14, 26)^{A}	1.44 (0.14, 33)^{B}	1.52 (0.17, 59)
Position			
Upper	1.56 (0.15, 8)^{AB}	1.54 (0.08, 13)^{BC}	1.55 (0.11, 21)
Mid	1.57 (0.13, 7)^{AB}	1.43 (0.17, 9)^{CD}	1.49 (0.17, 16)
Lower	1.69 (0.13, 11)^{A}	1.32 (0.07, 11)^{D}	1.51 (0.21, 22)
Year			
2002	1.60 (0.16, 7)	1.40 (0.12, 12)	1.48 (0.16, 19)
2003	1.62 (0.14, 19)	1.46 (0.15, 21)	1.54 (0.17, 40)
Month			
6	1.80 (0.05, 3)	1.54 (0.13, 6)	1.63 (0.17, 9)^{A}
7	1.66 (0.10, 12)	1.45 (0.16, 11)	1.56 (0.17, 23)^{AB}
8	1.63 (0.09, 5)	1.40 (0.11, 10)	1.48 (0.16, 15)^{BC}
9	1.44 (0.10, 6)	1.38 (0.14, 6)	1.41 (0.12, 12)^{C}

Note: Significant differences ($p=0.05$) based on ANOVA and Tukey's test. Burn and Month were significant main effects, while Burn * Position was a significant interaction effect.

Spring peaks in DOC, and higher DOC concentrations in the young mixed forest stand of the 1964 burn site are similar to the results of Hongve (1999), who found that rapid decomposition of fresh deciduous leaf litter produced higher DOC peaks in fall, whereas, coniferous leaf litter and organic soils release DOC more evenly. But, further analysis (Table 4.8) indicated that soil surface DOC concentrations were not significantly different in upper slope positions where the largest differences in canopy vegetation and forest floor vegetation would be expected. Instead, the largest differences in soil surface DOC concentrations were observed in the lower slope positions, despite the fact that the forest floor consisted of Sphagnum moss on the lower slope of both burn sites.

Regression analyses were conducted using data collected in 2002 and 2003 from the central transects of the 1964 and 1930 burn sites. Precipitation data compiled from standard rain gauges and datalogged tipping bucket rain gauges were summarized into 3-day precipitation, weekly precipitation, biweekly precipitation, and cumulative precipitation since June 1st of each year. Data collected according to sampling depth increments included DOC concentrations, soil tension, average percent SOC, and mass of SOC. This was supplemented by soil temperature data collected in reference to the soil surface. Regression analyses were conducted using both forward and backward elimination techniques, with and without an intercept for both DOC and log(DOC + 0.1 mg C L^{-1}), first for only surface lysimeters samples, and then for both lysimeter and piezometer samples at all depths. Multiple potential solutions were obtained with r^2 values ranging from 0.41 to 0.91, the best regressions being achieved using log(DOC + 0.1 mg C L^{-1}) without an intercept. Average percent SOC and/or mass of SOC were found to be significant ($p=0.05$) effects within all regression models. Weekly precipitation, cumulative seasonal precipitation, and soil temperatures at the 10 and/or 20 cm depth were significant ($p=0.05$) effects within most but not all regression models. Biweekly precipitation and soil temperatures at deeper depths (50 to 150 cm) were significant (p=0.05) effects within a few regression models. Cumulative 3-day precipitation wasn't significant (p=0.05) in any regression models, either due to the high variability or due to the potential inclusion of precipitation occurring later in the day during the day of sample collection. Soil tension was significant (p=0.05) in some DOC and most log(DOC + 0.1 mg C L^{-1}) regressions based on all lysimeter and piezometer sampling depths.

Using DOC data in 2002 and 2003 for all transects on the 1964 and 1930 burn sites, soil temperatures at the 10 cm depth and cumulative seasonal precipitation (Sum_PPT) were then added to a simplified ANOVA model. Statistical analysis using ANOVA repeated measures procedure with compound symmetry and iterative removal of non-significant factors (p>0.10) indicated that Burn, Depth, and Year were highly significant effects (p=0.01) followed by Sum_PPT, Burn * Depth, Month, Position, and Position * Depth. Soil temperatures at the 10-cm depth was not a significant factor controlling DOC concentrations (p=0.05). Removal of Sum_PPT from the model resulted in only Depth, Month and Year remaining as significant factors (p=0.05), whereas Burn, Depth, Position, Burn * Depth, and Position * Depth were all significant factors (p=0.05) when Sum_PPT, Year, and Month were removed from the model.

Although DOC concentrations were found to be correlated with cumulative seasonal precipitation, DOC concentrations may also be related to cumulative degree days. An overall depletion of DOC concentrations throughout the summer, combined with smaller peaks in the summer and fall, suggests that increased DOC production by microbial decomposition during warmer months may be largely offset, either by precipitation dilution or by DOC losses via increased oxidation to CO_2. Q_{10} values range from ~1.3 to 1.7 for DOC production

(Freeman et al., 2001; Moore and Dalva, 2001) versus ~2.6 for CO_2 production (Savage et al. 1997), thus indicating that a 10 °C increase in soil temperature would result in a 30 to 70 % increase in DOC production, but a 160 % increase in CO_2 production.

4.7 Conclusions

DOC concentrations were significantly different (p=0.05) between sampling depths in the soil profile, which was expected since the factors controlling DOC production (quantity and quality of soil carbon stocks, soil temperature and moisture) and transport (adsorption, hydraulic conductivity) are also related to depth within the soil profile. DOC concentrations decreased from 60 to 20 mg C L^{-1} in surface organic horizons, to ~ 3 to 4 mg C L^{-1} in mineral horizons at the 244-cm depth. Average % SOC content and mass of SOC were both significantly related to DOC and log transformed DOC concentrations. Observed DOC concentrations had a positively skewed log-normal distribution, with DOC concentrations and variability decreasing proportionally to one another with increasing depth in the soil profile, indicating a multiplicative effect of some factor(s), for example: % SOC, rate of production, percent adsorption, rate of decomposition, and dilution by precipitation. Precipitation driven leaching events may explain the observed dynamic variations in DOC concentrations and the associated log-normal distribution of DOC concentrations. Peak DOC concentrations occurred in spring, followed by an overall decrease in DOC concentrations until early-fall. The decline in DOC concentrations over time was significantly correlated to cumulative seasonal precipitation, but could also be related to other effects, such as cumulative degree days and depletion of soluble organic carbon by oxidation into CO_2. Forest stand age (burn site) had a significant (p=0.05) effect on DOC concentrations, but was smaller in importance than differences in DOC concentrations with depth and time. Differences in DOC concentrations between different aged forest stands and between landscape positions within a forest stand appear to be dependent on precipitation inputs, canopy interception, aspect, and their combined influence on soil temperature and moisture. On average DOC concentrations were ~3 mg C L^{-1} higher on the 1964 burn site than the 1930 burn site, but differences were greatest in surface organic horizons, especially in lower slope positions due to differences in aspect and the quantity of SOC stocks.

5. SOIL ORGANIC CARBON

5.1 Abstract

Detailed soil surveys were conducted between Thompson and Leaf Rapids, Manitoba, to measure the effect of drainage and forest stand age on organic horizon thickness and surface carbon stocks within a forest fire chronosequence developed on clay textured soils. Thickness of surface organic horizons was associated with soil drainage and forest stand age. Average organic horizon thickness in moderately well drained soils ranged from ~2 cm on recently burnt sites to ~16 cm in mature forest stands. Similar variations in organic horizon thickness also occurred within very short distances (< 1 m) due to the presence of relic earth hummocks and variations in local fire severity. Surface organic carbon (OC) stocks ranged from ~1 kg C m^{-2} in upper slope positions to ~30 kg C m^{-2} in poorly drained bog veneers. The ash method permitted the rapid estimation of % OC in organic horizons, but was unsuitable for estimating % OC in clay soils. Using the split sample LECO method, total OC stocks summed from the soil surface to the 244 cm depth were greater below the mature 1930 burn site (62 to 77 kg C m^{-2}), compared to the younger 1964 burn site (48 to 74 kg C m^{-2}), and increased from upper to lower slope positions within both sites. Cryoturbation redistributed surface OC stocks into the mineral soil profile, whereas leaching likely redistributed some dissolved organic carbon to greater depths.

5.2 Introduction

The study area is located in the northern boreal forest between Thompson and Leaf Rapids in north-central Manitoba. The accumulation of organic carbon at the soil surface is a long process, but its removal may occur in the matter of hours or days as forest fires are a common occurrence in the boreal and quickly remove large quantities of organic carbon from the soil surface. Quantity and distribution of soil organic carbon stocks in the northern boreal forest are associated with forest stand age, soil texture, drainage regime, and depth within the soil profile (Trumbore and Harden 1997; Veldhuis and Rapalee, 1999; Rapalee et al. 1999). Therefore, there is a need for more detailed carbon accounting by forest stand age and drainage class, especially within the dominant clay textured soils in the Thompson study area.

5.3 Objectives

Detailed soil surveys were conducted near Thompson, Manitoba to provide background soils information and site characterization to support several research projects relating to carbon distribution and cycling in a northern boreal forest fire chronosequence. The primary purpose of these projects is to quantify the effect of drainage and forest stand age on surface soil organic carbon content. i) characterize and quantify the effect of drainage and forest stand age on surface soil organic carbon content

5.3.1 Hypotheses

Organic horizon thickness and surface organic carbon stocks:

1) are significantly different between different aged forest stands and landscape

positions;

2) are significantly greater within older forest stands;

3) increases from upper to lower slope landscape positions;

5.4 Methodology

5.4.1 Selection of study sites

The study area is located in the northern boreal forest between Thompson and Leaf Rapids in north-central Manitoba. Collaborating researchers selected seven different aged forest stands (burn sites) between Thompson and Leaf Rapids in 2001 to represent a forest fire chronosequence developed on clayey glaciolacustrine parent materials. Forest fire activity resulted in the addition of a new burn site in 2003. Two of these sites, the 1964 and 1930 burn sites, were selected for detailed study as they represented young and mature forest stands located on clayey glaciolacustrine parent materials in gently undulating landscapes, and were in relatively close proximity to Thompson with easy access from the highway. Three parallel transects (toposequences) were established in the 1964 and 1930 burn sites to provide replication of upper, middle and lower slope positions. Piezometers, frost tubes, and thermistors were installed at these sampling locations as part of a separate study.

5.4.2 Site Characterization

Soil profile descriptions (17) were conducted at 50-m spacings along 4 transects radiating away from a CO_2 flux tower located in the upper slope position of each burn site. This provided a description of soil distribution within a 250 m radius of the tower (i.e. the tower footprint). Soil samples and detailed soil descriptions were collected at a minimum of one wet and one dry soil pit on each burn site. Additional soil samples and descriptions were collected as necessary to characterize the burn sites and any sub-sites which had been established outside the tower footprint. Fewer soil profile descriptions were collected on the 1995 burn site, since this site was abandoned by the majority of collaborating researchers due to inherent differences in soils and vegetation compared to the other burn sites (pre-burn vegetation on the upland of the 1995 burn consisted of jack pine, and the soils were shallow over bedrock). The 1995 burn site was also in close proximity to the town of Leaf Rapids, creating a risk of human disturbance to the study site and instruments.

5.4.3 Measurement of Soil Physical and Chemical Properties

Bulk density samples were collected using a variety of methods including triplicate soil cores, cut out blocks of soil, and augered samples. Mineral soil samples were oven dried at 100 to 105 °C, whereas organic samples were oven dried at 70 °C to minimize the loss of organic matter. Samples were weighed after 24 hours and at regular intervals thereafter until there was less than a 0.1% change in weight over a 6 hour period. Bulk density was then calculated as the oven dried weight of a soil sample divided by it's original volume.

The ash method (Page et al., 1982; Karam, A. 1993) was used to estimate organic matter content and organic carbon content by combusting soil samples at 600 °C for 24 hours. Percent organic matter (% OM) was calculated as 100 - % ash, where:

$$\%\ \text{Ash} = \frac{\text{Weight of oven dried soil (105°C) - Weight of ash remains (600° C)}}{\text{Weight oven dried soil (105°C)}}$$

and percent organic carbon (% OC) was calculated as:

% Organic Carbon = % Organic Matter * 0.58

Combustion of soil samples at low temperatures (375 to 600 °C) oxidizes organic carbon (OC), but some humic materials resist combustion at temperatures below 600 °C, particularly in the presence of gibbsite (Gallardo and Saavedra, 1987; Tiessen and Moir, 1993). Inorganic carbon (IC) contained in carbonates (calcite and dolomite) decompose only at higher temperatures. Dolomite reportedly decomposes at 740 °C, and calcite at 970 °C (Girard and Klassen, 2001). Combusting soil samples at high temperatures (900-1350 °C) volatilize carbonates as well so that total carbon (TC) is determined, where total carbon (TC) is the sum of total organic carbon (TOC) and total inorganic carbon (TIC) (Tiessen and Moir, 1993; Girard and Klassen, 2001).

Girard and Klassen (2001) compared seven methods for analysis of carbon in soils and recommended the measurement of total carbon (TC) and total inorganic carbon (TIC) using split samples and the direct measurement of CO_2 production during oxidation. This methodology was adopted for the current study, and was adapted as follows. Soil samples were air dried, ground to pass a 2-mm sieve, and then ball ground for 5 minutes. One sub-sample remained untreated, while the second sub-sample was oxidized (ashed) at 600 °C for 24 hours to remove volatile and readily oxidizable organic carbon so that only residual inorganic carbon remained in the ashed sample. The untreated and ashed samples (~0.2 g each) were then oxidized at high temperatures (1350 °C) in a LECO CNS-2000 analyser to determine TC and TIC, respectively, by direct measurement of carbon dioxide released during oxidation using infrared spectrometry techniques. Moisture content was measured from the remaining air dried untreated and ashed samples for correction of TC and TIC measurements, and % ash was used as a correction factor for TIC. TC was therefore corrected for moisture, and TIC was corrected for moisture and percent of original sample remaining as ash. Corrected total organic carbon (TOC) was then calculated as corrected TC minus corrected TIC. This methodology is hereafter referred to as the split sample LECO method.

5.5 Results and Discussion

5.5.1 Fire Severity

Seasonal and spatial precipitation trends can have a large impact on wildfires, creating excessively dry conditions in some areas. Differences in fire severity within and between burns are attributed to speed of fire advance as affected by fuel supply, moisture conditions, wind speed and direction, and topographic effects. Topography affects fire severity due to the moisture gradient as well as the fact that fire progresses rapidly up-slope and slower downslope (J. Harden, personal communication, USGS, Menlo, CA).

Standing dead trees often remain after the occurrence of forest fires in this boreal environment (Figure 5.2, and 5.5 to 5.7). Needles and small twigs were completely burnt in some parts of the burn, whereas, in less severely burnt areas, coniferous needles killed by the fire were subsequently deposited on the surface of the forest floor (Figure 5.2 and 5.3). The depth of surface organic horizons lost by fire can vary significantly within a one metre distance (Figure 5.1 to 5.4). The top few centimeters of the organic soil surface may be burnt over a large areal extent of the fire burn scar. Unburnt sphagnum hummocks may remain in lowland patches or in isolated mid-slope locations (Figure 5.2). As the fire continues to smolder, organic horizons may burn completely to the mineral surface in a dendritic like pattern in some locations (Figure 5.1) and burn larger patches in other locations (Figure 5.4).

The 2003 burn site had scattered regeneration of vegetation a month after the fire, and widespread regeneration the next year on areas where the duff layer was completely burnt (H. Veldhuis, pers. comm., AAFC, Winnipeg). The 1998 burn site had significant fireweed and trembling aspen regeneration within the first five years after the fire (Figure 5.6). On the 15 year old 1989 burn site (Figure 5.7), many of the standing dead trees had fallen, but were often not in direct contact with the soil. In mature forest stands, fallen dead trees were incorporated into surficial organic horizons as coarse woody debris and became overgrown with mosses and lichen (Figures 5.10 and 5.11). Although the burning of aboveground biomass and surface organic horizons results in a large and abrupt short term release of carbon, standing dead trees and accumulation of coarse woody debris at the soil surface (Figures 5.7 to 5.13) represent a form of mid to long term carbon storage.

Figures 5.1-5.4 Photos of a recent burn site.

Figure 5.1 Recent fire burn (2003) with approximately 20% of area with organic horizons burnt completely to the mineral soil surface.

Figure 5.2 Patches of burnt and unburnt moss on the 2003 burn. Fire scarred trees in background.

Figure 5.3 Patches of burnt and unburnt moss overlain by coniferous needles and regenerating forest floor vegetation .

Figure 5.4 Abrupt changes in organic horizon thickness occur along the edge of a ground fire.

Figures 5.5-5.11 Vegetation chronosequence photos.

Figure 5.5 Standing dead trees and burnt moss on the 2003 burn site.

Figure 5.6 Standing dead trees and fireweed on the 1998 burn site.

Figure 5.7 Regenerating trembling aspen and fallen dead trees on the 1989 burn site.

Figure 5.8 Coarse woody debris and young mixed forest stand on the 1981 burn site.

Figure 5.9 Mixed forest stand on the 1964 burn site.

Figure 5.10 Closed black spruce stand on the 1930 burn site.

Figure 5.11 Feathermoss groundcover and black spruce on the 1870 burn site.

5.5.2 Organic Horizon Distribution and Thickness

Organic deposits on upland sites (LFH horizons) are in the form of leaves, twigs, needles, feathermoss, lichen and coarse woody debris in various stages of decomposition. Peaty organic deposits (O horizons) in lower slope positions are developed primarily from decomposing sphagnum moss with minor quantities of feathermoss. Sedge and fen peat dominate in water saturated depressional landscape positions.

Comparison of data for the seven different aged forest stands (burn sites) indicates that drainage and forest stand age significantly affect the thickness of organic horizons. Average LFH thickness in well drained landscape positions varied from 2 cm thick on recently burnt forest stands, to 6 cm thick on young forest stands, and 16 cm thick on mature forest stands (Table 5.1).

Table 5.1 Thickness of organic horizons based on regular soil descriptions (updated from Cyr and Veldhuis, 2002b).

	Year of Burn						
Soil Drainage	**1998**	**1995**	**1989**	**1981**	**1964**	**1930**	**1870**
	Age of burn in years, 2002 reference year*						
	4 yr	7 yr	13 yr	21 yr	38 yr	72 yr	132 yr
	Thickness of Organic Horizons (cm)						
Moderately Well	2 (1,14)	5 (2,4)	3 (2,22)	6 (1,9)	6 (2,19)	15 (4,16)	17 (3,5)
Imperfect	4 (2,3)	7 (ND,1)	11 (0,2)	7 (4,2)	8 (1,2)	18 (5,4)	19 (8,5)
Poor	ND	ND	ND	38 (25,2)	37 (13,2)	25 (15,5)	45 (18,4)

NOTE: Mean (+/- standard deviation, count)
* Measurements were made between 2001 and 2003,
except for the 1995 burn site, which was measured in 2004.

Organic horizon thickness was highly variable in poor to very poorly drained landscape positions, with average thickness varying from 25 to 45 cm. This may be due to differences in the nature of poor to very poorly drained mineral and organic landforms within and between burn sites. Bog veneers are dominant, but palsas and alder swamps on the 1981 burn site, and fens on the 1930 burn site do not appear to have been burnt during the last stand-killing fire. Loss of organic deposits due to wildfire is expected to occur more frequently on well to imperfectly drained upland soils than poorly drained soils, with very poorly drained soils only rarely being affected. The net impact of wildfire is expected to be greater on imperfectly to poorly drained soils in mid-slope positions as they have large carbon stores in surficial organic horizons and are susceptible to wildfires during excessively dry periods.

Significant variability in organic horizon thickness also occurs within cryoturbated portions of the landscape. Organic horizon thickness on the 1998 burn site varied from 1 to 4 cm on top of a 30 cm high earth hummock, and 8 to 20 cm thick in an adjoining trough.

