INTERPRETING THE SPATIAL DISTRIBUTION OF SELECT SOIL PROPERTIES IN TWONEW BRUNSWICK UPLAND WATERSHEDS BY WAY OF THE FLOW ACCUMULATION CONCEPT

by

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ABSTRACT

This thesis investigates functional interrelationships among lateral water flow and accumulation, soil chemistry and soil physical characteristics at two contrasting upland watershed project areas near Gounamitz and Island Lakes in Northern New Brunswick. Soils and substrates are well drained at the Gounamitz Lake site, while soils at the Island Lake site suffer from restricted permeability at a half metre depth.

Flow accumulation, wetness index and slope gradient values, as topographic metrics of lateral subsurface water flow, were estimated for 38 and 41 plot locations at the Gounamitz Lake and Island Lake sites respectively. Guided by both plot-level observations (landscape position, flow regime, slope shape) and digitally-modelled flow networks, I derived a set of best-estimate values for flow accumulation at each plot. Wetness index was calculated as a function of both field-estimated slope gradient and flow accumulation.

Spatial differences in depth, % coarse fragment content and % clay of A, B and subsoil layers, as well as overall soil layer and rooting zone depth, were found to be weakly related to topographic metrics. Soil chemical concentrations within these same layers, however, displayed stronger relationships overall with water flow indices. In general, trends were found to be consistent between sites, but the strength of these correlations differed. Total elemental nutrient amounts per hectare of rooting zone were also influenced by topography, soil acidity and soil clay content; relationships were both linear and non-linear and varied by nutrient element and site. Overall, the basic differences in substrate permeability between sites has likely regulated the amount of lateral versus downward water percolation, thereby influencing the resultant ridge-to-depression pattern of soil accumulated nutrients and particulate matter. In general, basins with poor soil permeability show a stronger ridge-to-depression spatial accumulation pattern than basins with well-drained soils and substrates.

Also investigated were two field procedures to obtain accurate elevation data. Within a portion of the Island Lake site, point positions and elevations were surveyed using manual (chain and compass) and hybrid manual/GPS methods and geo-referenced using a number of known control points. Digital Elevation Models created from these data (10 – 20 m grid resolution) were visibly more capable of resolving finer scale landform features as compared to provincial data sets (70 m grid resolution).

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CHAPTER 1

THESIS INTRODUCTION

Water flow and accumulation have been recognised as mediating influences on soil development processes in many landscapes (Jenny 1980; Gerrard 1981; Moore et al. 1993), especially where the soil substrate becomes relatively impermeable with depth, resulting in lateral surface and subsurface water flow and variable soil moisture conditions (O'Loughlin 1986). The influence of water has been succinctly summarised by Hammer (1998): "Water shapes the landscape, participates in chemical and physical weathering, carries dissolved and suspended materials to different places in the soil profile, landscape, or drainage network, and is the solution within which new compounds are formed from the products of weathering."

Previous investigations have exhibited three main limitations in addressing the influence of water flow and accumulation on soil development. First of all, either directly or indirectly, studies have often lacked a consistent quantitative framework (Pennock et al. 1987; Moore et al. 1993). For example, the use of qualitative topographic descriptors such as slope position is subjective, may not link directly to the effect of water flow, and does not provide a quantitative means of duplication in other areas. Secondly, many studies have lacked the clear spatial contrasts necessary for understanding the form and function of soil-landscape relationships. Finally, many ecologists and soil researchers have limited their investigations to two-dimensional soil processes or those occurring in the surface soil (Hammer 1998), providing only a partial picture of actual soil development. The following thesis aims to provide both a logical framework and a quantitative methodology by which to address these shortcomings.

Two geomorphologically-contrasting headwater catchment areas in Northern New Brunswick are characterised (Chapter 2). For a given climate and geomorphology, watersheds become the natural unit of integration for soil processes (Hugget, 1975; Gerrard 1981) since (1) they provide discrete, bounded units where the flow of energy, water and chemicals can be quantified, as determined by the local topography and (2) they occur as repeating units across a given landscape, easily outlined with current GIS techniques. Within this framework, relationships between lateral water flow and accumulation indices and spatial patterns of soil properties within the rooting zone are investigated.

A main consideration, although rarely addressed, is the ability to *accurately* quantify or index water flow across the landscape. Digital Elevation Models (DEM's) provide a means of automatically deriving quantitative topographic attributes (see Moore et al. 1991) as quantitative indices of water flow processes. However, the accuracy of derived attributes is directly dependent on the resolution of the original elevation data and their usefulness in accurately characterising a landscape at the scale desired (Zhang and Montgomery 1994). I therefore examine the accuracy and adequacy of readily available DEM data in characterising the topography of these two areas, as well as in deriving topographic attributes for sample plots (Chapter 3). As an alternative to the above, automated approach, I assign a set of *a priori* "best-estimate" values to each plot using field observations and watershed flow networks, and compare them with DEM-derived values.

The quantitative topographic indices flow accumulation, slope gradient and steady-state wetness index are hydrologically-significant spatial indicators of water flow and accumulation mechanisms (Speight 1974; O'Loughlin 1986; Moore et al. 1991). These indices may provide a means to quantify the extent and direction of relationships between topography and soil properties; this quantitative approach is necessary to better understand the underlying mechanisms driving functional relationships. Walker et al. (1968) and Moore (1996) respectively found slope gradient and wetness index to be significant quantitative predictors of various soil properties; flow accumulation, however, has rarely been used in this way.

Using regression analyses, I explore spatial relationships between these indices and soil physical properties (Chapter 4) and soil chemical concentrations (Chapter 5) by soil layer across both sites. Subsequently, I examine whether similar relationships exist for rooting zone nutrient storage (Chapter 6) since the complete soil profile provides a more ecologically-significant indicator of site quality and sustainable productivity. Ultimately the objective of these investigations is to provide a more complete understanding of the potential significance of water flow and accumulation at two watershed sites in the context of topographic complexity, substrate and geology.

Since the resolution of available elevation data is quite often inadequate for fine-scale studies (Dikau 1989), I subsequently explore two field procedures (Chapter 7) for obtaining fine-scale elevation data often necessary for characterising local topographic complexity. These practical methods are suggested as a viable alternative to other automatic procedures for creating such data, including high precision GPS and digital photogrammetry. DEM's created for a portion of one study area using the two methods are qualitatively compared to DEM's derived from provincial elevation data for the same area.

CHAPTER 2

THE PROJECT SITES – SITE AND PLOT DESCRIPTIONS AND FIELD METHODOLOGIES

INTRODUCTION

This chapter provides a general overview of two experimental sites, the Island Lake and Gounamitz Lake project areas, their selection, the establishment of sample plots and field methodologies. Specifically, the objectives are to:

1. Outline the overall rationale for the selection of project sites,
2. Describe the general conditions at each site in terms of climate, vegetation, soils, and topography,
3. Outline sample-plot selection and establishment procedures, and
4. Describe plot-level site characteristics.

SITE SELECTION RATIONALE

Two headwater watershed sites were selected on industrial crown-licenses in north-central (Island Lake) and north-western (Gounamitz Lake) New Brunswick (Figure 2.1), such that: (1) bedrock geology, surficial geology, forest cover type, topography, and climatic conditions were different between sites, as representative of two contrasting landscapes; and (2) the above characteristics were relatively consistent within each site. Since this thesis deals primarily with

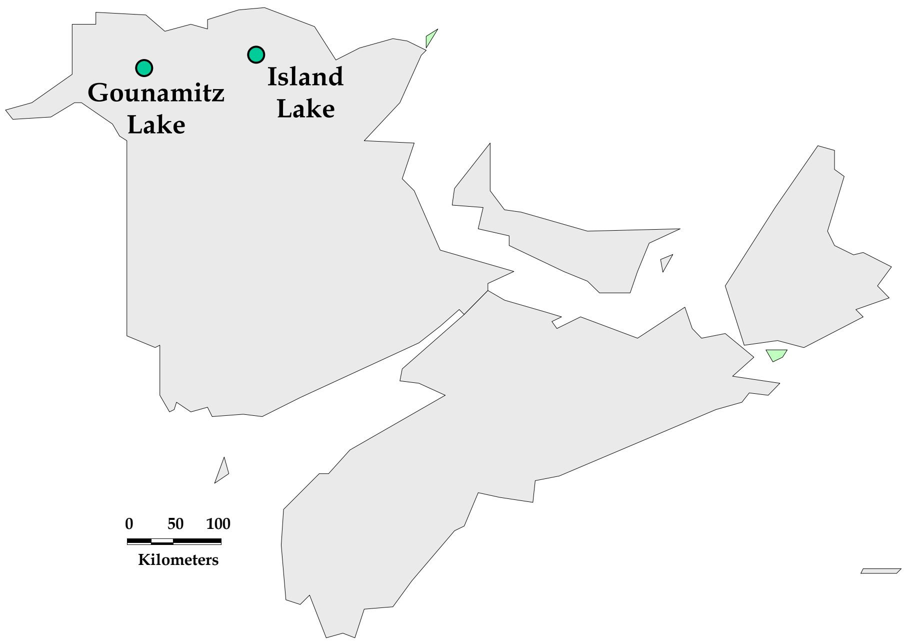

Figure 2.1. Location of study sites within the province of New Brunswick.

the influence of water flow and accumulation on measured biophysical site variables, sites were chosen to isolate differing biogeochemical and hydrological conditions, ultimately providing a study comparison between two independent landscape types. The chosen sites are in headwater areas where perennial streams are absent; the main hydrological influences on soil properties thus reflect surface and subsurface water flow occurring in these areas during periods of snowmelt and high precipitation conditions. Additionally, the two areas were selected within relatively undisturbed, mature forestland, within the context of normal historical forest practices.

The degree of overland and subsurface flow in a forested watershed depends on a number of factors including the permeability and depth of soil and parent material, the complexity and relief of topography, and the amount and frequency of precipitation (Gerrard 1981). O'Loughlin (1986) suggested that, because most forest soils generally are less permeable with depth, lateral water flow is expected to occur in both a down-slope direction and toward convergent topographic zones. At Island Lake and Gounamitz Lake sites, as is characteristic of glacial till, soil bulk density and the percentage of coarse fragments increased with depth causing a relative decrease in permeability; this was more characteristic of the Island Lake site where compact, cemented or clay-enriched subsurface layers were encountered. Further, the amount of storm-related surface and subsurface runoff is related to the overall temporal and spatial wetness conditions (Gerrard 1981; O'Loughlin 1986) and, thus, the water storage capacity (Burt and Butcher 1985) prevalent in an area. Numerous depressional areas, some of them water-logged in mid-summer, were evident at Island Lake; the rolling topography, gentle slopes and well to rapid drainage class at Gounamitz, however, suggested that the surface storage capacity of this area may be much lower. Initial examination suggested that these two sites would provide an interesting contrast of the effects of water flow in relation to substrate permeability and topographic complexity.

GENERAL PROJECT SITE DESCRIPTIONS

Island Lake Site

The Island Lake site, in the Upsalquitch site region, occurs fully within the Popple Depot Forest Soil Unit (Colpitts et al. 1995), characterised by a compact, fine to medium-textured glacial till of felsic volcanic and mixed igneous origin. The topography of the area is complex, consisting of hummocky terrain with many localised depressional areas that, upon field reconnaissance, appears to correspond closely to the configuration of the underlying basal till and igneous bedrock. The vegetation is principally mature black and red spruce and balsam fir, although pine and cedar can be found on ridge and low-lying sites, respectively. Additionally there is a component of trembling aspen and balsam poplar which grew as pioneer species after clear-cutting 60-70 years previous and are found mostly in gently sloping or low-lying areas.

Gounamitz Lake Site

The Gounamitz Lake site, in the Restigouche site region, falls within the Thibault Forest Soil Unit (Colpitts et al. 1995) and is characterised by a topography of gently rolling relief underlain by a medium-textured glacial till comprised of non to mildly-calcareous silt-stones and shales with a high coarse fragment content. Vegetation at this site is almost exclusively mature tolerant hardwood (yellow birch, sugar maple, and American beech), occurring along ridges and slopes, with white spruce and balsam fir occurring at toe-slope positions where groundwater seepage occurs. Partial cutting, removing 30% of the hardwood overstory, had been carried out in a portion of the site 3-4 years previous. The area experiences cool, wet summers and cold winters with deep snow (Zelazny et al. 1989).

PLOT SELECTION, ESTABLISHMENT AND SAMPLING

Four contiguous headwater catchments were identified within the Gounamitz Lake (Fig. 2.2a) and Island Lake (Fig. 2.2b) project sites. A combination of 1:50 000 topographic contour maps, aerial photo-interpretation and ground-truthing were used to locate sub-catchment divides. Once located and flagged, the sub-catchment boundaries were traversed with high-resolution GPS units. The sub-catchments provided a meaningful context for identifying local drainage networks, lateral flow conditions, and potential sample sites within each project site.

a)

b)

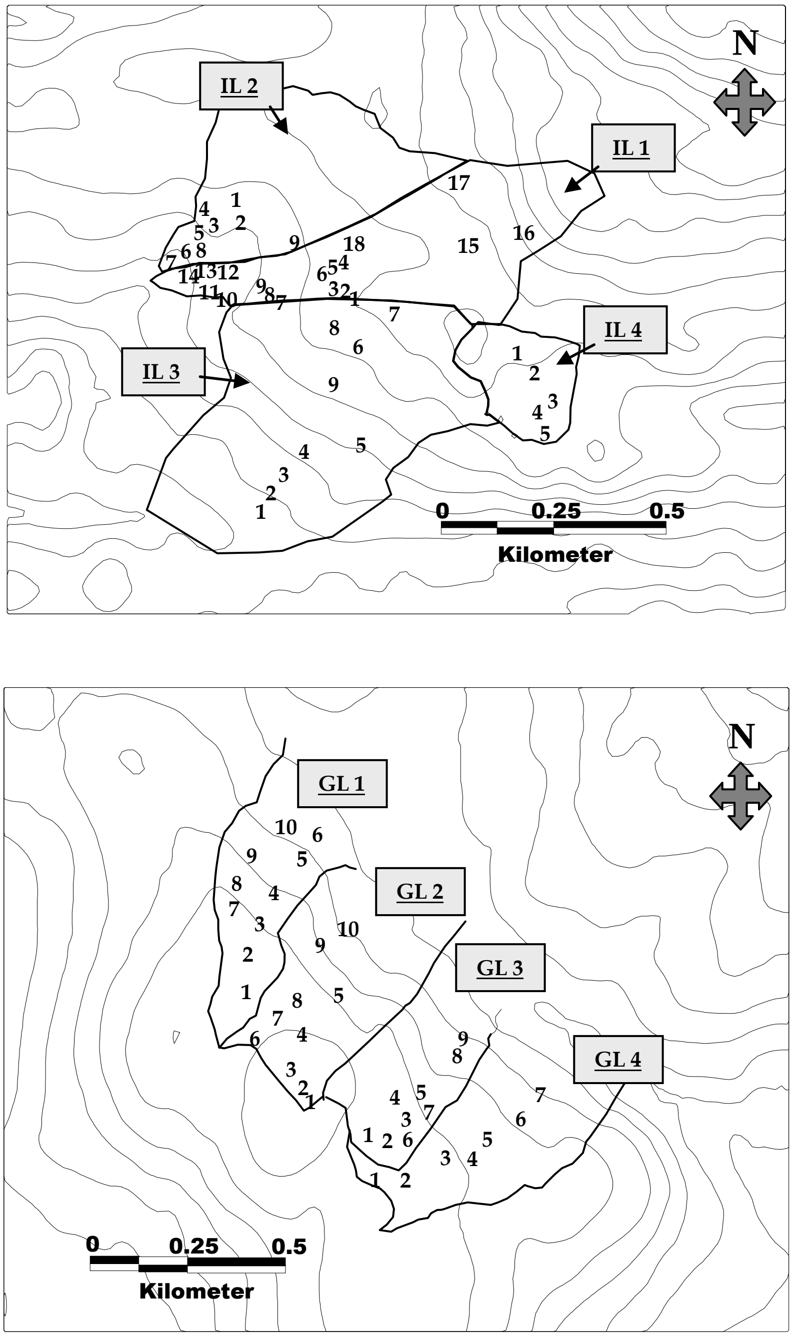

Figure 2.2. Plot locations within the a) Island Lake and b) Gounamitz Lake sub-catchments. Both plots and sub-catchments are numbered.

In July/August 1997, a total of 38 and 41 sample plots were located on the Gounamitz Lake and Island Lake sites, respectively (Figures 2.2a and b). Given time and budget limitations, 10 plots, on average, were located per sub-catchment, with the aim of representing both convergent flow-channel/flow-accumulation zones and divergent flow positions. More importantly, the aim was to achieve a sampling of perceived flow situations across the Gounamitz Lake and Island Lake project sites that were representative of the larger area. Each plot, once located, was geographically positioned with GPS to within a +/- 3 m accuracy.

Circular, 50 m^2 sample plots (3.99 m radius) were established at each point. One soil pit was dug at each plot down to either the C-horizon or to an impermeable layer. A full soil profile taxonomical description was carried out based on the Canadian Soil Classification System (Soil Classification Working Group 1998); organic and mineral soil horizon classifications identified in the field were later verified more accurately based on chemical data from these horizons. Further, horizons were characterised by thickness, texture class, structure, consistency, % coarse fragment content, degree of mottling, and root distribution using standard procedures. A representative sample of soil was taken from each horizon for chemical and physical analysis.

Local slope (%) and aspect were measured at each plot using a clinometer and compass respectively. A ground vegetation and forest shrub survey was carried out for a 30 m-radius circular area around each plot. Soil type, vegetation type, and treatment unit designations, as indicators of relative site quality, were determined for each plot using Forest Site Classification procedures developed for the province of New Brunswick (Zelazny et al. 1989). Drainage class was estimated using a standard drainage key (Jones et al. 1983).

PLOT-LEVEL CHARACTERISTICS

Island Lake Site

Plots at this site (Table 2.1) show a large range of variation in terms of topography (slope, aspect), soil classification, drainage, and site classification. This variation is characteristic of the area and can be attributed to differences in meso and micro-scale topography and the depth and compactness of the soil and the overall influence of these factors on lateral and vertical water flow and accumulation conditions. The 41 plots established at this site cover a range of aspects clockwise from east-southeast to north-northeast and slopes from 0 – 32 %. Well to rapidly-drained ridge, upper slope, and mid-slope plots, especially those >10 % slope or in upland positions in the drainage area, were generally humo-ferric podzols with occasional partially cemented or ortstein subsurface layers. Lower slope and gently sloping or terraced areas tended toward a dystric brunisolic soil type, while moderately-well to imperfectly-drained plots in convergent areas were generally melanic /eutric brunisols, gray luvisols or gleyed humo-ferric podzols, indicating richer, less acidic soils. At zones of confluence of intermittent stream channels lower in the watersheds, gleysolic and

Table 2.1. Summary of site and soil characteristics for plots within the Island Lake sub-catchments.

Sub-Catchment	Plot	Slope %	Aspect	Mineral Soil Thickness (cm)	Organic Layer Thickness (cm)	Soil Classification	Drainage Class	Site Classification: Veg. Type	Soil Type	Treatment Unit	Treatment Unit Description
IL1	1	10	NW	38	8	Orthic H-F. Podzol	rapid	5	7	3	Dry, Poor, IH-Mixedwood
	2	28	NW	60	13	Orthic H-F. Podzol	well	6	7	3	Dry, Poor, IH-Mixedwood
	3	15	NW	50	5	Orthic H-F. Podzol	well	7	7	3	Dry, Poor, IH-Mixedwood
	4	15	SW	65	8	Orthic H-F. Podzol	rapid	5	7	3	Dry, Poor, IH-Mixedwood
	5	17	SW	35	7	Ortstein H-F. Podzol	well	5	7	3	Dry, Poor, IH-Mixedwood
	6	13	SW	35	7	Eluviated Dystric Brunisol	mod. well-well	6	7	3	Dry, Poor, IH-Mixedwood
	7	17	NW	45	11	Orthic H-F. Podzol	rapid	5	7	3	Dry, Poor, IH-Mixedwood
	8	16	NW	50	5	Orthic H-F. Podzol	mod. well-well	7	7	3	Dry, Poor, IH-Mixedwood
	9	18	NW	40	19	Gleyed H.F. Podzol	imperfect	7	2	7	Wet, Mod. rich, Cedar-Softwood
	10	8	NW	85	4	Orthic H-F. Podzol	rapid	5	7	3	Dry, Poor, IH-Mixedwood
	11	25	NW	60	13	Orthic H-F. Podzol	well	7	7	3	Dry, Poor, IH-Mixedwood
	12	17	WSW	55	5	Orthic H-F. Podzol	well	5	7	3	Dry, Poor, IH-Mixedwood
	13	16	WSW	60	8	Orthic H-F. Podzol	well	6	7	3	Dry, Poor, IH-Mixedwood
	14	21	SW	60	4	Orthic H-F. Podzol	mod. well-well	7	7	3	Dry, Poor, IH-Mixedwood
	15	0	n/a	50	4	Orthic Dystric Brunisol	mod. well	7	3	5	Moist, Mod. Rich, IH-Mixedwood
	16	18	WSW	55	11	Ortstein H-F. Podzol	well	5	7	3	Dry, Poor, IH-Mixedwood
	17	<1	W	45	6	Orthic Sombric Brunisol	mod. well	7	3	5	Moist, Mod. Rich, IH-Mixedwood
	18	0	n/a	35	19	Gleyed Dark Grey Luvisol	mod. well-imp.	9	3	8	Moist, Rich, Cedar-Softwood
IL2	1	10	S	45	5	Orthic Dystric Brunisol	well	5	7	3	Dry, Poor, IH-Mixedwood
	2	7	SW	35	5	Orthic Grey Luvisol	mod. well	7	3	5	Dry to Moist, Mod. rich, IH-Mixedwood
	3	7	SW	35	3	Orthic Dystric Brunisol	mod. well-well	7	3	5	Moist, Mod. Rich, IH-Mixedwood
	4	<1	SE	35	6	Orthic Dystric Brunisol	mod. well	7	3	5	Moist, Mod. Rich, IH-Mixedwood
	5	8	SW	40	7	Orthic Dystric Brunisol	mod. well	7	3	5	Moist, Mod. Rich, IH-Mixedwood
	6	30	S	0	65	Histic Folisol	imperfect	78	Org.	n/a	n/a
	7	3	S	0	36	Orthic Gleysol	poor	9	1	7	Wet, Mod. rich, Cedar-Softwood
	8	15	WSW	45	13	Orthic Eutric Brunisol	mod. well	7	3	5	Moist, Mod. Rich, IH-Mixedwood
	9	5	W	50	4	Orthic H-F. Podzol	well	7	7	3	Dry, Poor, IH-Mixedwood
IL3	1	5	SW	40	9	Orthic Eutric Brunisol	mod. well	9	3	8	Moist, Rich, Cedar-Softwood
	2	10	SW	40	11	Gleyed Eutric Brunisol	mod. well	9\10	3	8\9	Dry to Moist, Rich, Softwood
	3	5	SSW	45	7	Orthic Melanic Brunisol	mod.well - well	9\10	3	8\9	Dry to Moist, Rich, Softwood
	4	5	SSW	45	5	Orthic Melanic Brunisol	mod.well - well	10	3	9	Dry to Moist, Rich, Softwood
	5	5	S	35	8	Gleyed Grey Luvisol	mod. well	9\10	3	8\9	Dry to Moist, Rich, Softwood
	6	10	SW	40	9	Orthic H-F. Podzol	well-rapid	5	7	3	Dry, Poor, IH-Mixedwood
	7	7	SW	35	7	Orthic H-F. Podzol	rapid	5	7	3	Dry, Poor, IH-Mixedwood
	8	5	S	40	9	Orthic H-F. Podzol	well	5	7	3	Dry, Poor, IH-Mixedwood
	9	0	n/a	50	8	Orthic H-F. Podzol	well	7	7	3	Dry, Poor, IH-Mixedwood
IL4	1	4	SE	30	5	Orthic H-F. Podzol	well	6	7	3	Dry, Poor, IH-Mixedwood
	2	5	S	45	7	Orthic Melanic Brunisol	imperfect	10	2	8	Moist, Rich, Cedar-Softwood
	3	3	ESE	40	11	Orthic Eutric Brunisol	imperfect	10	2	8	Moist, Rich, Cedar-Softwood
	4	32	N	60	4	Orthic H-F. Podzol	mod. well	8\9	3	8\9	Dry to Moist, Rich, Softwood
	5	5	NNE	30	3	Orthic H-F. Podzol	well - rapid	7	7	3	Dry, Poor, IH-Mixedwood

organic soils were present, typical of areas of high flow accumulation in this landscape. The effective rooting depth ranged from 30 to 50 cm with deeper soils occurring on steeper side and foot-slopes and more shallow soils on ridges and gentle-sloping areas. Overall, site classifications carried out at the sample plots agreed closely with the drainage and soil types found, as well as with the dominant tree species.

Gounamitz Lake Site

In contrast to the Island Lake project site, plots at the Gounamitz Lake site are more homogeneous in soil, drainage and vegetation characteristics (Table 2.2). Of 36 plots sampled across this site, 19 were described as orthic humo-ferric podzols, 12 as orthic ferro-humic podzols, and the remaining 5 were orthic dystric brunisols. In general, the podzolic soils were rapidly- to well-drained and were characterised by a strong eluvial A layer while the brunisols were moderately well to well-drained. Site classification results showed a similar degree of homogeneity; sites were classified as dry, rich, hardwood with little variation in dominant tree species, shrub species or soil type. Slope values ranged from 0 % to 15 % in the steepest areas and aspects were mainly north facing with values ranging between west and east. The most deeply rooted plots, as at Island Lake, occurred on the steeper side slopes while shallow-rooted plots occurred mainly on flat hilltops, where the bedrock was close to the surface.

Table 2.2. Summary of site and soil characteristics for plots within the Gounamitz Lake sub-catchments.

