EFFECTS OF FOREST DISTURBANCE ON WATER CHEMISTRY IN A FORESTED ECOSYSTEM: CASE STUDY FROM TERRA NOVA NATIONAL PARK, NEWFOUNDLAND

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Effects of Forest Disturbance on Water Chemistry in a Forested Ecosystem: Case Study from Terra Nova National Park, Newfoundland

by

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Abstract

Boreal forests, like all forests, are affected by disturbances. Whether natural or anthropogenic, disturbances have the ability to influence forest processes and alter existing conditions, eventually affecting the overall forest composition and distribution. Each type of disturbance, as well as each specific event, is unique in terms of its characteristics and its effects.

The overall objective of this study was to look at whether or not the disturbance history of boreal forests in Terra Nova National Park, Newfoundland was reflected in the water chemistry. One component of the study examined the long-term effects of fire and logging on water chemistry of park lakes, as well as the short-term effects of a forest fire in one area of the park. The second component of the study examined a specific forested watershed and how a local disturbance, moose herbivory, was affecting soil solution chemistry.

Overall, it appeared that with moderate disturbance and given sufficient time, forests are able to recover naturally and minimize any long-term chemical effects to their environment. Results from the short-term study of a recent forest fire did suggest chemical differences in soil solution. However, the local disturbance of moose herbivory showed no discernible effects in the short-term. Effects of this disturbance likely require a longer time to become apparent.

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Chapter 1 Introduction and Overview

1.1 Purpose and Objectives

Forest ecosystems are made up of terrestrial and aquatic environments, and these environments are influenced by a number of dynamic processes. It is these components and processes and their interactions that determine the character of the forest and provide many of the essential requirements for survival and functioning.

The hydrologic cycle provides living organisms with essential nutrients. Nutrient distribution throughout the system is dependent on available water, which is in turn responsible for the concentration of nutrients in soil solution. If a disturbance occurs in a forested ecosystem, many processes including the hydrologic cycle are affected and consequently nutrient cycles are altered. These changes in water and nutrient cycling, as well as other indirect effects on the forest ecosystem brought about by disturbance, play an important role in our understanding of how the hydrologic cycle functions and how it reacts to stress; however our understanding of these reactions is limited. By studying examples of specific disturbances in boreal forests we gain insight into how forests respond to such disturbances, which will only benefit forest and park management as well as ongoing conservation and preservation efforts.

This study focuses on the impacts of forest disturbances on water chemistry in a boreal forest environment. Specifically, using data from Terra Nova National Park, Newfoundland, surface water and soil solution were studied to determine whether past, as well as more recent disturbances, have had or are having any discernible effect on the chemistry of soil solution and nearby surface water. This work will add to the ongoing study of watersheds in Terra Nova National Park and, when combined with related studies, should lead to a better understanding of the effects of disturbances on the functioning of forest ecosystems.

Disturbances in forested ecosystems can result in both short-term and long-term effects. Before studying the effects of disturbances it is first necessary to understand what is meant by short- and long-term timeframes. In the boreal forest, forest rotation can be used as a measure of time, with forest rotation related to location and disturbance history. In the boreal forest, wildfire is considered to be the boreal forest's driving successional force (Johnson, 1992a; Payette, 1992; Payette et al., 2000; McCarthy, 2001) and forest rotations are a result of the occurrence of this disturbance. The boreal forest involved in this study had, for the most part, a forest rotation of 100 years, based on fire cycles (Power, 1996). This period can be used as a reference for long-term effects (greater than 100 years), with short-term denoting less than that; in this study, short-term represents anything from immediate up to nearly one decade later.

The overall objective of this study is to look at whether the disturbance history of boreal forests in Terra Nova National Park, Newfoundland is reflected in the water chemistry. The first part of this study looked at the short-term effects of a recent forest fire on stream and soil solution chemistry as well as the long-term effects of past disturbances on water chemistry. Based on observed direct impacts to the area, it is expected that the effects of the recent forest fire will be reflected in water chemistry. However, it is not expected that water chemistry data available for areas having experienced past disturbances will be distinguishable from water chemistry data available for areas having no record of any significant past disturbances.

The second component of this study looked at one specific boreal watershed in Terra Nova National Park. Regular monitoring of this watershed will provide useful information for the park on the functioning of boreal watersheds within its boundaries as well as helping to gain a better understanding of the chemical signature of such systems. This same area was used to study whether one specific form of disturbance, the presence of moose, was altering the chemistry of soil solution, as compared to soil solution chemistry from an area where moose were excluded. It is expected that there will be a difference in the chemistry of soil solution between the area where moose are present and where they are excluded.

Before going into the two studies specifically, it is important to have an understanding of how disturbance can affect forests and their potential impacts.

1.2 Literature Review

1.2.1 Introduction

There have been many studies on how forests respond to disturbances and in many cases entire areas have been set aside solely for research purposes, such as the Experimental Lakes Area (ELA) in Northwestern Ontario, the Hubbard Brook Experimental Forest (HBEF) in New Hampshire, the BOREAS site (BOReal Ecosystem-Atmospheric Study) in central Canada, and several sites from the National Forest Strategy's Model Forests across Canada. Information generated from these and many other studies have helped in our understanding of how specific disturbances affect forest dynamics.

The following section provides an overview of such research with each disturbance type presented individually. Prior to discussion on specific disturbances, a brief summary of the boreal forest, disturbances in general, and forest nutrient budgets is provided.

1.2.2 Boreal Forest

The boreal forest exists as a nearly continuous belt of coniferous trees across North America and Eurasia. It extends approximately 15 million km^2, over a tenth of the earth's northern land surface, and covers almost 25% of the world's closed canopy forest. Within Canada it occupies 35% of the total Canadian land area and 77% of Canada's total forest land (Natural Resources Canada, 2002).

The flora of the boreal forest in North America is primarily coniferous trees, including black spruce (*Picea mariana* (Mill.) BSP), white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill), jack pine (*Pinus banksiana* Lamb.), lodgepole pine (*Pinus contorta* Dougl.), and white pine (*Pinus strobus* L.). Deciduous species, such as trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera*), white birch (*Betula papyrifera* Marsh.) and alder species (*Alnus spp.*) are often mixed in with conifers. A vast number of shrubs, moss (primarily feathermoss (*Pleurozium schreberi*) and sphagnum moss (*Sphagnum spp.*)), and lichens are also key components of the vegetation within the boreal forest (Bourgeau-Chavez et al., 2000).

The fauna, like the flora of the boreal forest, is very diverse. The lynx and weasel family (i.e. wolverine, pine martin, and mink) are prominent predators and feed on other animals within the forest, such as the snowshoe hare, red squirrel, lemmings, and voles. Large herbivores, such as elk, moose and woodland caribou, also co-exist in the forest. The beaver is another common animal in boreal forests and is often considered an annoyance as it can alter the course of water through the construction of their lodges and dams. Many types of birds, both migratory and year-round, also make their home in the boreal forest (Woodward, 1996).

The boreal forest is characterized by long winters and short summers, resulting in a short growing season (Woodward, 1996). Climate contributes greatly to the characteristics of soils, also governed by parent material, mode of deposition, topography, vegetation and time since glaciation (Roberts, 1983). The Canadian System of Soil Classification (Soil Classification Working Group, 1998) associates podzols with boreal forests in cold, humid regions, such as found in Newfoundland; however gleysols, brunisols, regosols, and the organic order (which includes fibrisols, mesisols, humisols and folisols) are also present.

Organic matter, or humus, is one of the most important components of podzols (Tarnocai, 2000). Three main types of humus exist, mor, moder and mull, in order of least to most decomposed. Mor and moder humus are the dominant type in the boreal environment. They are extremely acid in reaction and are made up of surface accumulations with three distinct layers, L (fresh litter), F (partially decomposed litter), and H (litter that has been transformed into almost homogenous humus) and represent a substantial portion of total nutrient capital of a site. Due to the low soil pH, and the presence of secondary chemicals, many of the nutrients found in the humus are not unavailable for plants. Depending on location, the accumulation of organic matter at the surface can immobilize nutrients, making them unavailable for plant uptake (Prescott et al., 2000a).