5.5.3 Soil Organic Carbon Stocks

Estimates of soil carbon stocks based on the ash method are presented in Table 5.2 and Figures 5.12 to 5.18 for surface organic horizons (LFH, Of, Om, Oh) within seven different aged forest stands. SOC stock in surface organic horizons ranged from ~1 to 4 kg C m^{-2} within moderately well drained soils, and ~6 to 35 kg C m^{-2} within poorly drained soils. Surface SOC stocks of moderately well drained soils were slightly greater on the mature 1930 burn site compared to the younger 1964 burn site (3.6 ± 1.0 kg C m^{-2} versus 1.9 ± 1.0 kg C m^{-2}), but this difference was not statistically significant ($p=0.08$, one tailed t-test).

Surface SOC stocks of poorly drained soils were smaller on the mature 1930 burn site compared to the younger 1964 burn site (10.7 ± 4.0 kg C m^{-2} versus 19.1 ± 14.8 kg C m^{-2}), but this difference was also not statistically significant ($p=0.20$, one tailed t-test).

Table 5.2 Estimated surface SOC stocks based on the ash method (updated from Cyr and Veldhuis, 2002b).

	Year of Burn						
	1998	**1995**	**1989**	**1981**	**1964**	**1930**	**1870**
	Age of burn in years, 2002 reference year*						
	4 yr	7 yr	13 yr	21 yr	38 yr	72 yr	132 yr
Soil Drainage	Surface Soil Organic Carbon (kg C per square metre)						
Moderately Well	1.0	0.9	3.4	2.2 (0.7,2)	1.9 (1.0,3)	3.6 (1.0,2)	2.0
Poor	ND	22.5	6.4	ND	19.1 (14.8,3)	10.7 (4.0,3)	15.2
Poor, with permafrost	ND	ND	ND	ND	20.9	ND	20.7

Note: Mean (+/- standard deviation, count)
%OM = 100% - % Ash; and %OC = %OM x 0.58
* Measurements were made between 2001 and 2004.

SOC stocks in organic horizons varied due to local fire severity and occurrence of mineral and sphagnum hummocks. Bulk density and ash content changed rapidly with depth, especially within highly decomposed (humic) organic horizons. This made it difficult to accurately estimate organic carbon stocks. Sampling humic organic horizons (Oh horizons) using smaller (5 to 10 cm) depth increments will improve estimates of SOC stocks of poorly drained soils.

Figures 5.12-5.18 Photos of soil profiles and estimates of surface SOC stocks based on the ash method.

Figure 5.12 1989 burn site (Profile 89D1)
Wabowden series (O.GL)
Moderately well drained.
Surface soil carbon: 3.4 kg C/m^2

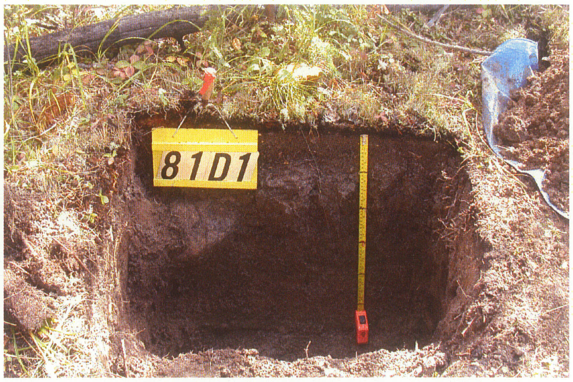


Figure 5.13 1981 burn site (Profile 81D1)
Wabowden series (O.GL)
Moderately well drained.
Surface soil carbon: 1.8 kg C/m^2

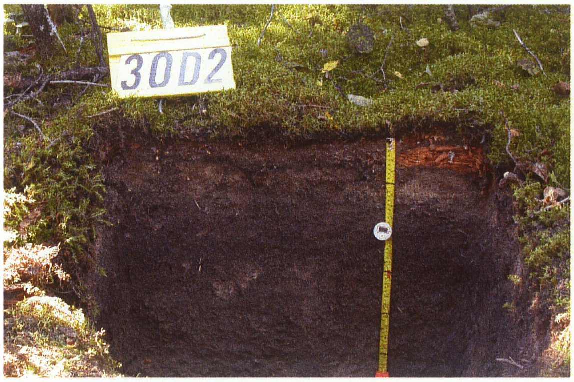


Figure 5.14 1930 burn site (Profile 30D2)
Sipewesk series (O.GL)
Moderately well drained.
Surface soil carbon: 2.9 kg C/m^2

Figure 5.15 1870 burn site (Profile OBD2)
Sipewesk series (O.GL)
Moderately well drained.
Surface soil carbon: 2.0 kg C/m^2

Figure 5.16 1930 burn site (Profile 30D1)
La Perrouse series (O.LG), peaty phase.
Poorly drained.
Surface soil carbon: 13.9 kg C/m^2

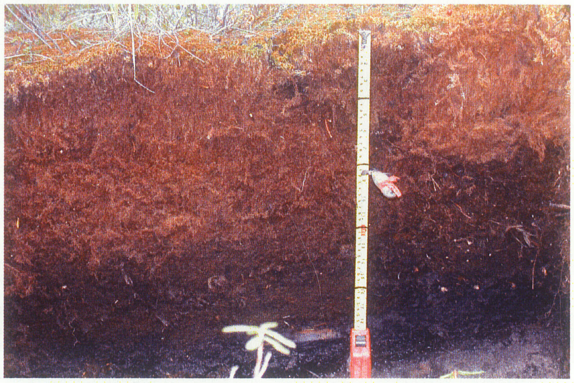


Figure 5.17 1870 burn site (Profile OBD1)
Cousin Lake series (T.F)
Poorly drained.
Surface soil carbon: 15.2 kg C/m^2

Figure 5.18 1870 burn site (Profile OBD3)
Nichols Lake series (TFI.OC), taxonomic variant. Poorly drained.
Permafrost from 52 to 90 cm.
Surface soil carbon: 20.1 kg C/m^2

Figure 5.19 Melting of permafrost causes trees to tilt, thus giving them a "drunken forest" appearance.

The ash method only provides an estimate of organic mater content as the weight loss attributed to combustion of organic matter may be due in part to the loss of carbonates, structural OH, or residual moisture from some clay soils (Goldin, 1987; Schulte, 1995). Furthermore, the calculation of organic carbon content is based on the assumption of a constant carbon content of 58% within soil organic matter, whereas carbon content varies between organic compounds and with various stages of decomposition. Soil organic matter contains 40 to 58% organic carbon by weight (Page et al., 1982).

The ash method provides rapid estimates of soil organic carbon stocks for surface organic horizons, but comparisons with data collected along the central transects of the 1930 and 1964 burn sites using the split sample LECO method indicates that the ash method seriously overestimates % SOC in clay soils (see Appendix Table 10.9). The OC/OM conversion factor, calculated as % TOC / (100 - % Ash), ranged from 48 to 58% for organic horizons (average of 53%), and from 10 to 46% for mineral horizons (average of 22%). A conversion factor of 58% will therefore seriously overestimates % OC within clay soils. Based on the 84 soil samples for which % ash, % TC and % TIC were measured, linear regression (Figure 5.20) indicates that a better estimate of % OC can be achieved using the equation $\% \text{OC} = 0.564(100 - \% \text{Ash}) - 2.7$, ($r^2 = 0.995$). Predicted % OC was within ± 2.4 % OC, 95 % of the time (two standard deviations).

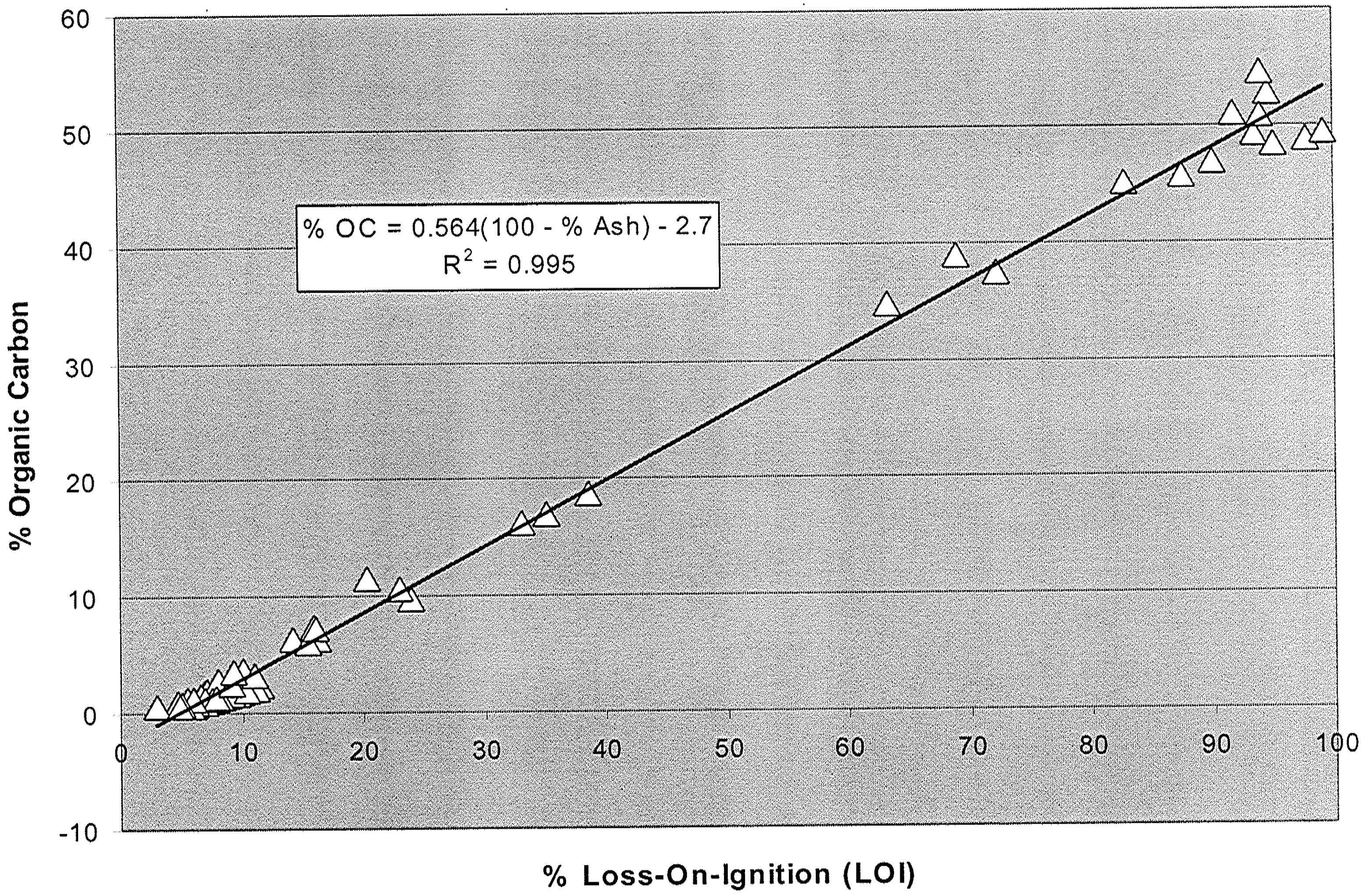


Figure 5.20 Linear regression of % OM as estimated by Loss-On-Ignition (LOI) and % OC determined by LECO analysis using split samples.

Percent OC determined using the split sample LECO method, was highly variable in organic horizons (Figure 5.21), and decreased with depth due to increased decomposition of older material. It was sometimes difficult to differentiate Oh (≥17 % OC) and Ah (< 17 % OC) horizons in the field, thus, the 18-cm thick Oh horizon identified on the lower slope of the 1964 burn site likely included some Ah. Therefore, weighted average % OC content (as shown in Figure 5.21) is misleading, as it aggregates data for several horizons with different thicknesses, % OC concentrations, and bulk densities. Data for individual organic horizons indicates that % OC content at the soil surface was slightly higher within the 1930 burn site (Table 5.3), but differences were not significant (p=0.05).

Table 5.3 Percent soil organic carbon in surface organic horizons, based on the split sample LECO method.

	Upper slope	Middle slope	Lower slope
1964 burn site	45.8	49.4	48.3
1930 burn site	54.6	52.9	48.8

SOC stocks measured on the 1930 and 1964 burn sites using the split sample LECO method support the conclusion that greater organic carbon stocks accumulate in wetter lower slope positions than in upper slope positions (Figures 5.22). Surface SOC stocks were greatest on the poorly drained lower slope of the 1964 burn site (30.6 kg C m^{-2}) where sporadic permafrost occurs, followed by the poorly drained lower slope of the 1930 burn site (16.5 kg C m^{-2}). Surface SOC stock in middle and upper slope positions ranged from 1.4 to 5.1 kg C m^{-2} and appear to be dependent on the local severity of past fires, and to a lesser degree, on the recovery of moss after fire, and the preservation of SOC stocks by cool and moist to cold and wet soil conditions.

SOC stocks in the mineral soil profile (from 0 to 60 cm) ranged from 8.8 to 16.4 kg C m^{-2}, with larger SOC stocks being dependent on the degree of cryoturbation. At the 60 to 122 cm depth, OC stocks were similar between landscape positions within the 1930 burn site (14.1 to 14.6 kg C m^{-2}), but showed a decreasing trend from upper to lower slope positions on the 1964 burn site (14.4 to 8.0 kg C m^{-2}). Higher than average surface OC stocks in the permafrost affected lower slope of the 1964 burn site suggests that colder soil temperatures have decreased organic matter decomposition. Lower than average OC stocks at the 60 to 122 cm depth at the same site suggests that the permafrost has decreased the transport of water and dissolved OC into the underlying parent materials. Deep OC stocks were significantly larger ($p=0.05$) on the 1930 burn site (32.1 to 39.2 kg C m^{-2}) compared to 1964 burn site (21.5 to 23.1 kg C m^{-2}), suggesting either: i) greater long-term (pre-fire) accumulation of dissolved organic carbon at depth within the 1930 burn site; or ii) inherent differences in background OC concentrations inherited from the parent material. Slightly larger OC stocks at the 122 to 244 cm depth in mid-slope positions might be due to lateral water and DOC transport from upper slope positions or increased downward leaching in mid-slope positions, but this trend does not continue in the lower slope position. Percent OC values were higher than expected in parent materials at the 60 to 244 cm depth , ranging from 0.7 to 2.3 % OC (average of 1.6 % OC, or 1.3 and 1.8 % on the 1964 and 1930 burn sites, respectively). Total organic carbon stocks summed from the soil surface to the 244 cm depth were greater on the mature 1930 burn site (62.4 to 77.4 kg C m^{-2}), compared to the younger 1964 burn site (47.8 to 74.0 kg C m^{-2}), and increased from upper to lower slope positions on both sites.

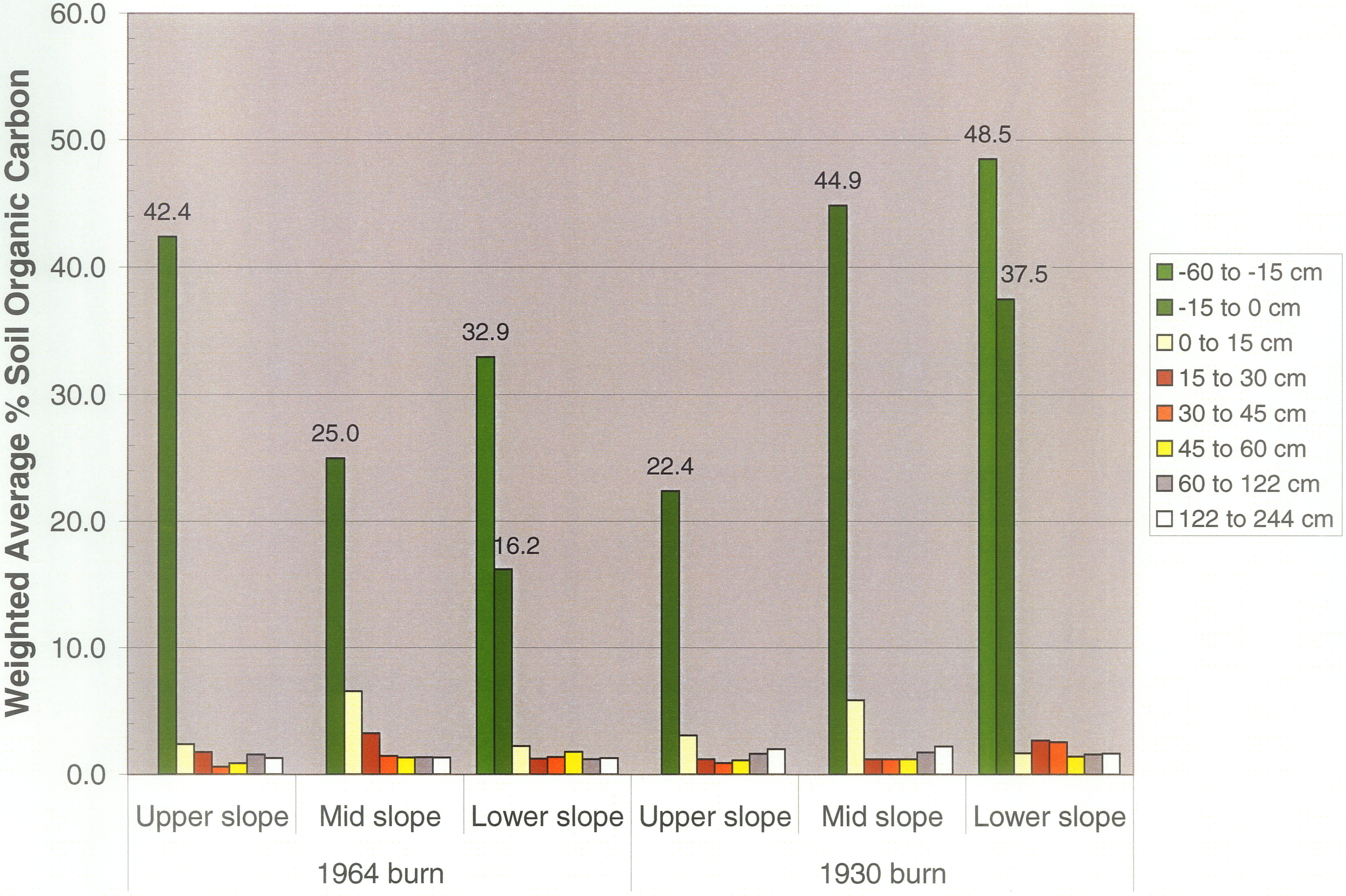


Figure 5.21 Weighted average % SOC (by depth) along the central transects of the 1964 and 1930 burn sites.