								Site Classification			
Sub-Catchment	Plot	Slope %	Aspect	Mineral Soil Thickness (cm)	Organic Layer Thickness (cm)	Soil Classification	Drainage Class	Veg. Type	Soil Type	Treatment Unit	Treatment Unit Description
GL1	1	7	NNE	46	4	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	2	3	NNW	51	6	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	3	3	NNE	70	5	Orthic Dystric Brunisol	Well	12	6	12	Very dry, mod. rich, hardwood
	4	5	N	54	4	Orthic H.-F. Podzol	Well	11	7	12	Very dry, mod. rich, hardwood
	5	8	NE	63	1	Orthic H.-F. Podzol	Well-Mod.Well	11	6	11	Dry-Moist, rich, hardwood
	6	4	NNE	43	6	Orthic Dystric Brunisol	Mod. Well	12	2	11	Dry-Moist, rich, hardwood
	7	4	N	54	4	Orthic H.-F. Podzol	Rapid	11	7	12	Very dry, mod. rich, hardwood
	8	10	NNE	55	5	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	9	4	NNE	57	6	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	10	10	NNE	58	3	Orthic Dystric Brunisol	Mod. Well	12	2	11	Dry-Moist, rich, hardwood
GL2	1	3	NNW	45	4	Orthic H.-F. Podzol	Rapid	11	7	12	Very dry, mod. rich, hardwood
	2	3	NNW	42	2	Orthic F.-H. Podzol	Rapid	11	7	12	Very dry, mod. rich, hardwood
	3	8	N	54	3	Orthic F.-H. Podzol	Well-Rapid	11	7	12	Very dry, mod. rich, hardwood
	4	6	N	54	4	Orthic F.-H. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	5	1	NE	54	4	Orthic F.-H. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	6	1	NE	59	4	Orthic F.-H. Podzol	Rapid	11	7	12	Very dry, mod. rich, hardwood
	7	5	N	43	3	Orthic H.-F. Podzol	Rapid	11	7	12	Very dry, mod. rich, hardwood
	8	8	NE	53	3	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	9	10	NE	65	5	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	10	7	NNE	50	5	Orthic H.-F. Podzol	Well	12	6	12	Very dry, mod. rich, hardwood
GL3	1	6	E	52	2	Orthic H.-F. Podzol	Well-Rapid	11	6	11	Dry-Moist, rich, hardwood
	2	2	NE	44	4	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	3	10	ENE	48	3	Orthic F.-H. Podzol	Well-Rapid	11	7	12	Very dry, mod. rich, hardwood
	4	15	ENE	78	3	Orthic F.-H. Podzol	Rapid	11	7	12	Very dry, mod. rich, hardwood
	5	5	NE	58	3	Orthic F.-H. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	6	1	N	58	3	Orthic F.-H. Podzol	Well-Rapid	11	6	11	Dry-Moist, rich, hardwood
	7	8	NW	48	3	Orthic F.-H. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	8	3	NE	55	5	Orthic F.-H. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	9	13	W	64	4	Orthic F.-H. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
GL4	1	0	n/a	46	4	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	2	2	ENE	50	5	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	3	3	ENE	43	3	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood
	4	8	NE	45	5	Orthic Dystric Brunisol	Well	12	6	12	Very dry, mod. rich, hardwood
	5	4	NE	44	4	Orthic Dystric Brunisol	Well	12	6	12	Very dry, mod. rich, hardwood
	6	13	NE	46	6	Orthic H.-F. Podzol	Well	12	6	12	Very dry, mod. rich, hardwood
	7	5	NNE	42	2	Orthic H.-F. Podzol	Well	11	6	11	Dry-Moist, rich, hardwood

CHAPTER 3

DERIVING WATER FLOW AND ACCUMULATION ATTRIBUTES: A CONSIDERATION OF SCALE AND TOPOGRAPHIC COMPLEXITY

INTRODUCTION

Topographic attributes such as slope, flow accumulation, and slope curvature are indices used to characterise morphologically or hydrologically significant landscape features influencing soil and biological processes while maintaining adequate realism. This abstraction is especially useful in a spatial context where complexity can be overwhelming. Digital Elevation Models (DEM's) have made possible the automatic derivation of these quantitative topographic indices; both Speight (1974) and Moore et al. (1991) provide excellent overviews of the derivation, calculation and importance of a range of topographic attributes. However, both the quality and the resolution of the elevation data used to create DEM's can have many implications for topographic attributes derived from them, and are often not addressed.

As such, the objective of this chapter is to provide a rationale for the choice and derivation of the topographic indices to be used with respect to the scale and accuracy of available New Brunswick provincial elevation data. Specifically, this chapter examines: (1) the assignment of topographic attributes using a) New Brunswick elevation data and b) a set of "best estimate" criteria developed from field observations; and (2) the implications of DEM resolution in accurately characterising topography and deriving attributes at a meso-scale (10-100 metres). The concept of scale is central to the use of DEM-derived attributes, and their computation should be at the scale appropriate for the processes of interest in a given study (Moore et al. 1991). In this case, the focus is on soil processes that are driven by meso-scale water flow and accumulation, and the derivation of topographic indices must therefore be discussed in this context.

FLOW ACCUMULATION AND WETNESS INDEX AS HYDROLOGIC INDICES

The topographic attributes of specific catchment area (flow accumulation) and steady-state soil wetness index are quantitative metrics of lateral water flow and accumulation conditions. Flow accumulation represents the amount of area (m^2) potentially draining to a given point in the landscape due to shallow surface and subsurface flow on runoff (Moore et al. 1991). In deriving this attribute it is assumed that lateral water flow is directly correlated with the shape of the landscape since it is calculated using the flow direction (aspect), flow gradient (slope), and the degree of convergence or divergence (curvature) within a catchment area. Thus it attempts to integrate several shape features into a hydrologically significant index.

The steady-state wetness index (WI) is defined as:

$$WI = \ln\left[\frac{a}{\tan\beta}\right]$$

where *a* is the flow accumulation for a given cell and tan *ß* is the local slope gradient (Moore et al. 1991). This attribute is a spatial index of potential zones of saturation and integrates the effect of slope gradient and flow accumulation such that areas of low slope gradient (i.e. ridge tops and flat areas) and high flow situations (i.e. convergent zones or confluence points) would produce higher WI values since these areas potentially receive and hold more water.

Like flow accumulation, WI assumes that piezometric gradients are reflected by topography, which parallels subsurface geometry, and that transmissivity is uniform across an area (O'Loughlin 1986; Moore 1996). Admittedly, spatial differences in porosity and transmissivity can occur due to variable soil textures, coarse fragment content, soil depths, and bulk densities. These differences, however, are hard to characterise accurately and in areas where annual precipitation outweighs evapotranspiration, as is the case here, topography is assumed to be the driving influence on water flow characteristics.

The calculation of flow accumulation is derived through the modelling of ephemeral flow networks and has been the focus of numerous studies (e.g. O'Callahan and Mark 1984; Mark 1988; Tarboton et al. 1991; Quinn et al. 1991; Jenson 1991; Costa-Cabral and Burges 1994). Wetness index has been used in hydrological research studies investigating controls of soil moisture (Burt and

Butcher 1985,1986; Moore et al. 1988) and is a key component of Beven and Kirkby's (1979) flood forecasting model, TOPMODEL. Despite the demonstrated utility of flow accumulation and wetness index in hydrological research and the knowledge that water flow greatly influences soil properties, these indices have rarely been applied in soil investigations.

METHODS

Deriving Topographic Attribute Values From Available DEM Data

Irregularly-spaced elevation measurements with an average spacing of approximately 70m were obtained from the province of New Brunswick for the Island Lake and Gounamitz Lake areas. From these irregular grids, regular grid DEM's were interpolated to a resolution of 15 m with the creation of Delaunay Triangles and subsequent fitting of smooth surfaces using a bivariate fifth order polynomial expression (Vertical Mapper v.2 1998). Costa-Cabral and Burges' (1994) DEMON (digital elevation model network extraction) algorithm is used here to derive flow networks (Figure 3.1) and to calculate flow accumulation values. With this algorithm, flow is weighted and dispersed among grid cells instead of flowing into only one grid cell, as with algorithms such as the D8 and Rho8 methods. Moore (1996), in comparing flow routing algorithms through sensitivity analyses, concluded that the computation of flow accumulation is highly dependent on the algorithm used and that distributed flow models such as DEMON are more realistic and preferable to the simple nearest-neighbour

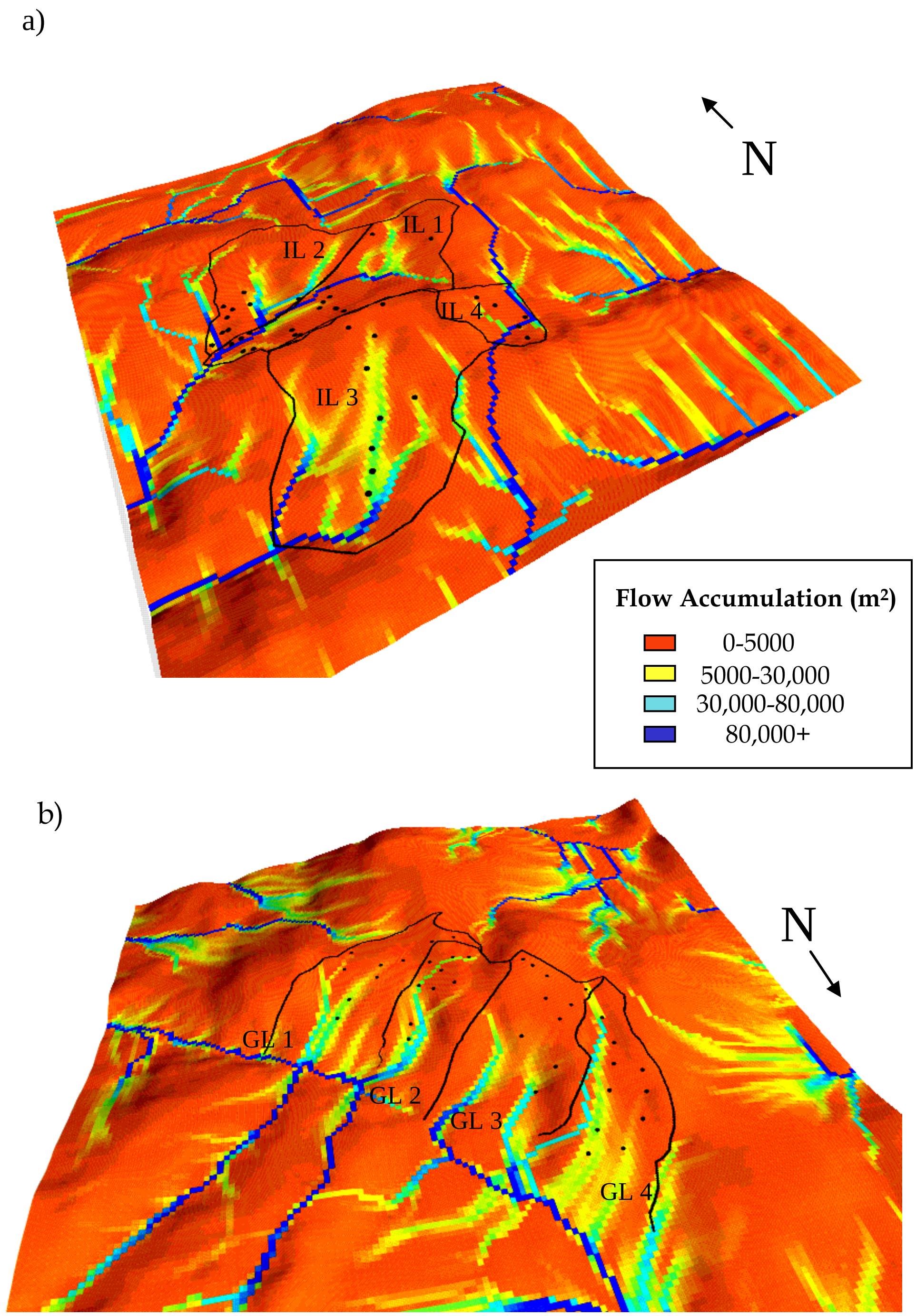

Figure 3.1. Flow networks generated using the DEMON algorithm for the a) Island Lake and b) Gounamitz Lake project sites draped over 15m interpolated DEM's. Sub-catchments and sample points are indicated with numbers and black dots respectively.

algorithms (i.e. D8 and Rho8). The steady-state wetness index (WI) was derived as a combination of cell-specific flow accumulation and slope, calculated directly from the DEM for each cell using a 3X3 submatrix of elevation points (e.g. Zevenbergen and Thorne 1987). Values for these topographic attributes were derived for each plot by overlaying cell-specific values and plot locations.

Deriving Expected Values as a Best Estimate

Upon exploratory 3-D rendering of the provincial DEM data, it was clear that certain field-observed terrain features could not be resolved with this elevation data set. Consequently, known flow paths, and plots established in these paths, did not coincide properly with modelled flow networks, resulting in errors in calculated flow accumulation values. As such, I developed a set of criteria, *a priori*, for deriving plot-specific "expected values" for flow accumulation to be used as a best-estimate comparison.

Expected flow accumulation assignments were *primarily based on observations of plot specific topographic conditions*. I used observed terrain convergence/divergence and the overall location of each plot along a given flow channel or slope (i.e. landscape position) as field-level indicators of the potential flow accumulation at a point. Subsequently, I assigned a specific flow accumulation value (m^2) at each point by *referencing the flow accumulation value of the nearest comparable cell along the modelled flow path*. This approach effectively aimed to correct the bias introduced by the coarseness of the DEM. In using this approach, I assumed that water flowing along a given modelled flow path was not redirected or obstructed in any way.

It could be argued that expected values were assigned somewhat arbitrarily. However, in lieu of accurate topographic data, I contend that these corrections provide valid flow accumulation comparisons based on field observation and best-available DEM data.

Three flow accumulation situations appeared to exist, defined as:

1. <u>Low Potential Flow Accumulation (500 – 2000 m^2 drainage):</u>

- These plots were located on divergent ridge positions or along shorter, even slopes and obviously accumulating little up-slope water.
- Assigned flow accumulation values reflected the estimated direct up-slope area draining to that point along the local slope gradient.

2. <u>High Potential Flow Accumulation (15000 – 80000 m2 drainage):</u>

- These plots were indicative of wet conditions in the field (seepage zones, depressions, toe-slopes, confluence points of ephemeral flow channels) or were lower in the watershed and appeared to be situated along major field-observed flow channels.
- Values were estimated using the most representative, nearest flow line convergence point portrayed by the DEMON flow algorithm. In most cases, the locations of modelled flow lines were displaced from their actual location in the field but were generally representative.

3. Moderate Potential Flow Accumulation (2000 – 15000 m2 drainage):

- These plots, not falling into either above category, were usually found along mild but even slope gradients, at the toe of shorter side-slopes or at mid-watershed positions and were most difficult to estimate.
- Overall, values were assigned to reflect the degree of convergence or divergence, the effective moisture condition and its overall macro-scale position in the watershed and were calculated based on the modelled flow area draining to that locale.

At the Gounamitz site, topographic convergence and divergence was subtle, and assignments of expected values relied more heavily on modelled flow networks. Consequently, each successive plot situated down a given flow line was assigned a progressively higher expected value for flow accumulation; these values essentially reflected the overall landscape position of each plot in the catchment.

Expected wetness index values were calculated as a combination of expected flow accumulation and field-measured percent slope gradient at each plot. DEM-derived and expected values were compared and assessed in the context of data quality and scale.

RESULTS AND DISCUSSION

Evaluation of DEM-derived Attributes and the Influence of DEM Scale

There is a clear disparity between DEM-derived topographic attribute values and estimated values assigned to each plot using proposed criteria at both the Island Lake (Table 3.1) and Gounamitz Lake (Table 3.2) sites. I speculate that these differences are largely due to the inability to resolve finer-scale landforms with readily available elevation data.

At Island Lake the topography is undulating and distance between pronounced hummocks and depressions are, at times, much less than the 70 m resolution of the NB elevation data. Consequently, any major landform occurring at finer intervals were likely misrepresented resulting in substantial differences between DEM-derived and expected values for topographic attributes. For example (Figure 3.1a), the lower sections of watershed IL1 and IL 2 were not properly resolved although clear flow channels defined these sub-catchments and guided the placement of plots in the field. In addition, catchment IL4 shows the modelled flow network exiting the watershed south through a ridge area, instead of flowing south-east towards the nearest stream; there is also a small perched pond in this catchment that could not be delineated using the DEM. Only plots in IL3 and in the upper sections of IL 1 appeared to have any correspondence between DEM-derived and expected values.

Table 3.1. A comparison of estimated and DEM-derived topographic attribute values for plot locations at the Island Lake site.

				Flow Accumulation		Wetness Index	
Watershed	Plot	[1]Easting	Northing	Estimated	DEM-derived	Estimated	DEM-derived
IL1	1	302 595	931 958	300	1590	3.4	6.9
	2	302 586	931 970	800	1610	3.4	6.7
	3	302 578	931 987	1000	2800	4.2	7.6
	4	302 585	932 053	500	2000	3.5	7.5
	5	302 556	932 040	800	7780	3.9	9.1
	6	302 536	932 018	1500	4000	4.7	8.1
	7	302 442	931 935	300	1485	2.9	7.0
	8	302 427	931 946	800	1374	3.9	6.8
	9	302 429	931 974	5000	2200	5.3	7.2
	10	302 303	931 960	200	6400	3.2	8.8
	11	302 275	931 972	800	7440	3.5	8.1
	12	302 313	932 035	400	595	3.2	6.3
	13	302 284	932 026	700	650	3.8	5.7
	14	302 253	932 023	700	1310	3.5	6.1
	15	302 875	932 087	10000	3825	10.8	7.8
	16	302 998	932 132	1000	2170	4.0	6.6
	17	302 841	932 276	4500	1184	10.0	6.7
	18	302 597	932 099	80000	176600	12.9	11.8
IL2	1	302 356	932 226	10000	4120	6.9	7.9
	2	302 356	932 165	15000	2170	7.7	9.0
	3	302 298	932 165	5000	410	6.6	6.2
	4	302 277	932 193	3000	870	8.7	6.0
	5	302 274	932 138	5000	1150	6.4	6.3
	6	302 243	932 085	50000	1080	9.7	5.9
	7	302 202	932 055	80000	11060	10.2	8.8
	8	302 263	932 084	5000	715	5.8	5.7
	9	302 498	932 101	5000	11065	6.9	9.1
IL3	1	302 398	931 358	35000	18000	8.9	9.7
	2	302 432	931 410	25000	20850	7.8	9.6
	3	302 460	931 471	12000	20720	7.8	9.8
	4	302 518	931 541	18000	22600	8.2	9.4
	5	302 631	931 555	15000	7000	8.0	8.7
	6	302 630	931 811	2500	8040	7.8	8.6
	7	302 709	931 918	300	1172	4.1	7.1
	8	302 577	931 880	700	883	4.9	6.5
	9	302 577	931 709	2000	10000	9.2	8.8
IL4	1	302 982	931 800	700	675	5.2	6.1
	2	303 014	931 745	10000	990	8.1	6.8
	3	303 070	931 658	15000	3500	8.5	8.0
	4	303 027	931 632	8000	297745	5.5	13.3
	5	303 020	931 574	300	835	4.1	6.8

[1] Easting and Northing co-ordinates are based on NB Sterographic Datum, NAD 83

Table 3.2. A comparison of estimated and DEM-derived topographic attribute values for plot locations at the Gounamitz Lake site.

				Flow Accumulation		Wetness Index	
Watershed	Plot	[1]Easting	Northing	Estimated	DEM-derived	Estimated	DEM-derived
GL1	1	213 721	919 429	10000	10400	7.3	9.7
	2	213 724	919 533	20000	1735	8.8	7.5
	3	213 751	919 603	30000	2260	9.2	7.3
	4	213 790	919 676	45000	5700	9.1	8.1
	5	213 859	919 777	60000	16950	8.9	9.7
	6	213 905	919 835	80000	10000	9.9	8.9
	7	213 686	919 648	2000	775	6.2	6.3
	8	213 698	919 713	5000	3150	6.2	7.3
	9	213 736	919 781	10000	2355	7.8	7.1
	10	213 815	919 848	20000	9170	7.6	9.2
GL2	1	213 880	919 144	500	270	5.1	6.3
	2	213 859	919 177	500	950	5.1	6.8
	3	213 829	919 228	500	1520	4.1	7.2
	4	213 859	919 316	3000	1745	6.2	7.7
	5	213 962	919 420	7500	4700	6.6	7.6
	6	213 729	919 305	1000	3600	4.6	8.9
	7	213 793	919 360	500	2655	4.6	8.2
	8	213 844	919 404	2000	2125	5.5	7.6
	9	213 903	919 552	20000	4500	7.6	7.5
	10	213 975	919 602	35000	5500	8.5	8.1
GL3	1	214 034	919 053	1000	615	5.1	6.9
	2	214 082	919 040	3000	2000	7.3	7.4
	3	214 131	919 087	5000	1170	6.2	6.7
	4	214 104	919 155	500	1700	3.5	7.1
	5	214 170	919 150	8000	3545	7.4	7.5
	6	214 157	919 033	2000	2170	5.3	7.6
	7	214 209	919 119	5000	15500	10.1	9.5
	8	214 261	919 258	45000	3730	9.6	7.9
	9	214 277	919 305	1000	25325	4.3	9.5
GL4	1	214 059	918 935	500	262	7.8	6.4
	2	214 131	918 935	1000	855	6.9	6.8
	3	214 237	918 995	5000	3055	7.4	8.3
	4	214 329	919 043	20000	5400	7.8	8.4
	5	214 426	919 099	30000	16000	8.9	9.2
	6	214 471	919 159	45000	21870	8.1	9.8
	7	214 308	918 993	1000	5490	5.3	8.8

[1] Easting and Northing co-ordinates are based on NB Sterographic Datum, NAD 83

At the Gounamitz Lake site, the topography was more subdued and elevation differences between areas were subtle; DEM resolution and accuracy would therefore be crucial in accurately depicting modelled flow channels and deriving water flow attributes. Many of the plots at this site were successively placed along perceived flow lines which, upon examination of Figure 3.1b, appeared to be fairly representatively modelled. However, it was obvious that there was some displacement between actual channel/plot locations and modelled flow networks due to the interpolation to a 15 m grid resolution, and ultimately resulted in incorrect calculation of plot-specific flow accumulation.

Primary attributes such as slope and flow accumulation are very sensitive to grid resolution (Moore 1996) since their calculation requires the shape of a given point in space be depicted accurately as a grid-cell or a combination of adjacent cells within the DEM. Wilson et al. (1998), for example, demonstrated that variations of only 0.05 % in mean elevations between two DEM grids resulted in substantial differences in calculated terrain attributes for a 20 ha farm field.

Further, the "mismatching" of study scale and data structure and resolution, though rarely considered in studies applying digitally-derived data, can be a significant problem (Zhang and Montgomery 1994). In a study of a spatial scale similar to this one, Zhu et al. (1997) found that a 7.5 minute quadrangle USGS DEM (25 m north-south grid spacings with 150 m between transects) was not sufficient to characterise local landforms and soil transmissivity in a 173 ha watershed of relatively subtle topography. Dietrich et al. (1993), using data of a similar resolution, were unable to delineate accurate channel networks in a study of erosion thresholds for a 120 ha watershed. In a study of geomorphological landform analysis, Dikau (1989) stated that DEM grids finer than 40 or 50 m were necessary to produce accurate geomorphological maps of micro and meso-relief. Similar to the above studies, the interpolation of elevation data in this investigation to a scale four times smaller than the original data greatly influenced the depiction of topography and the calculation of attribute values and was generally inadequate.

Estimated Values

Verifying the accuracy of attributes assigned using either the provincial DEM or the presented criteria would be a difficult task since it would require direct quantitative measurement of surface and subsurface water flow and distribution. However, studies that have correlated DEM-derived topographic attribute values to site-specific soil water properties (e.g. Burt and Butcher 1985,1986; O'Loughlin 1986; Moore et al. 1988) have provided some measure of validation of their practical application; this justification is important although most studies have used derived topographic attributes with little consideration of their accuracy in a given landscape.

A range of drainage classes from rapid to poor, indicating the average wetness at each plot, correlated strongly and positively with estimated values for both flow accumulation and wetness index at Island Lake (Figure 3.2). Plots that were well to moderately-well drained displayed the most variability; this is not surprising since these areas were situated at both dry divergent positions and convergent positions with varying amounts of estimated up-slope drainage.

At the Gounamitz site, plots were all rapidly to well-drained, indicating relatively fast vertical drainage relative to lateral water flow. Topographic attributes, however, showed three distinct groups based on soil class. Mean topographic attribute values were clearly different among Orthic Ferro-Humic Podzol, Orthic Humo-Ferric Podzol, and Orthic Dystric Brunisol (Figure 3.3) groups. Although plot-specific water flow was not expressed in drainage conditions, results indicated that obvious spatial differences existed, and that these differences were correlated with expected flow accumulation conditions.

Soil development is widely known to be strongly influenced by both lateral and vertical water flow. At this site, the influence of vertical water flow was clearly expressed in the contrasting soil profiles found; I propose that the spatial arrangement of these soil types, as indicated here, was most likely the result of lateral water flow conditions from up-slope to down-slope positions at a meso-scale. This effect is subtle, but the increase in bulk density lower in the profile would encourage some subsurface lateral flow in addition to the overland flow that would probably occur at peak flow periods (O'Loughlin 1986).

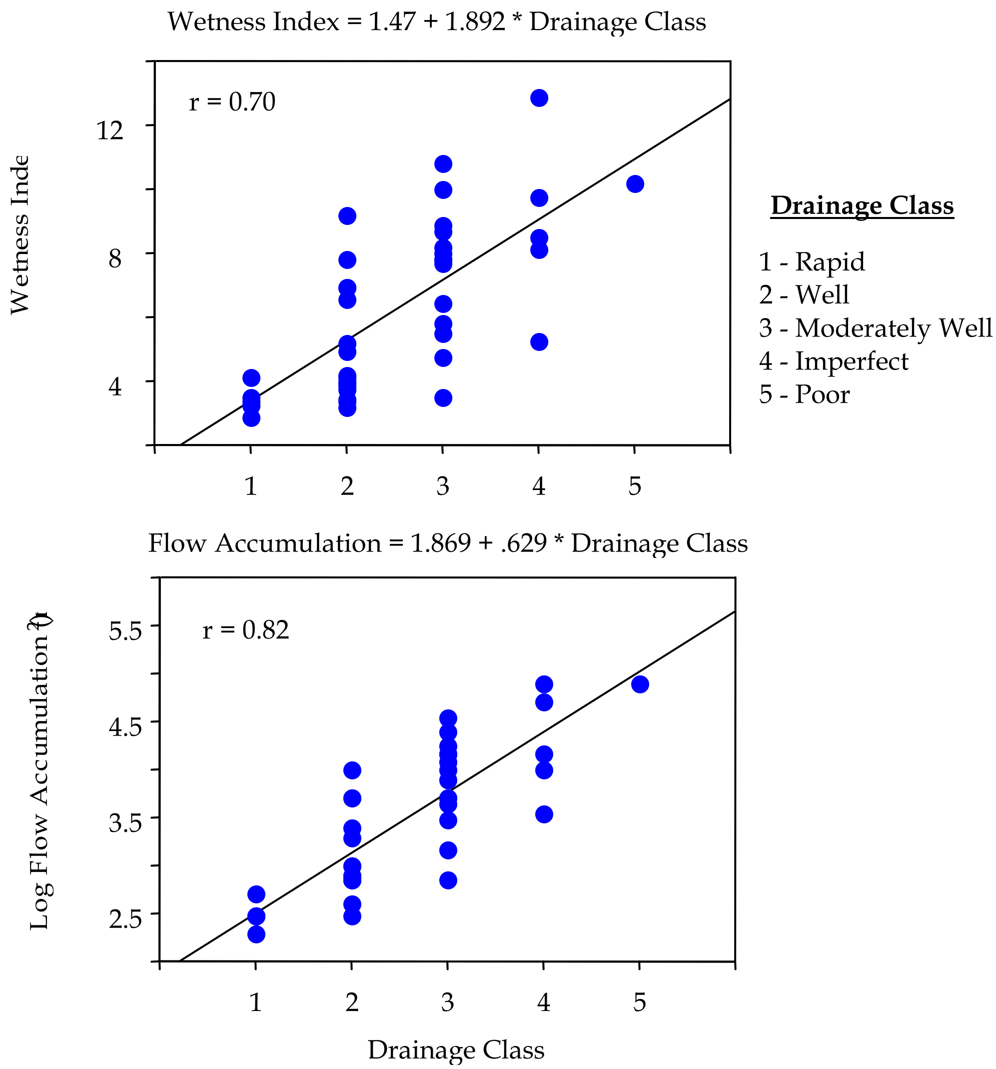

Figure 3.2. Correlation between expected values for topographic attributes and drainage class at Island Lake. Best-fit regression equations have been included.