It is commonly found that the podzols of the boreal forest have a bleached grey A horizon over a brown to reddish brown B horizon; the B horizon is the chief diagnostic horizon for classification purposes. The sharp colour contrast of these horizons is related to the movement of iron, aluminum, and organic material from the A to the B horizon (Bourgeau-Chavez et al., 2000). Climate, chemical composition of the substrate, vegetation, and topography are responsible for the movement of minerals through the soil horizons (Bourgeau-Chavez et al., 2000).

The characteristics discussed above apply to the boreal forest in general. However, every forest is different in its defining qualities due to differences in local conditions.

1.2.3 Disturbances

Boreal forests, like all forests, are dynamic environments governed by many factors and processes. One of the primary factors is forest disturbance, where past disturbances have led to the present distribution and composition of the forests.

White and Pickett (1985) define disturbance as "...any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment". They further this definition by saying that the cause of disturbance can be endogenous (within the community) or exogenous (outside the community), with the majority of natural disturbances classified as exogenous (White and Pickett, 1985). However, defining disturbances is not always so simple; for example, problems arise when looking at the disturbance created by predation including herbivory, which is endogenous and occurs over a longer period of time. White and Pickett (1985) were aware that their definition resulted in some misplacement of events thought of as disturbances and so they established "special cases" of disturbance which allowed these to be included in their definition.

In the context of this thesis, the term disturbance will apply to those events, both natural and anthropogenic, which affect the forest ecosystem. Natural disturbances include forest fire, windthrow, and insect and disease outbreaks. Logging is the most common anthropogenic disturbance with climate change and acid deposition often associated with this group. Classifying herbivory as a disturbance is complicated as it is a natural component of ecosystem processes; however, when population size of the herbivore reaches a level with the potential to alter the natural relationships and cycling in the environment, the herbivore can then become classified as a disturbance (McShea et al., 1997).

Using North American forests as an example, Oliver (1981) devised four stages of forest development following disturbances. The first stage, stand reinitiation, occurs in the first 1-10 years following disturbance when herbs and shrubs dominate. Stem exclusion follows, often referred to as crown closure, where woody species monopolize and water and/or nutrients are often limited. Understory reinitiation is the third stage, followed by the fourth and final stage of old-growth. If no other unexpected disturbance intervenes, first-generation trees die and may or may not be replaced by other species.

Many aspects of disturbances must be considered when attempting to examine how forests are affected by such events. The type and severity of the disturbance often dictates the impact on the environment, however, the environment in which the disturbance takes place must also be considered. In general, disturbances result in changes to the overall functioning of forest ecosystems. They have the potential to alter soil conditions, including temperature and soil moisture, and in doing so affect nutrient availability, nitrogen mineralization, organic matter decomposition, tree productivity and eventually forest floor chemistry (Van Cleve et al., 1983). As well, disturbances can impact hydrological processes, altering canopy interception and evapotranspiration as well as overland flow, soil solution, and eventually streamflow (Keenan and Kimmins, 1993; Martin et al., 2000; Putz et al., 2003).

Disturbances often result in changes in nutrient cycles and the availability of resources for plant growth (Canham and Marks, 1985). In the natural environment, many nutrients are returned to the forest floor through litterfall, throughfall, and stemflow (Gordon, 1983). Available nutrients may be taken up by trees and ground vegetation but may also be lost from the nutrient pool through leaching. Other forms of nutrients can become locked up in the organic matter of the forest floor where they may be gradually re-released and eventually enter nutrient cycles (Gordon, 1983).

Disturbances generally result in an opening of the canopy and a loss of biomass, which can eventually lead to a reduction in the use of resources as well as uptake rates. However, this increased exposure of the soil surface can also cause increases in decomposition and mineralization of organic matter and therefore increase nutrient availability (Canham and Marks, 1985). Nicolson et al. (1982) summarized how, in general, tree removal can disrupt the forest ecosystem: 1) the forest can no longer remove ions from the soil solution; 2) a greater amount of water passes through the soil due to decreased interception and evapotranspiration; 3) increases in surface soil temperature and moisture content results in changes in decomposition, mineralization, and carbon-dioxide production; and 4) a large amount of material may be left on the forest floor for decomposition.

In general, the degree to which nutrient concentrations are affected relates to the area of watershed disturbed, the intensity of the disturbance, the age of the area, and other specific characteristics of the location, such as geology and climate (Pinel-Alloul et al., 2002; Putz et al., 2003). The monitoring in this study looks at these dominant factors and their relationship to nutrient concentrations in Terra Nova National Park.

1.2.4 Nutrients and the boreal forest

Before examining the specific effects of disturbances on nutrients in the boreal forest, it is important to understand the natural conditions of the forest prior to any disturbance. The range of boreal forest types makes it difficult to generalize nutrient characteristics, as local conditions govern nutrient values.

Some researchers have attempted to overcome such difficulties by studying specific forest types and their processes and comparing them to other forest types. In Alaska, different forest types were studied in order to assess differences in biomass, heat sums, chemical characteristics, and productivity (Van Cleve et al., 1983). Black spruce forests had the greatest forest floor biomass, lowest nitrogen (N) concentrations, highest lignin concentrations, low calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations, the longest residence times for elements, and the most acidic forest floors when compared to other forest types including white spruce, birch, aspen, and poplar (Van Cleve et al., 1983). Longer residence times for biomass and chemical elements in the forest floor of black spruce were associated with slower mineralization of organic matter and recycling of chemical elements. Slower mineralization relates to the relationship between forest floor decomposition and N and lignin concentrations; decomposition is greater with greater concentrations of N and less lignin but in black spruce, N concentrations were low while lignin concentrations were high, resulting in reduced decomposition (Van Cleve et al., 1983). Van Cleve et al. (1983) supported their original hypothesis that black spruce was the least productive and most nutrient limited forest type in the taiga ecosystem.

Moser et al. (1998) studied northern boreal shield, muskeg, and sink lakes in Wood Buffalo National Park in Northern Alberta and the Northwest Territories. Shield lakes had lower pH values, lower specific conductivities, higher concentrations of aluminum (Al) and iron (Fe) and lower concentrations of ions (sulphate (SO_4^{2-}), sodium (Na^+), Ca^{2+}, and Mg^{2+}) than muskeg or sinkhole lakes. Muskeg lakes had higher concentrations of nitrate (NO_3^-) and organic carbon and greater productivity, as illustrated by high concentrations of particulate organic carbon (POC) and chlorophyll a (Moser et al., 1998). The results supported the idea that different sites had different physical and chemical properties, making generalizations about the boreal ecosystem nearly impossible. Different geological substrate, surrounding vegetation, as well as geographic location resulted in variations in the limnological properties of the sampled lakes, while all were classified as the boreal region (Moser et al., 1998).

Seven years of observations on nutrient solution chemistry for a boreal fir forest in Quebec were analyzed as part of a study on forests and soils affected by long-range transported pollutants (Robitaille and Boutin, 1990). Nutrients were measured in precipitation, throughfall, stemflow, soil solution below the roots, and stream output leaving the catchment area. Although the intended use of the data obtained was to examine the sensitivity of catchments to acid deposition, it also provided some base numbers on nutrient levels in different hydrological components in a boreal forest.

Sulphate was the dominant anion in all solutions except for soil solution below the roots, where NO_3^- dominated. This increased NO_3^- in soil solution was attributed to increased mineralization in this region (Robitaille and Boutin, 1990). Passage through the canopy increased the flux of all elements, except protons (H^+), Na^+, NO_3^-, and ammonium (NH_4^+). It appeared that the absorption of NO_3^- counterbalanced the absorption of NH_4^+, in terms of H^+, as NH_4^+ absorption results in a production of H^+ while uptake of NO_3^- consumes H^+ (Robitaille and Boutin, 1990).

The boreal forest also plays an important role in carbon cycling, acting as both a source and a sink of carbon. The boreal forest contains more carbon than temperate and tropical forests combined (see Table 1.1) (Kasischke, 2000a).