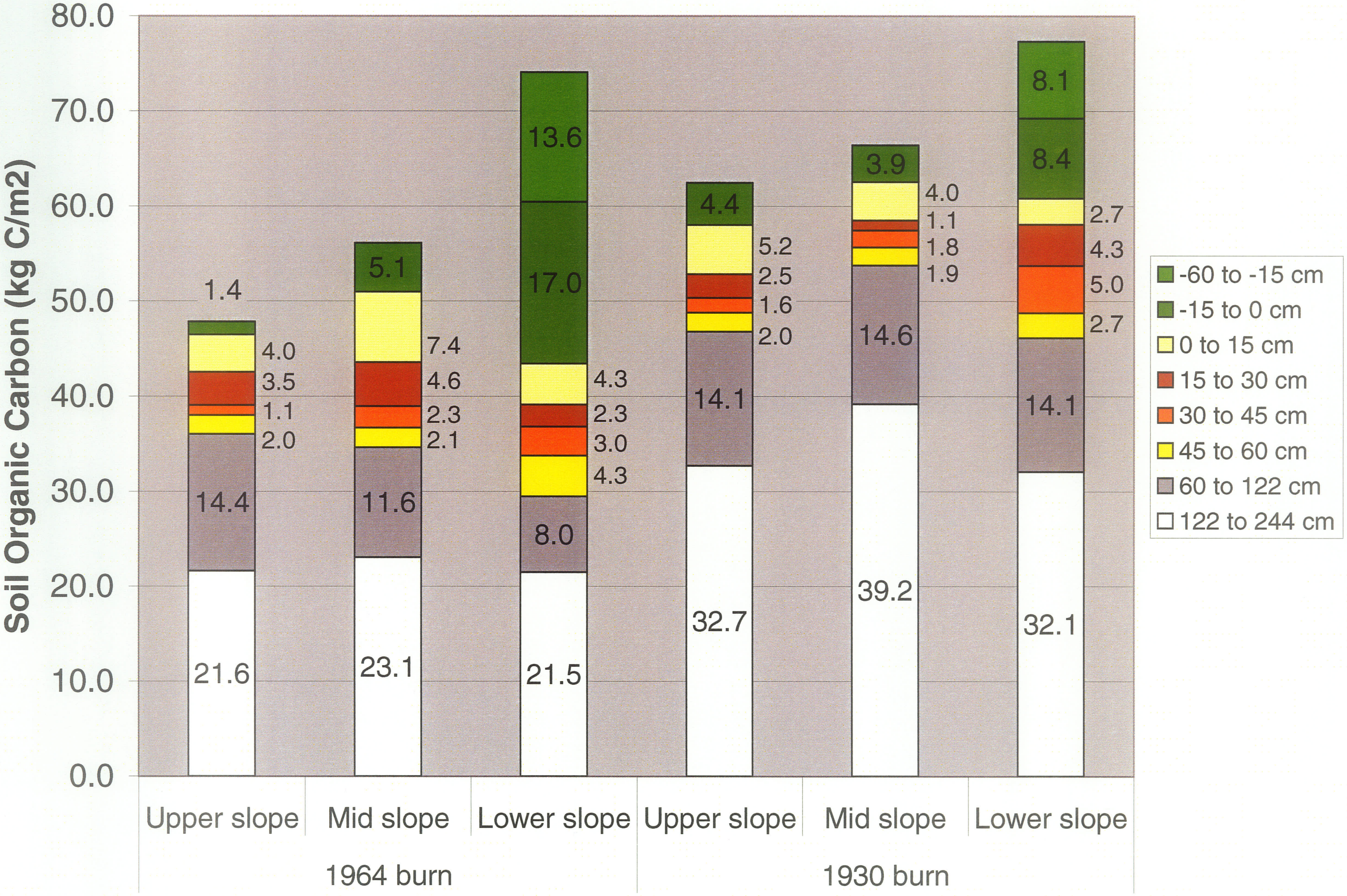


Figure 5.22 SOC stocks (kg C m^{-2}) along the central transects of the 1964 and 1930 burn sites.

5.5.4 Permafrost and Cryoturbation

Permafrost distribution is affected by latitude, slope aspect and gradient, organic horizon thickness, and tree canopy closure. The low thermal conductivity of organic materials combined with the high heat capacity of soil water influence the soil thermal and water regime, typically resulting in the prolonged duration of frozen soil conditions into the summer. Permafrost distribution is sporadic within the study area. Permafrost typically occurs in and under Sphagnum hummocks in veneer bogs, and in peat plateau bogs.

Evidence of past cryoturbation was found in the form of 10 to 15 cm high relic earth hummocks on the north facing slope of the 1964 burn site. Low, 10 to 15 cm high relic earth hummocks were occasionally found on the 1989 and 1981 burn sites, and also occur on the 1930 and 1870 burn sites, but are masked by the 15 to 20 cm thick duff (LFH) and moss groundcover. The largest mineral hummock (20-30 cm high) were found on the 1995 and 1998 burn sites. Cryoturbated mineral parent material often had a patchy "marble cake" appearance with contorted dark brown clay varves mixed in with pale brown silty clay varves.

Organic materials were often found mixed in with mineral materials below the Oh horizons of shallow organic soils in lower slope positions. These cryoturbated organic materials were abundant in peaty Gleysols and Terric Organic Cryosols located within the lower slope of the 1964 burn site. Significant quantities of cryoturbated organic materials were expected on the 1998 burn site, but were largely absent, except on lower slopes. Cryoturbated wood ash fragments were, however, found 20 to 40 cm below the mineral soil surface in relic earth hummocks on the 1998 burn site.

5.6 Conclusions

Organic horizon thickness and surface OC stocks were not only related to drainage and forest stand age, but also to slope aspect, the presence of mineral and organic hummocks, and the history of local fire severity. The top few centimetres of the organic soil surface were burnt over a large aerial extent of the 2003 fire scar. Abrupt changes in organic horizon thickness occurred where ground fires burnt almost completely to the ground along the edge of thick duff layers and/or Sphagnum hummocks. Surface OC stocks ranged from 1 to 5 kg C m^{-2} in moderately well drained upper and mid-slope positions, and 6 to ~30 kg C m^{-2} in poorly drained veneer bogs. The ash method permitted the rapid estimation of % OC in organic horizons, but was unsuitable for estimating % OC in clay soils. Even after developing an improved linear equation, % OC = 0.564(100 - % Ash) - 2.7, ($r^2 = 0.995$), predicted % OC was only within ± 2.4 % OC, 95 % of the time. Using the split sample LECO method, OC stocks on the 1964 and 1930 burn sites ranged from 9 to 16 kg C m^{-2} in the mineral soil profile (0-60 cm), and from 8 to 15 kg C m^{-2} in the 60 to 122 cm depth increment. OC stocks in the 122 to 244 cm depth increment were significantly larger ($p=0.05$) in the 1930 burn site (32 to 39 kg C m^{-2}) compared to the 1964 burn site (22 to 23 kg C m^{-2}). This is probably due to greater long-term (pre-burn) leaching of DOC on the 1930 burn site. Total OC stocks summed from the soil surface (top of duff/organic) to the 244 cm depth were greater below the 1930 burn site (62 to 77 kg C m^{-2}), compared to the 1964 burn site (48 to 74 kg C m^{-2}), and increased from upper to lower slope positions in both sites. Cryoturbation redistributed surface OC stocks into the mineral soil profile, whereas leaching likely redistributed some DOC to greater depths.

6. GENERAL DISCUSSION

6.1 Review of Objectives

Dissolved organic carbon (DOC) forms a small yet important part of the carbon cycle. The purpose of this study was to determine if DOC concentrations in northern boreal forest soils vary significantly between different aged forest stands, landscape positions, depths in the soil profile, and with time. Secondary objectives included: i) characterising and quantifying the effect of drainage and forest stand age on surface soil organic carbon content and soil temperatures; ii) examining the influence of soil organic carbon content and soil climate (temperature and moisture) on DOC concentrations; and, iii) estimating DOC fluxes in the two different aged forest stands.

6.2 SOC and DOC

Comparison of soil organic carbon (SOC) data with average DOC concentrations by depth and landscape position along the central transect within each burn indicates that average dissolved organic carbon concentrations were positively correlated with the natural log of percent soil organic carbon content (Figure 6.1).

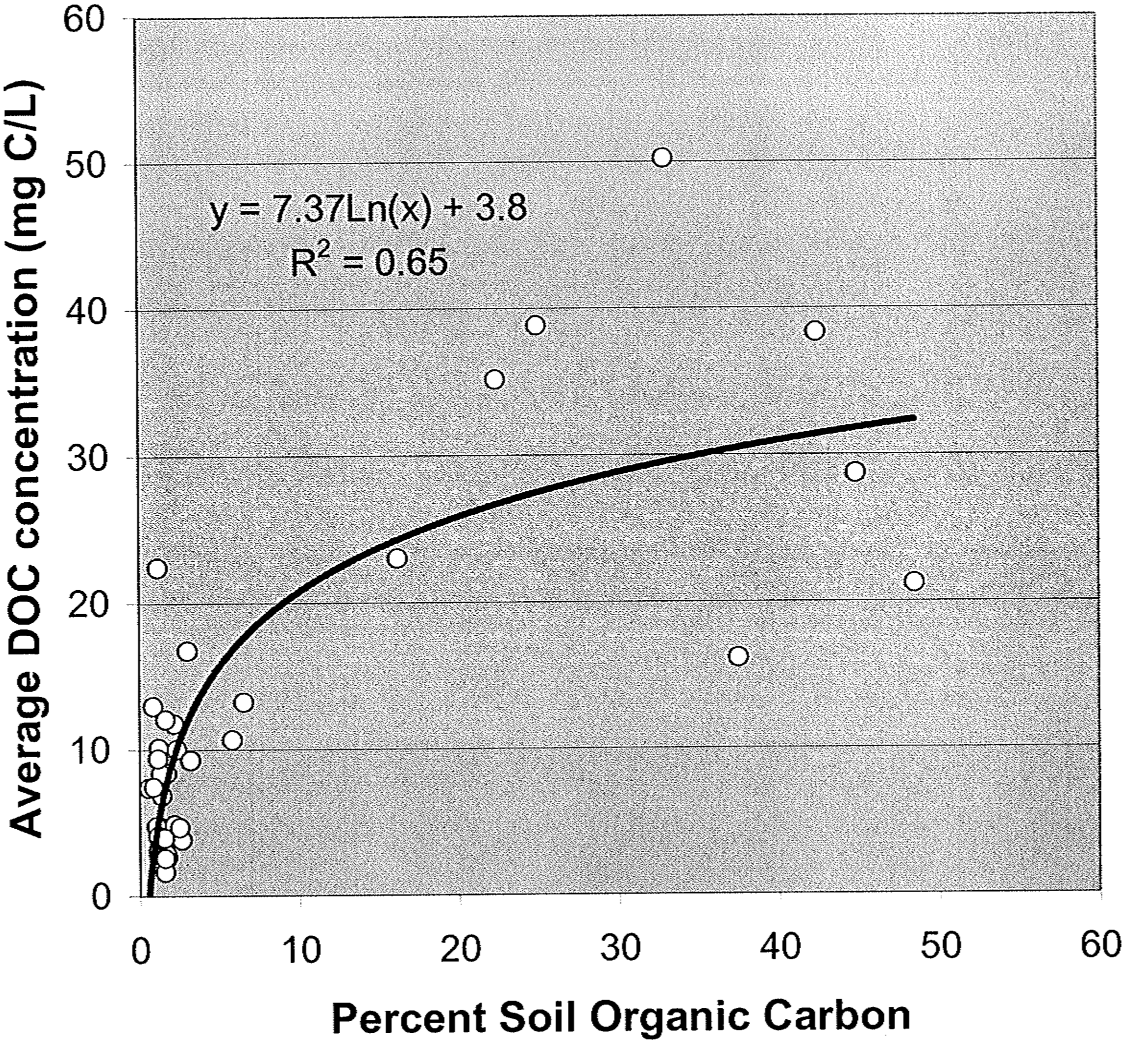


Figure 6.1 Average DOC concentration versus percent SOC for each sampling depth increment and landscape position along the 1964 and 1930 burn central transects. An extreme value was excluded from one of the averages which only had two measurements in total.

Radiocarbon analyses indicated that soil water collected from Oh and Ah horizons in the lower slope of the 1930 burn site contained DOC less than 40 years old (see Appendix 10.2.3). Therefore, this DOC is younger than the 72-year-old forest stand, and is derived primarily from recent organic materials at the soil surface, and not from deeper residual humic organic (Oh) horizons.

During the measurement of % SOC, an HCl pretreatment method was tested as a method to remove inorganic carbon prior to direct measurement of organic carbon by LECO analysis. Removal of excess HCl with distilled water released light green to dark brown or black leachate, which indicated the presence of dissolved organic carbon in the leachate. Three leachate samples were tested using the same instrumentation and methodology as the soil water samples. Results indicated that 3 to 23% of soil organic carbon was lost as dissolved and fine particulate organic carbon in this leachate (see Appendix 10.2.2.2). The HCl pretreatment method wasn't used for further analysis of SOC, but it did indicate that DOC is an important fraction of SOC, especially in Ck horizons below the soil profile where 23% of the SOC was composed of potentially labile DOC (Table 10.10).

Deep OC stocks were significantly larger ($p=0.05$) on the 1930 burn compared to 1964 burn site (Figure 5.22), suggesting greater long-term accumulation of dissolved organic carbon at depth in the 1930 burn site, but most of this accumulation must have occurred prior to the last fire. OC stocks in the 122 to 244 cm depth increment were ~ 36 % lower in the 1964 burn site compared to the 1930 burn site. Reduced deep OC stocks in the 1964 burn site may have been caused by prolonged occurrence of frost and a corresponding decrease in deep leaching, especially in the lower slope position where there is some sporadic permafrost. Compared to the upper slope position of the 1964 burn site, OC stocks in the 60 to 122 cm depth increment were ~19 % lower in the mid-slope, and ~ 44 % lower in the permafrost affected lower slope, despite higher predicted soil surface DOC fluxes in the mid and lower slope positions (Table 6.1). Piezometer installation was completed in 2003 and during that year, soil water samples were collected less frequently in the 60 to 244 cm deep piezometers of the 1964 burn site than the 1930 burn site (53 vs 172 samples, respectively), providing additional evidence for reduced deep leaching of DOC on the 1964 burn site, at least for that year.

DOC stocks along the central transects of the 1964 and 1930 burn sites (Figure 6.2) have a similar pattern to SOC stocks (Figure 5.22), with larger cumulative DOC stocks occurring in lower slope positions due the presence of thick organic horizons and prolonged saturated conditions. Surface SOC and DOC stocks were lowest in the upper slope of the 1964 burn site, and highest within the lower slope of the 1964 burn site. Both SOC and DOC stocks in the 0 to 15 cm depth increment were above average in the mid-slope of the 1964 burn site.

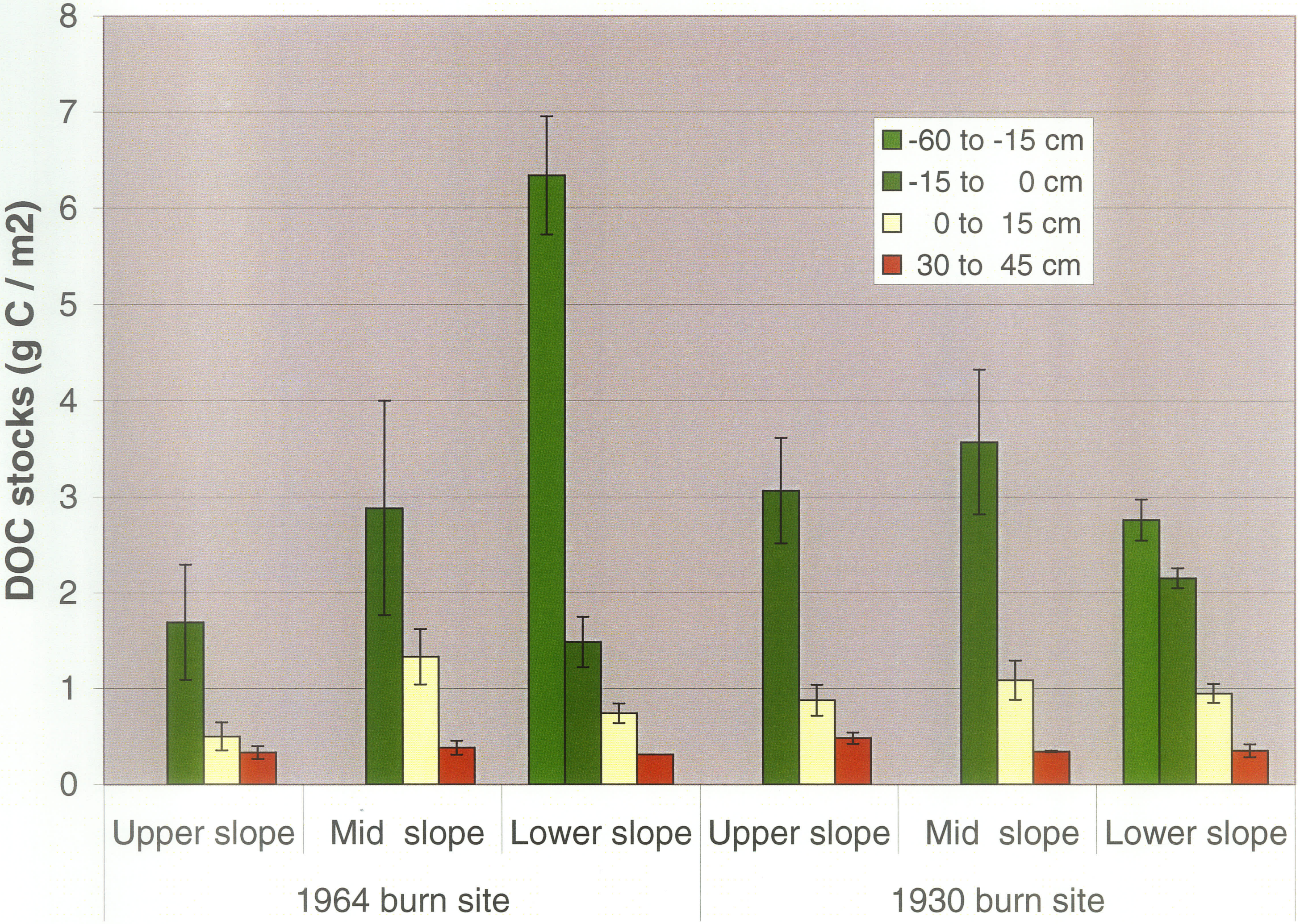


Figure 6.2 DOC stocks by depth and landscape position along the 1964 and 1930 burn central transects.

6.3 Soil Climate and DOC

Canopy cover was affected by drainage and forest stand age, and since canopy cover and aspect influence canopy interception of solar radiation and precipitation, interactions between landscape position, forest stand age and aspect have influenced soil temperature, moisture, DOC concentrations and, presumably, water and DOC fluxes.

Higher than average surface DOC concentrations were observed in the cooler, north facing lower slope of the 1964 burn site, and lower than average surface DOC concentrations were observed in the warmer, south facing lower slope of the 1930 burn site. These observations are in agreement with Kalbitz et al. (2000).

> "*For well and moderately well drained soils, there is often an inverse correlation between average soil temperature and DOC concentration in surface soil leachates (Cronan, 1990). Thus, DOC concentrations generally increase in cooler environments. In poorly drained areas, DOC concentrations in surface horizons often reach very high levels, regardless of the climate, from cool northern peatlands to warm southern blackwater swamps. These inconsistent data indicate no general climatic effect on DOC.*" (Kalbitz et al., 2000)

Higher log transformed DOC concentrations (Table 4.8) were associated with cool months and cooler landscape positions (Table 4.4). Trends in mean summer soil temperatures at the 10 and 20 cm depths matched the trends in log-transformed DOC concentrations near the soil surface when landscape positions were compared within a burn site, but not when they were compared between burn sites.

Statistical analysis of DOC concentrations revealed multiple potential solutions capable of explaining the variability in DOC concentrations (i.e. no unique solution). Weekly precipitation, cumulative seasonal precipitation, and soil temperatures at the 10 and/or 20 cm depth were generally found to be significant (p=0.05) factors affecting DOC concentrations along the central transects, but only cumulative seasonal precipitation remained as a significant factor (p=0.05) when DOC concentrations were examined along all transects on the 1964 and 1930 burn sites. However, suction lysimeters were only installed along the central transect, and most of the near surface DOC measurements were collected along the central transects. This may suggest that the influence of temperature on DOC concentrations (organic matter decomposition, root exudate production, production and decomposition of DOC) is primarily limited to the soil surface, whereas other processes (adsorption, water and DOC fluxes) dominate at greater depths. More rigorous testing of soil temperature and DOC concentration relationships at greater depths would require interpolation of measured soil temperatures to the sampling depths used for monitoring DOC concentrations. This analysis would however be hampered by the confounding influence of water fluxes, which transports both heat/cold and DOC to greater depths.

6.4 DOC Fluxes

As a carbon stock, dissolved organic carbon (DOC) may be relatively insignificant, yet its ability to be transported by surface and subsurface water suggests that DOC fluxes may be an important component of the carbon cycle. Transport of DOC in soil water within and between Northern Boreal ecosystems may significantly impact the quantity, location and form of greenhouse gas production.

Let us consider for a moment a hypothetical situation where a constant supply of ~50 mg C/L within surface organic horizons of an upland soil is leached at a rate equal to an annual precipitation of ~540 mm per year, assuming zero interception, evapotranspiration, and sublimation.

$$50 \text{ mg C L}^{-1} * (1 \text{ g} / 1000 \text{ mg}) * (1 \text{ litre} / 1000 \text{ cm}^3 * (54 \text{ cm precipitation per year} * 100 \text{ cm} * 100 \text{ cm}) \text{ per m}^2) = 0.050 \text{ g C L}^{-1} * 540 \text{ L m}^{-2}$$

$$= 27 \text{ g C m}^{-2} = 2.7 * 10^{-2} \text{ kg C m}^{-2}$$

This would represent a potential DOC transport of 1% of surface soil carbon stocks per year in comparison to surface soil carbon stocks of approximately 2.6 kg C m^{-2} on well drained upland soils in the area (Cyr and Veldhuis, 2002). This surface DOC flux would represent 6 to 12 % of the soil surface CO_2 fluxes in comparison to soil surface CO_2 fluxes of 226 to 416 g C yr^{-1} (Wang et al., 2003). Thus leaching of DOC from surface organic horizons may reduce surface CO_2 fluxes by ~10%.