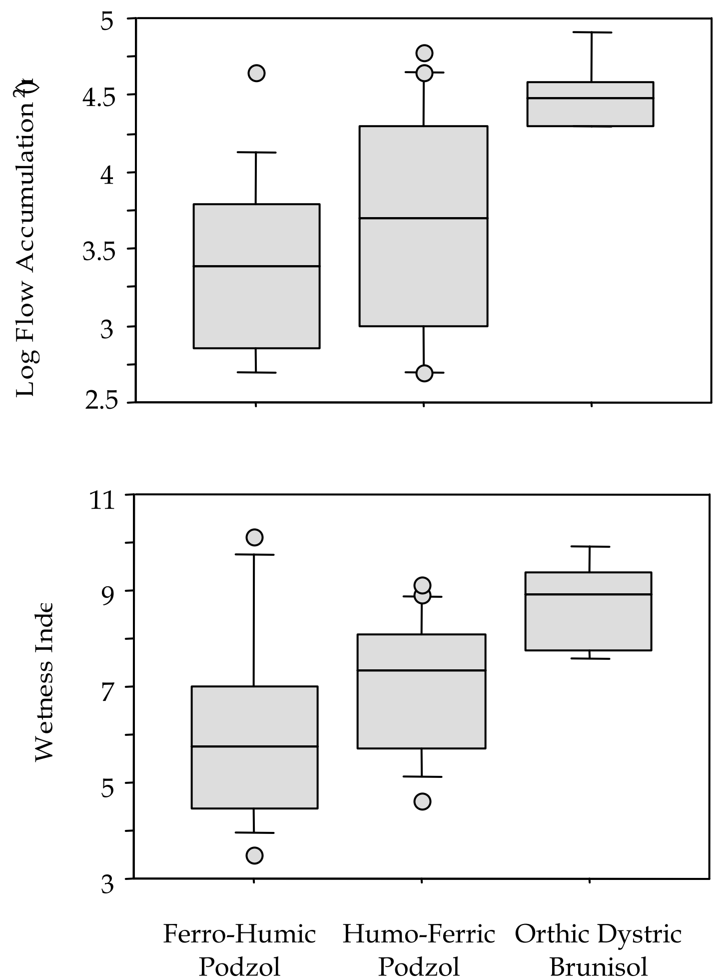

Figure 3.3. Box-plot diagrams showing variation in topographic attributes in relation to soil class at the Gounamitz Lake site.

SUMMARY

Results presented here illustrate the need for caution in using DEM-derived data in ecological studies where either the accuracy of the DEM is in question or when the study scale is finer than that of the DEM (Quinn et al. 1991; Moore 1996; Zhang and Montgomery 1994; Iverson et al. 1997; Brasington and Richards 1998). Results suggested that readily available New Brunswick Provincial elevation data were inadequate for characterising topography and deriving topographic attributes at a local, plot-specific scale.

Estimated topographic attribute values, however, appeared valid to the extent that they reflected the relative drainage conditions and soil development conditions at the Island Lake and Gounamitz Lake sites respectively; both characteristics are widely known to be strongly influenced by water flow and accumulation. In contrast, DEM-derived attributes showed no apparent relationship to drainage class or soil development at either site.

CHAPTER 4

THE INFLUENCE OF TOPOGRAPHY ON SOIL PHYSICAL PROPERTY DISTRIBUTION

INTRODUCTION

Texture, coarse fragment content and depth are a few of the intermediary soil physical properties that ultimately determine spatial differences in soil fertility. There is little question that the relatively steady-state-quality of soil physical parameters make them useful as indicators of complex soil processes that are difficult to measure spatially and are highly variable temporally. Consequently, measures of soil physical properties have been used extensively to model general aeration, moisture and nutrient regimes and forest productivity (Kimmins 1987). Soil-landscape investigations that lead to increased understanding of the possible mechanisms of physical property distributions across different landscapes are therefore extremely valuable.

Physical soil characteristics are the result of a host of influences that have acted on local surficial geology over long periods of time and may be largely attributed to: (1) the composition and mode of deposition of the soil parent material and (2) local topographic influences on surface and subsurface water flow and resultant spatial differences in weathering, erosional and horizonation processes (Gerrard 1981). As a result of the complexity of these combined influences, soil textures and depths are difficult to characterise; averaged soil map unit descriptions often do not provide an accurate depiction of meso-scale distributions of soil physical properties, particularly in terrain where lateral surface and subsurface water flow causes differential weathering and transport of fine particles across space.

The objective of this chapter is to investigate potential predictive relationships between several metrics of later water flow and soil physical characteristics at the Island Lake and Gounamitz Lake sites; relationships are examined by way of regression analysis and comparisons made between sites.

BACKGROUND

Potential relationships between topography and distributions of soil physical characteristics have been the focus of numerous soil science studies aiming to understand soil formation processes or to improve local soil mapping efforts. A summary of similar, frequently-cited investigations at a scale comparable to this study (Table 4.1) illustrates the diversity of investigations in terms of: (1) substrate and site characteristics; (2) the approach taken in characterising topography and; (3) the method of analysis of soil-landscape relationships.

Of the 14 studies summarised, the majority addressed the influence of topography on measured soil properties by partitioning the area into topographic classes or positions, delineated either arbitrarily or by using slope morphology

Table 4.1. A representative literature summary of typical meso-scale (5-100ha) investigations concerning the variability and spatial distribution of soil physical properties and the influence of topography.

Researchers	Parent Material and Site Characteristics	Topographic and Statistical Analyses	General Conclusions
Walker et al. 1968 (Iowa, USA)	Soils derived from medium to moderately fine, moderately calcareous, unsorted till; 6-9% slopes.	Calculated elevation, aspect, slope gradient, plan and profile curvature from contours; used Multiple Linear Regression to relate topographic attributes and soil properties.	Elevation and slope were the most significant parameters for each soil physical property investigated at three sites; subdivision of sites into concave and convex units improved regression precision; up to 50% of variation in A thickness and depth to mottles and carbonates explained; little discussion regarding reasons for relationships.
Dalsgaard et al. 1981 (Denmark)	Soils derived from calcareous, clayey, morainal till; 3-12% slopes.	Located soil sampling sites based on slope gradient, slope form and slope position; Descriptive Analysis.	Soil development and B horizon thickness are related to slope position and lateral movement of water in the sub-soil.
King et al. 1983 (Saskatchewan, Canada)	Soils derived from medium to moderately fine, moderately calcareous, unsorted till; 6-9% slopes.	Soils were sampled and described at 7 landscape positions along transects; slope morphology was measured along each transect; Descriptive Analyses were used to relate position and slope shape to soil types and properties.	Changes in soil type (as characterized by differing depths and soil processes) corresponded consistently with slope morphology, especially slope shape (concave vs. convex units); possible explanations for soil-landscape relationships were generally not addressed.
Evans and Franzmeier 1986 (Indiana, USA)	Loamy, glacial till overalain by silty loess; range of relief or scale of sampling not stated.	Sampled soils along 2 "toposequences"; no apriori classification of topography; Descriptive Analysis.	Soil types and soil colour related to landscape position and its influence on depth to groundwater and lateral flow along compact till layers.
Pennock et al. 1987 (Saskatchewan, Canada)	Hummocky glacial till, some glacio-fluvial and lacustrine sediments; 6-15% slopes.	Classified landscape positions based on DEM-calculated slope gradient and profile/plan curvature; ANOVA.	Thickness of the A horizon and depth to carbonates were greater in convergent positions and differed significantly between landscape positions; results attributed to differences in water movement and distribution.

Table 4.1. (*continued*)

Researchers	Parent Material and Site Characteristics	Topographic and Statistical Analyses	General Conclusions
Kreznor et al. 1989 (Northwest Illinois, USA)	undulating, cultivated, loess over silty-clay loam till; 10.5 ha; 6-10% slopes.	Classified landscape units based on slope position, shape, length and gradient and erosion class; ANOVA.	A horizon thickness decreased and clay% increased as a consequence of erosion and cultivation; degree of erosion related mainly to slope length, shape and the influence of overland flow.
Carter and Ciolkosz 1991 (Pennsylvania, USA)	Soils derived from non-fossiliferous arkosic sandstone and conglomerate; 2-57% slopes.	Sampled soils on two transects; pits were characterized by aspect and slope gradient; used Linear Regression to determine the effect of slope on soil properties for each aspect.	Thickness of O, A and E horizons not significantly related to slope gradient or aspect; solum depth, B thickness and clay negatively related to slope% as attributed to erosion and differences in effective precipitation at varying slope gradients.
Odeh et al. 1991 (Southern Australia)	Derived from grey to dark grey phyllites, siltstones and shales; relief not stated.	Used DEM-calculated slope angle, aspect, plan/profile curvature, upslope distance and flow accumulation as predictor variables in Redundancy Analysis and Canonical ordination.	% fine particles increased with a decrease in gradient and in areas of concave curvature; coarse particles showed opposite trend; slope and flow distance and accumulation related to soil colour; solum depth and depth to bedrock also influential variables; relationships found to be linear in general.
Brubaker et al. 1993 (Nebraska, USA)	Loess material; 4 cultivated fields; 2-10% slopes.	Used 6 qualitative landscape positions; ANOVA.	Sand and silt increased while clay decreased downslope; differences attributed to soil formation processes and soil erosion; conclusions unclear.
Donald et al. 1993 (Saskatchewan, Canada)	Soils derived from hummocky, morainal till with subdued relief; Luvisolic soils; <1 ha site.	Classified landscape positions based on DEM-calculated slope gradient, plan/profile curvature and slope position; ANOVA.	Organic, Bt thickness and Bt % clay greater in convergent positions; Ae thickness greater in divergent positions; results due to differences in moisture status, weathering, and lateral transport of fine particles downslope.

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Table 4.1. (*continued*)

Researchers	Parent Material and Site Characteristics	Topographic and Statistical Analyses	General Conclusions
Moore et al. 1993 (Colorado, USA)	Cultivated 5.4 ha area; soils fine-loamy/silty derived from calcareous alluvial or eolian deposits; 0-5% slopes.	Used DEM-calculated slope angle, aspect, plan/profile curvature, upslope distance and flow accumulation, wetness index, stream power index and sediment transport index as pridictor variables in Multiple Regression Analysis.	An average of 50% of the variability in A horizon thickness and silt/sand contents of the soil surface was explained by terrain attributes; slope gradient and wetness index most influential; results attributed to the effect of water flow on soil development although reasons for specific trends not addressed.
Stolt et al. 1993 (Virginia, USA)	Soils derived from colluvium, alluvium, saprolite or bedrock; 2-18% slopes.	Sampled soils along 4 "toposequences"; and 3 qualitative landscape positions; used ANOVA to partition soil variability among sites, positions, and horizons.	Variability in particle sizes only minimally due to landscape position; the majority of variability attributed to differences in parent material across space and vertical horizonation.
King et al. 1998 (France)	Soils derived from silty loess covering a limestone plateau; relief genly undulating with 0-2% slopes.	Calculated slope gradient, aspect, plan/profile curvatures from DEM; used Multiple Logistic Regression analysis to relate topgraphic attributes to presence of a clay-loam horizon.	Presence of non-calcareous clay-loam horizon strongly related to slope gradient and aspect but not with curvature; results attributed to influence of wind and solar radiation on the distribution and formation of clay materials.
Lark 1999 (England)	Soils derived from a range of parent materials including boulder clay, alluvium, colluvium and drift materials; 6 ha field, slope range not stated.	Used DEM-derived slope% and profile/plan curvature to create a continuous classification of landform; used Maximum Liklihood Regession to relate soil properties to membership in each class.	Gravimetric water content at two depths and sand/clay content were linearly related to membership values; reasons for presence of relationships were generally not discussed.

measurements taken in the field or from a DEM. Differences in measured soil property mean values among topographic classes and within profiles in these studies were often analysed using ANOVA procedures or, at times, by descriptive analysis of soil types found. While this approach partitions differences in soil characteristics among landscape zones, little direct understanding is gained about the extent or direction of the relationships between topography and soil properties.

Several of the cited studies (Walker et al. 1968; Moore et al. 1993; King et al. 1998; Lark 1999) used regression techniques to relate terrain attributes or fuzzy terrain classes to soil properties. This approach more adequately recognises the continuous nature of soil property distributions, provides a quantitative means of predicting spatial changes in these properties, and establishes a link between water-flow and slope-mediated processes and soil patterns.

The dependence of soil development and physical properties on topography, as illustrated by the reviewed studies, is highly variable. Walker et al. (1968) and Moore et al. (1993) explained up to 60 % of the variation in certain soil physical properties using topographic attributes while Stolt et al. (1993) found that topography exerted only a minimal effect on soil properties at their site. Nonetheless, slope shape, gradient, aspect, and flow accumulation were clearly influential as landscape surrogates for the effect of surface and subsurface water flow. For example, lateral water flow was explicitly stated as a substantial influence on such characteristics as horizon thickness and texture by Dalsgaard et al. (1981), Pennock et al. (1987), Donald et al. (1993) and Moore et al. (1993). The degree of influence of water flow clearly depends on the combined effects of soil parent material lithology and permeability, the complexity of topography (relief and configuration), the degree of disturbance and local climate effects.

METHODS

Description of Sites, Sample Plots, and Field Methodologies

A detailed description of the two study sites and field methodologies used in site selection, plot location and soil sampling were outlined in Chapter 2.

Laboratory and Statistical Methods

Soil samples were dried and subsequently sieved to remove coarse fragments. Particle size distribution was examined using two different approaches. Soil in each mineral horizon was first of all assessed for texture class in the field using a series of finger assessment tests as outlined in Jones et al. (1983), including moist cast, ribbon and various feel tests. As a comparison, samples from each horizon at each plot were also analysed in the lab using the hydrometer method (Day 1965) after dispersion, deflocculation and sedimentation in a column.

The percentage of coarse fragments, horizon thickness and the effective rooting depth were estimated in the field and were included here as dependent variables in addition to soil texture fractions. Layer thickness, coarse fragments and texture fractions were averaged for the “forest floor”, “A”, “B” and “subsoil (SS)” layers as weighted by the depth of the horizons in each layer. Flow accumulation, steady-state wetness index and slope % (see Chapter 3 for a detailed explanation of their derivation) were used as topographic indices of water flow and accumulation conditions at each plot. Scatter-plots of physical property data and topographic attributes were initially examined to determine the form of possible relationships. Flow accumulation generally displayed non-linear relationships with soil properties and was subsequently log-transformed. Subsequently, regression analyses were carried out to determine the degree of correlation between topographic attributes and soil physical properties at each site.

RESULTS AND DISCUSSION

Soil Texture Analysis

There were obvious discrepancies between the field test and hydrometer methods (Table 4.2), particularly at the Island Lake site. Normally, an analysis of particle size distribution yields results with an error of ±10 % (Indorante et al. 1990) . In this case, however, from 5 to 40 % of samples analysed using the hydrometer method showed a consistent bias toward the sand fraction that was obviously not evident in the field.

Measurement of these samples were likely confounded by a component of fine coarse fragments that remained after sieving and because, for some

Table 4.2. Cross-tabulation of outcomes for the feel test and hydrometer methods of texture determination for a) Island Lake and b) Gounamitz Lake sites.

a)

A Layer				Hydrometer					
Feel	S	LS	SL	L	SCL	CL	SiL	SiC	C
S									
LS									
SL			3						
L			13	19	1				
SCL									
CL					1				
SiL									
SiC									
C									

B Layer				Hydrometer					
Feel	S	LS	SL	L	SCL	CL	SiL	SiC	C
S									
LS		1							
SL	5	2	14		1				
L			10	4	3				
SCL									
CL			1	1					
SiL									
SiC									1
C									1

Subsoil				Hydrometer					
Feel	S	LS	SL	L	SCL	CL	SiL	SiC	C
S	3								
LS		2	1						
SL	1	2	16						
L			4	4					
SCL			1						
CL				1	1	2			
SiL									
SiC									
C					1				

b)

A Layer				Hydrometer					
Feel	S	LS	SL	L	SCL	CL	SiL	SiC	C
S									
LS									
SL		1	4						
L			1	3					
SCL									
CL									
SiL			1				26		
SiC									
C									

B Layer				Hydrometer					
Feel	S	LS	SL	L	SCL	CL	SiL	SiC	C
S									
LS		1							
SL		8	28						
L				4					
SCL									
CL									
SiL							1		
SiC									
C									

Subsoil				Hydrometer					
Feel	S	LS	SL	L	SCL	CL	SiL	SiC	C
S									
LS		5							
SL	2	1	20				1		
L				6					
SCL					1				
CL									
SiL									
SiC									
C									

horizons, there was a less than adequate quantity of soil to provide a representative sample. However, in samples where these problematic conditions were absent, hydrometer-measured texture classes agreed closely with field assessments, which were considered accurate since they were consistently estimated by an experienced soil technician. Field-averaged textural classes were deemed to be the more consistent standard in this study and were therefore used to estimate sand, silt and clay fractions for samples where there was disagreement between the two methods.

Overall Physical Property Variability

The most noticeable trend evident in physical properties (Table 4.3) is the difference in both % coarse fragments and particle size distribution between the two sites. Overall, the Gounamitz Lake site shows a significantly greater percentage of silt in the A and subsoil layers and coarse fragments in the B and subsoil layers. Conversely, the Island Lake site shows a higher average fraction of clay in each mineral horizon, possibly due to the presence of finer-grained rocks in the soil parent material. The range of % clay values is also much greater at this site indicating a lateral flow and deposition of fine material from divergent to convergent plots or, possibly, resulting from the action of freeze-thaw processes.

Table 4.3. Summary statistics of averaged physical property data for the forest floor (FF), A, B, and sub-soil (SS) layers at the Island Lake and Gounamitz Lake study sites.

		Thickness cm		Coarse Fragments %		Sand %		Silt %		Clay %	
		1IL	**GL**	**IL**	**GL**	**IL**	**GL**	**IL**	**GL**	**IL**	**GL**
FF	n	41	36	n/a		n/a		n/a		n/a	
	Mean	9.85	3.89	n/a		n/a		n/a		n/a	
	Min.	3.00	1.00	n/a		n/a		n/a		n/a	
	Max.	65.00	6.00	n/a		n/a		n/a		n/a	
	CV (%)	107.1	31.8	n/a		n/a		n/a		n/a	
A	n	39	36	38	36	39	35	39	35	39	35
	Mean	11.80	10.69	45.00	39.04	46.84	41.28	35.99	48.40	17.16	10.25
	Min.	2.00	3.00	5.00	10.00	36.78	27.42	22.00	21.00	7.28	4.30
	Max.	27.00	22.00	80.00	60.00	63.77	74.00	50.00	58.92	32.74	15.60
	CV (%)	49.3	35.6	45.5	38.2	11.6	29.1	16.8	22.9	30.9	24.7
B	n	39	36	41	36	41	36	41	36	41	36
	Mean	19.05	21.92	48.54	51.83	55.67	63.18	29.16	29.07	15.18	7.73
	Min.	9.00	10.00	5.00	10.00	16.48	29.84	16.07	14.79	4.40	3.02
	Max.	45.00	45.00	90.00	80.00	77.70	76.97	50.23	54.72	45.94	19.44
	CV (%)	47.6	38.8	43.6	35	20.3	15.5	24.9	26.1	54.2	50.8
SS	n	30	29	36	30	34	30	34	30	34	30
	Mean	17.20	19.10	53.61	65.67	65.51	63.89	20.60	25.33	13.89	10.77
	Min.	5.00	3.00	5.00	20.00	24.40	37.14	2.73	9.23	3.88	2.73
	Max.	37.00	41.00	90.00	90.00	92.26	85.90	41.79	45.26	41.10	24.24
	CV (%)	43.0	44.8	43.7	32.5	24.3	17	51.5	32.1	54.8	48.1

1 IL = Island Lake, GL = Gounamitz Lake

Thickness of Soil Layers and Rooting Zone

Weak to moderate relationships existed between soil layer thickness and topographic attributes with 22 % to 41 % and 19 % to 43 % of the variation explained for the Island Lake (Figure 4.1) and Gounamitz Lake (Figure 4.2) sites respectively. Furthermore, positive, linear trends existed at both sites between effective rooting depth and slope gradient; relationships were moderately strong with 31 % of the variation explained for this variable at Island Lake and 44 % at the Gounamitz Lake site.

Forest Floor Thickness

The thickness of the forest floor, which ranged from thin (3 cm) to relatively thick (20 cm) was positively related to the wetness index and slope gradient at Island Lake (Figure 4.1a). Similar to Donald et al.'s (1993) findings at a hummocky till site, these results reflected differences in decomposition among slope positions; ridge areas (low flow accumulation and low slope gradient) were dry and more exposed resulting in thin forest floors while footslope (high % slope, moderate wetness) and depressional (high flow accumulation) areas were generally wetter and accumulated a thick humus layer. At the Gounamitz site, the range in forest floor thickness was small (1-6 cm), reflecting the fast turnover of the tolerant hardwood litter. Even so, forest floor thickness was moderately and positively related to flow accumulation at this site (Figure 4.2a). High flow values here were consistent with low hill-slope positions in this rolling terrain;

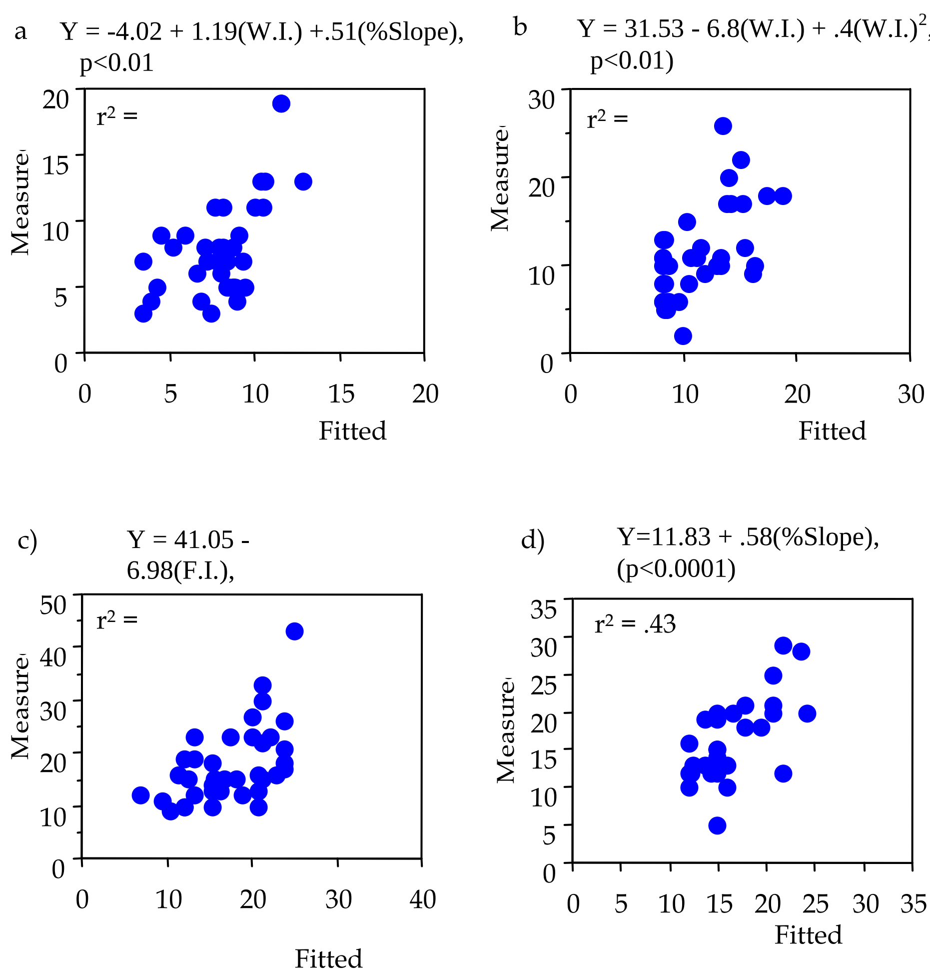


Figure 4.1. Best-fit regressions relating layer thickness(cm) and topographic attributes for the a) forest floor, b) A, c) B, and d) subsoil layers at the Island Lake site.

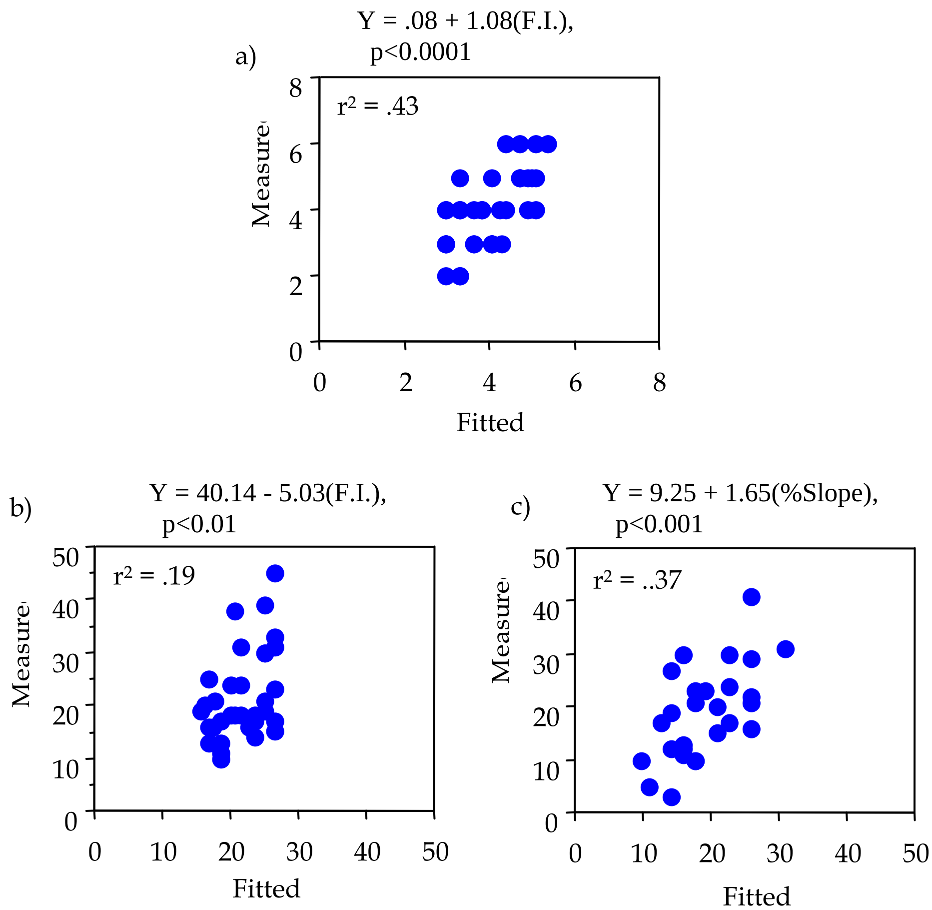


Figure 4.2. Best-fit regressions relating layer thickness(cm) and topographic attributes for the a) forest floor, b) B, and c) subsoil layers.at the Gounamitz Lake site.

plots in this area are generally north-facing and soils at lower-slope positions would be subjected to lower soil temperatures and decomposition rates.

A Layer Thickness

At Island Lake, A horizon thickness was related to wetness index and best described by an inverse quadratic equation (Figure 4.1b), with lowest thicknesses found at moderate wetness values (5.5 to 7.5). These values reflect gently-sloping, relatively shallow-rooted sites with thin Ah or Ahe horizons; at either extreme of this relationship, in high flow accumulation zones or on divergent side-slopes, A horizons are thicker due to more dominant lateral and vertical water flow processes. No significant trends were evident between A thickness and topographic attributes at Gounamitz Lake. With exception of a few thin Ah horizons, soils here were dominated by Ae horizons that varied only slightly in depth across the site.