Table 1.1: Carbon Storage in Different Forests (Woods Hole Research Center, 2004)

Biome	Area (x 10^6 ha)	Soil Carbon (Pg)	Plant Biomass Carbon (Pg)	Total Carbon (Pg)
Boreal	1,509	625	78	703
Tropical	1,756	216	159	375
Temperate	1,040	100	21	121

(based on Kasischke, 2000a)

One reason for the difference in carbon between boreal forests and other biomes is the organic soil (Tarnocai, 2000). A large amount of carbon is found in the soils of boreal forests, related to the cold temperatures generally associated with these areas. Cold ground conditions result in reduced decomposition rates, creating deep, undecomposed organic soils (Kasischke, 2000a). It is estimated that the vegetation in boreal ecosystems acts as a net carbon sink of 0.54 Gt C/yr while the soils and peatlands of the boreal forests are a net carbon sink of 0.70 Gt C/yr (Apps et al., 1993). However, it is expected that in the first half of the 21st Century boreal forests will become a net source of carbon due to an expected increase in deforestation activities, such as increases in forest fires related to climate change (Kasischke, 2000a).

In Newfoundland, the forests of Western Newfoundland and Labrador are part of the boreal forests of the Canadian Shield, while the boreal forests on the rest of the island are found on an extension of the Appalachian Mountain system of North America (Rogerson, 1981). Over 30 forest types have been recognized in Newfoundland (Meades and Roberts, 1992). This number is much reduced in central Newfoundland largely due to the absence of limestone and the nutrient rich glacial tills associated with such formations (Damman, 1964). In an attempt to determine the natural chemistry of surface water in Newfoundland and to see whether acid precipitation was having any effect on this water, a large number of lakes and streams distributed across the island from relatively remote and pristine locations were studied (Scruton, 1983; 1986). Results indicated that in lake water Na^+ and Ca^{2+} were the dominant cations, with Mg^{2+} and potassium (K^+) were present at lower concentrations. Chloride (Cl^-) was the dominant anion and was highly correlated with Na^+, indicating the marine influence on these lakes (Scruton, 1983).

Similar results were observed for stream concentrations. Calcium and sodium were the dominant cations and Cl^- was the dominant anion; sources for the sodium and chloride were concluded to be primarily of marine origin (Scruton, 1986).

In terms of the chemistry of the soils in Newfoundland, the organic horizons of podzols had greater concentrations of Ca^{2+} followed by Mg^{2+}, Na^+, and K^+ as the most abundant available nutrients, expressed as exchangeable cations, while Ca^{2+} and Na^+ were the dominant ions in the mineral horizons (Roberts, 1983). The increased amounts of exchangeable cations are dependent on soil texture and pH as well as the humus type, which relates to vegetation type. The lateral movement of water, i.e. soil seepage, is a major factor in site nutrient fertility (Damman, 1964; Meades and Roberts, 1992; Roberts et al., 1998).

While certain nutrient trends are expected in areas of the boreal forest, it is hard to specify exact concentrations for the boreal forest biome in general. Forests are unique in their defining characteristics and, therefore, are often studied on an individual area basis.

1.2.5 Disturbances in the boreal forest and nutrient effects

The following sub-sections will address different forest disturbances and their respective impacts to the boreal forest.

1.2.5.1 Wildfire

Wildfire is a natural disturbance in the boreal forest and plays an essential role in stand dynamics; it is often considered to be the boreal forest's driving successional force

(Johnson, 1992a; Payette, 1992; Payette et al., 2000), especially on drier coarse textured glacial parent materials.

When examining the role of fire as a disturbance one must consider the fire regime, comprised of fire intensity, frequency, interval, and type (Weber and Flannigan, 1997; Chen and Popadiouk, 2002; Chanasyk et al., 2003). Fire intensity is related to thermodynamics and the energy released per unit area per unit time, frequency is the number of fires per unit time in a given area, interval refers to the number of years between two successive fires in a given area, and type is primarily crown, surface, or ground (Payette, 1992). Another important factor to consider is the depth of burn. A light or shallow burn can result in high root sprouting and other forms of vegetative reproduction while a deep burn can kill such roots; alternatively a deep burn has the ability to create good seedbeds (Bourgeau-Chavez et al., 2000). Differences in any of these components results in different effects to the forest.

In general, fire can significantly increase ground temperature from an increase in solar radiation, related to both a decrease in canopy cover as well as the addition of charcoal creating a darkened surface able to absorb more radiation (Woodmansee and Wallach, 1981). This temperature increase can reduce soil moisture and in certain regions cause a reduction in the amount of permafrost. As well, increased ground temperature can increase forest respiration and cause changes in forest succession patterns (Kasischke, 2000b).

Woodmansee and Wallach (1981) proposed three levels of ecosystem response following fire: initial abiotic and biological responses, postfire abiotic responses, and postfire biological responses. Each of these general levels of response can be further broken down into sub-responses, summarized in Table 1.2.

Table 1.2: Ecosystem Response Following Fire (Woodmansee and Wallach, 1981)

General Response	Sub-responses
Initial abiotic and biotic	Direct loss of elements to atmosphere (volatilized) or particulates carried away in smoke
	Release and transformation of ions and their deposition as ash elements on surface
	Response of individual organisms to the heat generated by fire
Postfire abiotic	Element loss by wind erosion
	Element loss by water erosion
	Dissolution of ions
	Adsorption of ions onto exchange complexes
	Loss by leaching out of the rooting zone
	Volatilization of NH_3 from soil and litter
Postfire biotic	Mineralization and uptake of nutrients by microorganisms
	Uptake of nutrients by plants
	Nitrogen transformations

As illustrated by many of the sub-responses proposed by Woodmansee and Wallach (1981), one of the most important aspects of fire's impacts to the forest is the impact on nutrient cycles. In terms of fire intensity, a higher intensity fire can result in nutrients lost to the atmosphere through volatilization, resulting in lower concentrations remaining in the soil and in runoff draining to receiving streams and lakes. However, substantial amounts of nutrients may also be added to the soil, and associated streams, through leaching from the ash layer (Lynham et al., 1998). Fire intensity, and burn temperature, is also related to changes in pH, which can affect primary root lengths of seedlings and nutrient concentrations. Higher burn temperatures have resulted in increased soil pH which can improve seed bed conditions by decreasing the acidity of the soil (Mallik and Roberts, 1994). The burning of organic matter generally results in direct nutrient mineralization and a heightened nutrient release through organic matter decomposition (Bourgeau-Chavez et al., 2000). In black spruce ecosystems specifically, fire acts as a rapid decomposer and is essential for replenishing depleted available nutrient pools (Van Cleve et al., 1983). Such changes often result in increased site productivity and produce favourable conditions for the re-establishment of seedlings (Bourgeau-Chavez et al., 2000).

Studies conducted in the Experimental Lakes Area in Northwestern Ontario demonstrated that concentrations of nitrogen (NO_3^-, NH_4^+, total dissolved N, suspended N, total N) in streams draining burned regions increased in the years immediately following fire and began approaching pre-fire levels several years later (Schindler et al., 1980; Bayley et al., 1992). It appeared that fire intensity was responsible for the different magnitudes of increase observed in the studied basins, with lower intensity fires resulting in smaller increases. The observed increases were not expected to have any long-term effects on regeneration of vegetation in the area, as increases were not significant and were of relatively short duration (Bayley et al., 1992). The effects on phosphorus (P) concentrations were non detectable and only small losses were noted from the highest intensity burned areas (Schindler et al., 1980; Bayley et al., 1992).

A similar study of lakes in a burned region was conducted in the Caribou Mountains of Northern Alberta, where increases of both P and N concentrations in surface water were reported (MacEachern et al., 2000). Phosphorus increases were greater in this study as compared to in the Experimental Lakes Area due to differences in geology. While the Caribou Mountains are primarily peatland and able to retain more nitrogen, the Experimental Lakes Area is granitic and exports more nitrogen.

In the boreal forest region of Quebec, lakes in a burned region were compared to reference lakes, as well as lakes in a logged region, in attempts to determine how different disturbances affect nutrient concentrations. Results indicated that concentrations of K^+, Cl^-, Ca^{2+}, NO_3^-, SO_4^{2-}) all increased in the burnt lakes as compared to reference lakes (Carignan et al., 2000).

As well as water chemistry changes, fire is capable of changing soil chemistry. In general, fire increases mineral soil pH and exchangeable base concentrations, including P, K^+, Ca^{2+}, Mg^{2+}, and total N (Woodmansee and Wallach, 1981; Roberts and Mallik, 1994; Lynham et al., 1998). However, total N was found to decrease in organic soil, possibly due to either volatilization or infiltration to the mineral layers (Lynham et al., 1998).