If the entire volume of water flow occurred as subsurface flow with an average DOC concentration of ~5 mg C L^{-1} at the bottom of the mineral soil profile, it would represent only ~0.1% of surface carbon stocks, and ~1.0 % of soil surface CO_2 fluxes. Freeze/thaw events and root exudate production in the spring may, however, result in larger DOC fluxes, as approximately one third of annual precipitation occurs as snowfall and the highest DOC concentrations were observed in the spring.

Precipitation DOC fluxes from June till September 2003 were 1.1 to 1.5 g C m^{-2} yr^{-1}. In comparison, Moore (2003) reported higher precipitation DOC fluxes of 1.6 to 2.8 g m^{-2} from mid-May to mid-September in 1994, probably due to the extremely large area of Manitoba burned in 1994 (1,428,754 ha), compared to 2002 and 2003 (94,563 and 433,512 ha, respectively (Manitoba Conservation, 2003a)).

Table 6.1 DOC fluxes in precipitation and soil water for the year 2003.

		June	July	Aug	Sept	June-Sept 2003
				g C m^{-2}		
1964 burn site	Precipitation	0.5	0.5	0.2	0.3	1.5
	Upper slope	1.9	1.8	1.4	1.2	6.3
	Mid slope	1.9	1.9	1.8	1.3	6.8
	Lower slope	2.3	2.7	2.2	2.3	9.5
1930 burn site	Precipitation	0.2	0.3	0.2	0.3	1.1
	Upper slope	1.5	3.0	1.6	2.1	8.2
	Mid slope	1.4	2.5	-	-	-
	Lower slope	0.9	1.7	0.8	1.4	4.8

Note: Based on average monthly DOC concentrations for precipitation and soil water samples collected from suction lysimeters at the soil surface.

Despite 29 % greater precipitation on the 1930 burn site, June till September 2003 DOC fluxes from surface organic horizons were slightly less on the 1930 burn site (4.8 to 8.2 g C m^{-2}) compared to the 1964 burn site (6.3 to 9.5 g C m^{-2}) (Table 6.1). Moore (2003) calculated DOC fluxes from forest floor leachate as 6.3 g C m^{-2} within a pine forest on sandy soil, 2.7 g C m^{-2} within an aspen forest on clayey soils, and 3.0 g C m^{-2} within a spruce forest on clayey soils, with DOC fluxes of 3.4 g C m^{-2} in a bog, 2.0 g C m^{-2} in a fen, and 1.7 to 3.2

g C m^{-2} in watershed streams. Seasonal precipitation and the range of DOC concentrations were generally similar between the two studies, but higher DOC concentrations were observed in the forest floor of the young mixed forest stand on the 1964 burn site and the mature forest stand of the 1930 burn site than in Moore's (2003) aspen and spruce sites. Moore (2003) used zero tension lysimeters, whereas suction lysimeters were used in the current study. Moore's (2003) DOC measurements were, therefore, restricted to periods of saturated flow when DOC dilution by precipitation was probably the greatest, whereas the use of suction lysimeters in the current study also permitted the measurement of potentially higher DOC concentrations during periods of unsaturated flow. DOC fluxes in the current study are similar to those reported by Fraser et al. (2001), who calculated precipitation DOC fluxes as 1.5 ± 0.7 g C m^{-2} yr^{-1}, and soil DOC fluxes as 8.3 ± 3.7 g C m^{-2} yr^{-1} in an ombrotrophic bog in Ontario, Canada.

Seepage water was readily observed within humic organic (Oh) horizons in lower slope positions and in granular structured Bt horizons in mid and upper slope positions. Piezometer water levels also indicated that water was flowing from upper to lower slope positions via shallow (< 60 cm) flow paths. DOC concentrations decreased with depth in all landscape positions and these DOC concentrations were similar to the equilibrium DOC null point concentrations reported by Moore (2003), indicating that DOC adsorption and desorption processes had a significant role in controlling DOC concentrations and fluxes. Quantifying lateral and downward DOC fluxes will require the use of a two or three dimensional soil-landscape hydrology model which takes into account changes in soil hydraulic conductivity with depth and time, as seasonal changes in frost depth and ice content strongly influence water and DOC fluxes in northern boreal forests.

6.5 Summary of Results

- Observed DOC concentrations had a positively skewed log-normal distribution, with DOC concentrations and variability decreasing proportionally to one another with increasing depth in the soil profile, indicating a multiplicative effect of some factor(s).
- Measurable quantities of DOC observed in precipitation samples were attributed to forest fire activity.
- DOC concentrations varied significantly ($p=0.05$) with sampling depth and with time, but the effects of landscape position and age of forest stand appeared to be smaller in importance.
- DOC concentrations were significantly different ($p=0.05$) between sampling depths in the soil profile, which was expected since the factors controlling DOC production (quantity and quality of soil carbon stocks, soil temperature and moisture) and transport (adsorption, hydraulic conductivity) are also related to depth within the soil profile. DOC concentrations decreased from ~20 to 60 mg C L^{-1} in surface organic horizons, to ~ 3 to 4 mg C L^{-1} in mineral horizons at the 244-cm depth.
- Peak DOC concentrations occurred in spring (~40 to 80 mg C L^{-1}), followed by an overall decrease in DOC concentrations until early-fall (~20 to 30 mg C L^{-1}). The decline in DOC concentrations over time was significantly correlated to cumulative seasonal precipitation, but could also be related to cumulative degree days and

depletion of soluble organic carbon by oxidation into CO_2.

- On average DOC concentrations were ~3 mg C L^{-1} higher on the 1964 burn site than the 1930 burn site. Near surface DOC concentrations were significant different ($p=0.05$) between the 1964 and 1930 burn sites (44 and 30 mg C L^{-1}, respectively), but these differences were only significant in mid and lower slope positions. Differences in DOC concentrations between landscape positions within a forest stand appeared to be dependent on precipitation inputs, canopy interception, aspect, and their combined influence on soil temperature and moisture.
- DOC concentrations were significantly related to both % SOC content and mass of SOC.
- Thickness of surface organic horizons was related to drainage and forest stand age, but also to the presence of mineral and organic hummocks, and the history of local fire severity. In moderately well drained soils, average organic horizon thickness ranged from ~2 cm in recently burnt forest stands to ~17 cm in mature forest stands, but similar variations in organic horizon thickness also occurred within very short distances (< 1 m) due to the presence of cryoturbed mineral hummocks and variations in local fire severity. Although the top few centimetres of the organic soil surface are burnt over a large aerial extent of fire scars, abrupt changes in organic horizon thickness occur where ground fires have burnt along the edge of thick organic materials.
- Surface OC stocks were affected by local fire severity and drainage, and ranged from ~1 kg C m^{-2} in moderately well drained upper slope positions to ~30 kg C m^{-2} in

poorly drained veneer bogs associated with sporadic permafrost.

- The ash method permitted the rapid estimation of % OC within organic horizons, but was unsuitable for estimating % OC in clay soils. Even after developing an improved linear equation, % OC = 0.564(100 - % Ash) - 2.7, ($r^2 = 0.995$), predicted % OC was only within ± 2.4 % OC, 95 % of the time.
- Using the split sample LECO method, total organic carbon stocks summed from the soil surface to the 244 cm depth were found to be greater on the mature 1930 burn site (62 to 77 kg C m^{-2}), compared to the younger 1964 burn site (48 to 74 kg C m^{-2}), and increased from upper to lower slope positions within both sites. Deep OC stocks within the 122 to 244 cm depth increment were significantly larger ($p=0.05$) below the 1930 burn site (32 to 39 kg C m^{-2}) compared to the 1964 burn site (22 to 23 kg C m^{-2}), probably due to greater long-term (pre-burn) leaching of DOC on the 1930 burn site.

7. SUMMARY AND CONCLUSIONS

DOC concentrations were, on average, 3 mg C L^{-1} higher in the younger 1964 burn site than in the mature 1930 burn site, but this may have been due, in part, to lower cumulative precipitation on the 1964 burn site. DOC concentrations 3 mg C L^{-1} higher within the younger forest stand is consistent with the results of France et al. (2000) who detected DOC concentrations 2 to 3 mg C L^{-1} higher in Canadian boreal lakes with clearcut or burnt watersheds compared to reference watersheds.

DOC concentrations were strongly related to % SOC, decreased with depth in the soil profile, were log-normally distributed, and varied considerably with time. Peak DOC concentrations occurred in spring, followed by an overall decrease in DOC concentrations until early-fall. High DOC concentrations in the spring may be produced by freeze-thaw induced cellular breakdown. Higher soil surface DOC concentrations were associated with cooler soil temperatures, but seasonal frost and sporadic permafrost decreased the potential for deep leaching of DOC. Snow meltwater runoff and shallow subsurface flow over top of the thawing frost table in spring may transport significant quantities of DOC to rivers as shallow subsurface flow.

High DOC concentrations in precipitation were probably due to forest fire activity, but this could not be quantified with the methods being used. Analytical methods are required to quantify the contribution of forest fire ash, windblown soil, pollen, throughfall and other organic sources to DOC in precipitation. Significant variability in DOC concentrations remained unexplained with the use of ANOVA and regression models since they could not adequately represent the fundamental processes responsible for differences in DOC concentrations over time: organic matter production, dilution, transport, adsorption, and decomposition. Process-based models are required which can take into account transport, adsorption, desorption, and in-situ production and consumption of DOC, including the effect of freeze-thaw processes on DOC production and transport.

There is a growing need to integrate studies across scientific disciplines, including carbon cycling, ecology, hydrology, and pedology. Future research should integrate DOC, CO_2 and CH_4 studies, especially the production of DOC and its subsequent decomposition into CO_2 and CH_4 as these processes are not yet fully understood.

8. CONTRIBUTION TO KNOWLEDGE

DOC concentration in soil water were, on average, ~3 mg C L^{-1} higher in the younger mixed forest stand on the 1964 burn site, compared to the mature black spruce forest stand on the 1930 burn site, but forest stand age had a smaller influence on DOC concentrations than changes in DOC concentrations with depth and time. This study serves as an independent confirmation that DOC concentrations in clay soils decrease significantly with depth in the soil profile, are log-normally distributed, and are positively correlated to % SOC content. Peak DOC concentrations within this northern boreal forest environment occurred in early-spring during soil thaw, and DOC concentrations generally decreased until the end of the observation period in early-fall. Melt water flowing over top of the frost table in spring transported highly concentrated DOC as shallow subsurface flow.

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10. APPENDIX

10.1 Instrumentation

10.1.1 Preparation of study sites

Sampling platforms and walkways were constructed at central locations within each burn site and were then transported to the upper, mid, and lower slope sampling sites within each transect, where they were installed to minimize compaction of organic horizons during instrument installation and long-term monitoring activities (Figure 10.1 and 10.2). They were constructed using pressure treated spruce to minimize decomposition of the lumber.

Figure 10.1 Upper slope sampling platform on 1964 burn site.

Figure 10.2 Lower slope sampling platform on 1964 burn site.

10.1.2 Piezometers

10.1.2.1 Piezometer Construction and Installation

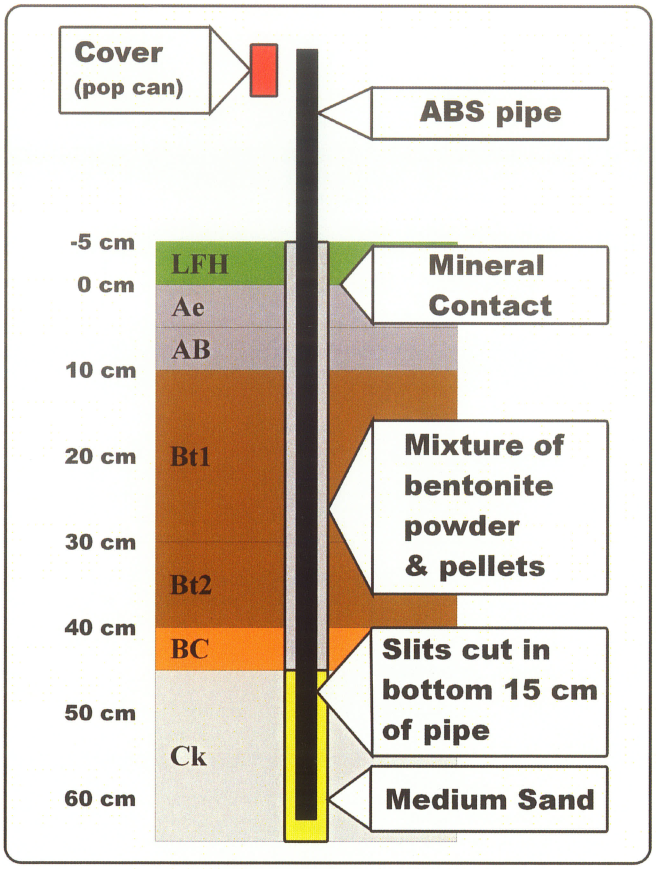

Figure 10.3 Conceptual piezometer design.

Acrylonitrile Butadiene Styrene (ABS) pipe was cut to the desired length. The length of the pipe was selected to provide 15 to 75 cm of pipe above the ground surface. At first, shorter pipe lengths were used to improve the stability of the shallow piezometers within upper and mid-slope positions on the 1964 burn site, but this was increased for subsequent sites in order to facilitate measurements, and improve access and visibility during winter months.

Slits were cut 0.5 cm deep and 1 to 1.5 cm apart along the circumference of the bottom 15 cm of each pipe. The pipe was rotated one third to one quarter turn after each cut to provide an equal distribution of perforations around the bottom 15 cm intake area of each piezometer, and to maintain the structural stability of the pipe. Shavings were scraped off the inside of the pipe and removed to prevent contamination of water samples & clogging of sampling equipment.

Shallow piezometers were installed up-slope of the sampling platform to minimize possible long-term contamination from decomposing lumber or compacted surface organic horizons. Deeper piezometers were sited on the downslope side of the platform. Piezometer access holes were manually augered to the desired depth (sampling depth plus ~1 cm) using a Dutch auger. Medium sand was then poured down the augered hole to cover the bottom 1 cm of the hole. The prepared piezometer pipe was then inserted into the hole to pack the sand and the depth of the pipe was then verified. With the piezometer in place, medium sand was then poured down the sided of the access hole to cover the bottom 16 to 17 cm of the pipe. The piezometer was lightly shaken from side to side and tapped during the backfilling process to assist the settling of added material. Approximately 10 cm of coarse bentonite pellets was added just above the sand to prevent fine bentonite powder from entering the piezometer.

A mixture of bentonite pellets and powder were used to backfill the rest of the access hole. Bentonite pellets were used at greater depths to ensure that the bentonite would reach the bottom of the hole. Fine bentonite powder was gradually added to the bentonite mixture, especially at shallower depths where structured and more permeable soil horizons are located. A mixture of bentonite powder and pellets provides a maximum seal to prevent water from flowing into the access hole and along the outside of the pipe.

Piezometers were then covered with an inexpensive pop can which was rinsed and had the top cut off. Shallow piezometers were subsequently reinforced by driving rebar into the ground alongside the piezometers, and then clamping the piezometers to the rebar.

10.1.2.2 Discussion of Piezometer Design

The sand used to cover the bottom 15 cm of the piezometer should ideally have been pure coarse silica sand to naturally filter the soil water and prevent sediment from entering the sampling equipment, rather than using fine silica sand which gets sucked-up by the sampling equipment, or medium sand of variable mineralogical origin. Differences in the mineralogical composition of the sand may potentially affect some types of biogeochemical measurements (such as strontium ratios), however, it is probably safe to assume that for the most part such effects will be minor noise in the measurements as sand has a low surface area and cation exchange capacity compared to the surrounding clay to silty clay parent materials.

The majority of the piezometers were constructed using 32 mm inside diameter (1 ¼" ID) ABS pipe. Wider 51 mm (2") ID pipe was used in upper and mid-slope positions on the 1964 burn site to improve the stability of very shallow piezometers and to permit the collection of larger volumes of soil water for various analyses. Smaller 12 - 19 mm (½" - ¾") ID piezometers would reduce disturbance and decrease response times (R. Eilers, pers. comm., AAFC, Winnipeg, MB), but only permit collection of small water volumes. Wider (2" ID) piezometers are more costly and time consuming to install for deep piezometers, but permit the future use of automated data loggers and instruments specifically designed for insertion into 2" ID wells. Attempts to use surplus 2" diameter pipes for this purpose for several of the deeper piezometers on the 1930 burn site resulted in a significant increase in the water available for analyses, but also resulted in a significant increase in the time required to purge the water from these piezometers, especially on the wetter lowland sites. Selection of an efficient vacuum pump therefore becomes an important consideration.

10.1.3 Suction Lysimeters

10.1.3.1 Suction Lysimeter Installation

Suction lysimeters (1900 Series Soil Water Samplers) consist of a 4.8 cm outside diameter PVC tube, a ceramic cup with a 2-bar air-entry value, and a Santoprene stopper with a Neoprene tube at the top (SoilMoisture Equipment Corp., 1999). Lysimeters access holes were manually augered using a Dutch auger. The ceramic tip and lower portion of the lysimeter tube were covered with moistened soil from the augered out access hole. A small quantity of water was added to the bottom of the access hole to provide good hydraulic contact with the soil and then the lysimeter was pushed down to the bottom of the access hole. Remaining soil was backfilled around the lysimeters and was supplemented with bentonite clay at shallow depths to prevent contamination from organic horizons.

10.1.3.2 Comparison of Suction Lysimeters and Piezometers

Suction lysimeters and piezometers both permit the sampling of the same soil water solution and drawn the soil water from the surrounding soil medium. When the sampling depth is in the saturated zone just below the water table, both instruments have the potential to create a zone of depression when water is extract in large amounts, thus potentially resulting in higher measurements of DOC concentrations if DOC rich water is supplied from above. This effect is much greater with suction lysimeters, but is also a concern with piezometers if excessive amounts of water are purged from shallow piezometers prior to sample collection. Suction lysimeters located above the water table may also draw water up from the water table. Except for these instances, water collected from suction lysimeters and piezometers during saturated conditions should not differ significantly from one another.

10.1.4 Water Sampling Instrumentation

The vacuum pump used to extract water samples from the piezometers and lysimeters should be lightweight, portable, easily maintained, produce a high flow rate and include a gauge to check proper functioning and permit calibration of tensiometer gauges. Of the three manually operated vacuum pumps tested, the vacuum hand pump sold by SoilMoisture Equipment Corp. was found to be the most efficient, producing a flow rate of 4.0 to 6.5 litres per minute and was very portable and easily maintained. A medium to light weight electric pump may be preferred if a portable, rechargeable and reliable power source is available on site. Smaller battery operated pumps may not provide a sufficient flow rate, and power requirements of larger electric pumps may limit portability.

Materials in direct contact with the water samples should ideally be made of glass or other materials which reduce the risk of particulate and dissolved organic matter binding or adsorbing to the material and should be chemically non-reactive with organic material. Any plastic materials used should be chemically resistant/non-reactive and resistant to photo-degradation as plastic materials may leach from the sampling equipment over time. Plastic tubing was used, but Teflon coated tubing or platinum-cured silicone tubing could be used to reduce the above risks. Glass tube connections for the rubber stopper and glass flasks were not practical as breakage easily occurred under field conditions.

Different sized tubing was required for many of the sampling instrument components. Attempts to use metal fittings to connect each of these tubes failed as the different fittings did not match, would often leak, and were time consuming to connect and disconnect. Reduced leakage and improved efficiency in assembly and disassembly of the sampling equipment were achieved by using intermediate sized plastic tubes to interconnect the different sized tubing.

The flask used to collect the water samples should be rigid to withstand the vacuum applied, unbreakable under field conditions, and have tubing connection(s) on the side of the flask at a 45° downward angle to reduce the chance of tipping.