B Layer Thickness

B thickness was negatively related to flow accumulation at both sites (Figure 4.1c). This trend was more pronounced at Island Lake, not surprisingly, since this site is more heavily influenced by lateral water flow along constricted subsoil layers and because these effects are most strongly reflected in the development of the B horizon. In low flow zones, lateral and vertical through-flow is strong and soils are deeper, resulting in well-developed illuvial B horizons. Conversely, B horizons in high flow zones are generally imperfectly drained, restricting soil development processes in these areas. At Gounamitz the same relationship with flow accumulation existed but was substantially weaker (Figure 4.2b); this site was consistently well-drained and dominant eluvial/illuvial processes were probably more related to micro-scale variations in vertical water flow, which may be greater in up-slope/hill-top areas where gradients are more gentle overall.

Effective Rooting Depth and Subsoil Thickness

Rooting zone (Figure 4.3) and subsoil thickness were both positively and moderately related to slope gradient at both sites. The depth of the effective rooting zone reflects both heterogeneity of the glacial till parent material and the influence of lateral water flow and accumulation. At Island Lake the latter influence was more prominent, showing a decrease in rooting depth in convergent areas where seepage water accumulates and restricts rooting, a common feature of hummocky-till sites such as this (Pennock et al. 1987, Donald et al. 1993). Variation in rooting depth was also partially explained by % slope at the Gounamitz site despite relatively mild gradients. Soils were somewhat thinner on flatter, ridge-top areas where bedrock or a less permeable C layer was encountered at several plots. It was also possible that vertical and lateral water

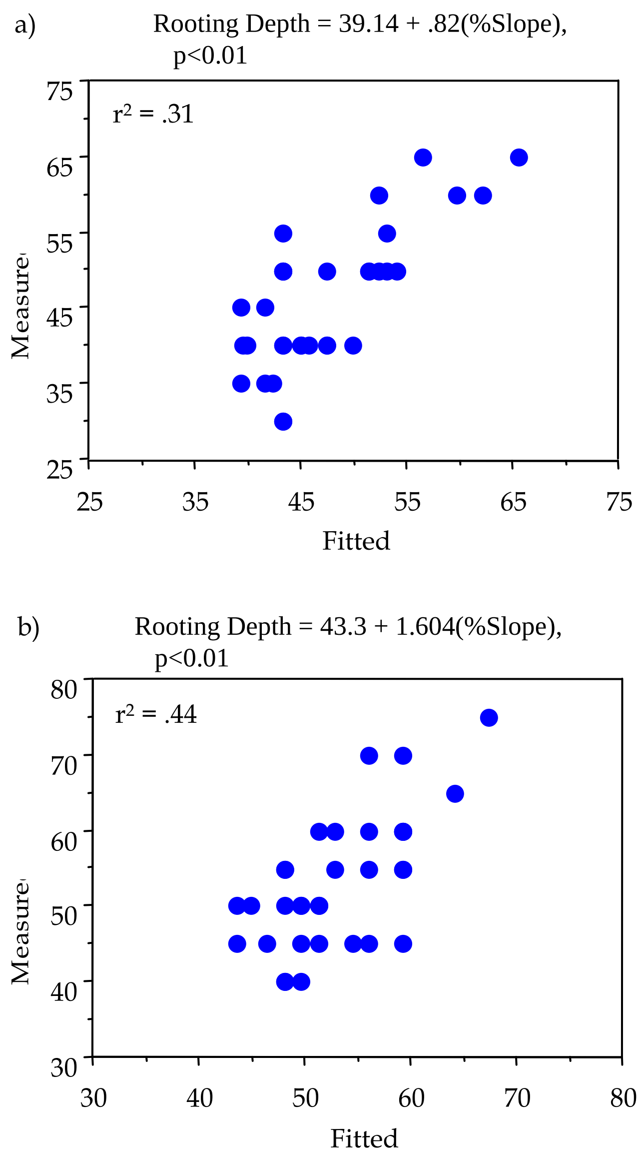


Figure 4.3. Best-fit regressions relating rooting depth (cm) and topographic attributes for the a) Island Lake and b) Gounamitz Lake sites.

flow occurring on steeper slopes may have increased soil weathering, thereby increasing the overall depth.

In this study, the subsoil was considered to be the BC or C layer(s) beneath the lower-most B horizon that contributes to the overall zone of rooting. The subsoil zone is generally not subjected to the same range of soil processes as the upper soil layers, thus making it weakly defined on its own; these results seemed to indicate that subsoil thickness covaried with the overall rooting depth at a given locale since both responded positively to slope gradient at each site (Figures 4.1d and 4.2c). This may be due to the fact that deeper, less restricted soils normally equate with increased rooting into thicker subsoil zones.

% Coarse Fragments

The percentage of coarse fragments in mineral soil layers were weakly correlated to topographic attributes at the Island Lake site (Figure 4.4) and very weakly to non-correlated at the Gounamitz Lake site. The amount and distribution of coarse fragments are rarely addressed in soil studies due to the difficulty in their estimation and because, in till soils, spatial distribution is largely related to the mode and distribution of parent material. Nonetheless, results for the Island Lake site indicated that in areas of greater through-flow of subsurface water (more divergent areas) there were fewer coarse fragments. This may have been a result of increased physical weathering in these areas or of a

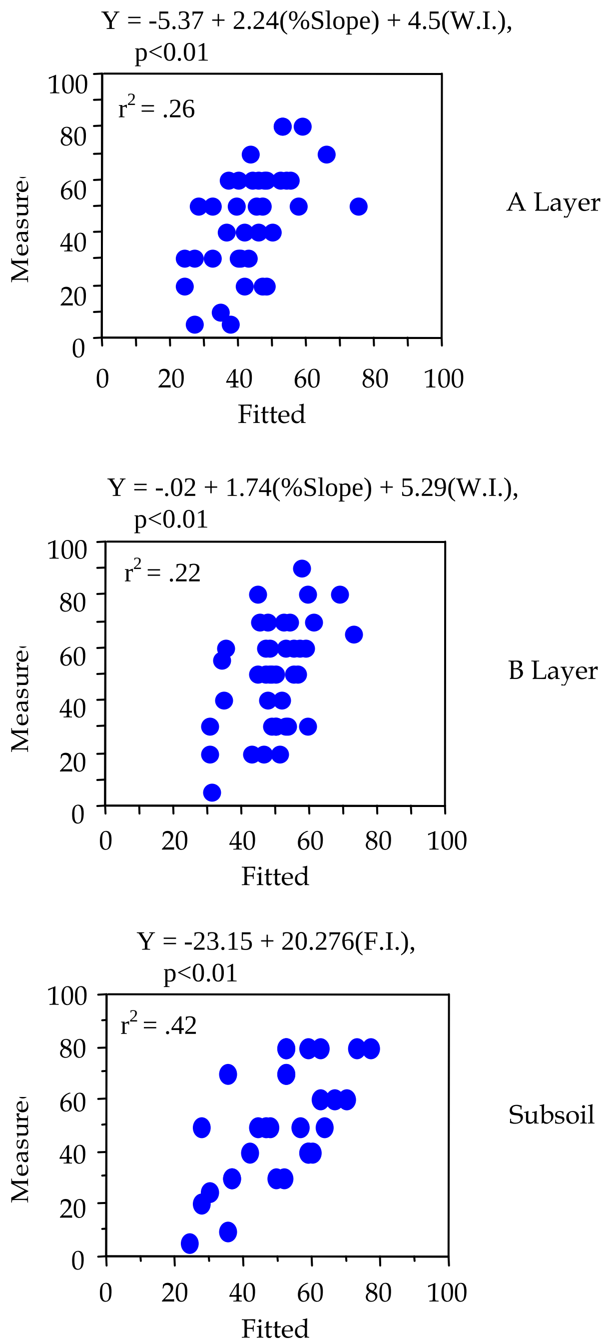


Figure 4.4. Best-fit regressions relating % coarse fragments and topographic attributes at the Island Lake site for the mineral soil layers.

transport of material to convergent areas. I suggest that the former was probably more likely since there was little evidence of significant erosional processes and because igneous-derived materials would have responded to physical and chemical weathering.

% Clay

Of the three particle size fractions examined, only the clay texture fraction in the B and subsoil layers at the two sites were correlated with topographic attributes (Figure 4.5). At Island Lake, clay was moderately and positively related to flow accumulation ($r^2 = .41$) in the B layer and more weakly and negatively related to slope gradient ($r^2 = .30$) in the subsoil. These findings indicated that there was a possible enrichment of clay in convergent areas of higher flow and where the slope gradient is milder at the bottom of slopes. Clay, the finest texture fraction, is know to be fairly mobile; in areas of subsurface water flow and moderate to strong slope gradients clay has been found to accumulate in convergent areas (e.g. Odeh et al. 1993; Brubaker et al. 1993; Donald et al. 1993). This is logical at this site where there were shorter, steeper slopes lead to many convergent depressional areas and where subsurface flow occurs along more compact B and subsoil layers. Secondly, mildly sloping areas appeared to have thinner, moister soils promoting freeze and thaw processes and the weathering of volcanic rocks such as basalt and tuff into clay-sized fractions.

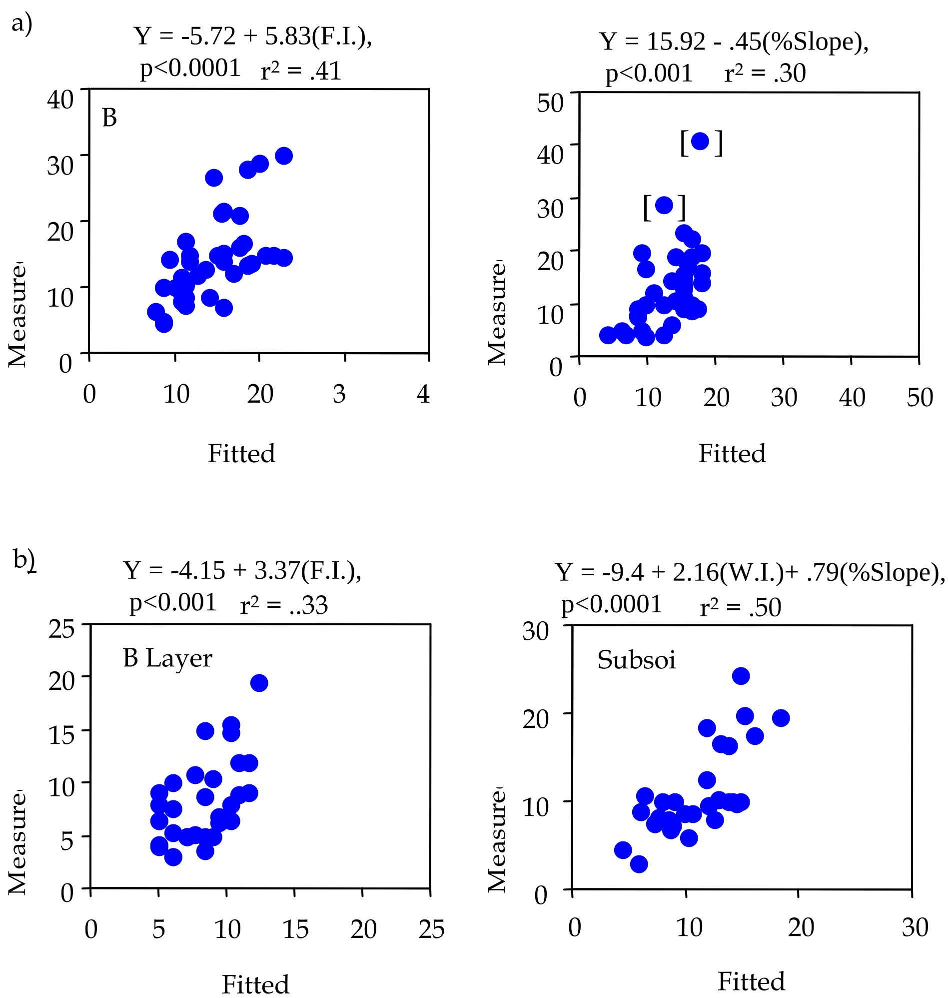


Figure 4.5. Best-fit regressions relating % clay and topographic attributes at the a) Island Lake and b) Gounamitz Lake site for the B and Subsoil layers. Bracketed points were removed from the analysis.

Although similar relationships were evident at the Gounamitz site, it is less likely that clay would accumulate due to water flow since slopes are gentler and the degree of convergence is subtler. I suspect that the increase in the clay fraction with increasing flow accumulation and wetness index reflected the increase in weathering of siltstone and shale in areas receiving relatively more water flow and moisture, laterally and vertically.

SUMMARY

As commonly concluded in studies relating physical soil properties to topography, there was still much variation unexplained in distributions of the physical characteristics investigated here. Few studies using analyses similar to those used here explained more than 50% of the variation in physical properties. The amount of topographic influence suggested by these results were not surprising for soils derived from basal till parent material; the depth and composition of glacially-deposited materials are known to be highly spatially heterogeneous and therefore difficult to predict.

Although relationships were weak, there were significant correlations between topographic attributes and layer and rooting thickness, % coarse fragments and % clay across horizons and between sites. Further, and more importantly, most physical variables appeared to be influenced in a similar manner and by the same topographic attributes at both sites. These results therefore suggest that water flow and accumulation have had a measure of influence on soil physical properties at these sub-catchments despite site-specific differences in topographic complexity and substrate permeability. Stronger results may be evident with a more quantitative measurement of these and other soil physical properties and with an increase in accuracy of topographic attribute derivation, especially in areas of subtle topography.

CHAPTER 5

THE INFLUENCE OF WATER FLOW AND ACCUMULATION AND PARENT MATERIAL ON SOIL CHEMICAL DISTRIBUTIONS

INTRODUCTION

Like physical soil characteristics, spatial distributions of soil-chemical properties are often highly variable in time and space (Hammer et al. 1987). Soil chemistry is influenced by both the physical composition of soil (e.g. soil texture, structure, coarse fragments) at a given location and factors such as local water flow and accumulation and soil temperatures which change throughout the year. At a meso-scale (defined here as distances of 10-100 m), in areas of relatively consistent geology, climate and vegetation, water flow and accumulation in the landscape has been recognised as a dominant driving-mechanism for many soil-related processes (Moore et al. 1991) and therefore contributes to overall spatial variability in soil chemical properties.

Various measures of landform shape and configuration, due to their influence on near-surface and surface hydrology, have proved to be useful predictors of the distribution of soil chemical and physical properties at the local topographic scale. Some researchers have divided study areas into qualitative terrain classes or landscape positions, striving to isolate catenary slope processes; significant differences in chemical soil properties were found at a range of sites as influenced by slope and aspect class (e.g. King et al. 1983; Carter and Ciolkosz

1991; Hairston and Grigal 1991; Odeh et al. 1991) and landscape position (e.g. Kreznor et al. 1989; Raghubanshi 1992; Brubaker et al. 1993; Silver et al. 1994; Osher and Buol 1998). Qualitative slope units, however, are simplistic two-dimensional classifications of landform and do not provide a consistent, quantitative measure of specific topographic attributes (Moore et al. 1993).

It has long been recognised by soil-landscape researchers that landscape paradigms characterising the landscape in three dimensions can more accurately address soil formation and chemical distribution since water flow and accumulation, as well as the distribution of energy, are complex three-dimensional phenomena (e.g. Jenny 1941, Aandahl 1948; Walker et al. 1968; Hugget 1975; Connacher and Dalrymple 1977, O'Loughlin 1986). Several studies carried out at a meso-scale have shown soil properties to be related to topographic attributes. Donald et al. (1993) found variations in certain soil physical properties and pH were largely explained by plan/profile convexity and slope gradient; Odeh et al. (1991) and Moore et al. (1993) showed that these same topographic indices, as well as flow accumulation and wetness index, were linearly related to soil properties. Each of the studies concluded that spatial distribution of soil properties observed were largely the result of a re-distribution of soil materials due to lateral water flow from divergent to convergent zones.

Morris and Boerner (1998) found N mineralization and nitrification, organic C and pH to be highly related to an integrated moisture index , calculated using a combination of various DEM-derived attributes, including flow accumulation. They concluded that many bio-physical processes operating at a meso-scale are dependent on local topography and its influence on soil moisture status.

In this chapter, I address two questions in comparing the two landscape types characterised by the Island Lake and Gounamitz Lake sites: (1) to what degree do derived indices of water flow and accumulation explain spatial trends in soil chemical properties in each soil layer? and; (2) since soil chemistry, at a fine scale, is usually also dependent on parent material factors, what is the additional influence of site-specific properties such as texture, coarse fragment abundance, and rooting depth in predicting soil chemical distributions?

METHODS

Description of Study Sites, Sample Plots, and Field Methodologies

A detailed description of the study sites and field methodologies used in site selection, plot location, and soil sampling were outlined in Chapter 2.

Soil Sample Preparation and Laboratory Analysis

Total nitrogen, total carbon, pH, exchangeable cations, and extractable phosphorous were measured for samples from all soil horizons described at each plot. Texture fractions were determined as outlined in Chapter 4.

Slurries made with 1:3 ratio of fresh soil and 0.01M $CaCl_2$ were analysed for pH using a digital pH meter. Samples were then dried at 70°C for 72 hours, ground with a mortar and pestle and passed through a 2 mm sieve to remove coarse fragments; dried samples were used for the remaining analyses.

Total nitrogen was measured via Kjeldahl digestion, steam distillation and analysis with a Buchi/Brinkmann nitrogen system. Total carbon was measured by dry combustion in a LECO EC-12 Induction Furnace. Exchangeable cations were extracted by shaking soils in 1M NH_4Cl for 30 minutes followed by suction filtering through Whatman 41 filter paper. A Varian Spectra atomic absorption spectrophotometer was used to analyse extracts for exchangeable cations, Al, Fe and Mn. Phosphorous was extracted using the bicarbonate method and measured colorimetrically, after pH adjustment using the ascorbic acid-molybdenum blue procedure (Murphy and Riley 1962), with an LKB Ultraspec 4050 spectrophotometer.

Topographic and Statistical Analyses

Expected values for flow accumulation, wetness index were derived as discussed in Chapter 3. Physical soil data, element concentrations and selected site variables were averaged for each soil horizon within the forest floor, A, B and subsoil, weighted by horizon depth. Descriptive statistics were generated to provide a comparison of the overall soil property variability for data averaged across plots at each project site. Most soil chemicals appeared to have positively-skewed frequencies (see Table 5.1), showed heteroscedasticity and were subsequently log-transformed using the equation: log(Y * 10,000), where *Y* is the chemical concentration multiplied by 10,000, to code low concentration values as a set of final values ranging between 0 and 10 for graphing purposes (Sokal and Rohlf 1981, p. 421). Scatter plots were used to analyse trends between layer-specific soil chemical and physical data and topographic variables. Simple linear regressions were used initially to determine the amount of variability in soil chemistry explained by expected flow accumulation alone; subsequently, other topographic and physical soil variables were added into a multiple regression to determine their contribution to the overall variation at each project site.

RESULTS AND DISCUSSION

Soil Variability

In an aspatial context, a substantial degree of variability existed in soil chemical properties at both project sites (Table 5.1). Overall, the coefficient of variation was the lowest for pH, while available Ca, Mg, Fe, Al and P all showed high CV's, mainly because mean values for these elements were low in comparison to a high total variance. This high range of variation and skewness is not uncommon with soil nutrient data (Young et al. 1999) and may have reflected the focus of sampling both perceived flow accumulation zones and up-slope ridge zones or was due to inherent heterogeneity in the glacial till parent material.

Table 5.1. Summary statistics of averaged chemical data for the forest floor (FF), A, B, and sub-soil (SS) layers at the Island Lake and Gounamitz Lake study sites.

								Exchangeable								Extractable				Available	
		pH		Total N %		Total C %		Na		K meq/100g		Ca		Mg		Fe meq/100g		Al		P meq/100g	
		[1]IL	**GL**	**IL**	**GL**	**IL**	**GL**	**IL**	**GL**	**IL**	**GL**	**IL**	**GL**	**IL**	**GL**	**IL**	**GL**	**IL**	**GL**	**IL**	**GL**
FF	n	39	36	39	36	37	36	39	36	39	36	39	36	39	36	39	36	39	36	39	36
	Mean	4.35	4.06	1.56	2.05	43.33	42.66	0.10	0.08	2.39	2.16	48.31	26.12	4.28	3.72	0.06	0.01	0.67	0.25	0.15	0.18
	Min.	2.61	3.49	1.13	1.65	21.45	31.50	<0.01	<0.01	0.49	0.85	9.80	10.69	1.60	1.78	<0.01	<0.01	<0.01	<0.01	0.02	0.05
	Max.	6.24	5.08	2.13	2.36	54.87	51.22	0.75	0.19	4.89	3.82	109.95	81.82	9.10	6.09	0.74	0.06	10.24	0.62	0.29	0.36
	CV (%)	27.9	10.2	16.6	8.5	16.4	12.3	111.9	58.5	39.6	33.4	67.5	60.5	45.1	22	188.6	105	230.6	66.6	37.3	43.8
	Skewness	0.17	0.84	0.22	-0.32	-0.97	-0.16	3.50	0.62	0.23	0.21	0.48	1.99	1.03	0.53	4.61	1.48	4.17	0.64	0.12	0.39
A	n	39	36	39	35	39	35	39	35	39	35	39	35	39	35	39	35	39	35	38	35
	Mean	4.40	3.63	0.31	0.24	5.19	2.50	0.06	0.04	0.15	0.13	3.01	2.98	0.70	0.40	0.09	0.02	3.28	0.69	0.07	0.03
	Min.	2.90	2.86	0.04	0.08	0.89	0.06	0.01	<0.01	0.06	0.04	0.15	0.07	0.11	0.07	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Max.	6.44	5.11	1.12	1.13	13.27	12.75	0.31	0.11	0.36	0.50	16.82	20.04	3.65	1.55	0.35	0.07	11.68	3.41	0.19	0.09
	CV (%)	28	19	83.2	109.2	65.5	121	94.9	61.8	48.2	76.8	105.9	154.5	118	92.8	116	113	119.4	120	80.9	51.6
	Skewness	0.29	0.97	1.35	2.18	0.90	2.22	3.10	1.54	1.40	2.59	2.60	2.64	2.49	1.97	1.09	1.31	0.84	1.42	0.73	1.36
B	n	41	36	41	36	41	36	41	36	41	36	40	36	41	36	41	36	41	36	41	36
	Mean	5.01	4.20	0.20	0.34	4.31	8.90	0.04	0.04	0.12	0.12	3.30	2.40	0.47	0.28	0.03	0.08	0.76	1.45	0.05	0.10
	Min.	3.77	2.83	0.07	0.02	0.51	0.50	<0.01	0.01	0.03	0.04	0.12	0.08	0.03	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Max.	6.52	5.68	0.65	0.63	15.72	17.45	0.10	0.09	0.24	0.40	20.58	12.56	2.45	0.94	0.16	0.30	4.48	5.49	0.34	0.41
	CV (%)	16.2	12.3	60.5	44.5	85.9	51.3	53.3	40.3	39.7	66.4	144.1	118.7	116.7	80.6	154.6	94.3	143.2	104	128.2	107
	Skewness	0.42	0.50	1.96	0.13	1.36	0.16	0.38	0.85	0.39	1.97	2.62	2.11	2.33	1.77	2.13	1.22	1.94	1.10	2.31	1.29
SS	n	36	30	36	30	36	30	36	30	36	30	36	30	36	30	36	30	36	30	36	30
	Mean	5.10	4.42	0.09	0.12	1.98	4.04	0.04	0.03	0.10	0.09	2.96	1.87	0.39	0.19	0.01	0.01	0.48	0.53	0.04	0.04
	Min.	4.00	3.95	0.01	0.03	0.13	0.23	0.01	0.01	0.04	0.03	0.15	0.03	0.04	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Max.	6.52	5.26	0.27	0.45	9.34	12.03	0.09	0.07	0.18	0.28	17.37	10.88	1.75	0.78	0.03	0.08	2.55	2.02	0.28	0.14
	CV (%)	16.3	7.3	64.6	62.7	102.0	77.7	54.3	41.6	39.3	73	128.0	122.9	106.5	90.8	107.7	143	114.8	109	145.3	119
	Skewness	0.45	0.51	1.22	2.41	2.06	1.01	0.69	0.78	0.39	1.53	2.36	2.28	1.94	1.40	1.23	2.41	1.76	1.11	2.83	1.55

1 IL = Island Lake, GL = Gounamitz Lake

Trends in variation were similar for most soil chemicals at both sites within soil horizons, although the Island Lake site displayed a greater range of variation. Similar trends existed in mean values between sites and among soil horizons. All soil chemical concentrations and acidity generally decreased vertically through the profiles; the Gounamitz Lake site, however, showed higher values of Fe, Al and organic matter within the B horizon, due to dominant eluvial/illuvial processes occurring across this site. Additionally, pH at the Gounamitz Lake site was surprisingly lower on average than at Island Lake's, suggesting that the surface geology is probably comprised mainly of sand and siltstones of low calcium content, contrary to soil map classifications.

Influence of Flow Accumulation on Soil Chemistry

Effects of water flow, either laterally, vertically or both, on the variability soil properties examined is clearly evident at both sites to varying degrees. Chemical concentration trends were log-linear with flow accumulation (Figure 5.1), with the greatest rate of change in soil chemicals occurring at flow accumulation values between 500 and 15,000 m^2, where there is a maximum transition from steeper divergent zones to convergent areas and the greatest effect from direct lateral flow. Much stronger relationships between soil chemistry and flow accumulation were evident at the Island Lake site as compared to the Gounamitz Lake (Table 5.2) site although both sites show similar directional trends (Figure 5.1).