A disturbance such as fire also has the potential to seriously alter the natural cycle of carbon. Most carbon in the boreal forest is contained in plant detritus, organic soil, and mineral soil and through fire and microbial respiration it can be transferred from these reservoirs to the atmosphere (Kasischke, 2000b). Fire has the potential to instantaneously release large amounts of carbon in the form of gas, in the range of 10-200 t C/ha (Kasischke, 2000a). Immediately after fire, the increase in ground temperature causes an increase in decomposition rates, resulting in the forest floor acting as a net source of atmospheric carbon-dioxide. However, by 10 to 20 years after the fire, vegetation, including mosses and lichens, has re-established itself, ground temperature has decreased, soil moisture has increased and decomposition rates decreased resulting in the forest floor once again acting as a net sink of atmospheric carbon-dioxide (Kasischke, 2000a).

In general, it appears that the impacts of fire on nutrient concentrations of both water and soil are not long-lasting, returning to pre-fire levels within 2 years, although some have taken up to greater than 10 years (MacLean and Wein, 1977; Lynham et al., 1998; MacEachern et al., 2000; Simard et al., 2001). In the absence of additional disturbances, the concentrations and values of most studied parameters continue to decrease over time and return to levels near those which existed prior to the disturbance (Brais et al., 1995).

Forest management practices in the last several decades have focussed on fire suppression and the use of prescribed burning. Although these will not be discussed in depth in this thesis, it is important to point out several effects of such proposals. Fire suppression results in a longer fire return interval and impedes biodiversity and long-term sustainability (Ward and Mawdsley, 2000). The entire ecosystem, including the hydrological cycle, nutrient cycles, landscape diversity, wildlife and plant species diversity, and species distributions and abundances are affected by an altered fire regime (Grissom et al., 2000).

1.2.5.2 Logging

Logging is another important disturbance to the boreal forest. Its effects are complicated by there being no one universal method employed in such practices; the method adopted depends on such variables as logging site, tree species, and intended use. A forest may be clear-cut or selectively logged, using whole-tree harvesting (WTH), where the whole tree above the stump is extracted and all residue is removed, or conventional harvesting (CH), where stems of a set diameter or greater are extracted. It is believed that WTH leaves a clean site, easier for replanting, and that the absence of residue is more visually pleasing and encourages faster development of ground flora (Stevens et al., 1995). However, WTH can also result in the loss of a substantial quantity of nutrients normally supplied to the ground by logging residue, resulting in the potential need for fertilizer applications (Stevens et al., 1995). There are several options for the disposal of this logging residue, also known as slash. It may be completely removed, left on site to decompose, or burned on site.

Studies have shown that whole-tree harvesting appeared to remove greater amounts of nutrients from biomass than CH, while nutrient losses in soil solution following CH exceeded those following WTH (Timmer et al., 1983; Maliondo, 1988; Titus et al., 1997; 1998). This increased loss of nutrients in soil solution noted after CH was related to slash being left on site, which can promote mineralization beneath residue, increased leaching from the residue, and decreased plant uptake (Titus et al., 1997). An interesting effect of CH is its ability to help buffer the soil from the effects of acid deposition. The addition of slash contributes base cations to the forest floor which aids in combating the negative effects of acid deposition (Maliondo, 1988). As well, slash left on site lessens the increase in ground temperature of the forest floor following the canopy opening, resulting in slower decomposition rates of organic matter than with WTH (Maliondo, 1988).

In general, logging removes the tree canopy, which promotes the leaching of nutrients into surrounding streams and lakes, similar to fire. A decrease in canopy cover increases soil temperature, with increased sun exposure, it can also increase soil moisture due to greater precipitation reaching the ground; these increases contribute to increased rates of decomposition. However, increased sun exposure can also cause soil moisture to decrease, thereby reducing decomposition (Prescott et al., 2000a). It is suggested that the major factor controlling decomposition increases or decreases with logging is regional climate (Prescott et al., 2000b). Once logging and all associated activity has ceased, vegetation begins to return. Revegetation of an area can result in reduced nutrient loss with time, as pioneer plants are generally fast-metabolizing plants and are able to mitigate any further loss.

Following clear-cutting of coniferous forests in Canada, differences were noted in water chemistry in areas characterized by high base saturation (e.g. Luvisols and Brunisols) versus those with low base saturation (e.g. Podzols) (Krause, 1982). In the high base saturation, increases in Ca- and Mg-bicarbonate concentrations were observed, while low base saturation areas showed an increase in dissolved organic carbon, a reduced pH and an increase in the ratio of monovalent (Na^+, K^+) to bivalent (Ca^{2+}, Mg^{2+}) cations (Krause, 1982).

In receiving streams draining logged forests, concentrations of phosphate (PO_4^{2-}), NH_4^+, NO_3^-, and K^+ increased; however, organism uptake regulated such increases (Keenan and Kimmins, 1993). Cut lakes in the boreal forest region of Quebec also showed increased concentrations of several nutrients, as compared to reference lakes, these included total phosphorus, total organic nitrogen, K^+, Cl^-, and Ca^{2+} (Carignan et al., 2000). Similar results were observed in hardwood forests, where harvesting resulted in increased Ca^{2+}, K^+, NO_3^-, and H^+ concentrations and decreased SO_4^{2-} concentration in streamwater; concentrations returned to preharvest levels within 3-5 years, primarily due to revegetation of the area (Martin et al., 2000).

In white birch stands of central Newfoundland, NO_3^- was the dominant form of nitrogen lost through leaching after harvesting, followed by NH_4^+; the greatest losses were noted in the first year following harvesting. Initial increases observed in K^+, Ca^{2+}, and Mg^{2+} decreased with time and were thought to be related to NO_3^-, a mobile anion produced through nitrification. During this process H^+ is formed which can displace cations on soil exchange sites, leading to them being leached out (Titus et al., 1997, 1998).

Similar results for nitrate concentrations were noted by Gordon and Van Cleve (1983) from white spruce forests of interior Alaska. In uncut regions, NH_4^+ was the dominant form of nitrogen and likely the preferred nitrogen species by plants (as less energy is expended to incorporate NH_4^+ than NO_3^-). Following harvesting, net rates of NH_4-N accumulation were lower in the harvested regions than in the control area. In contrast, nitrate increased immediately following harvesting and was expected to be rapidly leached from the site or assimilated by vegetation. These increases began to decline shortly after harvesting and returned to pre-harvest patterns within several years (Gordon and Van Cleve, 1983).

It is also important to consider how the re-establishment of vegetation following logging can affect nutrient concentrations. In general, regrowth of vegetation decreases overall nutrient availability (Vitousek, 1985). Decreased nutrient availability relates to vegetation uptake during growth as well as the ability of plants which have grown under reduced nutrient conditions to become more conservative in their nutrient use. Because of this, they are able to survive with lower nutrient levels and use the existing nutrients more effectively. In turn, this more conservative use results in the production of litter which contains less nutrients and only feeds the cycle of reduced nutrient availability (Vitousek, 1985; Roberts et al., 1998).

Recently, attempts to improve forest management have resulted in the suggestion of using silviculture practices to emulate wildfire. And while fire and logging both result in increased nutrient leaching to the surrounding environment, the magnitudes of such increases are not equal.

Many studies have been initiated in attempts to compare the impacts of fire versus logging. Carignan et al. (2000) compared nutrient concentrations of both cut and burnt lakes to reference lakes, with no disturbance. Cut lakes appeared to have the highest concentrations of Na^{+} and dissolved organic carbon (DOC), while burnt lakes had greater concentrations of Ca^{2+}, Mg^{2+}, NO_3^{-}, and SO_4^{2-} (Carignan et al., 2000). Garcia and Carignan (1999) and Lamontagne et al. (2000) also compared cut and burnt lakes to reference lakes; however, they studied elemental loss rates. As seen in Carignan et al (2000) study, greater amounts of Mg^{2+}, NO_3^{-}, and SO_4^{2-} were exported from burnt areas, while DOC was exported at a higher rate from the harvested areas (Lamontagne et al., 2000; Garcia and Carignan, 1999).

The increased SO_4^{2-} concentrations from burnt lakes was related to the combustion of the LFH layer and B horizon, which contains a large amount of organic sulphur, in comparison to the aboveground biomass, allowing it to be leached out and recorded in the nearby lake water (Carignan et al., 2000).