10.1.5 Tensiometers

10.1.5.1 Construction, Assembly and Installation

Tensiometers were assembled, installed and operated according to the manufacturer's operating instructions (SoilMoisture Equipment Corp., 1984A, 1984B, 1986, 2001). The 2725 Series Jet Fill Tensiometers consist of a 6 to 60" long tube with a porous ceramic tip at the bottom and an adjustable vacuum dial gauge and sealing cap / water reservoir at the top. The tensiometer service kit comes equipped with a concentrated blue fluid which consists of a mild biocide to prevent algae growth within the tensiometer and a coloring agent to make air bubbles and water level more visible in the tube. A blue fluid solution is prepared by diluting 10 drops of the concentrated blue fluid into a 16 oz. (~500 ml) plastic filler bottle. The assembled tensiometers are partially filled with the blue fluid solution and then water is allowed to drain through the ceramic tip for approximately five minutes to saturate the ceramic tip. Boiled (air-free) water should preferably be used, but under high tensions the dissolved air will form bubbles at the top of the tensiometer tube and these bubbles can then be removed by tapping the side of the tube and then adding more water. This is done by filling the tensiometer with water and applying a suction with the handheld vacuum pump. The tensiometer is then refilled and the pumping operation is repeated until there are no more air bubbles coming from the dial gauge. The filled reservoir cap is then attached to the top of the tensiometer and the refill button is pushed down several times to expel the remaining air. This procedure can be repeated as a regular servicing operation after each tension measurement. (SoilMoisture Equipment Corp., 1984B)

A 54" long metal rod is hammered into the ground and the resulting soil core extracted to create the access hole for the tensiometers (SoilMoisture Equipment Corp., 1984B). This may be done in several small increments for deep access holes or in difficult frozen or sticky clay soils. During the installation of the deeper tensiometers into the wet or frozen clay soils, pressure within the access hole would often build-up under the ceramic tip. A rapid stream of large bubbles was sometimes observed coming up the tensiometer tube, possibly due to the air entry value being exceeded within the pores of the ceramic tip. In some cases, the ceramic tip cracked due to the frost or when the tensiometer was pulled out due to suction applied by the wet clay. Many of the gauges on the 1964 burn lower slope position failed during early fall of 2003, either due to frost, or rapid changes in hydraulic pressure head.

10.1.5.2 Servicing, Testing and Gauge Calibration

Tensiometers are relatively simple instruments but may give faulty readings if they are not serviced regularly. Recommended tensiometer servicing, testing and calibration methods are presented by Smajstrla and Pitts (1997) and Evans et al. (1996), and supplement the instructions provided by SoilMoisture Equipment Corp. (1984A, 1984B, 1986, 2001).

At the beginning of the 2002 field season, vacuum dial gauges were set to 0 cbars in reference to atmospheric pressure. With the sealed tensiometer standing upright and the bottom half of the ceramic tip submerged in water, gauge readings compared well with expected values based on 3 cbars of tension applied per foot of water. No calibration checks were conducted during the 2002 field season, as there appeared to be no reliable method available to check the gauge calibration since their was no gauge on the vacuum pump. During the winter of 2002-2003, an additional gauge was purchased and installed onto the vacuum pump to permit comparison of tensiometer gauges to a reference gauge. It is strongly recommended to purchase a vacuum pump with a gauge to permit instrument calibration and maintenance. In 2003, vacuum dial gauges on the tensiometers were set to 0 cbars with the reservoir cap removed from the water filled tensiometer. The calibration of each tensiometer gauge could then be easily checked throughout the field season by comparing it to the reference gauge on the attached vacuum pump. The two gauges could therefore be directly compared over a range of tensions to ensure proper functioning of the gauges. When a steady tension is applied, failure of the readings to remain constant for several seconds indicates that air is leaking into the tensiometer. Air leaks may occur due to missing or damaged o-rings at either the ceramic, gauge or reservoir connections, or due a cracked or broken ceramic tip, or possibly a broken gauge. Obvious water leaks may occur at the gauge connection or from a visible crack in the ceramic tip. Leaks which are more difficult to detect can be tracked down by applying tension with the vacuum pump and observing the exact source of the stream of air bubbles. Missing or damaged o-rings are indicated by bubbles flowing along the threads of a connection. A damaged gauge is indicated by a continuous supply of bubbles coming from the inside of the gauge itself after a reasonable amount of air has been evacuated from the gauge.

10.1.5.3 Measurement Range, Accuracy and Precision

The tensiometer measurement range is approximately 0 to 80 cbars. As the soil suction reaches the air entry value of approximately 80 cbars, cohesive forces between adjacent water molecules is exceeded, water molecules separate, the tension is broken and air can enter the tube through the porous tip (Evans et al., 1996).

Tensiometer measurements are affected by changes in barometric pressure and air temperature. Expansion and contraction of air in the headspace above the water column and of tensiometer materials can cause diurnal oscillations in the tensiometer readings of ~2 cbars increase per 10°C increase (U.S. Department of Energy, 2002). Fluid loss from the tensiometer tube must also be taken into account when high accuracy measurements are required (Munster and Schulz, personal communication, USGS, Menlo Park, CA).

10.1.6 Operating Temperatures of Tensiometers and Suction Lysimeters

Freezing temperatures will cause water within the tensiometers and lysimeters to freeze and expand, causing damage to the dial gauge, the ceramic tip and the water reservoir. Tensiometer vacuum gauges and the jet-fill reservoir cap must be removed before the onset of freezing conditions. In warmer climates, both the tensiometer and lysimeter body tubes and the ceramic tips can be left in the ground if: 1) the ceramic tip is below the frost depth; 2) water is drained from the instrument; and 3) the top of the tube is covered with an insulating plastic bag. The risk of frost damage is however too great within the northern boreal forest, thus the tensiometers and suction lysimeters were removed from the ground by late-September of each year.

10.1.7 Thermistors

10.1.7.1 Thermistor Construction and Installation

Calibrated precision resistors (YSI Precision Temperature Group) were installed at standardized depth intervals (5, 10, 20, 50, 100, 150-cm) within wooden dowels coated with a protective resin. A corkscrew auger was used to create an access hole in the soil, and the wooden dowel was then gently hammered into the ground. Low thermal conductivity of the resin increases the time required for the thermistors to reach thermal equilibrium with the surrounding medium. Thermal conductivity and response time could have been improved by removing the resin from over top of the thermistors, or by adding aluminum to the resin (G. Winston, personal communication, University of California Irvine).

10.1.7.2 Calculation of Soil Temperatures

Soil temperatures were calculated based on the electrical resistance of thermistors using the Steinhart and Hart equation, $1/T = a + b(\text{Ln } R) + c(\text{Ln } R)^3$, where T is the temperature in degrees Kelvin, a, b and c are coefficients unique to each type of calibrated thermistor (or each individual non-calibrated thermistor), and R is the measured electrical resistance (Ohms) of the thermistor (YSI Precision Temperature Group, personal communication, Winnipeg, MB). Resistance was measured in the field in kOhms using a standard handheld voltage metre. Steinhart and Hart equation coefficients (Table 10.1) were calculated based on temperature-resistance conversion tables provided for each type of thermistor.

Historical soil temperature monitoring sites between Winnipeg and Thompson, and northeast of Thompson were resurrected as part of a long term soil temperature study.

Thermistor readings from some of these historical soil temperature monitoring sites matched the calibration table provided for the new thermistors purchased in 2002, whereas thermistors from the remaining historical monitoring sites matched a calibration table published in 1986 (Anon., 1986).

Table 10.1 Calculated Steinhart and Hart equation coefficients for replacement thermistors purchased in 2002, and older thermistors purchased around 1986.

Coefficients	2002 Thermistors	1986 Thermistors
a	1.33×10^{-3}	1.47×10^{-3}
b	2.86×10^{-4}	2.38×10^{-4}
c	1.32×10^{-7}	1.01×10^{-7}

10.1.7.3 Soil Temperature Differences Between a Sphagnum Hummock and a Micro-Depression

Permafrost occurrence is often associated with the presence of thick sphagnum hummocks. An additional thermistor was installed on the 1930 burn lower slope to monitor soil temperature differences between a hummock and a nearby micro-depression. Soil temperature data from this micro-depression was excluded from the larger data set during statistical analyses in order to maintain equal replication between landscape positions. Although no permafrost was observed at this site due to the south facing aspect and open canopy of stunted black spruce trees, a distinct difference was observed in the near surface soil temperatures (Figure 10.4). Soil temperatures at the 5 to 20 cm depth showed a greater range in annual temperatures under the sphagnum hummock than in the micro-depression. The reduced range in soil temperatures within the micro-depression is attributed to wetter soil conditions resulting in greater thermal heat storage capacity. Rapid decreases in surface soil temperatures observed in summer and fall are attributed to rainfall events which cool the soil surface and transfer thermal energy to greater depths within the soil profile.

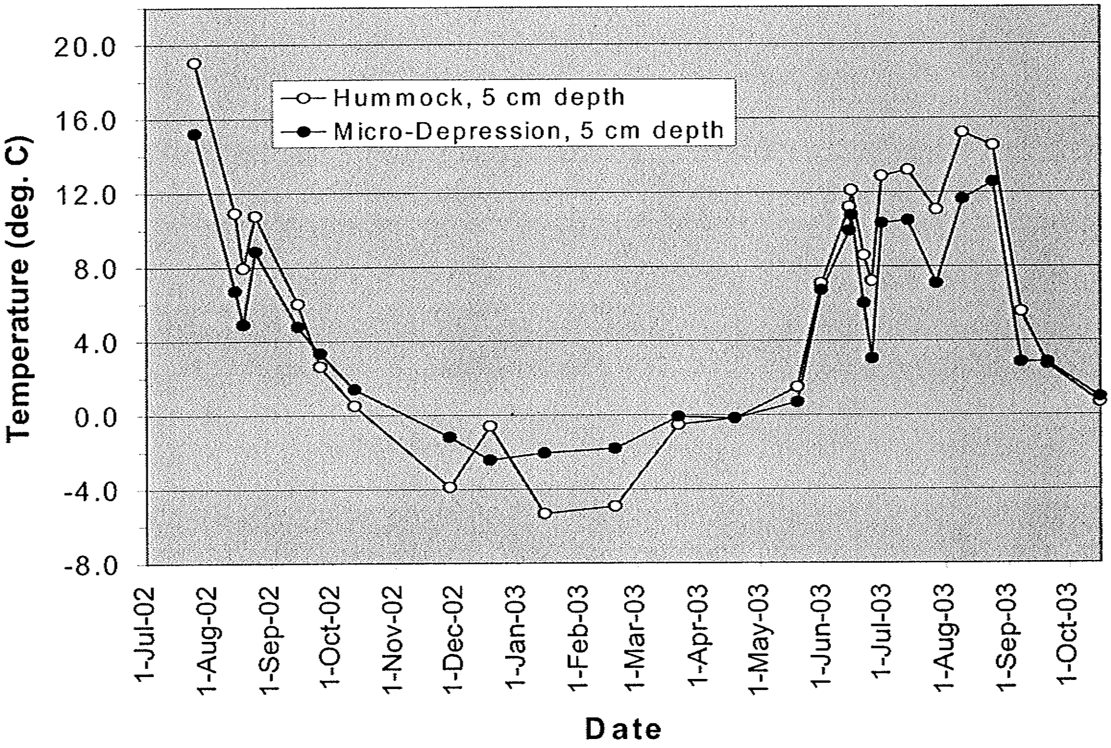

Figure 10.4 Differences in surface soil temperature between a sphagnum hummock and an adjoining micro-depression.

10.2 Soils and Landscapes

Detailed soils and landscape characterizations and surveys contribute to the understanding of soils and landscape processes and to carbon accounting efforts by characterizing and quantifying the spatial distribution and properties of soils (soil profile development, drainage, texture, structure, carbon content, etc.) and landscapes (landform, slope gradient, position, aspect, etc.). This information is required to support carbon accounting, ecosystem process modelling (GHG modelling, hydrology modelling), and as a decision support tool for land management.

10.2.1 Topography and Landscape Characteristics

10.2.1.1 Topographic Survey

Topographic surveys were conducted on the 1964 and 1930 burn sites using a laser theodolite (Sokia SET 4110). This required the clearing of sight lines and the establishment of GPS benchmark sites and turning points for the two burn sites.

GPS satellite reception was poor under the tree canopy, especially on the densely treed upland of the 1930 burn site, thus requiring the establishment of GPS benchmark sites on the lower slope positions of each burn site, where the open canopy of the stunted black spruce provided maximum GPS satellite reception. GPS benchmarks were constructed of 1.8-m-long threaded bars anchored into the ground with cement poured into a 7-cm diameter auger hole. These bars extended approximately 0.3 m above the organic surface and 1.0 to 1.2 m below the mineral soil surface.

Turning points were established at the intersects of sight lines using 1.2-m-long rebar extending ~0.3 m above ground and ~0.9 m below the mineral soil surface. Additional turning points were established near each sampling location using 15-cm-long galvanized nails. Maximum observed relative horizontal and vertical errors were 5.6 and 2.1 cm, respectively, excluding a single occurrence of a 1.0 metre vertical error which occurred for an unknown reason. Relative elevations are more accurate within each burn site than between burn sites, as the absolute positions are subject to GPS error as discussed below.

GPS benchmark sites and primary backsites were georeferenced with a Pathfinder Pro XRS GPS using 100% realtime differential correction from the LandStar satellite and a minimum of five GPS satellites. GPS measurements were averaged over a 45-minute period for the benchmark sites, and over a 20-minute period for the primary backsites. A maximum Position Dilution of Precision (PDOP) filter of 3.0 was used in the field and a postprocessing PDOP filter of 2.0 was used for the 1930 benchmark and backsite. GPS accuracy was tested at the provincially established 95R506 benchmark site (Manitoba Conservation, 2003b) and was found to be within the expected 1 m horizontal accuracy and 3 m vertical accuracy. Landscape and forest canopy obstructions can result in poor satellite reception as GPS satellite signals are either blocked or take multiple paths around these obstructions. The GPS unit used did not have multipath rejection software installed, thus resulting in potential multipath errors.

Table 10.2 GPS coordinates for primary benchmarks and backsites.

Location	Easting	Northing	Elevation	PDOP	Precision	
					Horiz.	Vert.
		1964 burn site				
GPS base	538717.28	6196602.18	254.26	2.0	0.68	1.07
Backsite	538745.93	6196538.91	256.33	2.8	0.91	1.22
		1930 burn site				
GPS base	529657.94	6195634.13	268.69	1.9	0.23	0.29
Backsite	529600.09	6195646.60	266.94	2.0	0.39	0.62

Table 10.3 Laser theodolite coordinates for benchmarks, backsites, and turning points.

Location	**Easting** (m)	**Northing** (m)	**Elevation** (m)	**Description**
		1964 burn site		
64T1S0	538693.10	6196541.83	255.16	Secondary TP
64T1S1	538690.77	6196562.92	254.14	Secondary TP
64T1S2	538687.79	6196591.17	252.67	Secondary TP
64T1S3	538683.55	6196632.97	251.48	Primary TP
64T2S1	538746.26	6196538.23	254.87	Backsite
64T2S0	538746.26	6196538.23	254.87	Primary TP
64T2S1	538739.36	6196553.83	253.80	Primary TP
64T2S2	538727.06	6196580.82	252.70	Primary TP
64T2S3	538717.49	6196602.23	252.27	Benchmark
64T3S0	538782.29	6196535.70	254.19	Secondary TP
64T3S1	538773.67	6196555.84	253.36	Secondary TP
64T3S2	538760.49	6196586.17	252.26	Secondary TP
64T3S3	538748.57	6196613.83	251.94	Primary TP
		1930 burn site		
30T1S1	529659.89	6195700.80	269.70	Primary TP
30T1S2	529659.14	6195671.27	268.80	Primary TP
30T1S3	529657.94	6195634.13	268.69	Benchmark
30T2S1	529639.94	6195685.58	269.03	Secondary TP
30T2, Y	529624.66	6195673.77	268.88	Secondary TP
30T2, L	529614.48	6195666.11	269.04	Secondary TP
30T2S2	529624.84	6195661.69	268.57	Secondary TP
30T2S3	529625.18	6195641.21	268.62	Primary TP
30T3S1	529599.89	6195681.70	269.46	Secondary TP
30T3S2	529599.82	6195658.26	268.75	Secondary TP
30T3S3	529599.75	6195646.68	268.45	Backsite

10.2.1.2 Landscape Classification

Landscape position was classified in the field based on field observations and was verified by using the Landscape Segmentation Model (LSM) (MacMillan, 2003) to classify the digital elevation models (DEMs) created from the above topographic survey data into 15 landform classes based on topographic and fuzzy attributes (slope, curvature, proximity to local pit/peak, etc.). These 15 classes were then grouped into four generalized categories (Upper slope, Mid slope, Lower slope, and Depression).

Table 10.4 Landscape Segmentation Model (LSM) classes and generalized categories (MacMillan, 2003).

Generalized Slope Position	ID	Code	Description
1) Upper Slope	1	LDR	Level Crest
	2	DSH	Divergent Shoulder
	3	UDE	Upper Depression
2) Mid Slope	4	BSL	Back Slope
	5	DBS	Divergent Back Slope
	6	CBS	Convergent Back Slope
	7	TER	Terrace
	8	SAD	Saddle
	9	MDE	Mid Slope Depression
3) Lower Slope	10	FSL	Foot Slope
	11	TSL	Toe Slope
	12	FAN	Fan
	13	LSM	Lower Slope Mound
4) Depression	14	LLS	Level Lower Slope
	15	DEP	Lower Depression

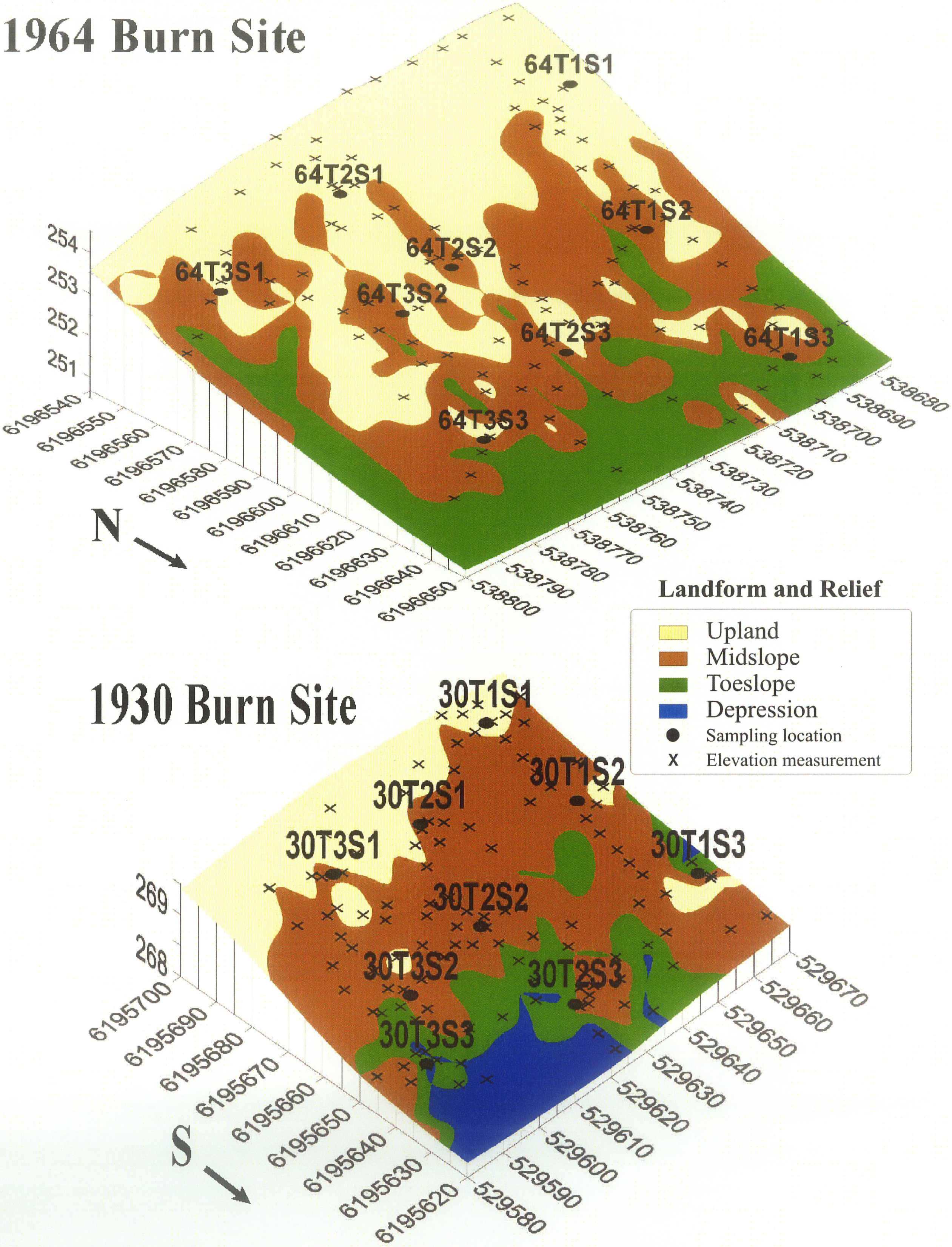

Figure 10.5 Landscape Segmentation Model classification for the 1964 and 1930 burn sampling sites. Accuracy is limited by the distribution of elevation measurements (small black x's in diagram). Sampling location 64T3S1 = 1964 burn site, transect 3, upper slope position.