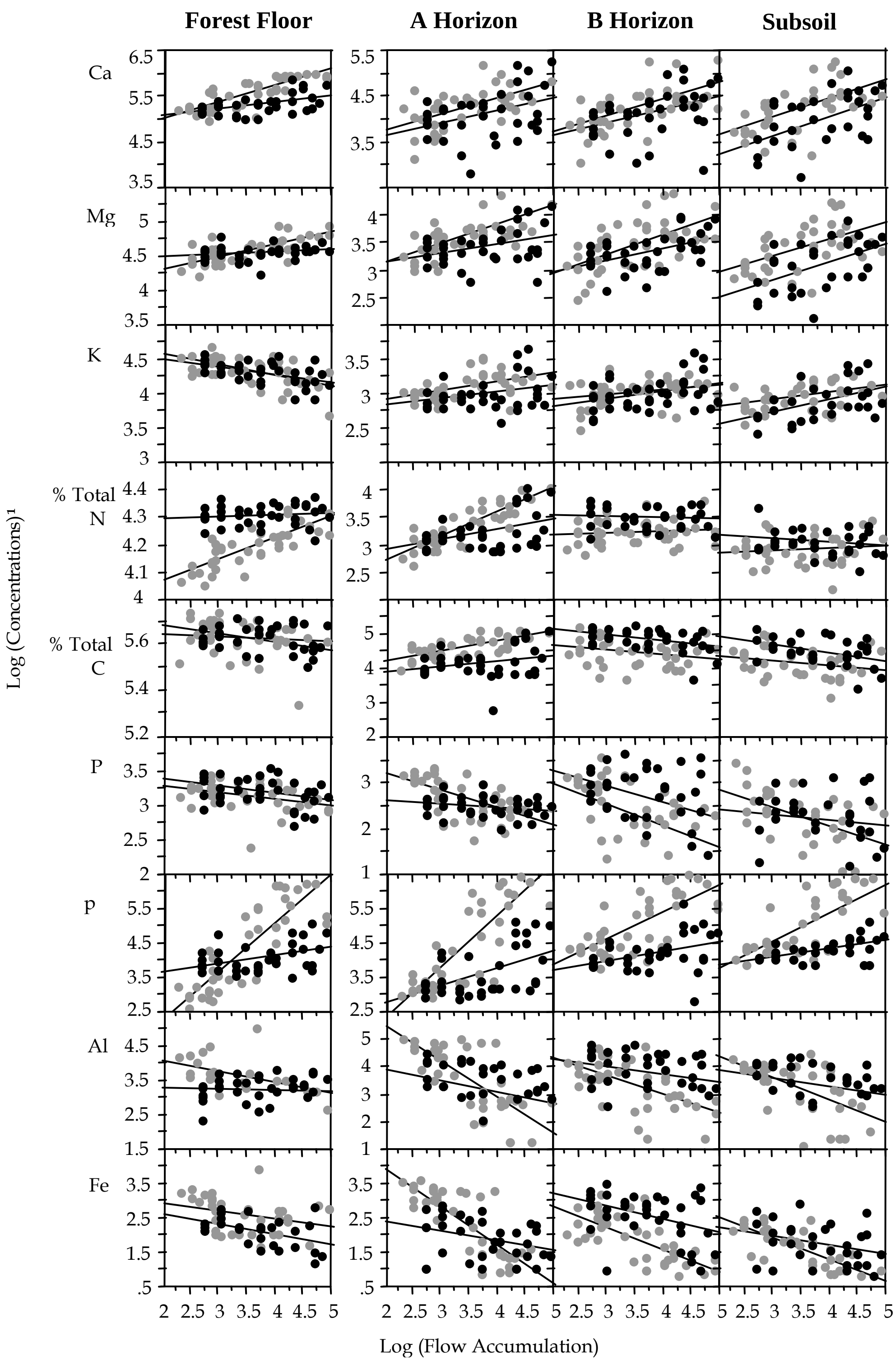


Figure 5.1 . Relationships between flow accumulation and select soil chemical concentrations by watershed (• Fraser, • Bowater) and soil horizon. Refer to Table 2 for coefficients of determination. [1] (except pH)

Table 5.2. Coefficients of determination for simple linear regressions between flow accumulation and soil chemical concentrations by soil layer and project site ($p<0.05$).

	pH	Total N	Total C	K	Ca	Mg	Fe	Al	P	Mn
		%		meq/100g						
Bowater										
FF	0.73	0.64	0.1	0.32	0.68	0.51	0.09	0.24	0.11	0.05
A	0.7	0.72	0.5	0.25	0.32	0.43	0.65	0.57	0.34	0.14
B	0.52	0.01	0.07	0.08	0.36	0.35	0.47	0.32	0.22	0.2
SS	0.51	0.02	0.06	0.19	0.34	0.28	0.62	0.35	0.23	0.21
Fraser										
FF	0.17	0.02	0.02	0.27	0.22	0.07	0.24	0.06	0.13	0.34
A	0.28	0.17	0.07	0.09	0.13	0.13	0.11	0.08	0.07	0.12
B	0.15	0	0.17	0.14	0.16	0.25	0.16	0.05	0.14	0.14
SS	0.25	0.04	0.17	0.22	0.22	0.27	0.11	0.06	0.02	0.21

Exchangeable cations, pH, and % N all displayed positive correlation with flow accumulation, while % C (except the A horizon), Al, Fe, and P showed negative relationships. As a whole, Ca, Mg, and pH were most highly correlated to flow accumulation at both sites, while Al, Fe, % N, % C and P were also significantly correlated at the Island Lake site. Flow accumulation explained from 10 to 73% of the variation in soil chemistry in the surface soil layers (FF and A) at Island Lake's, while moderate correlations were also evident at this site in the B and subsoil layers for pH, Ca, Mg, Al, Fe, and P with coefficients of determination ranging from 22 to 62%. In comparison, only <1 to 28 % of the variation in soil chemistry was explained by flow accumulation for the Gounamitz Lake site as a whole.

Assuming that the relative flow accumulation situation at each plot location was reasonably estimated using available DEM and field accounts, differences in correlation strength between project sites are most likely due to the permeability of the soil and bedrock at each site. The widespread presence of well-developed eluviated A horizons, a high coarse fragment content and underlying sandstone bedrock at the Gounamitz Lake site suggested that a large proportion of flood or melt-water infiltrated vertically through the profile to lower horizons, travelled laterally in the subsoil or left as deep seepage. Water at the Island Lake site, by contrast, appeared to flow laterally in many areas, either as seepage along compact/cemented subsoil horizons or eventually as ground-water, which came close to the surface in lower lying areas.

Although observed trends with flow accumulation were weaker at the Gounamitz Lake site, it is certainly noteworthy that there was a consensus in directional trends at both sites for all horizons and soil chemicals, suggesting that processes controlling soil chemical distribution respond to water flow and accumulation in a similar manner, even in such contrasting landscapes. This makes sense since the action of water flow is universal; it is how and where water flows (as influenced by topography and substrate) that determines the degree of influence.

Highest correlations were found for Ca, Mg and pH , which increased from areas of high flow accumulation to areas of low accumulation. The decrease in acidity down-slope has been observed in other studies (Donald et al. 1993; Moore et al. 1993; Silver et al. 1994) and is logically positively related to the lateral seepage of base-rich water to down-slope, convergent positions. Fe and Al , on the other hand, decreased with increasing flow accumulation and were strongly and negatively correlated with pH (Appendix I) and flow accumulation at both sites and for all layers. At the Island Lake site in particular, it appears that these elements occur in higher concentrations in ridge areas, decreasing along well-drained, steeper slopes and finally levelling off in convergent areas where flow accumulation values are greater than 10 000 m^2. In acidic forest soils, exchangeable Al and pH are inversely related (Brady 1990; Appendix I), while exchangeable Fe is higher in dry areas where it is present as Fe^{3+}, becoming reduced in seepage areas or where drainage is impeded (Silver et al. 1994).

Available phosphorous was also negatively, though weakly, correlated with flow accumulation; P is present in low concentrations at both sites and is notoriously difficult to quantify in a spatial context since its availability is dependent largely on mineral weathering and because it is quickly immobilised in acidic soils (Silver et al. 1994, Brady 1990). Similarly, % C, with the exception of the A horizon, shows a negative correlation with flow accumulation, though I would have expected it to be greater in convergent, high flow accumulation zones where organic matter normally accumulates from lateral transport and due to anaerobic conditions; % C, however, was also weakly related to flow accumulation indicating that this particular topographic attribute may not be a driving mechanism for organic matter distribution. High flow accumulation, especially at Gounamitz, does not necessarily equate directly with long-term moisture, shown to be important to carbon distribution in other studies (Pennock and van Kessel 1997; Arrouays et al. 1998; Morris and Boerner 1998) and probably a limiting factor at this site.

The Added Influence of Parent Material

Significant improvements in the prediction of mineral layer chemical concentrations at both sites were achieved with multiple regression analysis (Tables 5.3 and 5.4) as compared to simple regressions with flow accumulation

Table 5.3. Multiple regression equations ($p<0.10$) relating topographic/site variables to soil chemistry in mineral soil layers at the Island Lake site. R^2 values for simple regressions with flow accumulation alone (from Table 6.2.) are shown for comparison.

	pH	Total N	Total C	K	Ca	Mg	Fe	Al	P	Mn
		%		meq/100g						
A										
Intercept	-1.065	2.129	3.979	2.78	12.064	2.467	6.158	8.594	3.133	3.034
Flow Acc.	2.729	0.423	0.271	0.135	0.371	0.353	-1.92	-2.635	-0.455	
Wetness Index	-0.499						0.341	0.534		0.09
Slope	-0.076						0.06	0.078		
Thickness				-0.008						
Rooting Depth									0.012	
Coarse Fragments										
% Sand					-2E-05					
% Silt					-0.136				0.025	
% Clay					-0.134					
r^2	0.81	0.73	0.55	0.42	0.43	0.43	0.75	0.70	0.54	0.28
r^2 Table 6.2.	0.7	0.72	0.5	0.25	0.32	0.43	0.65	0.57	0.34	0.14
B										
Intercept	1.986	2.552	4.561	2.481	3.926	3.094	4.181	5.645	-2.198	1.635
Flow Acc.	1.592			0.1	0.285	0.332	-0.65	-0.675		0.297
Wetness Index	-0.327		-0.068							
Slope	-0.045	0.007								
Thickness						-0.624				
Rooting Depth				0.004						
Coarse Fragments		0.006	0.008							
% Sand					-0.012				0.054	
% Silt		0.012							0.05	
% Clay										
r^2	0.62	0.45	0.37	0.15	0.42	0.44	0.47	0.32	0.36	0.20
r^2 Table 6.2.	0.52	0.01	0.07	0.08	0.36	0.35	0.47	0.32	0.22	0.20
Sub-Soil										
Intercept	1.721	2.59	4.877	6.018	2.358	4.83	3.819	5.978	2.75	1.814
Flow Acc.	1.234			0.312	0.76	0.606	-0.63	-0.811	-0.389	0.22
Wetness Index	-0.145			-0.09	-0.126	-0.137				
Slope				-0.015						
Thickness									-1.067	
Rooting Depth									0.033	
Coarse Fragments		0.006	0.004						0.008	0.012
% Sand				-0.029		-0.03				-0.011
% Silt				-0.031		-0.034				
% Clay			-0.926	-0.796						
r^2	0.56	0.23	0.41	0.46	0.45	0.52	0.62	0.35	0.61	0.53
r^2 Table 6.2.	0.51	0.02	0.06	0.19	0.34	0.28	0.62	0.35	0.23	0.21

Note: highlighted cells indicate significance of $p>0.10$ but variables were included for their improvement of the overall r^2

Table 5.4. Multiple regression equations ($p<0.10$) relating topographic/site variables to soil chemistry in mineral soil layers at the Gountmitz Lake site. R^2 values for simple regressions with flow accumulation only (from Table 6.2.) are shown for comparison.

	pH	Total N	Total C	K	Ca	Mg	Fe	Al	P	Mn
		%		meq/100g						
A										
Intercept	3.579	4.448	5.356	3.754	60.102	3.219	2.447	3.782	2.875	3.69
Flow Acc.	0.407	0.084	0.064		0.201		-0.29			0.265
Wetness Index								-0.139	-0.041	
Slope						-0.046				-0.049
Thickness	-0.06	-0.02	-0.023				0.045			-0.107
Rooting Depth										
Coarse Fragments									0.005	
% Sand					-0.56					
% Silt	-0.017	-0.016	-0.017	-0.015	-0.57					
% Clay		-0.024	-0.031		-0.559			0.076	-0.032	
r^2	0.52	0.71	0.63	0.52	0.39	0.65	0.20	0.37	0.32	0.55
r^2 Table 6.2.	0.28	0.17	0.07	0.09	0.13	0.13	0.11	0.08	0.07	0.12
B										
Intercept	4.349	3.68	4.94	2.499	4.457	3.259	3.905	3.394	3.341	3.315
Flow Acc.	0.253			0.165	0.261	0.188				
Wetness Index							-0.1			
Slope										
Thickness								-0.098		
Rooting Depth				-0.009						-0.015
Coarse Fragments		0.005	0.0001	0.007		-0.01			0.012	0.006
% Sand	-0.017				-0.019			0.018		
% Silt									-0.025	
% Clay		-0.02	-0.041				-0.07		-0.077	
r^2	0.47	0.55	0.64	0.50	0.61	0.34	0.43	0.22	0.55	0.26
r^2 Table 6.2.	0.15	0.00	0.17	0.14	0.16	0.25	0.16	0.05	0.14	0.14
Sub-Soil										
Intercept	4.274	2.432	4.124	2.238	3.511	1.739	2.155	4.677	1.934	0.74
Flow Acc.	0.123				1.297		0.551		0.728	
Wetness Index		-0.025		0.042	-0.594		-0.23	-0.156	-0.195	
Slope			0.021		-0.154	0.074				
Thickness										
Rooting Depth	-0.011	-0.006								
Coarse Fragments		0.009	0.009	0.006		0.005				0.013
% Sand										
% Silt		0.013		-0.015						
% Clay	0.025		-0.033	0.033	0.072	0.046	-0.07		-0.095	0.06
r^2	0.58	0.54	0.79	0.79	0.62	0.52	0.59	0.32	0.59	0.46
r^2 Table 6.2.	0.25	0.04	0.17	0.22	0.22	0.27	0.11	0.06	0.02	0.21

Note: highlighted cells indicate significance of $p>0.10$ but variables were included for their improvement of the overall r^2

alone (Table 5.2). Indeed, flow accumulation was statistically non-significant for several soil chemicals on the Gounamitz Lake site, although the effect of texture and coarse fragments was fairly wide-spread and considerable. Conversely, flow accumulation remained the dominant predictor at the Island Lake site, with wetness index, slope and aspect all adding significant components to the equations; these topographic parameters were important in the subsoil layer at Gounamitz Lake as well. Overall, 20 – 70 %, 22 – 64 % and 32 – 79 % of the variation in acidity and soil chemical concentrations at Gounamitz Lake could be explained for the A, B and subsoil horizons respectively with the addition of multiple factors, while 28 – 81 %, 20 – 62 % and 23 – 62 % of the variation was explained at Island Lake's for the same soil layers.

Multiple regression results at the Gounamitz Lake site were complex and somewhat unexpected, probably due to the influence of strong micro-scale eluvial/illuvial processes dominating the A and B layers across the area. For example, % silt and % clay were negatively related to various soil chemicals in these layers while coarse fragments were positively related to most chemicals in the B and subsoil layers. Differences in texture here co-varied significantly with soil acidity and reflected micro-scale variations in weathering of sandstone and siltstone parent materials. Soil development responded to spatial changes in pH (ranging from 5.6 to 3.5) across the site, varying from dystric brunisolic (most basic) to orthic ferro-humic podzol and orthic humo-ferric (most acidic). Subtle differences in acidity and soil development processes were possibly the mediating influence on soil chemistry at the Gounamitz site. Although the direct relationship of these factors to the mechanisms of nutrient distribution are somewhat unclear here, predictions were nonetheless improved by the inclusion of soil physical properties, due to their combined influence on acidity, aeration and soil structure in these horizons.

Flow accumulation remained most significant at the Island Lake site, re-iterating the influence of lateral water flow and moisture distribution in this hummocky, relatively impermeable landscape. Soil physical properties generally did not contribute much more to predictions than flow accumulation alone, although the inclusion of slope and wetness index led to slight improvements. I suspect that predictions would be improved at this site by increasing the resolution and precision of topographic indices describing landform morphology and spatial and temporal patterns of subsoil water flow.

Most noticeable at both sites was the improvement in % C and % N with the inclusion of physical variables. Areas of increasing flow accumulation positively influenced the presence of these components in the A horizon at both sites but was not a statistically significant factor in the B or subsoil layers. Organic matter distribution in these horizons was probably most related to the decomposition of fine roots as influenced by soil aeration factors and soil acidity. Correlation among soil chemicals showed % C to be strongly correlated with the presence of % N, and moderately related to P and base cation concentration at both sites (see Appendix I), suggesting that organic matter plays a key role in the availability of nitrogen and the adsorption of other nutrients. The role of organic matter in lower mineral soil layers is frequently not included in soil nutrient studies though these horizons may, in certain regions, contain more organic carbon than surface layers (Hammer et al. 1995). Predictions of P, K and base-cation concentrations, at the Gounamitz Lake site in particular, were also much improved by the inclusion of soil physical factors for their effect on supply and retention of these nutrients. Moore et al. (1993) stated that it would be unreasonable to expect more than 70 % of the variance in soil properties to be explained, even with accurate depiction of micro-scale topography. I, therefore, consider the amount of soil chemical variability explained at both sites in this study to be significant and encouraging.

SUMMARY

Knowledge of the scales at which various soil processes controlling available supplies of nutrients operate is extremely valuable in various aspects of forest ecology, yet this cross-scale knowledge is rarely readily available and difficult to obtain (Moore et al. 1993; Hammer 1998). In this study, supporting the findings of other similar investigations, I presented strong evidence that topography provides a crucial link between soil processes (as influenced by water flow and accumulation) and spatial patterns of soil chemical properties at a meso-scale. This study also further suggests that these relationships may be similar in form for different soil-landscapes and that the strength of this linkage is related to substrate permeability and its influence on overland and subsurface water flow patterns. Therefore, the degree to which a given landscape is made up of repeating topographic patterns and identifiable substrates may determine to what extent results such as these can be scaled up. Watershed sub-catchments are ideal for this purpose since they are basic, nested hydrological units that can be automatically delineated and related to other GIS coverages.

Similar to Hairston and Grigal's (1991) study findings, soil nutrients were highly variable at sites in this study even though they lie within single soil-map units; certain soil processes, especially those controlling fine-scale soil nutrient availability, were localised to each landscape type and variably dependent on both lateral water movement and vertical parent material composition within a profile. Therefore, depending on the nature of the substrate in a given landscape, elucidation of soil chemical property trends relies on the inclusion of both meso-scale topographic and micro-scale site-inherent factors. This may be especially important in delineating and modelling spatial distributions of carbon, nitrogen and phosphorous which are complex and respond to multiple factors.

Also clear was the variation among soil layers; B and subsoil horizons are rarely sampled or examined in most soil-landscape studies even though conditions in these layers are rarely correlated to surface horizon conditions (Hammer, 1998).

Given the substantial within and among-horizon variability in chemical concentrations encountered at these sites, explanations regarding soil-landscape processes posited in this study may be further clarified by investigating other areas with differing substrates and relief.

CHAPTER 6

ROOTING ZONE NUTRIENT POOLS AT THE ISLAND LAKE AND GOUNAMITZ LAKE SITES: THE INFLUENCE OF SITE AND TOPOGRAPHY

INTRODUCTION

Rooting zone quantities of organic matter and available nutrients are essential components in assessing the fertility and sustainable productivity of forest stands in the face of human and natural disturbance and, therefore, for prescribing appropriate management interventions. Indeed Kimmins (1987) stated that " In order to make management decisions that are biogeochemically rational, the forester must...understand...the quantities, distribution, and cycling of nutrients within the forest..." Additionally, in light of recent concerns about global warming, this information is extremely valuable in making accurate assessments of carbon sources and sinks in various ecosystems, at different scales, subjected to a range of management regimes (Johnson 1995).

The calculation of nutrient reservoirs requires plot-specific measurements of available nutrient concentrations as well as estimates of the root sorption zone and the bulk density of the soil. These components are difficult to accurately characterise (Kimmins, 1987) but are nonetheless necessary in determining the *potential* fertility of one site relative to another, all things being equal. Despite investigations quantifying the available pools of carbon and nutrients at sites within boreal forests (e.g. Van Cleve et al. 1991; Vogt et al. 1995; Huang and Schoenou 1996), there is generally a paucity of knowledge in the available soils literature of the mechanisms controlling nutrient distributions in a spatial context, particularly at a meso-scale. The landscape distribution of nutrient reserves have been shown to vary as a result of landscape position (Boudeman 1989; Hammer et al. 1995, Huang and Schoenau 1996), elevation and aspect (Van Cleve et al. 1991), slope gradient (Arrouays et al. 1998) and steady-state moisture index (Morris and Boerner 1998). This chapter investigates the functional relationship between derived topographic attributes, select soil physical properties and rooting zone nutrient pools at the two study sites.

METHODS

Bulk density was measured for organic and mineral soil horizons at a selection of plots at both sites. Forest floor horizons were sampled by excavating a 20 X 20 cm^2 area down to the top of the mineral soil while mineral soils were sampled from the undisturbed walls of excavated pits using a copper cup of a known volume. Samples were oven-dried and weighed to obtain soil mass. Bulk densities were calculated by dividing soil mass (g) by the volume of soil sampled (cm^3).

Although a complete set of bulk densities were obtained for organic horizons, mineral soil bulk density samples were difficult or impossible to sample for many of the soil horizons due to abundant coarse fragments and compact soil layers. As such, representative samples were taken from A, B and subsoil horizons and used in a multiple regression with other soil variables to obtain a best-fit prediction of bulk-density (Db). Data were pooled for the two study sites and for horizons of a given layer to obtain the following average best-fit regression equations:

1. A Layer Db = 2.864 - .449(Log(A Layer % OM)); $r^2 = .61$, n = 24
2. B Layer Db = -.004 + .280(B Layer pH) - .023(B Layer % Silt); $r^2 = .59$, n = 23
3. Subsoil Db = -1.454 = .595(subsoil pH); r2 = .82, n = 12

A total of 54 A, 71 B and 71 subsoil horizon bulk densities were subsequently estimated using regression models.

Quantities (kg/ha) of C, N, P, K, Ca and Mg were calculated for the effective rooting zone at each plot using bulk densities and nutrient concentrations measured for each soil horizon (see Chapter 5). Totals were adjusted to account for the percentage of coarse fragments found in each soil horizon. The extent of the rooting zone was clear at the Island Lake site since it generally ended at a compact BC/C, a gleyed or a waterlogged horizon. However, there were a few plots at the Gounamitz site where coarse roots were still observed in lower, less permeable BC or C layers; excavation was not continued past these layers since the bulk of fine roots were observed in upper horizons.

Average nutrient totals were described and discussed by study site and by soil layer. Subsequently, rooting zone nutrient quantities were analysed for spatial relationships with flow accumulation and wetness index, slope and layer-specific texture fractions and pH through multiple and non-linear regression analysis. Certain nutrients were log-transformed prior to analysis to approximate normality.

RESULTS AND DISCUSSION

Overall Distribution and Trends

Bulk density increased vertically in profiles at both sites (Figure 6.1). In comparing the two sites, the forest floor, B and subsoil layers displayed higher bulk densities at the Island Lake site due to increased compaction in these horizons while the Gounamitz displayed a higher mean A layer bulk density, reflecting the predominance of finer, silty-loam textures in this horizon.

The Island Lake site showed higher average coarse fragment-weighted totals of all nutrients and higher variation in these amounts as compared to the Gounamitz Lake site (Table 6.1). Further, with exception of slightly higher values for A horizon-N, K, and Ca and B horizon-P at the Gounamitz site, totals were also higher at Island Lake for each soil layer (Table 6.1). The occurrence of fine-grained igneous minerals in the parent material at the Island Lake site, as opposed to the coarser sand and silt-stones at Gounamitz, likely contributed to

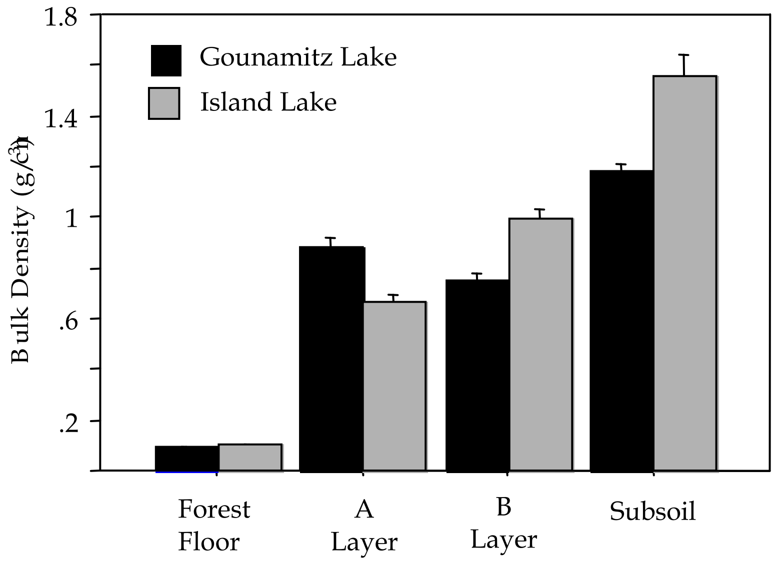


Figure 6.1. Mean values for bulk density across soil layers at the two study sites.

Table 6.1. Descriptive statistics for rooting zone totals of carbon and major nutrients at the two study sites.

Site	Totals (kg/ha)	Mean	SD	Minimum	Maximum	C.V. (%)
Island	Total C	178864	130072	32908	572966	73
Lake	Total N	7886	4761	1278	26661	60
	K	176	103	38	478	58
	Ca	3142	4869	230	26128	153
	Mg	221	294	26	1401	133
	P	43	92	4	597	213
Gounamitz	Total C	109006	46364	43065	240528	43
Lake	Total N	4876	1521	2259	9611	31
	K	127	46	65	264	36
	Ca	1248	1476	91	6217	118
	Mg	98	81	24	370	83
	P	36	32	2	129	89

higher levels of carbon and nutrients here since less acidic parent materials generally result in higher clay and organic matter contents (Van Cleve and Powers 1995). Topography also exerted an influence on differences in nutrient pools between and within sites and will be discussed later in this chapter.

Total Carbon and Nitrogen

Overall, carbon and nitrogen contents (Table 6.1) at Island Lake (Total C = 178 Mg/ha; Total N = 7 Mg/ha) and Gounamitz Lake (Total C = 109 Mg/ha; Total N = 4.9 Mg/ha) were comparable to values found for other studies in boreal ecosystems. For example, Van Cleve and Powers (1995) cited a range of 149 and 170 Mg/ha for boreal ecosystem mineral soil carbon while Tetema and Verstraten (1991) found the total N storage of the F, H and top 26 cm of mineral soil of a Netherlands forest site to be 6.4 Mg/ha. Huang and Schoenau (1996) reported mean total pools of 200 Mg/ha for total carbon and 8.0 Mg/ha for total nitrogen within the forest floor and mineral soil (1m depth) at a boreal aspen forest site in Saskatchewan. Disparities in values are partly due to the horizons and total depths used in calculations.