The noted increased concentrations of the mobile ions (K^+, Cl^-, SO_4^{2-}, NO_3^-) reported by Carignan et al. (2000) declined with time, whereas other constituents (total P, total organic N, DOC, Ca^{2+}, Mg^{2+}) showed little change or were slowly increasing at the end of the three-year study period. Calcium and magnesium, both divalent cations, are less mobile than other ions such as potassium and chloride; this would help explain why they continued to show no detectable decrease over the course of the study (Carignan et al., 2000).

Fire and harvesting also result in differences within the forest floor. Lower mass of organic carbon, higher pH, and higher concentrations of total and available nutrients were reported from burnt regions than from cut regions, whereas cut regions had greater mass of organic matter and of total nutrients, related to increased biomass inputs as well as higher levels of potentially mineralizable N (Simard et al., 2001).

Regeneration of vegetation must also be considered when comparing fire to harvesting, as certain species require a heat source to initiate reproduction. Many species have adapted well to fire, some produce serotinous cones, where heat acts as the stimulus that allows seeds being held to be released, while others are able to regenerate quickly through sprouts from the roots of the dead tree or root suckers (Larsen, 1980). Trees that are conducive to regeneration following fire include black spruce, jack pine, lodgepole pine, and pitch pine. For these species, if harvesting is used to emulate natural fire, the stimulus required for regeneration is lost.

The ecological impacts of forest harvesting and wildfire on forests ecosystems will not be discussed in this paper. However, an in-depth review of these impacts is provided by McRae et al. (1998), which analyzes the potential benefits and drawbacks of emulation silviculture.

1.2.5.3 Herbivory

Herbivores impact many aspects of the boreal forest primarily through their grazing and browsing habits. They alter forest structure, biomass, production, and species composition, which in turn can alter nutrient cycling in soils, sediments, and water (Naiman, 1988; McInnes et al., 1992). The size, longevity, and food and habitat requirements of large animals make them a serious threat to forest ecosystems (Naiman, 1988).

The moose (*Alces alces* L.) is one example of a herbivore capable of disturbing the natural processes in the boreal forest (McLaren et al., 2003). Moose prefer to browse on balsam fir and hardwood species, leaving black spruce to dominate in browsed forests (Thompson et al., 1992). This shift in composition towards spruce results in reduced nutrient availability, as spruce have slow growth rates, high leaf-retention rates, low litterfall, low quality litter, and slow litter decomposition rates (Pastor et al., 1988; McInnes et al., 1992; Pastor et al., 1993).

Most of the information on the impacts of moose to boreal forests has come from studies conducted in Isle Royale National Park, Michigan, where moose have been present since the early 1900s. Four moose exclosures were erected between 1948 and 1950 and have been used extensively in studying how moose browsing can impact the forest (McInnes et al., 1992).

In terms of biomass, browsing appeared to cause a decrease in tree biomass while shrub and herb biomass increased (McInnes et al., 1992). Because browsing decreased canopy cover, less shade was provided to the ground, which promoted the growth of shrubs and herbs (McInnes et al., 1992). Productivity of trees also decreased with browsing as species composition shifted towards those characterized as less nutritious. Browsing did not appear to alter the number of plant species present; however, more time might be required for a change in diversity to become apparent (McInnes et al., 1992).

In terms of chemistry, browsing affected exchangeable cation concentrations, with soil samples from exclosures having higher concentrations of Na^{+}, K^{+}, Mg^{2+}, Ca^{2+}, and higher cation exchange capacity than from soil sampled outside the exclosures (Pastor et al., 1993). The exclusion of moose also resulted in increased total nitrogen and carbon concentrations as well as increased pools of potentially mineralizable N and C (Pastor et al., 1993).

Plant composition changes and changes in the associated litter quality brought about by moose browsing have the potential to decrease nitrogen mineralization and production (Pastor et al., 1993). This change in litter quality is due to conifer litter constituting a lower percentage of the total litterfall in the exclosures, with hardwoods dominating. Hardwood litter has higher N concentrations and lower cellulose content than conifer litter. A greater concentration of cellulose in leaf litter relates to lower quality litter and lower N mineralization (Pastor et al., 1993).

Pastor et al. (1993) summarized the drawbacks of increased spruce predominance, in terms of depressed rates of N cycling. Nitrogen uptake and growth rates are slower for spruce than fir and hardwoods, therefore a shift to spruce means the plant sink for N is weakened, which could lead to greater N leaching. As well, the needle retention time for spruce is greater than for fir and hardwoods, thus any N that is present in spruce needles is retained longer by the tree and therefore not available to the soil. Because spruce litter is of low quality, even when the needles are released to the soil the N content is less and is released at slower rates than from hardwood litter.

Pastor et al. (1993) summarized the overall effect of moose browsing as follows: increased moose consumption causes a decrease in tree productivity due to a shift to spruce communities. The dominance of spruce results in a decrease in the chemical quality of the leaf material (an increase in the cellulose content). Lower quality litter has reduced N mineralization and therefore lower total net primary production. Associated with the increased browsing is an opening of the canopy and an increase in shrub layer productivity, with tree productivity decreasing. These processes will continue until all net primary production is concentrated in unbrowsed spruce and eventually moose consumption by moose will surpass browse production and the moose population would collapse due to food limitations (Pastor et al., 1993).

It is more than simply through browsing, however, that animals can affect their environment. Their excretions can add nutrients to the ground, which can potentially change its composition as well as affect biological activity. Pastor et al. (1993) attempted to study this possibility by looking at how, if at all, the addition of moose pellets altered nutrient availability and whether it stimulated N mineralization.

Moose pellets appeared to have significantly different chemical properties than humus (Pastor et al., 1993). The pellets had a greater carbon content, greater N content in late summer, and a greater C:N ratio in early summer than humus alone. When the pellets were combined with the humus, C and N mineralization was stimulated, however not enough to compensate for the negative effect of increased spruce dominance due to moose browsing. They concluded that because areas outside the exclosures did not report higher mineralization rates than inside the exclosure, it appeared that manuring did not significantly increase N mineralization, and therefore did not alter nutrient supply (Pastor et al., 1993).

In Newfoundland, moose are not native but were introduced in 1878, when one male and one female moose were brought over from Nova Scotia; in 1904 four additional moose (two female, two male) were transported from New Brunswick (Dodds, 1983). Since their introduction, moose have thrived on the island and while they have been a benefit to tourism and an important part of Newfoundland folklore, they have also been viewed negatively due to their effects on the forest industry, their complications to conservation of native biodiversity, as well as causing management issues near highways where moose-vehicle collisions are frequent (McLaren, 2004).

During the 1960s, a vegetation survey was conducted in central Newfoundland in response to concerns that forest regeneration following logging was being affected by moose browsing (Bergerud and Manuel, 1968). It was suggested that a reduction of balsam fir due to moose browsing would lead to an increase in *Kalmia angustifolia* (sheep laurel) (Thompson and Mallik, 1989). In the original study, Bergerud and Manuel (1968) made four predictions on the long-term effects of moose browsing on balsam fir and white birch: (i) white spruce would become the dominant tree species; (ii) white birch would be excluded from the canopy; (iii) the commercial value of the forest would be reduced or eliminated in its second rotation; and (iv) the carrying capacity of the area for moose would be reduced.

A later study of the same region found that a significant positive relationship existed between the density of conifer trees and browsing damage to balsam fir recorded as severe or dead as well (Thompson and Curran, 1993). Evidence also supported two of Bergerud and Manuel's (1968) original four predictions regarding future forest condition: moose have substantially altered forest structure through suppression and killing of balsam fir, and birch sapling were in poor condition due to browsing; no evidence was found to support the prediction that the commercial value of the forest had been reduced or eliminated due to moose browsing and no conclusion was made with regards to the fourth prediction, of reduced carrying capacity, although it was suggested that carrying capacity had not undergone a substantial decline (Thompson and Curran, 1993). Although it was not believed that browsing would eliminate balsam fir from future forests, as it appeared to have remained a common species in the overstorey and understorey of many areas, it was suggested that long-term effects of moose browsing might be felt in the soil, competing plants, and local moose density (Thompson and Curran, 1993).

Reindeer (*Rangifer tarandus* sspp.) are another herbivore capable of disturbing forests in a similar manner as moose. Studies of reindeer are primarily conducted in Scandanavian countries and the Finnish subarctic and have shown that overgrazing by reindeer is influencing the vegetation cover and the physical and chemical properties of the soil (Broll, 2000). With grazing, the organic carbon content and nitrogen content of the soil decreased, as did soil moisture, while soil temperature was shown to have increased (Broll, 2000).