Table 10.5 Landscape Segmentation Model classification and topographic characteristics for the toposequence transects on the 1964 and 1930 burn sites.

Site	Slope position		Aspect		Elevation	Slope	Curvature	
			Cardinal	Deg.	(m)	(%)	Profile	Plan
64T1S1	Upper	Div. shoulder	N	1	254.1	4.4	3.7	6.6
64T2S1	Upper	Div. shoulder	N	353	253.8	5.9	6.9	14.4
64T3S1	Upper	Upper dep.	N	346	253.1	5.5	-11.4	3.6
64T1S2	Middle	Conv. backslope	N	357	252.5	3.6	-9.3	-9.9
64T2S2	Lower *	Lower footslope	N	352	252.7	3.5	-13.4	-20.3
64T3S2	Middle	Conv. backslope	NW	332	252.4	3.9	-8.2	-5.3
64T1S3	Lower	Lower footslope	N	340	250.9	3.0	-20.1	-6.7
64T2S3	Lower	Toe slope	N	353	251.6	3.0	0.8	-1.2
64T3S3	Lower	Lower footslope	N	357	251.1	2.5	-7.9	4.1
30T1S1	Upper	Div. shoulder	S	195	269.2	2.8	14.3	11.7
30T2S1	Middle *	Div. backslope	SW	207	269.2	4.0	20.5	12.6
30T3S1	Middle *	Conv. backslope	S	169	269.2	3.1	-13.7	-23.0
30T1S2	Middle	Mid slope dep.	SE	146	268.8	1.0	7.9	3.5
30T2S2	Middle	Div. backslope	SE	155	268.6	1.9	6.8	4.1
30T3S2	Lower *	Lower footslope	S	163	268.5	2.7	-23.4	-26.1
30T1S3	Lower	Lower footslope	NW	324	268.6	1.7	-13.0	6.1
30T2S3	Lower	Lower footslope	E	112	268.2	1.6	-19.8	-16.1
30T3S3	Lower	Level lower slope	SW	220	268.3	1.0	16.3	4.6

T1-T3 = Transect number; S1 = Upper slope, S2 = Middle slope, S3 = Lower slope
* = different LSM classification of slope position than field observation
Curvature: Convex (+), Concave (-)

Accuracy of the LSM classification (MacMillan, 2003) was limited by the low density and poor distribution of the elevation data and by the small size of the area covered. The LSM landscape classification requires a regularly spaced elevation grid with a sufficiently high spacial resolution to capture local elevation differences of interest and to permit the accurate calculation of topographic attributes. A sufficiently large area is also required to ensure that there are true crests, pits and peaks within the elevation data.

Tree cover made it difficult to capture a sufficient number and distribution of elevation points. Cutting sight lines is destructive, time consuming, and not very practical for large areas. LIDAR (light emission detection and ranging) may be a more efficient and effective method to produce future elevation surveys in these forested areas, if the signal can penetrate the canopy cover.

The presence of organic hummocks on the lower slope, and subdued mineral hummocks on the upper and middle slope positions made it difficult to accurately capture the local relief as measured elevations varied significantly within very short distances. The LSM classification agrees with field observations in that upper slope positions were generally divergent shoulders and backslopes, but not crest positions. Site 64T3S1 is incorrectly classified by LSM as an upper slope depression. Mid-slope positions were selected in the field based on their transitional landscape position, thus resulting in a greater variety in LSM classifications. Some of the mid-slope positions are in close proximity to the lower slope transition and could be classified either way. Organic hummocks within lower slope positions have been incorrectly classified by LSM as upper slope divergent shoulders and mid-slope convergent backslopes. The LSM taxonomic system confuses organic hummocks and palsas for mineral upper slopes because only elevation data is used as input. A divergent peak could be classified as a hummock, a hill, or a mountain depending on the taxonomic system and the vertical and horizontal scale used.

10.2.2 Soils

10.2.2.1 Soil Morphology and Distribution

Initial soil surveys conducted in 2001 identified the Sipewesk series as being dominant on the 1930 burn site and the Wabowden series as being dominant on the 1964 burn site. Soils classified as the Sipewesk soil series are characterized by having a granular or fine to medium subangular blocky structured B horizon, whereas soils of the Wabowden soil series typically have columnar structured B horizons.

Table 10.6 Relationship between soil series, drainage, and structure of the B horizon for clay textured soils in the Thompson area.

		Structure of B horizon	
Drainage Class	**Taxonomy**	**Massive, Columnar, Prismatic, or Coarse Blocky**	**Granular (shotty), or Fine to Medium Subangular Blocky**
Moderately Well	O.GL	Wabowden (WBW)	Sipewesk (SWK)
Imperfect	GL.GL	Thompson (TOP)	Roe Lake (ROK)
Poor	O.LG	La Perouse (LPR)	

Note: Taxonomic abbreviations are based on the Canadian System of Soil Classification, Third Edition (Soil Classification Working Group, 1998).

Field observations suggested possible correlations to various factors including local variations in topography and stratigraphy of parent material as they influence soil texture and water flow. Relationships were observed between landscape position, stratigraphy, water flow and soil structure development. Soils with a well developed shotty (granular) structure in the Bt horizon were often associated with the presence of varves in the underlying parent materials, consisting of stratified very thin to moderately thick very strongly calcareous light gray to beige silty clay (SiC) to silty clay loam (SiCl) layers alternating with moderately calcareous dark brown clay (C) layers. Soils with strong coarse columnar structures in the Bt1 horizon were associated with clay soils developed on moderate to high relief upper slope positions. Soils with fine to medium subangular blocky structure in the Bt1 or Bt2 horizon were associated with dominantly clay textured soils in mid to lower slope positions subjected to lateral and downward seepage flow. Shotty (granular) structures and fine to medium subangular blocky structures were thus indicative of a strong lateral flow component, with subangular structures indicating slightly slower, randomly oriented flow, and columnar structures indicating preferential downward flow through vertical cracks between columns. Topography and parent materials have thus influenced the progressive development of these soil horizons.

Table 10.7 Soil legend for clay textured soils in the Thompson study area. (Veldhuis, 1995; H. Veldhuis, personal communication, AAFC, Winnipeg, MB)

Drainage	**Taxonomy**	**Series/Complex**	**Code**	**Modifier**
Moderately to very strongly calcareous, clay textured glaciolacustrine				
Moderately Well	O.GL	Sipewesk	SWK	
	O.GL or SZ.GL	Wabowden	WBW	
Imperfect	GL.GL	Roe Lake	ROK	
	GL.GL or SZ.GL	Thompson	TOP	
Poor	HU.LG	La Perouse	LPR	
	HU.LG	La Perouse, peaty	LPR	p
	R.G	Medard	MDR	
	R.G	Medard, peaty	MDR	p
Frozen (MW)	L.SC	Torrance	TOR	
Moderately to very strongly calcareous, clay textured glaciolacustrine over bedrock				
Moderately Well	O.GL	Kinasota	KIT	
	O.GL or SZ.GL	Warren Landing	WRD	
	GL.GL	Turnbull	TBL	
	R.G	Tyrell	TYL	
Moderately to strongly calcareous, clay textured glaciolacustrine grading into strongly to extremely calcareous, silt and clay textured glaciolacustrine				
Moderately Well	O.GL	Pipun	PPU	
Imperfect	GL.GL	Roe Lake	ROK	1
Poor	R.G	Button	BTT	
40-160 cm of dominantly, moderately well to well decomposed, forest and sphagnum peat over clay textured glaciolacustrine				
Poor	T.F	Cousins Lake	CSK	
to Very Poor	THU.F	Cousins Lake 3	CSK	3
Fozen (P)	TFI.OC	Nichols Lake 1	NIC	1

Taxonomic abbreviations are based on the Canadian System of Soil Classification, Third Edition (Soil Classification Working Group, 1998).

Table 10.8 Soils found along the toposequence transects of the 1964 and 1930 burn sites.

Site	Latitude	Longitude	Soil Series Code	Organic Thickness (cm)	Drainage	Profile
64T1S1	55.91294	-98.38116	WBW	4	Mod. Well	64U1
64T2S1	55.91287	-98.38019	WBW	10	Mod. Well	64U2
64T3S1	55.91290	-98.37958	WBW	8	Mod. Well	6420
64T1S2	55.91323	-98.38099	ROK	7	Imperfect	6422
64T2S2	55.91310	-98.38030	ROK	15	Imperfect	64M2
64T3S2	55.91313	-98.38001	WBW	11	Mod. Well	6421
64T1S3	55.91360	-98.38099	MDRp	46	Poor	64L1
64T2S3	55.91337	-98.38035	MDRp	42	Poor	64L2
64T3S3	55.91345	-98.37982	MDRp	46	Poor	64L3
30T1S1	55.90577	-98.52561	WBW	9	Mod. Well	3019
30T2S1	55.90567	-98.52607	WBW	14	Mod. Well	30U2
30T3S1	55.90568	-98.52644	SWK1	19	Mod. Well	3022
30T1S2	55.90556	-98.52558	ROK	25	Imperfect	3020
30T2S2	55.90548	-98.52616	ROK	14	Imperfect	3027
30T3S2	55.90545	-98.52651	ROK	14	Imperfect	3023
30T1S3	55.90529	-98.52551	CSK3	51	Poor	3021
30T2S3	55.90526	-98.52613	CSK	61	Poor	30L2
30T3S3	55.90533	-98.52666	CSK3	52	Poor	3024

Soils classified as SWK1 had typically shallower soil profiles associated with seepage flow and accumulation of carbonates in the BCk or Ck1 horizon, or strongly to extremely calcareous silt and clay textured parent materials.

Table 10.9 Soil physical and chemical properties. Compiled from soil profile, piezometer, and frost tube soil samples and descriptions collected along the central transects of the 1964 and 1930 burn sites.

Horizon	Depth (cm)	Structure	Bulk Density (g/cm³)	Texture	Particle size Sand (%)	Particle size Silt (%)	Particle size Clay (%)	Ash (%)	Estimated OM (%)	Estimated OC (%)	LECO Analysis TC (%)	LECO Analysis TOC (%)	LECO Analysis TIC (%)
1964 burn upper slope, Wabowden series, Orthic Gray Luvisol (Site 64T2S1 and 64T2S1FT)													
L	10-2		0.02					12.5	87.5	50.8	45.8	45.8	0.0
F	2-0		0.08					31.1	68.9	40.0	39.0	39.0	0.1
Ahe	0-3	MS-M -GR	0.49	HC	3	33	64	84.1	15.9	9.2	7.4	7.3	0.1
AB	3-5	MS-C -PL	0.95	HC	2	26	72	93.1	6.9	4.0	1.9	1.8	0.1
Bt1	5-28	M -C -CO S -C -SB	1.34	HC	1	26	73	93.0	7.0	4.1	2.0	1.9	0.1
Bt2	28-50	S -M -SB	1.20	HC	0	14	86	94.1	6.0	3.5	0.7	0.6	0.1
BC	50-55	S -FM-SB											
Ck1	55-75	M -F -SB,PS	1.78	HC	0	25	75	92.5	7.5	4.3	1.3	1.1	0.2
Ck2	75-104		1.36	HC	0	25	75	90.1	9.9	5.8	1.9	1.8	0.1
	104-127		1.42	HC	0	29	71	90.7	9.3	5.4	1.9	1.7	0.2
	127-155		1.61	HC	0	28	72	90.5	9.6	5.5	2.1	1.7	0.4
Ckgj	155-200		1.33	HC	0	31	69	93.1	6.9	4.0	2.2	1.2	1.0
	200-250		1.27	SiC	0	41	59	93.7	6.3	3.6	2.7	1.0	1.7

Note: Soil horizon designations are defined in Soil Classification Working Group (1998). Soil structure (Grade - Class - Kind) and texture abbreviations are defined in Expert Committee on Soil Survey (1982) and in Aglugub and Fraser (1997). Particle size analysis was conducted using the pipette method (Haluschak, 1986) where silt and clay are separated according to sedimentation rates in a constant temperature water bath and sand fractions are separated using sieves. Measurement methods for bulk density, ash content, and carbon analyses are described in the chapter on soil carbon.

Column Abbreviations:

OM = Organic Matter
OC = Organic Carbon
TC = Total Carbon
TOC = Total Organic Carbon
TIC = Total Inorganic Carbon

Table 10.9 (cont.) Soil physical and chemical properties.

Horizon	Depth	Structure	Bulk Density	Texture	Particle size			Ash	Estimated		LECO Analysis		
					Sand	Silt	Clay		OM	OC	TC	TOC	TIC
	(cm)		(g/cm^3)		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
1964 burn mid-slope, Roe Lake series, Gleyed Gray Luvisol (Site 64T2S2 and 64T2S2FT)													
LF	15-11		0.04	-	-	-	-	0.8	99.2	57.6	49.4	49.4	0.0
F	11-06		0.08	-	-	-	-	17.2	82.8	48.0	45.2	45.1	0.1
H	06-00		0.25	-	-	-	-	64.8	35.2	20.4	17.1	17.0	0.1
Ahy1	00-26			HC	0	10	90	77.0	23.0	13.4	10.7	10.6	0.1
Bty	26-70			HC	1	29	70	89.9	10.1	5.9	3.8	3.7	0.1
Ahgy	65-70			SiC	1	43	56	90.8	9.2	5.3	2.5	2.5	0.1
Ahe	00-10	S -F -GR		HC	0	14	86	83.8	16.2	9.4			
			0.68	HC	0	6	94	84.6	15.4	8.9	6.2	6.1	0.0
AB	10-14	S -F -GR											
Bt	14-25	S -FM-GR	0.92	HC	1	3	96	88.9	11.1	6.4	3.3	3.3	0.1
			0.98	HC	1	30	69	87.8	12.2	7.1			
BC	25-62	WM-F -SB	1.04	SiC	2	48	50	94.0	6.0	3.5	1.3	1.2	0.1
BCk	62-79		1.38	SiC	1	44	55	94.4	5.6	3.3	1.5	0.7	0.8
Ck1	79-100		1.56	HC	1	31	68	91.6	8.4	4.9	1.5	1.4	0.2
	100-125		1.31	HC	0	27	73	91.0	9.0	5.2	2.0	1.7	0.3
	125-175		1.50	HC	0	27	73	90.9	9.1	5.3	1.9	1.7	0.2
Ckgj1	175-230		1.37	HC	0	28	72	93.0	7.0	4.1	2.4	1.0	1.4
Ckgj2	230-250		1.37	HC	0	32	68	93.3	6.7	3.9	2.4	1.1	1.4

Table 10.9 (cont.) Soil physical and chemical properties.

Horizon	Depth	Structure	Bulk Density	Texture	Particle size			Ash	Estimated		LECO Analysis		
					Sand	Silt	Clay		OM	OC	TC	TOC	TIC
	(cm)		(g/cm^3)		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
1964 burn lower slope, Medar series, peaty Rego Humic Gleysol, turbic and texture variant (Site 64T2S3 and 64T2S3P8)													
Of1	00-10		0.05	-	-	-	-	4.8	95.2	55.2	48.3	48.3	0.0
Of2	10-24		0.11	-	-	-	-	6.0	94.0	54.5	50.9	50.8	0.1
Oh/Ah	24-42		0.70	-	-	-	-	66.9	33.1	19.2	16.2	16.2	0.1
Ah	42-44	M -F -GR		CL	38	33	29	84.0	16.0	9.3	7.3	7.2	0.1
Cky	44-52	SL, MA	1.42	Si	7	83	10	95.6	4.4	2.6			
				Si	6	84	10	97.0	3.0	1.8	3.0	0.6	2.4
Ahy	52-58	SL, MA	1.18	SiL	7	74	19	90.8	9.3	5.4	3.7	3.5	0.2
Ckgj	58-71		1.23	SiL	5	76	19	94.6	5.5	3.2	2.4	1.1	1.3
Ck	71-78		1.42	SiL	4	78	18	95.3	4.7	2.7	3.0	1.0	2.1
Ckg	78-88		1.51	SiL	5	73	22	93.2	6.8	4.0	2.8	1.6	1.2
Ckgj	88-98		1.69	SiL	5	74	21	92.2	7.8	4.5	2.8	2.0	0.7
Ck2	98-150		1.39	SiCL	3	67	30	93.4	6.6	3.8	2.1	1.2	0.9
2Ck	150-200		1.27	HC	0	26	74	91.8	8.2	4.7	1.6	1.4	0.2
	200-250		1.22	HC	0	24	76	92.9	7.1	4.1	2.0	1.2	0.8
1930 burn upper slope, Wabowden series, Orthic Gray Luvisol (Site 30T2S1 and 30T2S1P6)													
LF	14-04		0.05					5.9	94.1	54.6	54.6	54.6	0.0
H	04-00		0.37					79.7	20.3	11.8	11.6	11.5	0.1
Ae	00-04	MS-F -SB	0.92	HC	1	6	93	85.8	14.2	8.2	6.5	6.4	0.1
AB	04-10	S -FM-SB	1.01	SiC	0	45	55	92.0	8.0	4.7	3.0	2.9	0.1
Bt1	10-21	M -C -CO MS-M -SB	1.18	HC	1	7	92	93.4	6.6	3.8	1.6	1.5	0.1
Bt2	21-32	S -F -SB	1.11	HC	0	34	66	93.1	6.9	4.0	1.0	0.9	0.1
BCk	32-50	WM-F -SB,PS	1.16	HC	0	34	66	93.8	6.2	3.6	1.5	0.9	0.6
Ck1	50-92	VW-F -SB,PS	1.24	HC	1	37	62	92.5	7.5	4.4	3.2	1.2	2.0
Ck2	92-125		1.55	SiC	0	46	54	90.8	9.2	5.3	3.4	2.0	1.5
	125-200		1.38	SiC	0	50	50	90.2	9.8	5.7	3.1	2.0	1.2
Ckgj	200-250		1.26	SiC	0	45	55	90.5	9.5	5.5	2.8	2.0	0.8

Table 10.9 (cont.) Soil physical and chemical properties.