Overall pooled values for total C and N were strongly correlated at both the Island Lake ($r = 0.72$) and at Gounamitz ($r = 0.64$), as is commonly the case (Brady 1990) and displayed similar trends across soil layers at both sites (Figure

6.2). Often, the forest floor layer contributes the majority of organic matter and nitrogen in boreal forests (e.g. Huang and Schoenau 1996). At these study sites

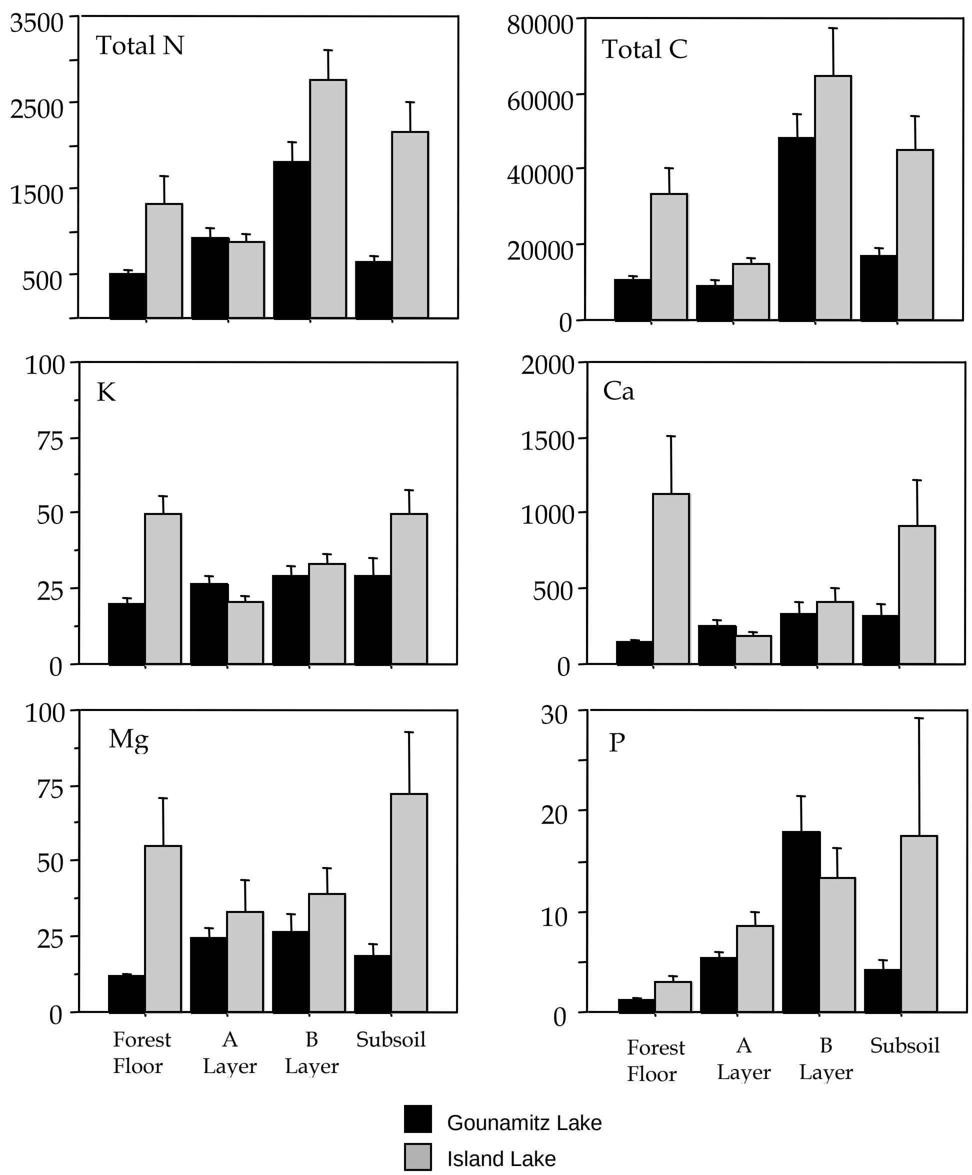


Figure 6.2. Trends in mean values (+ 1 S.E.) for carbon and nutrient quantities across soil layers for both study sites.

highest totals were found within B horizons overall, as is common for soils with podzolic profiles (David et al. 1995). There was considerable evidence of illuviation of humic substances into the B layer, especially at the Gounamitz site; lateral water flow and transport within this layer throughout the Island Lake site contributed to poor soil aeration at several plots and higher storage of carbon in mineral soil layers. Certainly, these conditions led to a much larger range of values at Island Lake for all elements and probably resulted in relatively greater mean values at this site.

Phosphorous

The mean amount of available phosphorous in the rooting zone totalled 43 and 36 kg/ha at the Island Lake and Gounamitz Lake site respectively (Table 6.1). Data on phosphorous quantities and forms in forest soils is less common than other nutrients (David et al. 1995). However, the quantities calculated at these sites agreed with the mean value of 34 kg/ha found by Huang and Schoenau (1996) for eluviated Luvisolic soils in Saskatchewan, also analysed using the bicarbonate method.

By soil layer, phosphorous pools were greatest in the B layer at the Gounamitz site while both the B and subsoil layers contained the largest proportions of P at Island Lake (Figure 6.2). The availability of phosphorous is dependent on the weathering of primary minerals and is related to the presence of clay, iron, aluminum and organic matter in acidic soils (Brady 1990). As has been addressed in previous chapters, the lower mineral soil horizons in these study sites contain a less-weathered source of coarser mineral fractions and the lower layers were more enriched with iron, aluminum and organic matter. The organic horizons contained the highest concentrations of available P but, on a mass basis, comprised a relatively small pool of this nutrient.

Potassium, Calcium and Magnesium

Quantities of major cations were available in the order of Ca >> Mg >K at Island Lake and Ca >> K > Mg at the Gounamitz site (Table 6.1). Calcium and magnesium were especially variable at both sites, probably due to their tendency to be highly exchangeable and mobile within the soil solution as influenced by local pH, water flow, soil texture and organic matter.

Layer-specific stores of calcium, magnesium and potassium showed similar within-site but different between-site trends (Figure 6.2). At Island Lake, these nutrients generally displayed large pools in the forest floor which decreased substantially within the A and B and increased again to relatively high quantities in the subsoil. Organic horizons were relatively thick at this site due to differences in spatial moisture conditions and, as a result, led to the effective adsorption of relatively high concentrations of exchangeable cations. Conversely, in the subsoil layers nutrient concentrations were low and comparable to A and B layers but bulk densities were high. Plots this site receiving up-slope seepage throughflow and groundwater inputs (Chapter 5) displayed relatively higher cation concentrations and an increase in weathering of primary minerals, which, at this site were partially comprised of base-rich basalt.

At Gounamitz, cation quantities increased vertically from the forest floor to the B layer and then decreased slightly into the subsoil. Although forest floor nutrient pools were somewhat less than mineral soil pools, the relatively thin organic layers contributed a substantial quantity of these nutrients at this site. Generally, results were characteristic of the well-drained podzolic soils found here, where the B horizons provided a sink for cations as well as carbon, nitrogen and phosphorous.

The Influence of Water Flow and Accumulation

Topography exerted both a direct and indirect influence on quantities of C, N, P, Ca, Mg and K at both study sites. Directly, flow accumulation and wetness index, in addition to slope gradient, were significantly related to several nutrients at Island Lake and only to potassium at the Gounamitz site. However, rooting zone pools were also strongly correlated with pH and clay texture fractions for various nutrients at both sites. Both soil reaction processes and texture influence the cycling and availability of nutrients and carbon (Kimmins 1987; Brady 1990). In this case, pH and % clay also acted as indirect and intermediate indices of the effect of subsurface water flow and slope processes because their distributions have been shown to be related to topography (Chapters 4 and 5 respectively).

Total Carbon and Nitrogen

Chapter 6 illustrated the difficulty of predicting % C and % N distributions based on topographic attributes of water flow alone. Instead, I concluded that their distributions were likely multivariate. Results for rooting zone storage of these nutrients were similar in this respect. Spatial distributions of Total C pools were best explained by negative exponential relationships with subsoil clay at Island Lake and A layer pH at Gounamitz. Total N values, on the other hand, were linearly and positively related to flow accumulation and Total C at the Island Lake site and to subsoil clay and Total C at Gounamitz Lake. This latter result is not surprising given the strong co-relationship of nitrogen and carbon.

Total C was related to both SS clay and B clay at Island Lake, although the former provided the clearest relationship (Figures 6.3a and b). Further, the distribution of clay increased in convergent and mildly-sloping zones as a result of the action of subsurface water flow along impermeable subsoil layers and accumulation in convergent zones (Chapter 4). These results, therefore, suggest an indirect relationship between organic matter distribution and topography. The negative functional relationship of Total C pools with clay would seem to indirectly indicate that organic matter was greater in drier zones. Although forest floor organic layers were thicker in wetter areas, these layers only represented a portion of rooting-zone organic matter storage. Lower mineral soil horizons were deeper in drier side-slope areas and contained a substantial proportion of organic

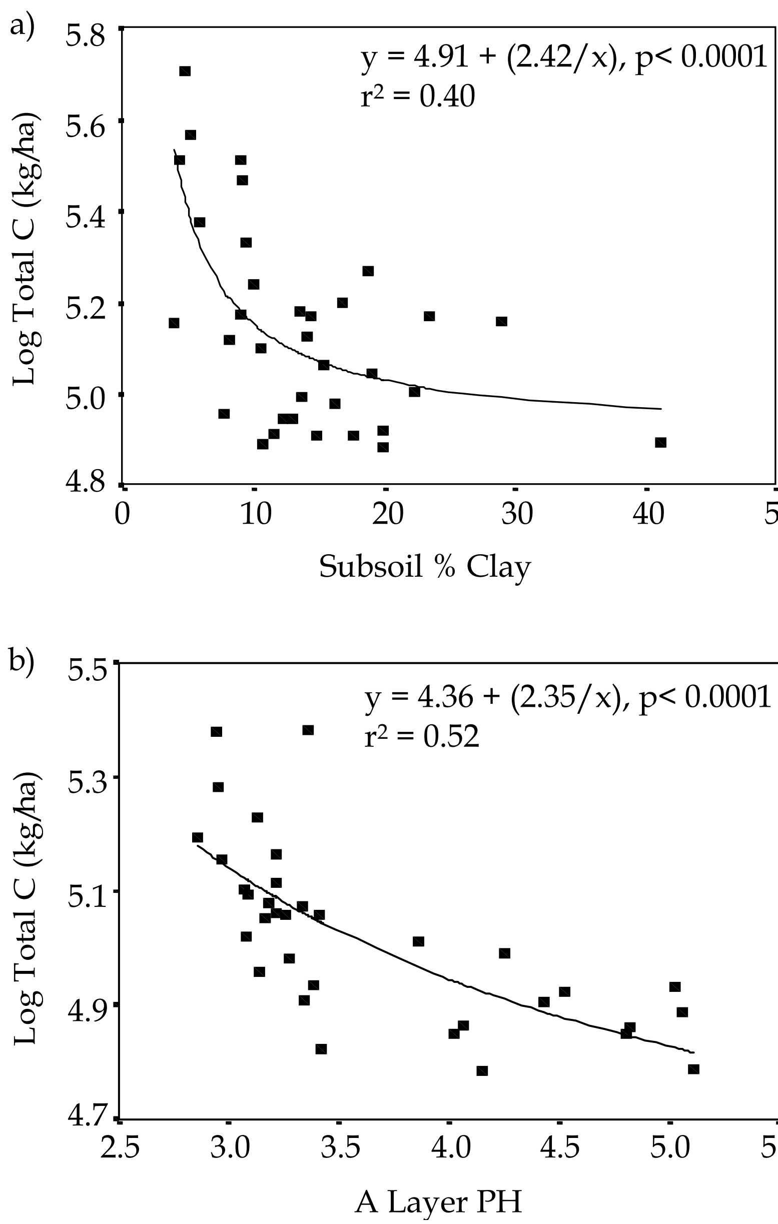


Figure 6.3. Scatter plots showing trends between Total C pools (kg/ha) and % Clay and Subsoil pH for the a) Island Lake and b) Gounamitz Lake sites respectively.

matter due to decomposing roots and illuviated humic materials. This observation is similar to Hammer et al. (1995) who found the majority of organic carbon to exist in subsoil layers.

Similar to the Island Lake site, organic matter distributions at Gounamitz were also indirectly related to topography (Figure 6.3b). The pH of the A and B layers, previously shown to be related to flow accumulation and soil texture at this site, was negatively related to carbon quantities. Soil acidity in the surface layers appeared to closely index soil development and soil classification at this site. Consequently, higher pH values generally correlated spatially to the occurrence of brunisolic profiles characterised by Ah horizons and ferro-humic podzols with Bhf horizons, both enriched with organic matter.

Information on the function or importance of organic matter in lower mineral soil horizons is scarce (Hammer 1998) despite evidence, as presented here, that these horizons may act as substantial carbon sinks or may be an important source of nutrient uptake by deeper-rooted fine roots. This emphasises the importance of accurately identifying the effective rooting zone at a given site since it is may be only within the zone of effective uptake that organic matter acts as a significant influence on forest productivity.

Total nitrogen quantities co-varied strongly with carbon at both sites and less strongly with flow accumulation and subsoil clay at Island Lake and Gounamitz respectively (Figures 6.4a and b). This indicated that the spatial distribution of nitrogen, while clearly dependent on carbon, is also multivariate,

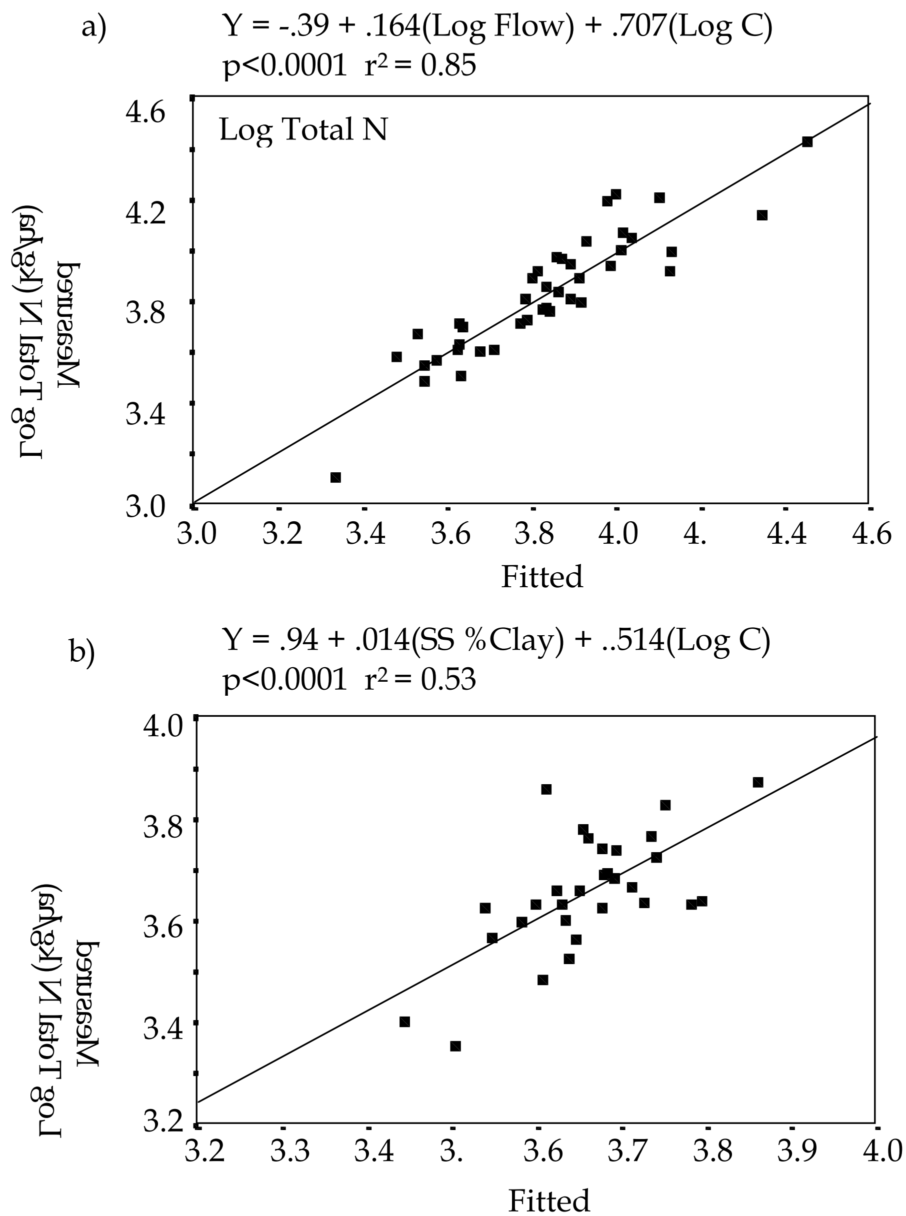


Figure 6.4. Best-fit relationships between Total N pools (kg/ha) and topographic and soil variables for the a) Island Lake and b) Gounamitz Lake sites.

responding to topographic and site influences. This supports Morris and Boerner's (1998) results where spatial differences in N mineralisation and nitrate production were best explained by a host of influences including organic carbon, pH and an integrated moisture index calculated at a meso-scale.

Phosphorous

Phosphorous quantities for the rooting zone correlated negatively and non-linearly with flow accumulation at the Island Lake site (Figure 6.5a). This trend suggested that toe-slopes and other areas of convergence, where water accumulation was greatest, were areas of least P availability at this site. Instead, P quantities were highest along mid and lower slope areas where P accumulated due to down-slope through-flow of subsurface water, as in Xiao et al.'s (1991) study. Areas with increased water through-flow would also have a concomitant increase in mineral weathering, the predominate source of this element.

Conversely, across the Gounamitz Lake site, P quantities were positively related to carbon and negatively related to surface pH distributions (Figure 6.5b). This finding makes sense since phosphorous availability is known to be adsorbed by organic matter content and chelated or fixed by iron and aluminum (Brady 1990), which were more abundant in more acidic and highly leached humo-ferric podzols. Carbon was clearly important at this site for P sorption and availability and may be crucial at sites such as this, where primary minerals are relatively

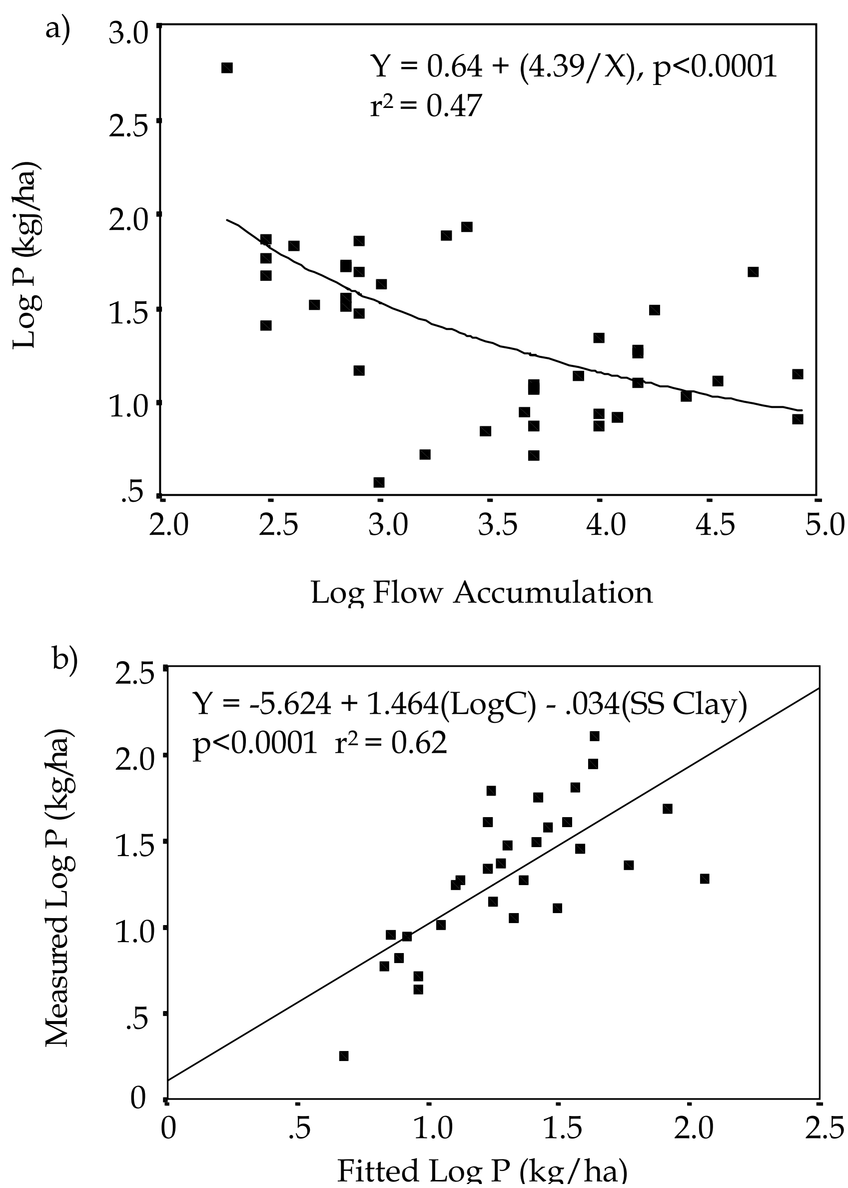


Figure 6.5. Relationships between available P pools (kg/ha) and topographic and soil variables for the a) Island Lake and b) Gounamitz Lake sites.

high in silica or where there is little redistribution of nutrient elements from lateral water flow.

Potassium, Calcium and Magnesium

Rooting zone cations were positively related to the flow and accumulation of subsurface water at the Island Lake site (Figures 6.6 and 6.7). Both Ca and Mg were strongly correlated to topographic attributes while all three cations were related to subsoil pH, which increased from divergent to convergent areas. These results provide clear evidence of the increase in base saturation and consequent richness of seepage zones and other convergent areas due to the accumulation of base-forming nutrients as water flows laterally through subsurface layers although this influence is normally ignored in most soil investigations (Kimmins 1987).

At Gounamitz, Ca and Mg were positively and logarithmically related to the pH of the A layer, while K was positively and linearly related to slope and wetness index (Figure 6.8 and 6.9). Similar to phosphorous, quantities of Ca and Mg were related to water flow and accumulation, as indexed by the spatial distribution of pH and its effect on horizonation. Potassium, on the other hand, was directly, though weakly, related to topographic attributes.

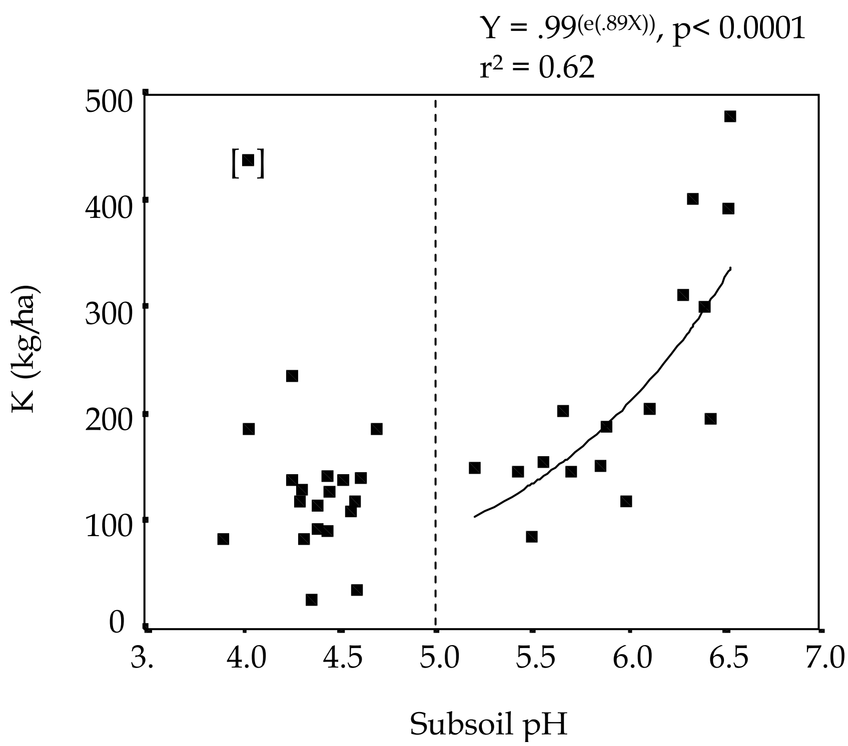


Figure 6.6. Scatter plot showing trend between K pools (kg/ha) and Subsoil pH for the Island Lake site. Dotted line indicates evident groupings of values based on pH. Bracketed outlier was removed from regression.

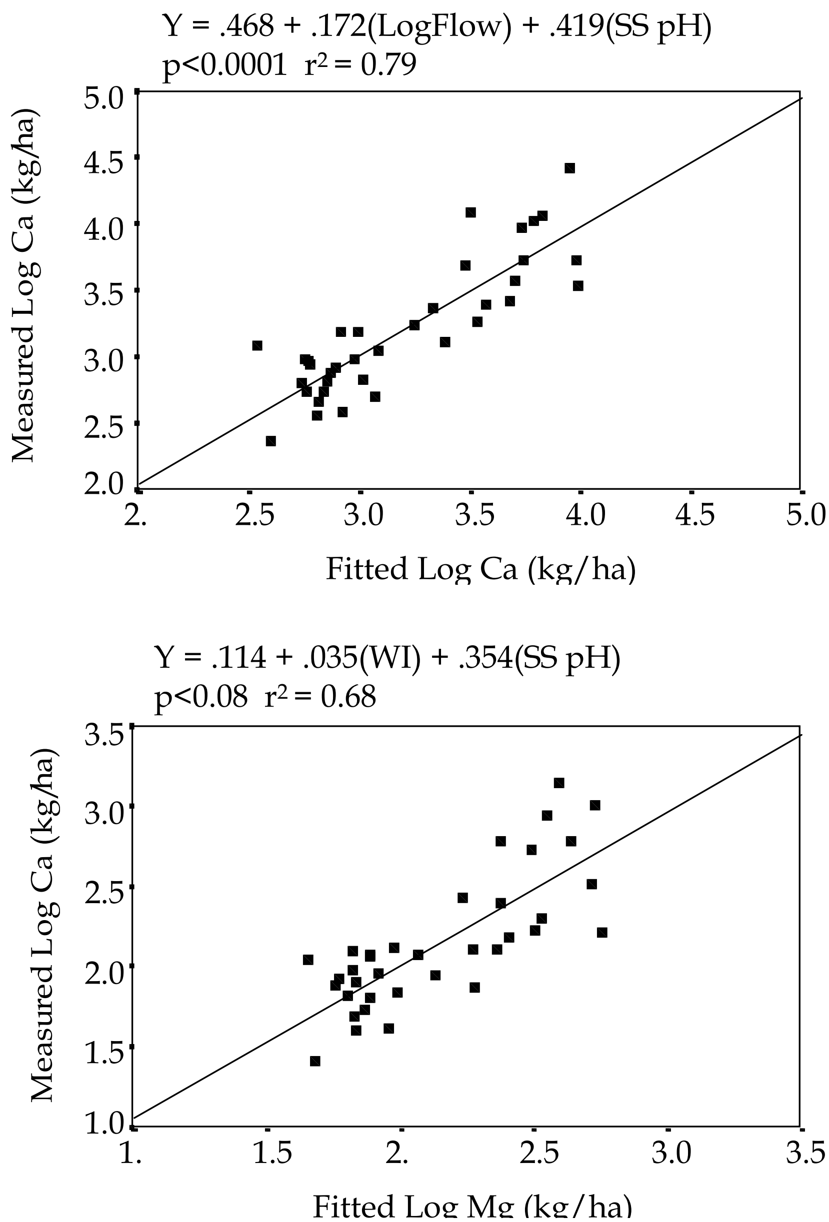
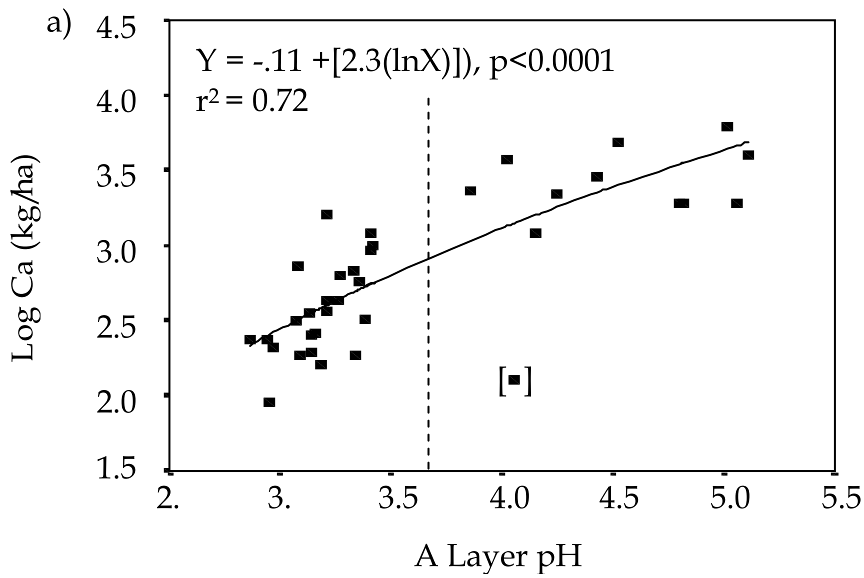


Figure 6.7. Best-fit relationships between available a) Ca and b) Mg pools (kg/ha) and topographic and soil variables for the Island Lake site.