In North American boreal forests the beaver (*Castor canadensis caecutor* Bangs) is another mammal which must be considered when discussing herbivory. Impacts from beavers arise primarily from the cutting of trees and the flooding of streams and rivers. The extent to which beavers can alter their environment and influence ecosystem structure and dynamics include modifying channel geomorphology and hydrology, increasing retention of sediment and organic matter, creating and maintaining wetlands, modifying current nutrient cycling and decomposition dynamics, modifying the riparian zone, influencing the character or water and materials transported downstream, and modifying habitat, which influences community composition and diversity (Naiman et al., 1986).

Beaver activity creates patch bodies in the landscape which cycle nutrients in different ways than the original forest, as they hold a large reservoir of carbon and other nutrients (Naiman et al., 1988; Pastor and Mladenoff, 1992). Beaver activity in streams has shown to change absolute amounts of carbon inputs, standing stocks, and outputs (Naiman et al., 1988). Flooding of soils surrounding streams has resulted in increases in reduced nitrogen, as well as in available forms of N in soil solution (Naiman et al., 1988).

Another herbivore that alters the vegetation of the boreal forests is the snowshoe hare (*Lepus americanus struthopus* Bangs). The snowshoe hare feeds on the young shoots of trees and if populations are of sufficient size they are capable of preventing the growth of certain trees. Young trees that are able to avoid consumption by the hare are able to grow to a height which becomes out of reach to the hare, making them no longer at risk to hare predation. The snowshoe hare was introduced to the Island around 1860 (Government of Newfoundland and Labrador, 2004).

As explained, herbivores have the potential to alter forest dynamics, however to what extent generally depends on the population sizes of the herbivore in question.

1.2.5.4 Insects and Disease

In areas where fire is less frequent, generally regions with more humid climates, small-scale disturbance, such as insect outbreaks and windthrow, play a more important role in forest dynamics (Pham et al., 2004).

Insects play a significant role in forest dynamics at both normal and epidemic population sizes (Filion et al., 1998). In general, they influence forest productivity and biogeochemical cycles; however, when populations are considered epidemic they have more serious impacts, such as the vegetation suppression and tree mortality either through feeding activity directly or indirectly through the transmission of diseases (Schowalter, 1985). It is then that insects and disease are classified as disturbance agents.

Tree mortality due to insects results in an opening of the canopy and an increase in fuel accumulation to the forest floor. This can result in increased nutrient availability through increased decomposition and mineralization as well as increase the risk of other disturbance, such as fire (Schowalter, 1985; Stocks, 1985). Alternatively, a previous disturbance to a forest, such as fire, drought, or simply age, might predispose the forest to insect and/or disease outbreaks (Oliver and Larson, 1990). Such combinations of disturbances are thought to produce regressive forests (Payette et al., 2000).

In boreal forests, one of the most common insects to impact the forest is the native spruce budworm (*Choristoneura fumiferana* Clem.), preferring balsam fir but also capable of feeding on spruce. In 1977, the Canada-United States (CANUSA) Spruce Budworm Program was created, intended to study the spruce budworm and to address the problem of reducing its impacts on forests; the program was active until 1984. In 1985 they published the proceedings of the CANUSA Spruce Budworm Research Symposium, which included sections on the biology, ecology and population dynamics of the budworm, the economic and social impacts of the budworm, tactics and strategies for prevention and suppression of damage by the budworm, and management ideas (Sanders et al., 1985). Many studies stemmed from this program, however few looked at the chemical impact of the budworm to forests.

Insect outbreaks have been reported to have serious hydrological impacts, related primarily to evaoptranspiration (Swanson, 1982). A spruce budworm attack can reduce individual tree transpiration and stand evapotranspiration, with a stand transpiration reduction of 30% in the first four years of an attack, and 80% in the sixth to seventh year (Swanson, 1982). As well, spruce budworm outbreaks were found to be related to fluctuations in forest composition and age, with outbreaks predominantly in mature balsam fir stands (Blais, 1985). Outbreaks did not normally result in changes in composition of balsam fir forests, as stands were generally able to regenerate, but oscillations in the age-class distribution of balsam fir were observed (Blais, 1985).

If outbreaks are left uncontrolled, it is possible for almost all trees in a dense mature stand to be killed. The method once used for controlling outbreaks was the application of the insecticide DDT, by means of aerial spraying. However, scientific evidence later showed that DDT was harmful to the environment and its use was terminated (Armstrong, 1985). Recent spraying techniques have made use of a biological insecticide, *Bacillus thuringiensis*, which is pathogenic to insect larvae (Cunningham, 1983). Other natural and biotic controls which exist include diseases, viruses, microorganisms, predators, and parasites; however, these are most effective at endemic levels and not epidemeic levels (Blais, 1985). The main natural cause of an outbreak's termination appears to be food depletion.

Recent concern has focussed on how spruce budworm outbreaks will respond to climate change. During the 20th Century the frequency of outbreaks greatly increased, primarily related to human interactions with the forest, such as harvesting operations, fire suppression, and the application of pesticides which encourage spruce-fir stands and make them more susceptible to future outbreaks (Blais, 1985). Experimental studies have found that warm, dry conditions increased per capita growth rates of insect defoliators which could in turn cause an increase in serious outbreaks (Fleming and Volney, 1995).

Overall, on a controlled level, insects and disease are part of the natural forest environment, however if populations reach numbers which can not be managed by the forest, their presence can have more serious effects on the environment.

1.2.5.5 Windthrow

Windthrow is another example of a natural forest disturbance, which, as previously mentioned, plays a serious role in forest dynamics in locations where fire is less common (Pham et al., 2004). Potential effects to forests depend on the characteristics of the storm, the stand-site, and the individual trees (Everham and Brokaw, 1996; Cooper-Ellis et al., 1999; Ostertag et al., 2003; Peterson, 2004). An additional complication is that post-windstorm mortality takes several years to become evident (Cooper-Ellis et al., 1999). The complexity of the factors involved in wind storms has resulted in there being few studies which have examined the impacts of wind to forests (Ostertag et al., 2003; Peterson, 2004).

Trees tend to build up natural resistance to winds from the prevailing wind direction; therefore, for wind to disturb the forest, windstorms must be unusually strong, affect trees that have become exposed directly to the wind or made more vulnerable in other ways, or the wind must come from an unusual direction (Oliver and Larson, 1990). Other reasons for trees to be susceptible to wind include poor growing conditions preventing the root systems from penetrating deep into the soil, or having been weakened from a previous disturbance, such as insects or disease or fire.

Wind can snap off stems and branches or cause whole trees to be uprooted with the end result being an addition of debris to the forest floor. This additional debris contains large pools of nutrients and promotes organic matter decomposition within the soil and can also release tied-up nutrients, (Pastor and Mladenoff, 1992; Bormann et al., 1995; Sanford et al., 1991; Schaefer et al., 2000; Ostertag et al., 2003). However, such changes are often not significant or long-lasting due to biotic controls, such as the re-establishement of vegetation (Bowden et al., 1993; Cooper-Ellis et al., 1999).

In forests where the number of large-scale disturbances has decreased, smaller-scale events, such as windstorms and insect outbreaks, have become more dominant in controlling forest dynamics. These smaller-scale disturbances are capable of altering forest structure and in turn changing the chemical flows within the ecosystem.

1.2.5.6 Acid Deposition

Acid deposition has received much focus since the 1980s, with many studies initiated and panels created in order to better understand the problem as well as to establish ways of eradicating the source of the problem. The greatest impacts of acid precipitation are felt close to pollution sources; however, long-range transport has resulted in locations at great distances from these centres also reporting impacts.

For soils to become more acidic, the proportion of exchange sites occupied by acidic cations must increase (Binkley, 1992). This can occur with the addition of acidic precipitation or naturally with the decomposition of organic matter (Binkely, 1992). When acidic cations occupy soil exchange sites H^+ is released and results in a net H^+ load to the system (Binkley, 1992).