Horizon	Depth	Structure	Bulk Density	Texture	Particle size			Ash	Estimated		LECO Analysis		
	(cm)		(g/cm^3)		Sand (%)	Silt (%)	Clay (%)	(%)	OM (%)	OC (%)	TC (%)	TOC (%)	TIC (%)
1930 burn mid-slope, Roe Lake series, Gleyed Gray Luvisol (Site 30T2S2P5 and 30T2S2P6)													
F	09-05		0.06					5.4	94.6	54.9	52.9	52.9	0.0
	05-02		0.09					8.2	91.8	53.3	51.0	51.0	0.0
FH	02-00		0.18					36.7	63.3	36.7	34.9	34.9	0.1
Ahe	00-05	MS-F -SB	0.37	HC	0	31	69	76.0	24.0	13.9	9.8	9.7	0.1
Ae	05-13												
Btgj	13-35	S -F -GR	0.59	HC	1	23	76	93.3	6.7	3.9	1.3	1.2	0.1
BC	30-35	S -F -GR											
Ck1	35-69	WM-F -SB	1.06	HC	1	37	62	92.1	7.9	4.6	1.5	1.2	0.3
Ck2	69-87		1.36	SiCL	1	64	35	90.3	9.7	5.6	3.2	1.8	1.4
Ck3	87-125		1.43	SiC	0	46	54	90.3	9.7	5.6	2.7	1.8	0.9
Ckgj	125-200		1.44	HC	0	35	65	88.5	11.5	6.7	3.0	2.3	0.6
	200-250		1.47	SiC	0	45	55	88.8	11.2	6.5	2.8	2.1	0.7
1930 burn lower slope, Cousin Lake series, turbic and taxonomic variant, Terric Humic Fibrisol (Site 30T2S3 and 30T2S3P8)													
Of1	00-25		0.02					2.3	97.8	56.7	48.9	48.8	0.0
Of2	25-40		0.05					6.5	93.5	54.2	49.2	49.2	0.0
Om	40-46		0.07					9.9	90.1	52.2	46.9	46.9	0.1
Oh	46-61		0.15					27.7	72.3	41.9	37.6	37.5	0.1
Bgy	61-90	MS-FM-GR	1.10	HC	0	36	64	93.1	6.9	4.0	1.3	1.2	0.1
Ahgy				HC	0	34	66	83.8	16.3	9.4	6.5	6.4	0.1
Ohy								61.4	38.6	22.4	18.8	18.7	0.1
Ckgjy				HC	0	40	60	89.6	10.4	6.0	2.0	1.9	0.1
Bg				HC	0	31	69	94.1	5.9	3.4	0.8	0.7	0.1
Ckg	90-106		1.37	HC	0	21	79	90.0	10.0	5.8	2.0	1.8	0.3
Ckg2	106-128		1.21	HC	0	29	71	92.1	8.0	4.6	2.0	1.1	0.9
	128-150		1.29	HC	0	32	68	92.3	7.7	4.5	2.5	1.2	1.2
	150-200		1.55	HC	0	39	61	90.3	9.7	5.6	2.7	1.9	0.8
	200-250		1.61	HC	0	40	60	91.2	8.8	5.1	3.2	1.6	1.5

10.2.2.2 Acid Pretreatment of Soil Samples Leaches Dissolved Organic Carbon

An acid pretreatment can be used to remove carbonates so that combustion at high temperatures (≥900 °C) will only measure organic carbon (OC) (e.g. Tiessen and Moir, 1993). This method was tested but was found to be time consuming, and subject to numerous sources of error. Treatment with HCl requires several steps including HCl treatment on a hot plate, followed by leaching with water to remove any residual HCl, and then oven drying the remaining soil sample for further analysis. HCl is a strong acid which easily reacts with calcium carbonate, releasing gaseous CO_2, but is much slower to react with dolomite, thus potentially resulting in incomplete removal of carbonates. Removal of residual HCl also leaches CaCl, MgCl, and dissolved and particulate matter smaller than the filter pore size (1.2 um). Soil weight loss can be significant in highly calcareous soils, but percent soil weight loss could not be easily and reliably determined as oven drying the remaining wet soil and filter paper resulted in a deterioration of the filter paper, some of the soil remained on the filter paper and some of the soil was simply lost. The initial and final weights of the filter papers also varied, due in part to moisture retention. Therefore, the soil should be washed off the filter paper into a beaker prior to oven drying the soil. Beaker and soil weights must also be measured before and after treatment.

During initial testing of an HCl pretreatment method to permit the direct measurement of OC by LECO analysis, dissolved and fine particulate (<1.2 um) organic carbon (DOC & fine POC) were readily observed in the leachate from soil samples treated with HCl. DOC concentrations were measured using a Technicon AutoAnalyzer II for three leachate samples representing the range in clear, to green, to black leachate colour.

Table 10.10 DOC and fine POC leached during acid pretreatment.

Horizon	**Depth**	**Leachate Colour**	**Soil TOC**	**Leached DOC & POC (<1.2 μm)**	**% OC Leached**
	cm		mg C per gram oven dry soil weight		%
Cky	44 - 52	Clear	6	0.2	3%
Ahy	52 - 58	Dark brown	35	2.4	7%
Ck	62 - 75	Green	8	1.8	23%

Note: Total organic carbon (TOC) was measured using the split sample LECO method TOC=TC-TIC, where TIC is determined from an ashed sample.

These results indicate that a significant percentage of organic carbon (3 to 23 %) is lost as DOC within the leachate of soil samples treated with HCl. A loss of 1 mg C per gram oven dried soil weight is equal to the LECO method detection limit of 0.1% C. Thus, the HCl pretreatment method measurably underestimates % OC content within 2 of the 3 soil samples examined.

10.2.2.3 Filtration of POC and DOC in Soils

Soils act as filter or sieve, retaining organic matter residue at the soil surface. Precipitation water infiltrates into the permeable soil, transporting organic matter particles into the soil matrix until they become trapped by smaller pores, thus permitting only fine particulate and dissolved OM to leach beyond the soil profile. As soil tension increases and the soil dries out, water flow is restricted to smaller pores, and fine particulate OM may become physically trapped or chemically absorbed. To confirm, or refute this, trial calculations were conducted using the capillary equation (Brady and Weil, 2002) relating soil tension to pore diameter in order to compare pore size distribution in soils to POM and DOM filter pore sizes.

Tension head (cm) $= [2T*\cos(\alpha)]/rdg$ $= 0.15\ \text{cm}^2$ / radius (cm), at 20 °C

Table 10.11 Relationship between tension, pore size diameter, and fractionation of organic matter in soil water.

Tension (kPa)	Pore Diameter	Reference
0.3	1 mm	Coarse POM (> 1 mm); Fine POM (1 mm to 0.45 µm)
80	3.7 µm	Air entry potential of tensiometers
110	2.7 µm	Whatman GF-D filter
200	1.5 µm	Air entry potential of suction lysimeters
250	1.2 µm	Whatman GF-C filter
650	0.45 µm	Fine POM (1 mm to 0.45 µm); DOM (< 0.45 µm)
1500	0.20 µm	Considered as residual moisture
150000	1 nm	colloidal OM (0.45 µm to 1 nm); true DOM (< ~2 nm)

Based on these results, coarse POM (>1 mm) is rapidly filtered out of soil water in all but coarse textured soils or highly structured soils. Fine POM (1 mm to 0.45 µm) would gradually be filtered out within dry to very dry soils, and DOM (<0.45 µm) would only be filtered out of soils during extremely dry conditions.

10.2.3 Radiocarbon Dating

Charcoal fragments (partially burnt wood) and soil samples were collected for radiocarbon dating during the initial BOREAS project from 1994 to 1996 (Trumbore and Harden, 1997; Veldhuis, 1995), and during the Fires-ExB project from 2001 to 2004 (Cyr and Veldhuis, 2002a and 2002b), including samples from the long term Soil Climate Thompson Clay belt (SCTC) study site northeast of Thompson (Veldhuis and Eilers, 2003). Soil water samples were collected in 2003 from the 1930 and 1964 burn sites (Cyr et al., 2004) for radiocarbon dating dissolved organic carbon. Radiocarbon analyses were conducted by S. Trumbore in 2004 for the BOREAS samples which had not yet been analysed, and for new soil samples, charcoal fragments, and DOC water samples.

The following methodology for sample preparation and radiocarbon analysis is based on the description provided by S. Trumbore (personal communication, University of California, Irvine). An acid-base-acid extraction was used to remove adsorbed and potentially younger organics from soil and charcoal. DOC samples were acidified to remove inorganic carbon, and were then dried. Sample remains were then combusted and analysed using an accelerator mass spectrometer.

10.2.3.1 Age of Soil Horizons and Buried Charcoal

The radiocarbon age for organic and cryoturbed soil horizons and buried charcoal fragments (Table 10.12) appear to be within the expected limits. The younger carbon on the 1998 burn site (310 and 530 BP) probably corresponds to cryoturbation during the Little Ice Age (~1550 to 1850 AD = ~154 to 454 years BP). The second group of dates is 1315 to 1350 BP for lower slope positions within the SCTC site and the 1964 burn site, respectively.

The third group ranges from 1910 to 2145 BP for lower slope positions within the 1930 and 1964 burn sites. The oldest group of carbon-14 dates were found on the mid-slope of the 1964 burn site (4020 BP) and in the BOREAS-NSA Fen site (3685 and 5290 BP). These dates are all younger than ~7500 BP when the final drainage of Glacial Lake Agassiz into the Tyrrell sea occurred (Klassen, 1983).

10.2.3.2 Age of DOC water samples

According to S. Trumbore (personal communication, University of California, Irvine) many difficulties were encountered with the radiocarbon analysis of dissolved organic carbon (DOC) water samples. In order to successfully obtain results, DOC concentration must be at least 5 mg C / L with a total DOC load of at least 2 mg C in order to minimize the volume and drying time while maximizing the sample available for carbon dating. Alkaline water samples must be acidified to a pH of 5 or less to remove inorganic carbon, but this produces excessive salt concentrations which interferes with the radiocarbon analysis. Deep water samples also suffered from low DOC concentrations thus requiring larger water volumes and excessive drying time. Excessive salt concentrations and excessive drying times may have contributed to the shattering of tubes during the combustion stage.

Only two soil water samples with high DOC concentrations survived the combustion stage (Table 10.12). These soil water samples were collected from the lower slope of the 1930 burn site using suction lysimeters, and correspond to organic (Om/Oh) horizons and mineral (Ah/Bgy) horizons 15 cm above and below the organic-mineral horizon contact, respectively. Radiocarbon values were positive, indicating the presence of bomb carbon in both samples, with DOC being fixed on average more than 1, but less than 40 years ago.

Therefore, this DOC is younger than the 72 year old forest stand, and is derived primarily from recent organic materials at the soil surface, and not from deeper residual organic horizons. This young carbon source is probably derived from recently decomposed organic matter at the soil surface, where warmer soil temperatures promote microbial decomposition. Root exudates and dead microorganisms may also contribute to this younger carbon (S. Trumbore, personal communication, Univ. of California, Irvine). The average age of DOC is expected to increase as water flows deeper into the soil profile and incorporates older carbon sources into the soil solution, but there is currently insufficient data to accurately quantify this effect.

Table 10.12 Carbon 14 and delta 13 data for organic and cryoturbated soil horizons, buried charcoal, and dissolved organic carbon in soil water near Thompson, Manitoba. (S. Trumbore, unpublished data, University of California, Irvine)

Site	Description	Depth (cm)	del 13C	del 14C (+/-)	14C age year BP	Location
30T2S3	water in Om/Oh	~30 to 45 cm	-27.2	166.8 (2.4)	Modern	55.90526 -98.52613
30T2S3	water in Ah/Bgy	~45 to 60 cm	ND	76.9 (2.5)	Modern	55.90526 -98.52613
98-02	charcoal	~20 to 40 cm	-25.1	-69.7 (1.9)	530	56.63594 -99.94752
98-D3	charcoal in Bt1	~20 to 40 cm	-25.3	-44.1 (2.1)	310	56.63444 -99.94827
SCTC-C1B	Oh	45 to 50 cm	-26.1	-156.4 (1.7)	1315	55.91145 -97.69606
64T3S3	Ahgy	90 cm	-26.1	-160.2 (1.7)	1350	55.91345 -98.37982
30T2S3	charcoal in Ahy	123 cm	-26.1	-216.8 (1.6)	1910	55.90526 -98.52613
64T2S3	Ahy	52 to 58 cm	-26.3	-220.5 (1.6)	1950	55.91337 -98.38035
64T2S3	Ahy	52 to 58 cm	-25.9	-234.9 (1.7)	2100	55.91337 -98.38035
64T2S3-#2	Oh	49 to 62 cm	ND	-239.5 (1.6)	2145	55.91338 -98.38032
64T2S2	Ahgy	65 to 70 cm	-26.1	-397.6 (1.4)	4020	55.91310 -98.38030
FEN-04	Of4	215 cm	-26.4	-372.2 (1.4)	3685	~ 55.91481 ~ -98.42072
FEN-04	Om1	310 cm	-26.6	-485.7 (1.3)	5290	~ 55.91481 ~ -98.42072

Trumbore, S., Veldhuis, H., and Cyr, P. 2004. Carbon 14 and delta 13 data for organic and cryoturbated soil horizons, buried charcoal, and dissolved organic carbon in soil water near Thompson, Manitoba. Preliminary data and personal communications.

10.3 Soil Hydraulic Properties

Hydrology models are used to predict the movement of water and solutes in soils, but their accuracy depends on our ability to reliably measure or estimate the hydraulic properties of the medium under both saturated and unsaturated conditions. Direct measurement of saturated and unsaturated hydraulic conductivity in the field or the lab is costly and time consuming, therefore requiring the use of theoretical, statistical and empirical models to predict hydraulic conductivity parameters based on more easily measured data. It is often more feasible to estimate soil hydraulic parameters using soil texture, soil structure, bulk density and soil moisture retention data (e.g. McKeague et al., 1982; Soil Water Interest Group, 1982; Expert Committee on Soil Survey, 1991; Schapp et al. 2001).

Saturated and unsaturated hydraulic conductivity vary spatially and with depth in the soil profile, as they are dependent on soil structure, bulk density, and texture differences which affect pore size distribution. Hydraulic conductivity may vary i) with the direction of flow due to anisotropy (difference in soil properties in the x, y and z directions); ii) with time due to changes in moisture content (organic soils and clay soils of smectite mineralogy will shrink and swell with changes in soil water content); and iii) with the presence of frozen soil conditions (water vapour moves towards the freezing front, and ice lenses restrict water flow).

Hydraulic conductivity of soils is reduced during unsaturated conditions as water flowing through the soil matrix must pass through smaller pores and follow an increasingly tortuous path as it detours around air filled pore spaces. Under natural conditions, saturated soils contain dissolved air or pockets of entrapped air and the measured saturated water content can be 5 to 10% smaller than the total porosity due to this presence of air filled pore spaces (van Genuchten et al., 1991). This results in a decrease in hydraulic conductivity of soils and results in a smaller field saturated hydraulic conductivity (Kfs) than the maximum measurable saturated hydraulic conductivity (Ksat).

During unsaturated conditions, water is held under tension within soil pores against the pull of gravity by capillary action due to the surface tension of water and its contact angle with the soil particles (Hillel, 1982). This soil water is therefore held under tension (a.k.a. suction or negative pressure). Soil water content can be measured at several different tensions and when these discrete soil water retention measurements are graphically plotted, they form a curve known as a soil water characteristic curve (SWCC) which can be described mathematical by hydraulic retentivity functions (eg. van Genuchten, 1980) to interpolate soil water contents within the tension measurement range. Soil water retention is dependent on pore size distribution and can be measured directly or estimated based on bulk density and particle size distribution data (eg. Saxton et al., 1986; Schapp et al. 2001).

10.3.1 Estimation of Soil Hydraulic Properties

Saturated hydraulic conductivities were estimated during the 2001 field season based on soil properties observed in the field (texture, structure, density). Moderately slow saturated hydraulic conductivities of 0.5 to 1.5 cm/hour (12 to 36 cm/day) were estimated most frequently (24 times), with moderate hydraulic conductivities of 1.5 to 5 cm/hour (36 to 120 cm/day) being the second most frequently estimated saturated hydraulic conductivity (6 times).

Initial soil surveys conducted in 2001 identified the Sipewesk series as being dominant on the 1930 burn site and the Wabowden series as being dominant on the 1964 burn site. Sipewesk series are characterized as having a granular or fine to medium subangular blocky structured B horizon, whereas Wabowden series have a columnar structured B horizons. Saturated hydraulic conductivities (Ksat) were expected to change with depth as structure, texture, bulk density and parent material stratification change with depth. Platy structures within the Ae horizons are indicative of eluviation, but ice lenses upto 5 mm thick have been observed in these northern clay soils, suggesting that frost heave may be a major contributing factor to the formation of platy structured Ae horizons as water near the soil surface will repeatedly freeze and thaw in the spring and fall. Platy Ae horizons were expected to have a higher horizontal versus vertical hydraulic conductivity (moderate horizontal Ksat vs moderately slow vertical Ksat, except for moderately rapid flow where vertical cracks occur). Lateral water flow of snow melt water through the Ae horizon may be significant in the spring as the underlying frozen soil will act as a barrier to downward flow. Ksat was expected to be significantly different between the columnar structured Bt horizons of the Wabowden soil series and the granular to subangular blocky structured Bt horizon of the Sipewesk soil series. Columnar structured Bt horizons were expected to have a high degree of anisotropy, with moderately slow vertical and horizontal Ksat within the soil matrix, and moderate to moderately rapid Ksat within vertical preferential flow pathways occurring in between columns and along old root channels, thus resulting in a high initial Ksat which declines with time as water passes through smaller pores within the soil matrix. Granular structured Bt horizons were expected to have moderate Ksat, similar in both the vertical and horizontal directions. The subangular blocky structure of the Bt2 horizon and

BC transition suggested that water flows randomly, both laterally over the Ck horizon and downward into the Ck horizon. Water flow is expected to slow once it reaches the less permeable Ck horizon.

Table 10.13 Classification categories for saturated hydraulic conductivity.

		Saturated hydraulic conductivity			
		Low	High	Low	High
		cm/hour		cm/day	
H - HIGH	H2 - Very rapid	50.00		1200.0	
	H1 - Rapid	15.00	50	360.0	1200
M - MEDIUM	M3 - Mod. Rapid	5.00	15	120.0	360
	M2 - Moderate	1.50	5	36.0	120
	M1 - Mod. Slow	0.50	1.5	12.0	36
L - LOW	L3 - Slow	0.15	0.5	3.6	12
	L2 - Very slow	0.05	0.15	1.2	3.6
	L1 - Extr. slow	0.00	0.05	0	1.2

Table 10.14 Predicted vertical and horizontal saturated hydraulic conductivities (Ksat) for heavy clay textured soil horizons within the Thomson study area.

		Saturated Hydraulic Conductivity (Ksat)		
Horizon	Description	Category	(cm/hour)	(cm/day)
Ae	Vertical cracks	Moderately Rapid	(5-15)	(120-360)
	Horizontal platy voids	Moderate	(1.5-5.0)	(36-120)
	Platy matrix	Mod. Slow	(0.5-1.5)	(12-36)
Bt	Granular	Moderate	(1.5-5.0)	(36-120)
	Vertical cracks	Moderate	(1.5-5.0)	(36-120)
	Columnar matrix	Mod. Slow	(0.5-1.5)	(12-36)
Ck	Si-SiL	Mod. slow	(0.5-1.5)	(12-36)
	SiC	Slow	(0.15-0.5)	(3.6-12)
	HC	Very slow	(0.05-1.5)	(1.2-3.6)

Table 10.15 Predicted hydraulic conductivity parameters based on soil texture, bulk density, and water retention data.

Soil Properties of Selected Sites (from BOREAS-NSA data set)										Estimates of hydraulic parameters (Using Rosetta in Hydrus 2D)				
Horizon	Depth (cm)	Bulk Density (g/cm³)	Texture	Sand (%)	Silt (%)	Clay (%)	Soil Water Retention (g water / g soil) 10 kPa	33 kPa	1500 kPa	θr (cm³/cm³)	θs	Alpha (cm⁻¹)	n	Ksat (cm/day)
1870 burn upland, Wabowden series, Orthic Gray Luvisol (Site OBS07)														
L	11-04	-		-	-	-	-	-	-					
F	04-00	-		-	-	-	-	-	-					
Ae	00-06	0.77	HC	3%	13%	85%	0.380	0.363	0.243	0.143	0.666	0.056	1.29	65
AB	06-14	-	HC	2%	10%	88%	-	-	-					
Bt1	14-26	1.16	HC	1%	4%	95%	0.502	0.425	0.313	0.109	0.583	0.030	1.19	41
Bt2	26-48	1.12	HC	0%	2%	98%	0.510	0.408	0.287	0.110	0.594	0.029	1.21	47
BC	48-56	-	HC	0%	6%	94%	-	-	-					
Ck	56-95	1.21	HC	7%	24%	69%	0.546	0.403	0.296	0.111	0.546	0.031	1.19	39
1870 burn upland, Sipewesk series, Orthic Gray Luvisol (Site OBS02)														
L	18-10	-		-	-	-	-	-	-					
F	10-02	-		-	-	-	-	-	-					
H	02-00	-		-	-	-	-	-	-					
Ae	00-07	0.79	HC	2%	14%	84%	0.319	0.280	0.219	0.201	0.643	0.078	1.63	74
AB	07-14	1.03	HC	1%	4%	95%	0.421	0.355	0.255	0.144	0.609	0.051	1.27	68
Bt	14-32	1.06	HC	1%	3%	96%	0.449	0.355	0.242	0.126	0.601	0.040	1.26	64
BC	32-62	-	HC	1%	7%	92%	-	-	-					
Ck	62-86	1.35	SIC	1%	50%	49%	0.435	0.394	0.211	0.085	0.491	0.005	1.43	9
Ckz	86-100	-	HC	1%	39%	60%	-	-	-					

Note: Soil properties for the old black spruce (OBS) 1870 burn site are based on the BOREAS-NSA data set (Veldhuis, 1995). Hydraulic parameters were only estimated when both soil texture and bulk density data were available. Soil water retention data (33 and 1500 kPa) was also included within the parameter estimation, when this data was available.