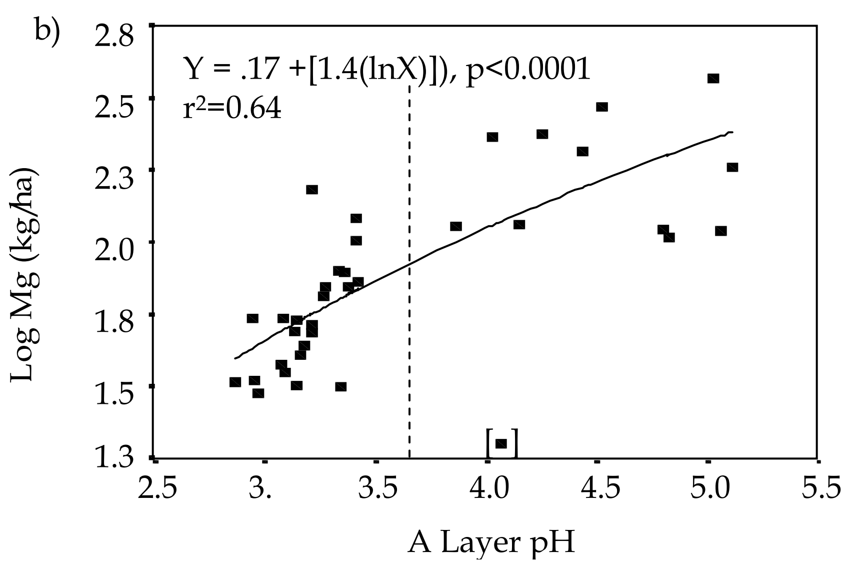


Figure 6.8. Scatter plots showing trends between available a) Ca and b) Mg pools (kg/ha) and A Layer pH for the Gounmitz Lake site. Cation values show obvious grouping as indicated by dotted lines. Bracketed outliers were omitted from regressions.

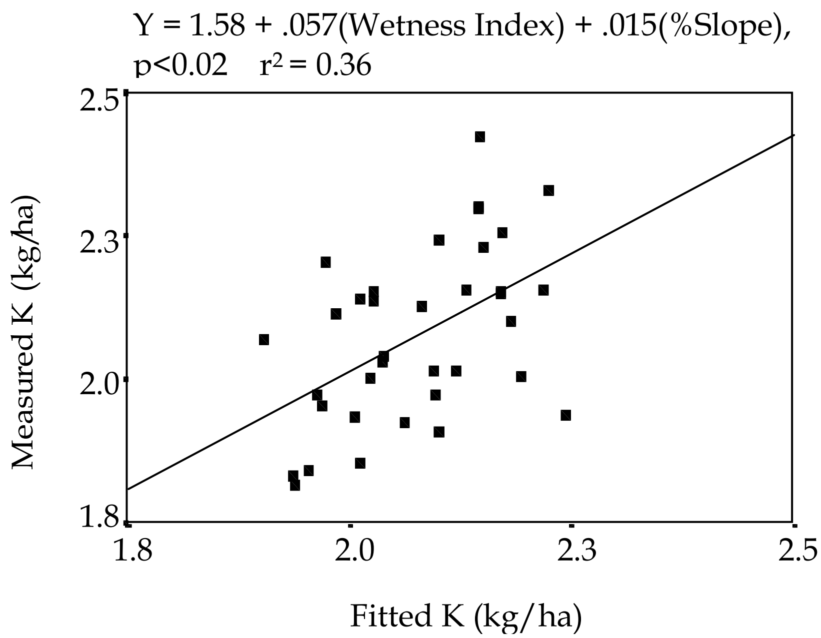


Figure 6.9. Best-fit relationship between available K pools (kg/ha) and topographic and soil variables for the Gounamitz Lake site.

SUMMARY

Rooting zone quantities of carbon, nitrogen, phosphorous and nutrient cations varied substantially across two headwater catchment study areas. Spatial analyses suggested that relatively simple yet significant functional relationships existed between spatial patterns of available nutrients, indices of water flow and accumulation, soil acidity and soil texture, although these trends differed by site. Results also suggested that carbon and nitrogen, phosphorous, and the three cations (K, Ca, Mg) formed three separate functional groups that responded to similar landscape factors within a site.

The range of spatially aggregated rooting zone values for carbon, nitrogen and phosphorous were found to be similar to other investigations carried out in a boreal forest setting although these studies differed in terms of the soil depth used to characterise the vertical extent of available soil nutrients. Kimmins (1987, p. 246) noted this as a potential problem in nutrient studies since the depth of maximum rooting does not necessarily equate to the sorption zone of a given root system. In this analysis, only horizons with fine roots were included as a part of the effective rooting zone.

Spatially, available nutrients were either indirectly or directly related to lateral and vertical water flow and accumulation processes occurring at both sites, although trends were specific to each site. At the Island Lake site, where there was strong lateral water flow and accumulation due to impermeable subsoil zones, expected flow accumulation and wetness index values were significant indicators of N, P, Ca and Mg pools. Additionally, subsoil pH and/or % Clay were also strongly related to all nutrients; these factors, previously shown to be highly related to topographic indices, are functional indicators of seepage influences along lower mineral horizon layers at this site.

Topographic indices were much less influential at the Gounamitz site while processes influencing the pH of surface layers across this site were more important indicators of rooting zone nutrient quantities. Soil descriptions identified strong spatial differences in A horizon development at this site and previous results showed that A horizon pH distributions were at least partially the result of lateral water movement, although to a lesser degree than at Island Lake.

Delineating adequate indicators of nutrient and carbon pools at these sites are clearly complex and data regarding micro-climatic (e.g. soil temperature) and temporal nutrient turnover influences may shed further light on this matter. Spatial patterns of soil nutrients as presented here would certainly be more ecologically meaningful in the context of tree uptake and growth (Silver et al. 1994). This work would benefit greatly from a more complete analysis of biogeochemical differences between and within the conifer stands dominating Island Lake site and tolerant hardwood forest found at the Gounamitz Lake site. This would provide a clearer picture of how the sites and plots differ with respect to nutrient demand, nutrient partitioning, rooting distribution, turnover rates and, ultimately, whether the influence of water flow and accumulation is expressed above-ground as within the soil medium.

CHAPTER 7

TWO SURVEY METHODS FOR CREATING FINE-SCALE DEM'S UNDER A FOREST CANOPY: A QUALITATIVE ANALYSIS

INTRODUCTION

In light of the concerns presented earlier in this thesis, there is a clear need for exploring methods of obtaining accurate elevation data at a meso-scale such that local topographic complexity is adequately represented. This fine-scale characterisation is crucial in ecological studies where the aim is to identify and understand local topographic influences on meso to micro-scale ecological processes.

Meso-scale investigations relating DEM-derived attributes to soil properties within agricultural field sites, carried out by Odeh et al. (1991) and Moore et al. (1993), used fine-scale data generated from field surveys using traditional survey equipment. Similarly, Wilson et al. (1998) used a high precision truck-mounted Global Positioning System (GPS) on a farm field to derive fine-scale elevation data while Dietrich et al. (1993) used digital photgrammetry for a sparsely vegetated site. Unfortunately, these methods are useless in areas of dense forest cover as found at the Island Lake site.

As such, presented in this chapter are two field techniques for generating relatively fine-scale elevation data under thick to moderate forest canopy conditions using both manual methods and a hybrid manual/GPS procedure. Elevation data collected using these methods are used to create two DEM's for a sub-section of the Island Lake site and are compared to Provincial DEM's to illustrate the effect of scale.

METHODS

Two Field Survey Methods For Creating a Fine-Scale DEM

Polychain Method

A section of the Island Lake site (~7.5 ha) covering most of the lower part of sub-catchment 1 was used as the study area for demonstrating this survey approach. This areas was selected because it consisted of a well-defined gully (representative of hummocky terrain) with a central intermittent flow channel that could not be resolved using the provincial elevation data set.

Traditional survey methods using either a normal transit or a laser transit were initially considered but rejected for two main reasons. First of all, these methods require that the transit be levelled for each new survey section and that the target be visible to acquire measurements. The Island Lake site, however, contained many dense stands of black spruce and balsam fir, which rendered these methods too time-consuming to use. Secondly, the aim was to achieve better overall representation and relative accuracy of elevations, and the higher precision of traditional survey methods was deemed unnecessary.

Several control points of known elevations were identified along a ridge area and along a nearby logging trail and were used to geo-reference the surveyed points. Transects, spaced at 25 m, were established at a given compass direction perpendicular to the gully slopes such that maximum differences in slope change were measured.

The survey was carried out with two people: a chain-bearer and a note-taker. The chain-bearer, carrying the 0 m end of a 50 m polychain, followed a pre-set bearing until a perceived break in slope was encountered, or until visibility was lost due to forest conditions, and subsequently established a station at that location. At this point, to minimise errors due to inaccurate navigation along the bearing, the path taken by the chain-bearer was verified by the note-taker using his/her compass, and lateral adjustments were made accordingly. At each station a distance and % slope reading, between the note-taker to the chain-bearer, was measured using the polychain and Suunto clinometer respectively.

GPS Method

As a possibly less time-consuming alternative to the above field survey method, a trial approach using Corvallis Microtechnology MC-GPS, C/A code receivers (horizontal accuracy of 3-5 m after correction) was carried out to cover an area comprising the remaining unsurveyed portion of sub-catchments 1 and 2 at Island Lake. Using a nearby road and several ridge high points as control points, transects at ~50m intervals were established and traversed by a crew of three people. Two people, each with a GPS receiver, followed a general bearing from the note-taker, perpendicular to the prevalent slope gradient. To cover more area efficiently, two procedures were used depending on the complexity of terrain:

1. In less complex terrain (i.e. less hummocky) the first GPS user followed a bearing set by the note-taker and proceeded to the next break in slope while the second GPS user continued past the first, along the same bearing, until the next successive slope-break was encountered. A % slope reading was taken by the note-taker to the first GPS user while both GPS users recorded GPS positions at their given stations. During this time, the note-taker proceeded to the location of the nearest GPS-user and took another slope reading to the second GPS user. The first GPS user then set out again along the same bearing locating the next slope break. Thus point locations and slope measurements were taken in a “leap-frog” manner along a particular compass direction.
2. Alternately, in more locally complex terrain, one GPS user was used as a “floater” and directed by the note-taker to acquire GPS positions at nearby landform features (hummocks or depressions) not on the transect route that were deemed substantial enough to affect the proper characterisation of meso-scale topography. The other GPS user continued, as in the first method, to the next break in slope along the original transect bearing. Slope readings to each GPS user and GPS positions were taken as described earlier and then each GPS user and the note-taker proceeded along the transect to another set

of points in this fashion. This more flexible method attempted to identify and account for obvious features in this terrain that may have been missed by stringently following a transect route.

Six ten-second GPS points were recorded at each station and each recorded point was comprised of ten positions (one per second). For most cases, positions were only recorded when the receiver was tracking enough satellites to acquire a 3D fix. This meant that 4 or more satellites were being adequately tracked; at times, due to poor satellite geometry, thick forest canopy or inclement weather, positions were recorded from only 3 satellites.

Positions, identified by station number, were downloaded from the GPS receiver to a laptop computer and differentially corrected with data collected for that given day at a base-station 50 km away in Dalhousie, NB. Each set of corrected positions at a given elevation point were viewed with MC-GPS software, obvious outlier points were discarded, and the remaining cluster of points were averaged to give a mean location for each point. The six point values were then averaged to provide mean location for a station. These multiple measurements, in effect, helped isolate and minimise positional dilution of precision (PDOP) error due to the temporary loss or poor positioning of satellites or inadequate reception. By geo-referencing at least one end of each transect relative to known control points, elevations were calculated using the slope measurements taken from point to point.

Organisation and Analysis of Survey Data

Using known control points, obtained from a 1: 10 000 ortho-photo topographic map, elevations could be calculated along transects for both methods. For the Polychain method, simple geometrical relationships were applied to derive X and Y co-ordinates for each point and the vertical rise for each interval using distance and % slope measurements along a known bearing. Each successive transect was connected to the previous transect, allowing a grid of elevations to be developed. The GPS method simplified these calculations since the X and Y co-ordinates were automatically positioned and only the vertical rise needed to be calculated using percent gradient measurements from point to point.

Figures 7.1a and b display the distribution of elevation points as derived using the two survey methods as well as those obtained from the Province of New Brunswick respectively. Points surveyed using the Polychain procedure are presented in Figure 7.1a as an outlined grid of points imbedded within the elevation grid created using the GPS method. DEM's were created by interpolating these irregular elevation grids (Vertical Mapper Software v.2 1998) to regular 10 and 15 m grids for the Polychain and GPS data-sets respectively; New Brunswick Provincial elevation data were also interpolated to the same resolution for corresponding areas. These two sets of DEM's were examined qualitatively to assess the ability of the two methods to characterise topography in comparison to two provincial DEM's covering the same spatial extent.

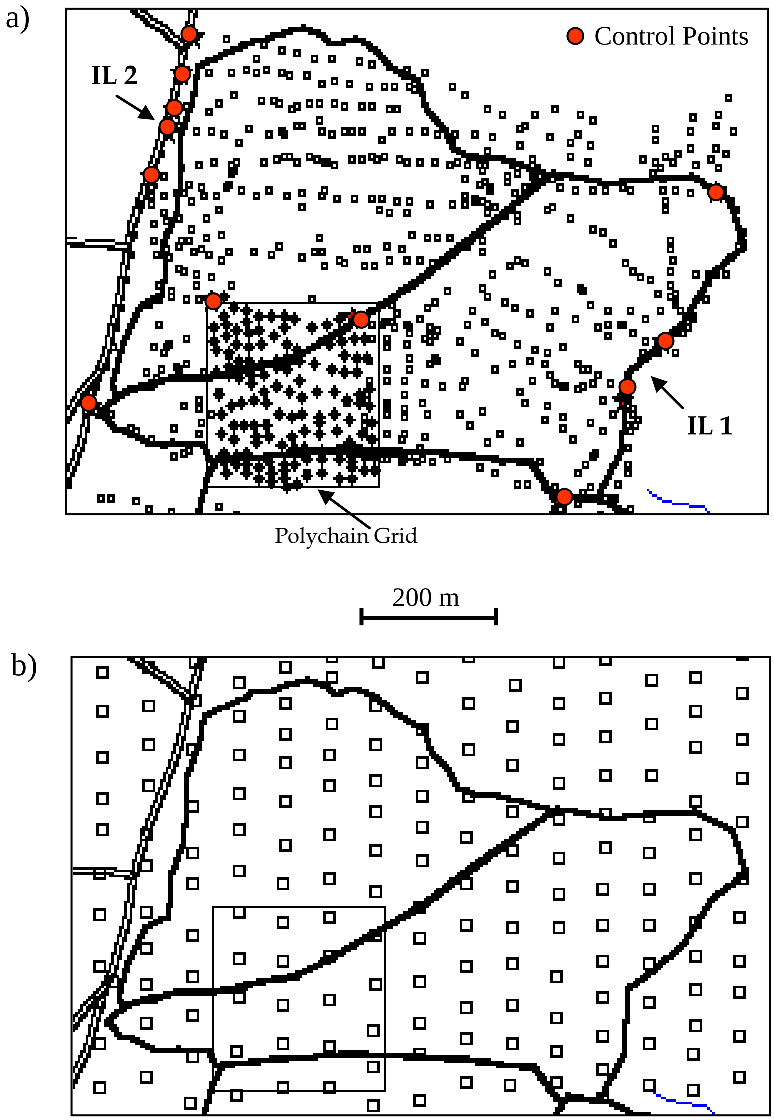


Figure 7.1. Distributions of elevation sample points obtained from a) polychain and GPS survey methods and b) New Brunswick Government.

RESULTS AND DISCUSSION

Polychain Method

The area surveyed using the Polychain comprised approximately 7.5 ha and 170 sampling points while the provincial grid, by contrast, comprised only 20 points for the same area. The influence of sampling intensity was clear (Figures 7.2a and b) as there was a striking improvement in the ability to resolve landform elements that are separated by small distances (10-30 m) with this method. A well-defined flow channel, with two major wet spots, was resolved in addition to several other depressional areas. These hummocky elements are the characterising features of the Island Lake site and are crucial for deriving plot-specific attributes of water flow and accumulation. As can be seen in Figure 7.2a, the positioning of plots along slopes and within depressions are more truly represented with finer-scale data.

GPS Method

Six hundred points were surveyed using the GPS method, covering approximately 32 hectares at an average spacing of 25 m as compared to the 110 points sampled at a spacing of 70m by the province of New Brunswick for the same area. Similar to the Polychain method, there were obvious differences in landscape characterisation between DEM's created with the GPS method and the provincial elevation data (Figures 7.3a and b). Although both DEM's were quite useful in delineating major ridges and depressions, finer-scale hummocks and

a)

b)

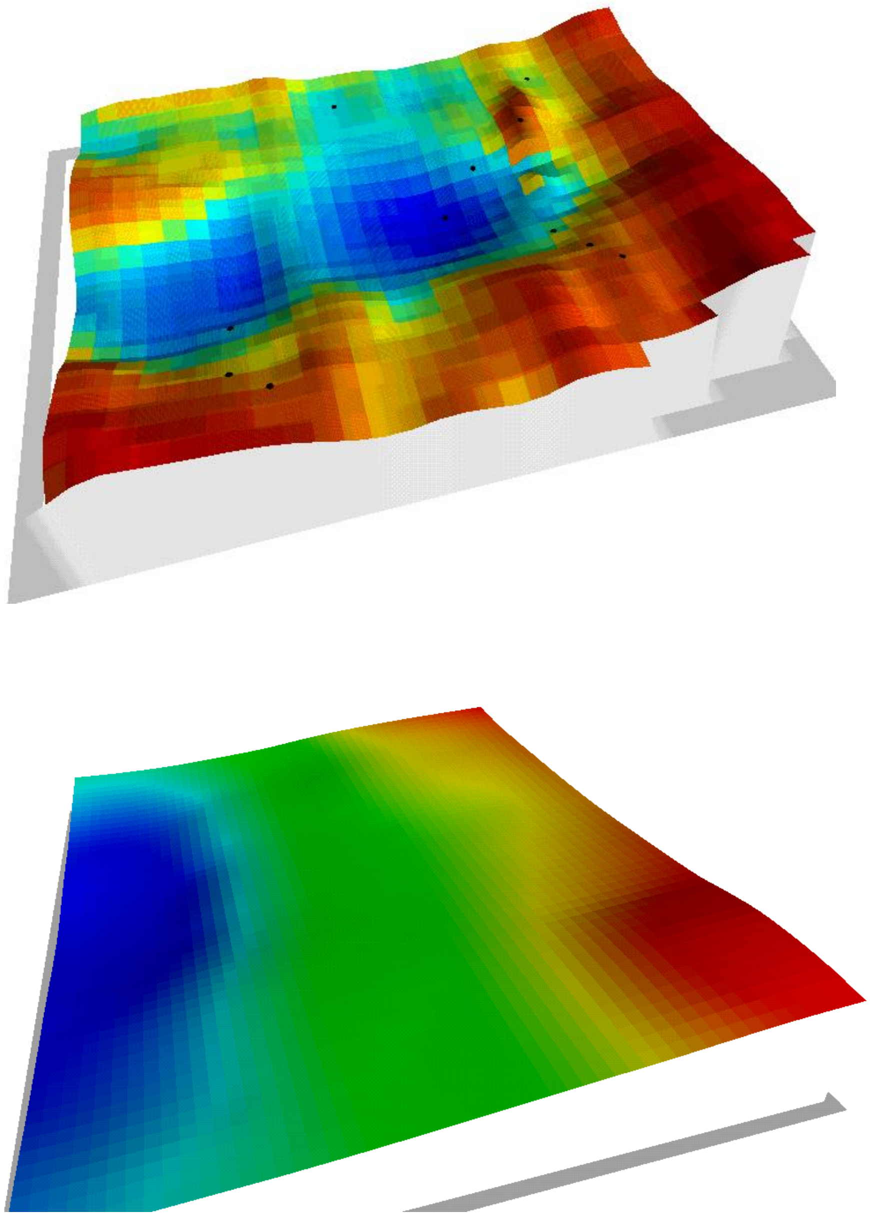
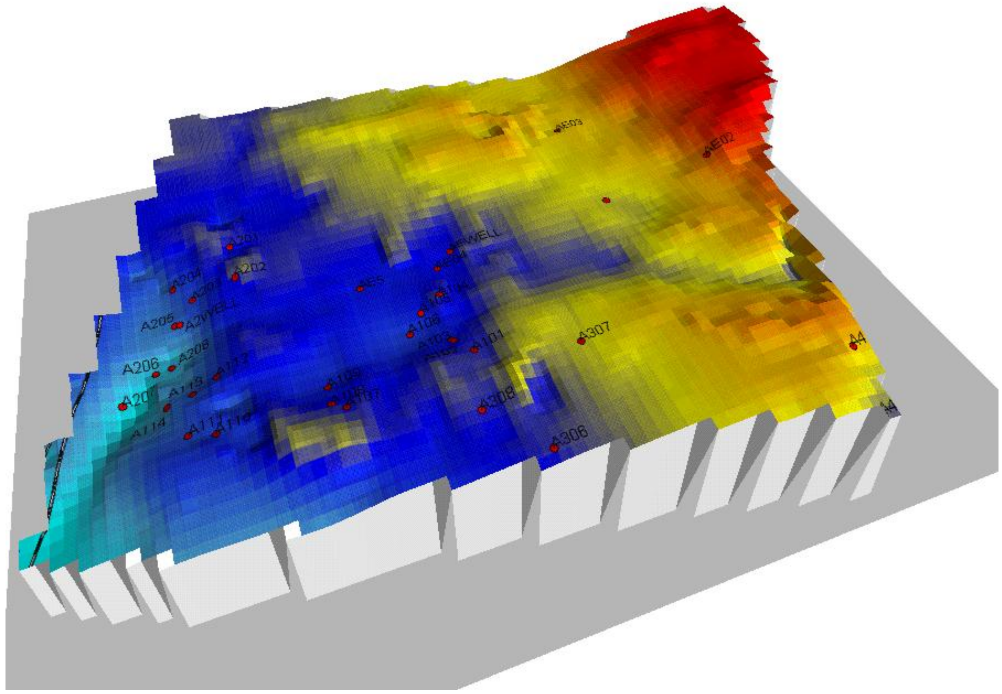


Figure 7.2. A comparison of DEM's created with a) data collected using the Polychain method and b) New Brunswick provincial elevation data for the lower portion of the IL 1 sub-catchment.

a)



b)

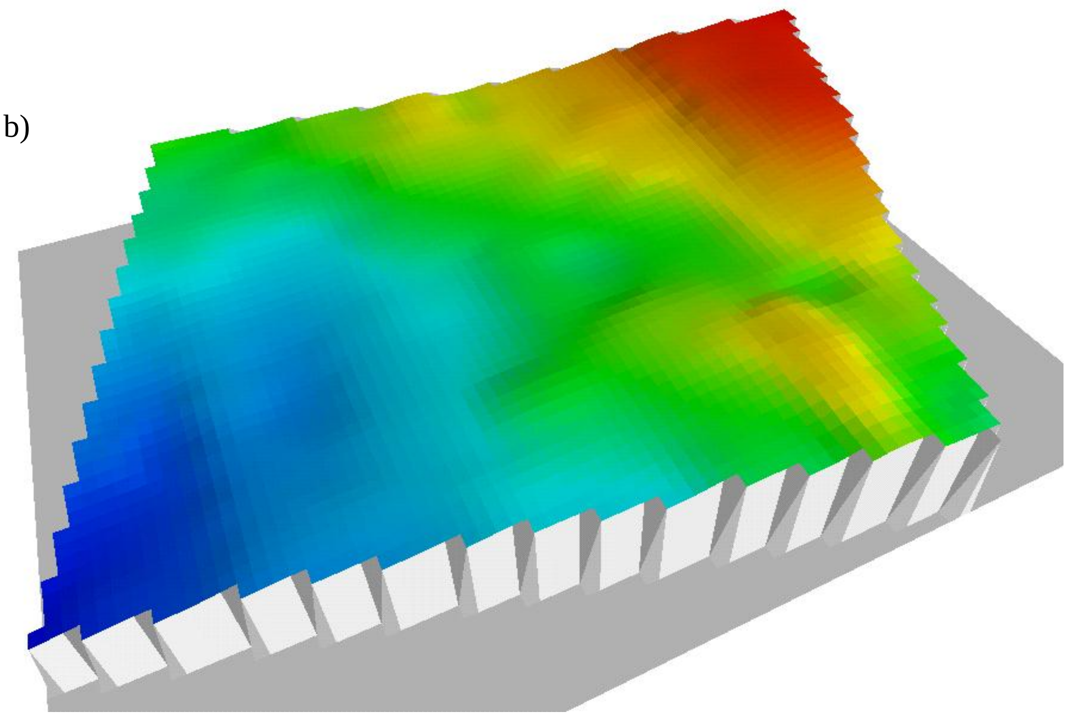


Figure 4.3. A comparison of DEM's created with a) data collected using the polychain/GPS methods and b) NB provincial elevation data for the IL 1 and 2 sub-catchments.

depressions were better represented with the GPS method. Additionally, the definition of the lower sections of the two watersheds (Figure 7.3a, bottom left) was more accurate and representative of field conditions. These lower areas are crucial in deriving water flow networks since they are confluence points for up-slope drainage.

Identifying Sources of Error: A Caveat

For either method described above, there are two main sources of potential error: positional error in horizontal co-ordinates and elevation or vertical dimension error.

Using the Polychain method, positional error arises from small deviations between the set transect bearing and the path actually followed in the field. This error was somewhat minimised by having the two surveyors correct each other's bearing from point to point until a location was agreed upon. This error could be potentially worse along longer transects since it may accumulate over distance. However, if spacings between transects are relatively small and the transects themselves are short, the amount of error in calculations would be negligible. Error in this study using the Polychain method was considered reasonable at ±2 metres.

Although the GPS method was somewhat faster than the Polychain method, there are potentially more sources of error in positional accuracy including: poor satellite geometry, receiver clock error, multipath error (e.g. from tree crowns), and atmospheric interference (French 1996). In this study, satellites were periodically lost and gained causing a range in Positional Dilution of Precision (PDOP) error from 2 to 8, although values were generally lower than 5. It is recommended that a position be recorded only if the PDOP value is between 2 and 6 (French 1996; Darche and Forgues 1998).

Accurate characterization of point elevations is dependent on the accurate determination of horizontal co-ordinates as well as the proper characterization and measurement of slope gradient cumulatively from point to point. Inaccurate horizontal locations influence calculated distances between points and, consequently, calculated elevation values. For example for a measured slope gradient of 10 % between points spaced at 20 m in the field, the vertical rise is 1.99 m. If, however, the distance between the same two points using either survey method was inappropriately measured as 15 m, the vertical rise now becomes 2.23 m, an increase in elevation of 0.24 m. Although this is a seemingly small value, this error can accumulate over space. I suspect that this was more of a potential problem here with the GPS method because positional error could have been up to 5 m in any direction and because transects were fairly long (200 – 400 m).

Additionally, it is crucial that control points be accurate and abundant to allow for proper geo-referencing of point values. In this study elevation values of control points were estimated from ortho-photo maps and were therefore dependent on the accuracy of map contours and the ability to accurately measure locations from the map.