The base cations important to the forest system, Ca^{2+}, K^+, Mg^{2+}, Na^+, are the most sensitive to acid deposition, thus the introduction of H^+ promotes their loss through cation exchange or weathering processes and may also result in soil and foliar leaching (Johnson, 1992b). It has been reported that ozone and acid deposition have accelerated the process of foliar and canopy leaching of base cations (Lovett and Schaefer, 1992). Acid deposition causes cation exchange between H^+ and the foliar base cations on exchange sites and in the case of ozone, the leaf cellular membranes become damaged, leading to the leakage of cell contents via rainfall (Lovett and Schaefer, 1992).

The sulphate ion, very important to soil chemistry, is related to cation concentrations. Forests exposed to greater levels of SO_4^{2-} in forest floor solution reported accelerated rates of cation leaching (Harrison and Johnson, 1992). With reported reductions of SO_2 in air pollution, SO_4^{2-} inputs and deposition to the soil decreased (Lindberg and Garten, 1988). However, such decreases in SO_4^{2-} inputs might initiate a release of previously stored SO_4^{2-} which could in turn promote the leaching of cations, thereby altering soil and associated stream concentrations (Lindberg and Garten, 1988). Although reduced SO_4^{2-} concentrations in precipitation and reduced SO_4^{2-} concentrations at watershed outlets have been observed, no changes have yet been noted in pH levels, and losses of Ca^{2+} and Mg^{2+} have remained relatively high (Houle et al., 1997).

Nitrogen is also a key concern when discussing the effects of acid deposition on forest ecosystems. Nitrogen saturation is the forest soil condition when nitrogen input from mineralization and the atmosphere exceeds retention capacity. As a result, NO_3^-, begins leaching out of the system (Aber et al., 1989; Cole, 1992). When NO_3^- production is high, accelerated leaching rates of cations also occurs leading to potential nutrient deficiencies (Van Miegroet et al., 1992).

In 1983, a study of 109 lakes in Newfoundland was initiated to see if the global issue of water acidification due to acid precipitation was affecting Newfoundland lakes (Scruton, 1983). Analysis of plankton, sediment, benthos, fish, and water samples showed no evidence of a chronic acidification problem in the lakes at that time; however, it was difficult to separate natural acidity from anthropogenic at some sites (Scruton, 1983).

Whether forests can continue to offset acidic deposition will depend on the dominant process for their output of base cations in the system (Binkley, 1992). The desired effect of neutralizing H^+ added to ecosystems from acid deposition, resulting in a decrease in soil acidification, can sometimes lead to the leaching of aluminium (Al^{3+}), which has its own negative impacts to the system (Binkley, 1992). However, with efforts toward reducing acidic components in atmospheric emissions, it is hoped that acid deposition will no longer continue to threaten the forests of the future.

1.2.5.7 Climate Change

Climate change is a global issue and is affecting all environments. It is expected that the boreal forest will experience the largest temperature increases of all forest types, with both summer and winter temperatures warming (WCMC, 2004). Of immediate importance to the boreal forest is not the cause of the current climate trend but instead the impacts to the forest and what changes might be expected.

Climate change directly affects tree species distribution, growth rates, and nutrient cycling (i.e. Peng and Apps, 1995), as well as indirectly affecting rates and magnitudes of other disturbances, such as fire regimes (i.e. Bergeron and Flannigan, 1995) and insect outbreaks (i.e. Fleming and Volney, 1995).

The most frequently used technique to study climate change is the use of models, which simulate different climate scenarios as determined from Global Circulation Models (GCM). The most common climate change scenarios are: i) climate change alone, involving changes in temperature and precipitation; ii) a doubling of ambient carbon dioxide (CO_2) levels; and iii) a combination of the two, temperature and precipitation changes as well as CO_2 doubling. All three scenarios reported a net primary production and total biomass increase; however, only the combination of climate change with CO_2 doubling yielded an increase in decomposition rates and net N mineralization rates (Peng and Apps, 1998).

Models have also been used in attempts to determine future forest composition and forest and species distribution. First, how the climate of an area might change is studied followed by what tree species, and therefore forest type, would grow in this new climate. Numerous studies have reported that predicted climate change would result in many boreal species no longer being able to survive in their current location (Burton and Cumming, 1995; Hogg and Hurdle, 1995; Sykes and Prentice, 1995; WCMC, 2004). Eventually, new species would dominate in these areas, creating different soil chemical properties (Weber and Flannigan, 1997).

On the watershed level, models have been used to predict how watershed processes would react to different climate scenarios. The most serious impacts noted were an increase in the magnitude of winter runoff, a decrease in summer runoff and a decrease in summer soil moisture (Bobba et al., 1999).

Another important aspect of climate change is the impact to other disturbance regimes. With further increase in CO_2 levels it is expected that the fire frequency of the southeastern boreal forest would decrease, due to increased precipitation and relative humidity, while elsewhere in Canada forest fire danger would increase (Bergeron and Flannigan, 1995; Flannigan et al., 2001). Climate change also affects insect populations. A decline in the frequency of late spring frosts and an increase in the frequency of droughts was reported to cause population densities of spruce budworm to remain high for longer periods in northern white spruce stands and such chronic defoliation of balsam fir stands could potentially lead to their complete elimination (Fleming and Volney, 1995).

The data generated through the use of models has provided information on the potential effects of future climate change. Whether actual climate change will follow these predicted changes is not yet known, however studies of past climate change have shown that forests have been affected by changes thus far and are at risk to further change.

As described, there are many disturbances associated with the boreal forest. While not all are capable of causing significant effects, it is important to understand their potential impacts on the forest and how they can directly and indirectly affect forest processes.

1.2.6 Terra Nova National Park

As exhibited in many of the previously discussed studies, one way of examining how disturbances affect forest chemistry is to study them in controlled environments, such as experimental forests or national parks. There are two National Parks in Newfoundland: Gros Morne National Park, located on the west side of Newfoundland, and Terra Nova National Park, located on the eastern side of Newfoundland. Terra Nova represents an excellent example of a boreal forest and has a history marked by disturbance events. Because of Terra Nova National Park's history of both natural and human influenced disturbance it was chosen as the central location for this study.

1.2.6.1 Description

Terra Nova National Park was established in 1957. It is situated at 54^{o} 00'W, 48^{o} 30'N on the east coast of Newfoundland, off Bonavista Bay, and covers an area of approximately 400 km^2. The vegetation is representative of eastern boreal forests: tree species are predominantly black spruce and balsam fir, sheep laurel (*Kalmia angustifolia)* is the dominant shrub, and a number of different species of flora, moss, and lichen exist (Power, 2000).

The climate of Newfoundland is largely influenced by the Labrador Current. The northern hemisphere, mid-latitude atmospheric circulation and the proximity to mainland Canada also exert an influence over Newfoundland climate (Banfield, 1983). Summers in Terra Nova National Park are cool and short with a mean summer (May-Sept) temperature of 12.6 °C and mean summer rainfall of 448.9 mm; average summer relative humidity is 68%. The majority (75%) of the 1184.3 mm of total annual precipitation falls as rain. Winds are predominantly from the south-southwest and summer winds average 20.6 km/hr (Power, 2000)

Newfoundland has a unique geologic history, it is believed that it was once part of two continents, separated by a proto-Atlantic Ocean, which later collided. The island is made up of four tectonic plates, the Humber, Dunnage, Gander, and Avalon, where Terra Nova National Park is found (Rogerson, 1983).

The Late Wisconsinian glaciation, 20,000 to 10,000 years ago, played a significant part in Newfoundland's geologic history and is primarily responsible for the topography and soil conditions seen today (Sommerville, 1997). Terra Nova National Park has low relief and is relatively flat or gently rolling with large glaciofluvial deposits (Roberts, 1983). The soils are generally acidic in nature and nutrient poor. Although the total nutrient content may be high, the low pH makes the nutrients unavailable for vegetation (Roberts, 1983). According to the Canadian System of Soil Classification, the soils of Terra Nova National Park are primarily podzols.

In attempts to reconstruct past environments of Newfoundland, pollen records recovered from lake sediments have been analyzed, through which the past vegetation and climate have been interpreted (Anderson and Macpherson, 1994; Wolfe and Butler, 1994; Macpherson, 1995).