Where

θr	Residual soil water content	θs	Saturated soil water content
Alpha	Parameter α in the soil water retention function [cm-1]	n	Parameter *n* in the soil water retention function
Ksat	Saturated hydraulic conductivity [cm day-1]		

Table 10.15 (cont.) Predicted hydraulic conductivity parameters based on soil texture, bulk density and water retention data.

Soil Properties of Selected Sites (data collected as part of the current study)										Estimates of hydraulic parameters (Using Rosetta in Hydrus 2D)				
Horizon	Depth (cm)	Bulk Density (g/cm^3)	Texture	Sand (%)	Silt (%)	Clay (%)	Soil Water Retention (g water / g soil) 10 KPa	33 KPa	1500 KPa	θ_r (cm^3/cm^3)	θ_s	Alpha (cm^{-1})	n	Ksat (cm/day)
1964 burn upper slope, Wabowden series, Orthic Gray Luvisol (Site 64T1S1, Profile 64U1)														
L	04-03	0.05		-	-	-	-	-	-					
FH	03-00	0.07		-	-	-	0.13	-	-					
Ae	00-05	0.64	HC	2%	31%	67%	0.291	0.224	-	0.189	0.660	0.026	3.46	67
AB	05-11	0.76	HC	1%	23%	76%	-	-	-	0.131	0.711	0.047	1.21	94
Bt1	11-32	1.32	HC	0%	30%	70%	0.459	0.426	-	0.104	0.509	0.027	1.17	16
Bt2	32-44	1.24	HC	0%	31%	69%	0.461	0.431	-	0.105	0.535	0.029	1.17	23
BC	44-54	1.13	HC	0%	28%	72%	-	-	-	0.115	0.581	0.024	1.24	21
Ck	54-105	1.19	HC	0%	29%	71%	-	-	-	0.112	0.560	0.022	1.25	16
1964 burn lower slope, Medar series, peaty Rego Humic Gleysol, turbic and texture variant (Site 64T2S3, Profile 64L2)														
Of1	00-10	0.05					0.287	0.168	-					
Of2	10-24	0.11					-	-	-					
Oh/Ah	24-42	0.7					0.532	0.443	-					
Ah	42-44		CL	38	33	29	-	-	-					
Ahy	52-58	1.18	SiL	7	74	19	-	-	-	0.079	0.495	0.005	1.66	46
Cky	44-62	1.42	Si	7	83	10	0.31	0.29	-	0.057	0.421	0.006	1.62	36
Ck	62-75	1.29	SiC	1	44	55	-	-	-	0.104	0.522	0.016	1.31	12
1930 burn upland, Sipewesk series, Orthic Gray Luvisol (Site 30T2S1, Profile 30U2)														
LF	14-04	0.05		-	-	-	-	0.178	-					
H	04-00	0.37		-	-	-	-	0.273	-					
Ae	00-04	0.92	HC	1%	6%	93%	-	0.271	-	0.208	0.583	0.018	3.23	178
AB	04-10	1.01	SiC	0%	45%	55%	0.335	0.308	-	0.103	0.571	0.037	1.35	33
Bt1	10-21	1.18	HC	1%	7%	92%	0.382	0.358	-	0.145	0.533	0.026	1.60	80
Bt2	21-32	1.11	HC	0%	34%	66%	0.451	0.429	-	0.105	0.576	0.034	1.18	40
BCk	32-50	1.16	HC	0%	34%	66%	0.454	0.432	-	0.105	0.561	0.030	1.18	31
Ck	60-110	1.24	HC	1%	37%	62%	0.433	0.412	-	0.104	0.530	0.024	1.20	21

10.3.2 Measurement of Soil Hydraulic Properties

10.3.2.1 Saturated Hydraulic Conductivity

Saturated hydraulic conductivities were measured in the field in 2003 and 2004 using a Guelph permeameter (Table 10.17). Matrix flux potential, the alpha parameter, and field saturated hydraulic conductivity (Kfs) were calculated using the two pressure head method (SoilMoisture, 1991). Saturated hydraulic conductivity was also calculated using the single pressure head method (Reynolds, 1990). The single pressure head method requires the selection of appropriate C factors and Alpha parameters as input to the hydraulic conductivity calculation. Reynolds (1990) suggests the use of a C factor of 0.9 for a 5 cm head, and 1.4 for a 10 cm head, whereas the C factor values derived from the graph in SoilMoisture's instruction manual (1991) indicate that a value of 0.8 should be used for a 5 cm head, and 1.2 to 1.3 for a 10 cm head based on a well radius of 3 cm. Reynolds also uses an alpha parameter value of 0.12 cm^{-1} whereas the alpha parameter may vary significantly, as shown in Table 10.16 .

Table 10.16 Estimation of alpha parameter based on soil texture and structure (SoilMoisture Equipment Corp., 1991).

Soil texture / structure category	Alpha (1/cm)
Compacted, structureless, clayey materials	0.01
Unstructed fine textured materials	0.04
Unstructured medium to fine sand or structured clays to loams	0.12
Coarse and gravelly sands or highly structured soils with large cracks and macropores	0.36

Table 10.17 Calculated field saturated hydraulic conductivity (Kfs). Based on measurements obtained in the field using a Guelph Permeameter.

		Two Pressure Head Method			Single Pressure Head Method	
Horizon	Lower Depth (cm)	Matric Flux Potential	Alpha (1/cm)	Kfs Pooled (cm/hour)	Kfs 10 cm head (cm/hour)	Kfs 5 cm head (cm/hour)
<u>Moderately well drained, Wabowden series (O.GL), Site 64T1S1</u>						
Ae & AB	10	-0.2739	-0.2038	200.95	68.03	13.7
Bt1	24	-0.0022	-0.9385	7.27	4.11	2.66
Bt1	25	-0.0033	-0.2837	3.37	1.40	0.58
Bt1	24	-0.0034	-0.2221	2.69	0.97	0.26
Bt1	24	-0.0058	-0.2016	4.18	1.40	0.26
Bt1 & Bt2	31	0.0044	-0.0194	-0.31	0.75	1.09
Bt2	34	0.0002	0.0012	0.00	0.05	0.06
Ck	70					3.44
<u>Moderately well drained, Wabowden series (O.GL), Site 64T2S1</u>						
AB	10	-0.0182	-0.2657	17.41	7.06	2.73
Bt1	20	-0.0047	-0.5543	9.37	4.88	2.89
Bt2	30	0.0004	-0.0858	-0.13	0.01	0.06
BCk	45	0.0001	-0.0817	-0.02	0.00	0.01
Ck	73					0.18
<u>Moderately well drained, Sipewesk series (O.GL), Site 30T2S1</u>						
Bt	20					1.28
Bt	21	0.0093	0.1059	3.56	4.24	4.21
<u>Poorly drained, Cousin Lake series (T.F), Site 64T1S3</u>						
Of		0.1026	0.3692	136.41	107.65	89.95
<u>Poorly drained, Cousin Lake series (T.F), Site 64T2S3</u>						
Of	20					203.03

Negative values were not expected for the matrix flux potential (ϕ_m) and the alpha parameter (α), however this may be the result of the rapid decrease in hydraulic conductivity with depth. The absolute value of the calculated alpha parameter (0.9 to 0.2 cm^{-1}) is upto an order of magnitude greater than values reported by Cuenca et al. (1997) and Nijssen et al. (1997), and estimates calculated using the Rosetta model (Schapp et al. 2001) in HYDRUS2D. The larger absolute value of the alpha parameter may indicate that macropore flow is significant, since highly structured soils with large cracks and macropores may have alpha parameter values near 0.36 cm^{-1} (Reynolds, 2003a). A negative value for Kfs or matrix flux potential does indicate the presence of a hydrologic discontinuity (SoilMoisture, 1991) and results in a negative value for the Alpha parameter.

The calculated field saturated hydraulic conductivity (Kfs) for the two pressure head method (pooled Kfs) is essentially a weighted difference of 'steady state' rate of flow under 5 cm and 10 cm pressure heads and assumes that the hydraulic properties are uniform throughout the 10 cm measurement depth. Steady state is defined as a steady rate of flow over three consecutive measurement periods, and can be difficult to establish in structured clay soils. Furthermore, the assumption of uniformity easily becomes false when there are rapid changes in texture, structure and pore size distribution with depth, such as near abrupt horizon boundaries.

Field saturated hydraulic conductivities calculated using the single pressure head method (Reynolds, 1990) were more realistic (Table 10.17). Kfs was very rapid within Of horizons, moderately to very rapid within Ae horizons, moderate to rapid within AB horizons, and slow to moderate within columnar Bt horizons. Extremely slow hydraulic conductivity measurements within the upper slope Bt2 and BCk horizons was thought to be caused by perched water table conditions. This was confirmed for site 64T2S1 by measuring water levels within nearby piezometers.

Field saturated hydraulic conductivities (Kfs) were more variable than initially expected. Observed oscillations in the measured Kfs were attributed to extremes in pore size distribution as faster rates of flow occur through macropores and slower rates of flow occur through the finer micropores of the soil peds. The range in measured Kfs values appeared to decrease over time, suggesting that soil heterogeneity became less important over time. Ksat measurements conducted over longer time periods are expected to decrease in magnitude, as smaller pores will restrict water flow when the larger cracks become saturated. Deeper soil horizons and geologic materials may also restrict downward flow of water and decrease the measured hydraulic conductivities within the overlying materials over time.

Measurement methodology may also account for some of the measured variability as two different types of auger bits are used. The first auger bit is more destructive of the soil structure and should only be used to auger the first part of the hole. The second auger bit with the blade on the flat bottom should be used to auger out the soil in the measurement zone. Smearing of the soil may occur with both types of augers, requiring the use of a cylindrical spike brush to remove the smear layer. Reynolds (1993a) suggests several additional methods to improve measurement accuracy, which should be used in future measurements. These include the "two-finger/two-turn" rule for augering out soil in the measurement zone, not using distilled water as it may result in clay dispersion, and avoiding siltation by backfilling the measurement zone with pea gravel.

10.3.2.2 Unsaturated hydraulic conductivity

Preliminary measurements of unsaturated hydraulic conductivity (Kψ) were conducted using a tension infiltrometer. The calculated unsaturated hydraulic conductivities in Table 10.18 are suspect as unsaturated hydraulic conductivity should increase with decreasing tension. Unsaturated hydraulic conductivity of the LFH increased from 3 to 8 cm/hour (67 to 197 cm/day) as expected with decreasing tension of 25 cm to 10 cm. Hydraulic conductivity then decreased to 4 cm/hour (97 cm/day) as zero tension was reached. The presence of less permeable H and Ae horizons may account for the decreased hydraulic conductivity at tensions of 5 cm and 0 cm, as these horizons may act as a barrier to downward flow. The measured hydraulic conductivities are otherwise within the expected range for Fibric to Mesic organic materials, >6 and 6-0.1 cm/hour respectively (Boelter, 1969).

Results for the Ae horizon are however more difficult to explain and may be due in part to soil heterogenity, a strong vertical water content gradient, non-attainment of steady flow, poor hydraulic contact, or potential errors in measurement methodology. The measurements for the Ae horizon were the author's first attempt at measuring unsaturated hydraulic conductivities with a tension infiltrometer and the written instructions were not very clear. No retaining ring, mesh cloth or contact material were used, thus resulting in potential errors in measurements due to the presence of cracks or unevenness in the soil, and potential lateral seepage flow away from the porous disk (Reynolds 1993b). Additional errors for the Ae horizon measurements may be due to an improper seal between the reservoir and the base requiring new o-rings and the use of Vaseline sealant, applying an increasing tension, and not knowing which air entry tube needed to be plugged (the plug must be kept on the reservoir air entry tube and removed from the Marionette Bubbler prior to starting measurements). Thus the measured values for the Ae horizon are unreliable.

Table 10.18 Calculated unsaturated hydraulic conductivity. Based on field data collected within an upland soil on the 1964 burn site using a Guelph Permeameter and a tension infiltrometer.

HORIZON	**DEPTH cm**	**HEAD cm**	**KΨx cm/hour**	**KΨx cm/day**
LFH	surface	-25	2.79	66.9
LFH	surface	-15	6.79	162.9
LFH	surface	-10	8.21	197.1
LFH	surface	-5	4.83	116.0
LFH	surface	0	4.03	96.7
Ae	0	-20	-28.13	-675.0
Ae	0	-10	2.17	52.0
Ae	0	-5	32.46	779.0

10.4 Water Analyses

10.4.1 Methods

Additional field and laboratory measurements were made for pH, temperature, redox potential, electrical conductivity (EC), ammonia, and iron content of the soil water using pH and ORP testers, a digital thermometer, an EC meter, and chemical test kits. Limited data exists for these properties due to time constraints in the field and lab, and due to the time sensitive nature of these measurements. Field data is limited to a few analyses conducted in 2002. Due to time constraints, soil solution pH was only measured in the field for a limited number of samples. A limited number of reduction-oxidation potential measurements were conducted in the field in July and September of 2002, and in the lab for samples collected in September of 2003. Precipitation and soil water samples analysed in the lab for pH, redox potential and electrical conductivity were kept cool using ice packs and portable coolers in order to approximate soil temperature conditions in the field. However, in situ measurement of pH and redox in conjunction with automatic temperature calibration is the preferred method.

10.4.2 Results and Discussion

10.4.2.1 EC

DOC concentrations had very weak yet significant negative correlations with electrical conductivity (EC) (r^2=0.04, p=0.01, n=262). This is attributed to the fact that DOC concentrations tend to decrease with depth, whereas EC and pH should increase with depth in the soil profile. Soil EC values ranged from 0.03 to 5.5 mS cm^{-1}. Average EC values increased from near zero in precipitation water, to 0.04-0.12 mS cm-1 for soil water in organic horizons, and 0.2 mS cm-1 for soil water at the 15-cm depth in mineral soil profile, to 0.7 mS cm-1 for soil water in the calcareous parent materials at the 244-cm depth below the organic-mineral horizon contact. These relationships proved useful as EC provided an independent method to check for and correct suspected data recording errors where the order of sample collection in the field had either been reversed or not recorded at all.

10.4.2.2 pH

DOC concentrations had very weak yet significant negative correlations with pH (r^2=0.03, p=0.01, n=250) of soil water samples, but removal of a single outlier in the DOC vs pH scatter plot resulted in the DOC vs pH relationship shifting to an very weak positive correlation. Soil solution pH values ranged from 6.4 within surface organic horizons, to 8.8 at the 244-cm depth on the 1930 burn lower slope, but were otherwise quite variable. Soil solution pH was only slightly higher within the 1930 burn site compared to the 1964 burn sites (8.0 and 7.8, respectively), but laboratory measurements of soil solution pH were measured several weeks to months after sample collection and cannot be considered truly representative of field conditions. Furthermore, measured pH may be slightly offset by ~0.1 pH unit from true pH due to temperature dependent calibration errors.

Although pH is often considered the “master variable” controlling ion exchange, dissolution/precipitation, reduction/oxidation, adsorption, and complexation reactions (McBride, 1994) and pH effects have been reported on DOM dynamics in the laboratory (eg. Jardine et al., 1989), pH effects on DOC in the field seem to be small and within the normal pH range of the soils (Kalbitz et al. 2000). Effects of pH on DOC adsorption and desorption are likely dependent on the ionic strength of the soil solution, the reactive surface area and buffering capacity of the soil, and the local nature of pH dependent processes (eg. redox conditions).

In nature, soil pH is strongly dependent on parent materials, soil depth, and duration and intensity of soil profile development. Soils contain a reserve of acidity in the form of organic acids, Al3+-organic complexes and soil minerals which may release acidity by dissociation, cation exchange, or hydrolosis (McBride, 1994), and a reserve of bases in the form of carbonate minerals. Changes in soil and solution pH are induced by precipitation inputs which contain weak acids, addition of dissolved organic acids and bases supplied by decomposing leaf litter and soil organic matter and production of root exudates, and by microbial and root respiration which produces CO2 and carbonic acid. Leaching of dissolved organic acids may impact solution pH over the short term and soil pH over the long term, but pH effects on microbial metabolism of DOM and DOC adsorption are likely limited to major pH changes associated with soil depth.

10.4.2.3 Redox Potential (ORP)

Redox measurements ranged from 105 to 225 mV and were not correlated with DOC measurements ($r^2=0.00$, $p=0.70$ $n=76$). Comparison of the pH and redox data with solubility diagrams (McBride, 1994) indicates that conditions of incipient (imperfect) reduction exist within the observed pH range of 7 to 8 and redox range of 105 to 225, with conditions being favourable to the formation of water soluble Mn2+, but not Fe2+. Formation of water soluble Fe2+ becomes possible at lower soil pH and redox potential values.

Very fine in-ped mottles were occasionally observed at shallow depths within soils on the 1930 lower slope, and fine to medium distinct to prominent mottles were found at depth during installation of frost tubes and 244-cm deep piezometers on most of the 1964 burn sites and all of the 1930 burn sites. This indicates that alternating reducing-oxidizing conditions do occur within these soils during prolonged perched water table conditions. On the 1930 burn site, the presence of oxidized fine to very-fine in-ped mottles within mid and lower slope soil profiles and the frequent occurrence of water within shallow (<60 cm deep) upper to lower slope piezometers are consistent with Fanning and Fanning's (1989) model for mottle development in clay soils with seasonally perched water tables.

Strongly reduced gleysolic colours were also observed in the very poorly drained mineral soils beneath the 1930 burn fen site (located ~75 m west-southwest of the 1930 burn DOC-hydrology sites), where the groundwater table remains at or near the soil surface throughout the year.

10.4.2.4 Total and Soluble Iron

Measurements of water soluble Fe2+ and total Fe were conducted in the field and lab in 2002 using a commercially available test kit. With the intercepts set to zero, correlations between field and laboratory iron measurements was moderate for total iron ($r^2=0.42$, $p<0.01$, n=17; $r^2=0.08$, p=0.28 with an intercept) and moderately high for soluble iron ($r^2=0.55$, $p<0.01$, n=18; $r^2=0.26$, p=0.03 with an intercept). Differences are due in part to the difficulty of accurately determining iron content colorimetrically within cloudy samples or samples with a green colour caused by chlorophyll. Based on laboratory measurements, total iron ranged from 0-3.5 mg/L (n=28) and soluble iron ranged from 0-3 mg/L (n=94), comprising approximately 83% of total iron ($r^2=0.99$, $p<0.01$, n=23).

DOC concentrations appeared to be positively, yet very weakly, correlated to laboratory measurements of soluble iron content (r^2=0.05, p=0.03, n=94) but not to the field measurements of soluble iron content (r^2=0.07, p=0.18, n=27). Two distinct linear groups within the scatter plot for DOC vs laboratory measured soluble iron suggests that distinctly different relationships may exist between soluble iron and two separate DOC fractions, but this requires further examination.

10.4.3 Conclusions

DOC concentrations were very weakly correlated to soil water pH (r^2=0.03, p=0.01, n=250), EC (r^2=0.04, p=0.01, n=262), and laboratory measurements of soluble iron content (r^2=0.05, p=0.03, n=94), but were not correlated with field measurements of soluble iron content (r^2=0.07, p=0.18, n=27), or ORP measurements (r^2=0.00, p=0.70 n=76). Comparisons are hampered by the limited number of in-field measurements, and the narrow range of values observed. Further measurements would benefit from improved calibrations.