SUMMARY AND RECOMMENDATIONS

Both the Polychain and GPS methods outlined in this Chapter show much promise in improving the characterization of fine-scale topography. In comparing Digital Elevation Models created from surveyed elevation data and those available from the province of New Brunswick, it was clear that the former were better able to resolve such fine-scale landform features as local depressions, hummocks and flow channels; these features are characteristic of the Island Lake area and are important determinants of water flow and accumulation. The Polychain method, though somewhat more time consuming, may be more appropriate in areas such as this where landform changes are frequent. The GPS method is potentially more efficient but care must be taken to obtain accurate positions at each point with no less than four satellites. The consequences of the ±5m receiver error in this study may not be as detrimental in areas of more subdued or rolling topography.

To minimize potential positional and vertical error, I suggest that:

1. Accurate control points be established at the beginning of each new transect if possible. A dual frequency GPS unit would provide extremely accurate X,Y

and Z positions for control points in open areas as compared to deriving values from contour maps.

2. Transects be laid out perpendicular to the slope gradient and kept relatively short to minimize cumulative error. To facilitate this, accurately geo-referenced baselines could be initially established as known start and end points for transects.
3. The density of transects be varied depending on the complexity of topography in a given area. This will help maximise overall accuracy and area coverage and increase efficiency.
4. A clear record be kept of DOP values and the number of satellites used to locate a given position so that errant points can be identified later. To minimise error further, GPS positions should be recorded only when adequate satellites are being tracked and when DOP values are below the five to six range.

CHAPTER 8

THESIS CONCLUSION

SYNTHESIS

The relationship between lateral water flow and soil development and distribution has long been suggested in theory by Jenny (1941, 1980), Hugget (1975) and Conacher and Dalrymple (1977) while investigations, varying in study design and scale, have provided substantial supporting evidence (e.g. Walker et al. 1968; King et al. 1983; Pennock 1987; Carter and Ciolkosz 1991; Hairston and Grigal 1991; Odeh et al. 1991; Brubaker et al. 1993; Moore et al. 1993). In this study, flow accumulation and steady-state wetness index were examined as predictive indices of soil property distributions mainly because: (1) they are recognised as important, hydrologically-significant indices of lateral subsurface water flow (Speight 1974; O'Loughlin 1986; Moore et al. 1991, 1993, 1996); (2) they have rarely been used to predict soil chemical and physical property distributions; and (3) such metrics provide a better means of identifying and delineating the possible quantitative form and function of established relationships.

Initially, it was clear that elevation data readily available from the Province of New Brunswick were too coarse to adequately characterise topography and to automatically derive topographic metrics at this study scale. Systematically derived "expected values" of flow accumulation and wetness index, although based mainly on field observations, were a justified comparison in this case given available data. Expected values were verified to the extent that they correlated with soil drainage at Island Lake and soil horizonation at Gounamitz Lake. In retrospect, it would have been more valid to measure and document the presence, depth, direction, and amount of laterally-flowing water at points within a given flow catchment, especially at high flow periods. This would have provided a more quantitative validation of the nature of lateral water flow at a field level.

Admittedly, the desired aim is the ability to adequately and accurately derive consistent values for a range of hydrologic attributes using automatic methods for any point in the landscape (Moore et al. 1993). Results presented in this thesis, however, indicate that elevation data must be of fine enough resolution to characterise topographic variation at the proposed scale of study. Few past studies in the available literature have discussed scale effects and the adequacy of available topographic data; field-level verification of these data is essential, especially since topography provides the foundation for many landscape studies.

A main problem in remote areas such as the Island Lake and Gounamitz Lake sites is the lack of an efficient way to obtain fine-scale elevation data with automatic methods due to thick forest cover. The two field-level survey methods presented in this thesis clearly improved the characterisation of meso-scale topography and thus demonstrate a legitimate way to obtain elevation data, provided that care be taken to minimise positional and vertical sampling error and to maximise registration of co-ordinates. Most likely new GPS or satellite imagery analysis technologies will provide a solution to this dilemma in the near future.

Despite the limited ability to obtain accurate topographic attribute values from DEM's for the study areas, spatial patterns of soil physical and chemical properties and nutrient pools were nonetheless significantly related to expected values of flow accumulation, wetness index, and slope at both sites. Figures 8.1 and 8.2 diagrammatically summarise the hypothesised topographic, hydrologic and geologic conditions occurring at the two sites. Although the form of relationships was similar across soil layers at both sites, the strength the relationships likely corresponded to differences in topographic complexity and permeability of the underlying substrate and bedrock. At Island Lake (Figure 8.1), the hummock and pit topography, in addition to a relatively impermeable subsoil and igneous bedrock, led to strong lateral water flow and accumulation of water in wet areas. At Gounamitz Lake, by contrast, topography is more simple and evidence of strong soil horizonation supports the idea of dominant vertical water flow, potentially through a more permeable parent material and bedrock.

Overall, these findings lend credence to the ubiquitous influence of lateral water flow as mediated by the strength of the hydraulic gradient. Landscape contrasts, as found at these two sites, are possibly a key criteria in

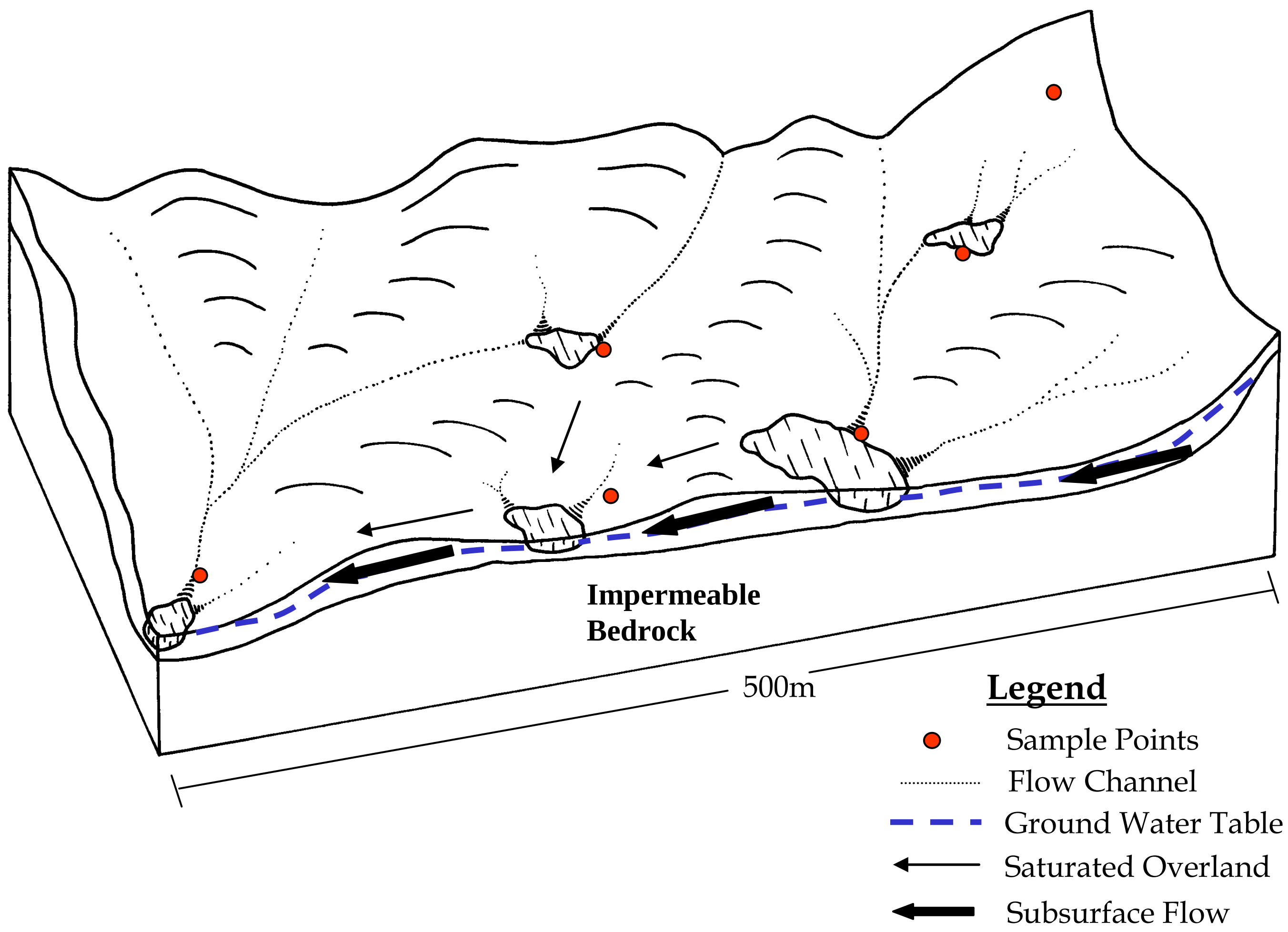


Figure 8.1. Diagrammatic representation of hypothesised hydro-geologic conditions occurring at the Island Lake site. At this hummocky site, water flows laterally along subsurface soil layers from divergent to convergent areas. Overland flow conditions may also occur at peak flow events as hollows fill with water.

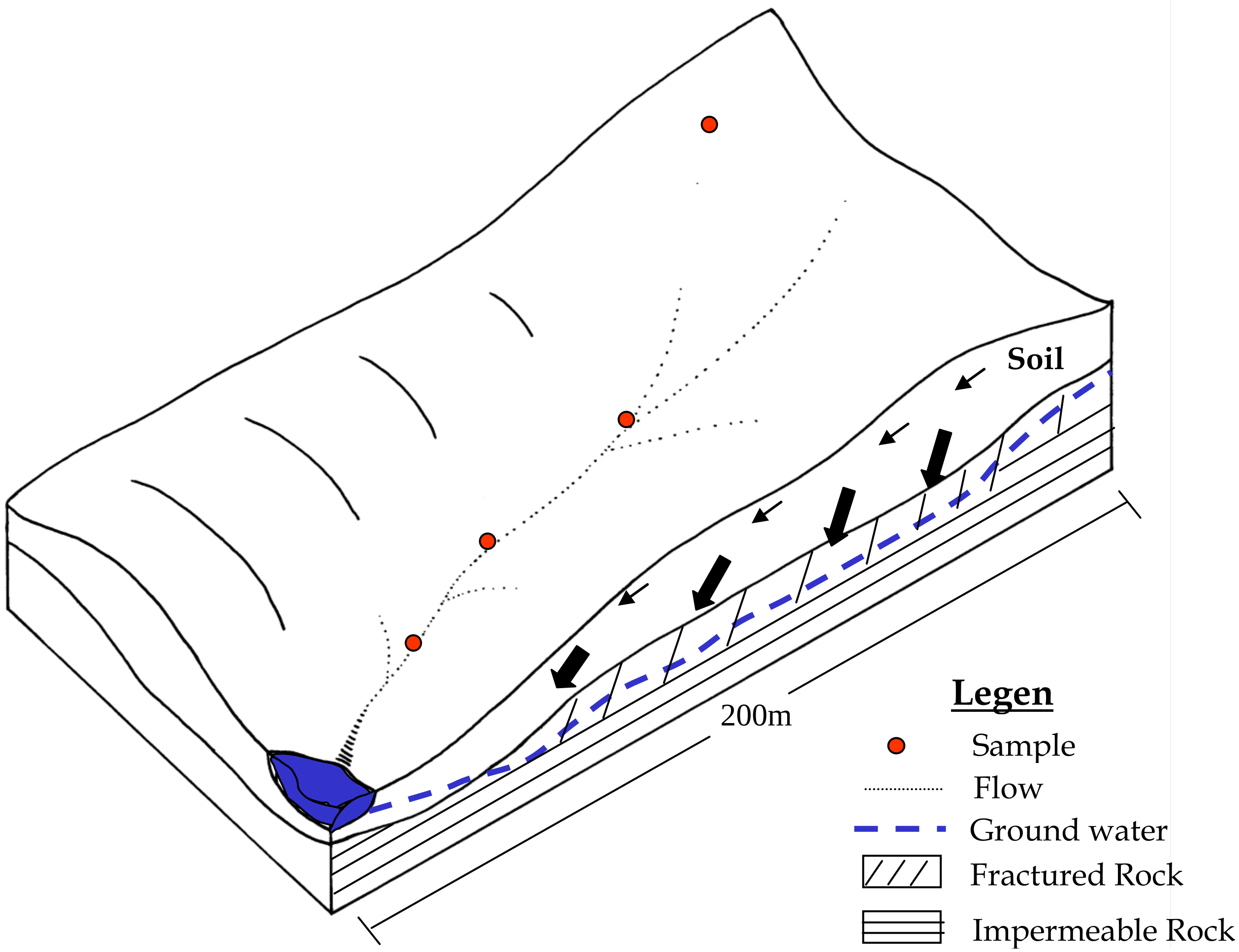


Figure 8.2. Diagrammatic representation of hypothesised hydro-geologic conditions present at the Gounamitz Lake site. Vertical water flow through soil parent material and fractured bedrock outweighs surface and subsurface flow at this rolling site.

garnering a better understanding of ecological processes that are potentially common across landscapes.

Although the topographic attributes employed showed substantial spatial correlation with soil properties, results also suggested that soil chemicals and total nutrient pools were partially related to parent material. The multivariate nature of soil development, as influenced by a host of "state factors" (Jenny 1980), is widely recognised. Certainly there is a degree of randomness in the distribution of physical soil variables, as outlined in Chapter 4, that is especially evident in glacial environments. I suspect, however, that a greater proportion of unexplained variance could be accounted for in this study by including micro- or meso-scale climatic factors and by exploring other metrics that accurately describe landform shape, water flow and moisture conditions. Further, this study essentially represents one sample in time; temporal fluctuations in chemical properties in particular may be substantial (Hammer et al. 1987) and should not be ignored.

OVERALL CONTRIBUTIONS

In the context of soil-landscape research, this thesis has provided the following main contributions:

1. A thorough synthesis of methodologies and outcomes of previous investigations concerning water flow and accumulation and its influence on soil properties in a spatial context;

2. Results that support the working hypothesis that soil physical and chemical properties vary horizontally and vertically at relatively fine scales, largely due to the degree of terrain divergence/convergence, slope position, and the resultant effect of lateral surface and subsurface water flow;
3. Evidence that the function of water flow, as measured in this study, is ubiquitous and the strength of its influence is mediated by the complexity of the local topography and the permeability of the solum and underlying substrate;
4. Statistical evidence of the underlying form of potential relationships between flow accumulation, soil physical characteristics, and soil chemistry.

Indirectly, this thesis has also provided further support for using watersheds as functional ecological units. Watersheds provide the logical framework for investigations concerning hydrologic processes because they are self-contained, defined by local topography, hierarchically structured, and easily delineated with automatic methods. Watershed investigations are clearly quite relevant from a forestry perspective since knowledge of water flow and quality is one of the basic determinants of forest productivity. Headwater stream watersheds are of moderate relief and, as such, are areas that are frequently accessible for harvesting. Intermittent feeder streams within these sites, therefore, play an important role in contributing to the overall water quality of higher order streams, and yet are generally overlooked during harvest.

Investigations such as this, at the very least, create a greater awareness of the importance of headwater streams and may contribute to the establishment of specific best management practices (BMP's) for forestry activities such as road location, harvesting methods, and buffer-strip design.

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APPENDIX I

NUTRIENT CORRELATION TABLES - ISLAND LAKE SITE

Forest Floor

	pH	Total N	Total C	Na	K	Ca	Mg	Fe	Mn	Al	P
		%		meq/100g							
pH	1.00	0.70	-0.45	0.01	-0.65	0.90	0.62	-0.62	-0.18	-0.56	-0.43
% Total N	0.70	1.00	0.14	0.03	-0.23	0.72	0.58	-0.48	-0.20	-0.33	-0.38
% Total C	-0.45	0.14	1.00	0.11	0.40	-0.31	-0.15	0.06	-0.11	0.28	0.14
Na	0.01	0.03	0.11	1.00	-0.06	0.10	0.28	0.19	-0.42	0.18	-0.24
K	-0.65	-0.23	0.40	-0.06	1.00	-0.48	-0.48	0.44	0.59	0.36	0.55
Ca	0.90	0.72	-0.31	0.10	-0.48	1.00	0.56	-0.69	-0.09	-0.67	-0.47
Mg	0.62	0.58	-0.15	0.28	-0.48	0.56	1.00	-0.32	-0.45	-0.22	-0.40
Fe	-0.62	-0.48	0.06	0.19	0.44	-0.69	-0.32	1.00	0.11	0.69	0.42
Mn	-0.18	-0.20	-0.11	-0.42	0.59	-0.09	-0.45	0.11	1.00	-0.08	0.61
Al	-0.56	-0.33	0.28	0.18	0.36	-0.67	-0.22	0.69	-0.08	1.00	-0.02
P	-0.43	-0.38	0.14	-0.24	0.55	-0.47	-0.40	0.42	0.61	-0.02	1.00

A Layer

	pH	Total N	Total C	Na	K	Ca	Mg	Fe	Mn	Al	P
		%		meq/100g							
pH	1.00	0.79	0.64	0.38	0.44	0.48	0.58	-0.92	0.22	-0.87	-0.71
% Total N	0.79	1.00	0.91	0.41	0.65	0.60	0.67	-0.79	0.32	-0.69	-0.51
% Total C	0.64	0.91	1.00	0.33	0.63	0.49	0.55	-0.64	0.31	-0.62	-0.29
Na	0.38	0.41	0.33	1.00	0.51	0.15	0.23	-0.40	0.39	-0.38	-0.44
K	0.44	0.65	0.63	0.51	1.00	0.44	0.41	-0.51	0.51	-0.38	-0.23
Ca	0.48	0.60	0.49	0.15	0.44	1.00	0.66	-0.52	0.20	-0.43	-0.37
Mg	0.58	0.67	0.55	0.23	0.41	0.66	1.00	-0.64	0.11	-0.41	-0.44
Fe	-0.92	-0.79	-0.64	-0.40	-0.51	-0.52	-0.64	1.00	-0.30	0.87	0.57
Mn	0.22	0.32	0.31	0.39	0.51	0.20	0.11	-0.30	1.00	-0.21	0.01
Al	-0.87	-0.69	-0.62	-0.38	-0.38	-0.43	-0.41	0.87	-0.21	1.00	0.61
P	-0.71	-0.51	-0.29	-0.44	-0.23	-0.37	-0.44	0.57	0.01	0.61	1.00

B Layer

	pH	Total N	Total C	Na	K	Ca	Mg	Fe	Mn	Al	P
		%		meq/100g							
pH	1.00	-0.21	-0.45	0.25	0.26	0.59	0.57	-0.76	0.25	-0.81	-0.52
% Total N	-0.21	1.00	0.67	0.27	0.44	0.20	0.17	0.23	0.07	0.19	0.11
% Total C	-0.45	0.67	1.00	-0.01	0.06	-0.08	-0.19	0.44	-0.21	0.29	0.43
Na	0.25	0.27	-0.01	1.00	0.54	0.41	0.45	-0.20	0.06	-0.20	-0.47
K	0.26	0.44	0.06	0.54	1.00	0.39	0.48	-0.12	0.35	-0.11	-0.25
Ca	0.59	0.20	-0.08	0.41	0.39	1.00	0.88	-0.54	0.42	-0.46	-0.41
Mg	0.57	0.17	-0.19	0.45	0.48	0.88	1.00	-0.39	0.37	-0.40	-0.57
Fe	-0.76	0.23	0.44	-0.20	-0.12	-0.54	-0.39	1.00	-0.46	0.71	0.36
Mn	0.25	0.07	-0.21	0.06	0.35	0.42	0.37	-0.46	1.00	-0.40	0.11
Al	-0.81	0.19	0.29	-0.20	-0.11	-0.46	-0.40	0.71	-0.40	1.00	0.35
P	-0.52	0.11	0.43	-0.47	-0.25	-0.41	-0.57	0.36	0.11	0.35	1.00

Subsoil Layer

	pH	Total N	Total C	Na	K	Ca	Mg	Fe	Mn	Al	P
		%		meq/100g							
pH	1.00	-0.09	-0.45	0.37	0.59	0.69	0.72	-0.64	0.19	-0.82	-0.59
% Total N	-0.09	1.00	0.79	0.12	0.18	-0.02	-0.17	0.10	0.25	0.30	0.33
% Total C	-0.45	0.79	1.00	-0.15	0.00	-0.29	-0.39	0.47	0.00	0.49	0.59
Na	0.37	0.12	-0.15	1.00	0.36	0.41	0.42	-0.30	0.34	-0.22	-0.32
K	0.59	0.18	0.00	0.36	1.00	0.51	0.54	-0.44	0.37	-0.41	-0.22
Ca	0.69	-0.02	-0.29	0.41	0.51	1.00	0.92	-0.71	0.36	-0.51	-0.48
Mg	0.72	-0.17	-0.39	0.42	0.54	0.92	1.00	-0.59	0.37	-0.61	-0.55
Fe	-0.64	0.10	0.47	-0.30	-0.44	-0.71	-0.59	1.00	-0.36	0.43	0.34
Mn	0.19	0.25	0.00	0.34	0.37	0.36	0.37	-0.36	1.00	-0.28	0.16
Al	-0.82	0.30	0.49	-0.22	-0.41	-0.51	-0.61	0.43	-0.28	1.00	0.41
P	-0.59	0.33	0.59	-0.32	-0.22	-0.48	-0.55	0.34	0.16	0.41	1.00

APPENDIX I (CONT.)

NUTRIENT CORRELATION TABLES - GOUNAMITZ LAKE SITE

Forest Floor

	pH	Total N	Total C	Na	K	Ca	Mg	Fe	Mn	Al	P
		%					meq/100g				
pH	1.00	0.36	-0.10	0.34	-0.22	0.67	0.66	-0.48	-0.28	-0.11	-0.30
% Total N	0.36	1.00	0.57	0.31	0.35	0.37	0.45	-0.35	0.00	-0.06	0.06
% Total C	-0.10	0.57	1.00	-0.06	0.34	0.18	0.09	-0.03	0.12	0.19	0.14
Na	0.34	0.31	-0.06	1.00	0.17	0.08	0.15	-0.51	0.23	-0.41	0.20
K	-0.22	0.35	0.34	0.17	1.00	-0.19	0.22	0.37	0.25	-0.12	0.62
Ca	0.67	0.37	0.18	0.08	-0.19	1.00	0.73	-0.51	-0.32	-0.12	-0.49
Mg	0.66	0.45	0.09	0.15	0.22	0.73	1.00	-0.24	-0.33	-0.24	-0.09
Fe	-0.48	-0.35	-0.03	-0.51	0.37	-0.51	-0.24	1.00	0.13	0.18	0.26
Mn	-0.28	0.00	0.12	0.23	0.25	-0.32	-0.33	0.13	1.00	-0.10	0.41
Al	-0.11	-0.06	0.19	-0.41	-0.12	-0.12	-0.24	0.18	-0.10	1.00	-0.31
P	-0.30	0.06	0.14	0.20	0.62	-0.49	-0.09	0.26	0.41	-0.31	1.00

A Layer

	pH	Total N	Total C	Na	K	Ca	Mg	Fe	Mn	Al	P
		%					meq/100g				
pH	1.00	0.81	0.77	0.52	0.54	0.71	0.52	-0.54	0.75	-0.44	-0.31
% Total N	0.81	1.00	0.97	0.62	0.80	0.67	0.55	-0.24	0.68	-0.61	-0.04
% Total C	0.77	0.97	1.00	0.62	0.78	0.63	0.52	-0.19	0.68	-0.60	0.01
Na	0.52	0.62	0.62	1.00	0.34	0.46	0.39	-0.21	0.48	-0.42	-0.17
K	0.54	0.80	0.78	0.34	1.00	0.36	0.33	-0.09	0.47	-0.42	0.17
Ca	0.71	0.67	0.63	0.46	0.36	1.00	0.92	-0.48	0.60	-0.40	-0.40
Mg	0.52	0.55	0.52	0.39	0.33	0.92	1.00	-0.38	0.47	-0.28	-0.44
Fe	-0.54	-0.24	-0.19	-0.21	-0.09	-0.48	-0.38	1.00	-0.67	-0.03	0.47
Mn	0.75	0.68	0.68	0.48	0.47	0.60	0.47	-0.67	1.00	-0.20	-0.18
Al	-0.44	-0.61	-0.60	-0.42	-0.42	-0.40	-0.28	-0.03	-0.20	1.00	-0.19
P	-0.31	-0.04	0.01	-0.17	0.17	-0.40	-0.44	0.47	-0.18	-0.19	1.00

B Layer

	pH	Total N	Total C	Na	K	Ca	Mg	Fe	Mn	Al	P
		%					meq/100g				
pH	1.00	-0.14	-0.62	0.34	0.51	0.50	0.61	-0.74	0.35	-0.53	-0.62
% Total N	-0.14	1.00	0.62	0.44	0.48	-0.05	0.00	0.24	0.54	0.07	0.42
% Total C	-0.62	0.62	1.00	0.02	-0.05	-0.39	-0.45	0.67	-0.06	0.52	0.83
Na	0.34	0.44	0.02	1.00	0.54	0.43	0.33	-0.13	0.36	-0.32	-0.06
K	0.51	0.48	-0.05	0.54	1.00	0.13	0.31	-0.48	0.78	-0.43	-0.07
Ca	0.50	-0.05	-0.39	0.43	0.13	1.00	0.75	-0.11	0.19	-0.27	-0.40
Mg	0.61	0.00	-0.45	0.33	0.31	0.75	1.00	-0.33	0.34	-0.31	-0.46
Fe	-0.74	0.24	0.67	-0.13	-0.48	-0.11	-0.33	1.00	-0.35	0.64	0.62
Mn	0.35	0.54	-0.06	0.36	0.78	0.19	0.34	-0.35	1.00	-0.36	-0.13
Al	-0.53	0.07	0.52	-0.32	-0.43	-0.27	-0.31	0.64	-0.36	1.00	0.39
P	-0.62	0.42	0.83	-0.06	-0.07	-0.40	-0.46	0.62	-0.13	0.39	1.00

Subsoil Layer

	pH	Total N	Total C	Na	K	Ca	Mg	Fe	Mn	Al	P
		%					meq/100g				
pH	1.00	-0.27	-0.41	0.22	0.60	0.77	0.75	-0.59	0.52	-0.41	-0.36
% Total N	-0.27	1.00	0.66	0.33	0.05	-0.27	-0.27	0.43	0.08	0.17	0.30
% Total C	-0.41	0.66	1.00	0.05	-0.06	-0.37	-0.38	0.71	0.06	0.23	0.62
Na	0.22	0.33	0.05	1.00	0.44	0.37	0.41	-0.17	0.27	-0.14	0.11
K	0.60	0.05	-0.06	0.44	1.00	0.56	0.66	-0.42	0.81	-0.55	0.04
Ca	0.77	-0.27	-0.37	0.37	0.56	1.00	0.95	-0.49	0.54	-0.31	-0.06
Mg	0.75	-0.27	-0.38	0.41	0.66	0.95	1.00	-0.51	0.62	-0.35	-0.01
Fe	-0.59	0.43	0.71	-0.17	-0.42	-0.49	-0.51	1.00	-0.16	0.59	0.62
Mn	0.52	0.08	0.06	0.27	0.81	0.54	0.62	-0.16	1.00	-0.38	0.18
Al	-0.41	0.17	0.23	-0.14	-0.55	-0.31	-0.35	0.59	-0.38	1.00	0.20
P	-0.36	0.30	0.62	0.11	0.04	-0.06	-0.01	0.62	0.18	0.20	1.00