Between 13.5 and 11 ka BP, shrubs appeared to dominate the vegetation in the south and the southwest of the island, while herbs dominated in the northwest. The dominance of shrubs was interpreted as signifying a warming trend in the south and southwest, while it remained cooler in the northwest (Anderson and Macpherson, 1994). A cooling event occurred between 11 ka BP and 10 ka BP as indicated by a shift back to herb dominance however the presence of shrubs between 10-8 ka BP signified the return of warmer conditions (Anderson and Macpherson, 1994). White spruce was the first conifer to colonize the island, around 10 ka BP in the south-west of the island and at 9.5 ka BP in the northshore and central regions; black spruce arrived approximately 1,000 years later followed by balsam fir a few centuries later (Anderson and Macpherson, 1994; Macpherson, 1995). Shrubs reappeared around 9.7 ka BP, indicating cooler conditions. Spruce, balsam fir and tree birch returned around 8.5 ka BP(Anderson and Macpherson, 1994).

Lake-sediment records showed an increase in charcoal deposits between 8-6 ka BP, which were interpreted as signifying warm, dry summer weather conditions (Macpherson, 1995). Between 6.5-6 ka BP and 4.5-4 ka BP, a decrease in fire importance was reported and pine extended to its present limits. In central and eastern

Newfoundland, the period between 6.5-4 ka BP was a time of great fire importance and increased moisture, as illustrated by an increase in Sphagnum (Macpherson, 1995). From 4 ka to present, spruce and balsam fir increased and fire importance decreased (Macpherson, 1995).

Pollen and siliceous microfossils found in basal lake sediment from core samples from Pine Hill Pond in Terra Nova National Park were used to determine past vegetation as well as climatic oscillations for this area specifically (Wolfe and Butler, 1994). Herbs dominated the bottom of the core, interpreted as a sparse herb-shrub tundra community. The concentrations of shrubs in the core began to increase, implying the development of a greater dominance of a shrub-tundra community, likely formed in response to progressing soil development and improving climatic conditions (Wolfe and Butler, 1994). The presence of shrubs in the core began to decrease as herbs increased, indicating a return to sparse herb-shrub tundra and interpreted as the presence of a cooling trend (Wolfe and Butler, 1994). After the Younger Dryas (11-10 ka BP) a warming trend began and shrub tundra or heath-like vegetation developed, as seen by a rise in shrub percentages in the core. Around 9 ka BP, mixed forest communities became established, with balsam fir, spruce and pine concentrations all increasing.

Currently, eight forest classes are found within Terra Nova National Park, with 80% of the total area composed of black spruce, scrub spruce, and balsam fir communities. The remaining 20% is classified as non-forested, such as Kalmia barren, barren, fens, and bog (Power, 2000).

1.2.6.2 Establishment

In order to fully understand the disturbance history of Terra Nova National Park, it is beneficial to have some background information on the establishment of the area as a national park.

The first idea of a national park in Newfoundland was discussed during negotiations surrounding Newfoundland's entrance into Confederation (MacEachern, 2001). After Confederation, the Government of Canada greatly desired a park in the new province. Newfoundland, however, was not prepared to sign over a section of land that it felt could potentially support a third pulp and paper mill (MacEachern, 2001). Over the next few years the creation of a National Park in Newfoundland was heavily debated. But in the end Newfoundland's desire to have the Trans-Canada Highway completed and financed by the Government of Canada and the Government of Canada's desire for a new national park resulted in the provincial government agreeing to the park in its current location and the federal government agreeing to allow the province minimal cutting in the area if indeed a third pulp and paper mill was constructed (Lothian, 1987).

In the end, a third pulp and paper mill did not materialize in eastern Newfoundland, meaning that extensive cutting in the park did not take place. Nevertheless, cutting in the park did continue following its establishment, although no records account for its magnitude. Wood was reported to have been taken for the construction of infrastructure in the park as well as to have been allowed for personal purposes of residents in park enclave communities (MacEachern, 2001).

1.2.6.3 Disturbance history

Terra Nova National Park has experienced many disturbances prior to and following its designation as a national park, with records of disturbances dating back to the late 1800's. During most of the 19^{th} Century, fisheries dominated the industry of Newfoundland and any logging that took place occurred during the fishing off-season and primarily for domestic use or the construction of fishing boats, wharves, and other such needs (Major, 1983). It was not until the late 1890's with the construction of a railway link in the area that logging and sawmills became more prominent (Major, 1983). By the 20^{th} Century, both Newman Sound and Clode Sound were heavily involved in woodcutting and sawmilling, with permanent communities established in these areas (Munro, 2001).

Logging activity peaked at slightly different times for the different areas in the region. In the Glovertown-Traytown area logging peaked in the early 1920's; in the Southwest Arm activity was most intense in the 1930's; and around Newman Sound and Clode Sound logging took place from the turn of the century and continued until after the establishment of the park (Major, 1983).

A table of those areas most heavily logged was generated from logging information available in human history studies (Major, 1983), studies on logging in Newfoundland (Munro, 2001), and information on the history of the park (Lothian, 1987; MacEachern, 2001); see Appendix 2-1.

Harvesting has not been the only disturbance to have affected the park. Wildfire has had significant impacts for the forest on a somewhat regular basis for a long period of time. A history of fire in the park, compiled by Power (1996), revealed that fire has long been prominent in the ecology of the park, with 63 of 86 field plots revealing charcoal in their upper horizons and/or lower duff layer. Although fire has occurred in the past, the rate at which it currently occurs has decreased over the last 70 years or so (Power, 1996). Decreased fire frequency is suggested to be related to improvements in fire suppression, differences in fire history methodology, or unfavourable climatic condition (Johnson, 1992a). From records of fires in Newfoundland (Wilton and Evans, 1974) and from the park and surrounding area (Power, 1996, 2000), a list of fires having directly affected Terra Nova National Park was compiled; see Appendix 2-2.

Concerns raised about effects of herbivores in the park are primarily due to moose browsing, although the snowshoe hare is also capable of affecting forest processes. As previously mentioned, two moose were introduced to Newfoundland in 1898, with four additional moose brought in 1904, and have since been very successful. In 1997, the density of moose in Terra Nova National Park was 0.81 moose/km^2 (Murphy, 1997), below the calculated critical carrying capacity of 1.3 moose/km^2 (Oosenburg et al., 1991). However, even below the predicted carrying capacity, their impacts on the forest are still of concern. Approximately 13 km^2 of forest in Terra Nova National Park once classified as balsam fir is now classified as birch-aspen; this shift in forest type is related to moose browsing preferences (Power, 2000). As well, there is concern that moose browsing will encourage the growth of *Kalmia* and inhibit the regrowth of balsam fir. A greater *Kalmia* presence leads to lower nutrient concentrations as well as limiting the potential for original forest communities to grow (Damman, 1971; Titus et al., 1995; Wallstedt et al., 2002).

The snowshoe hare was introduced to Newfoundland around 1864 and populations grew rapidly (Dodds, 1983). Unfortunately, no specific studies have been completed regarding the impacts of hare on the forests of Terra Nova National Park.

Significant outbreaks of the spruce budworm have not been common in Newfoundland and therefore their effects to the park have not been great. The last major outbreak observed lasted from 1972 to 1984. In 1983, the total volume of stands with tree mortality was greater than 40 000 000 m^3 (Raske, 1983), representing over 22% of the spruce-fir inventory of Newfoundland[1]. Outbreaks of the hemlock looper occurred in the late 1960s, mid to late 1980s, and the most recent one beginning in 1993 (Canadian Forest Service, 1993; Canadian Council of Forest Ministers, 2003). Outbreaks of the hemlock looper appear to be a continual problem in some areas of Newfoundland and there is also concern over an expansion of the yellowhead spruce sawfly (NLFPA, 2000). Current concern is that insect defoliation combined with the effects of mammalian herbivores, specifically moose, will result in many ecological problems for the park (Power, 2000). Under natural conditions, forests regenerate as they were prior to the disturbance, but herbivores can exert a strong impact on succession after outbreaks and blowdowns (Peterson and Pickett, 1995).

Although wind and insect outbreaks are disturbances that affect the park, generally they occur at endemic or below catastrophic levels and much of the wind damage is not distinguishable from trees which have blown down following insect disturbance (Power, pers. comm.). Therefore, the low level of such disturbances in the

[1] Calculated from information in MacLean (1984) which stated that in 1981 31.7 mill m^3 of forest was affected which equaled 18% of spruce-fir forest

park combined with the time requirement for the effects to transpire makes studying them in the context of the park lakes extremely difficult.

In terms of acid deposition for the park, Clair et al. (1997) suggested that the lack of acidification related trends seen in lake data from the park indicated that the low acid deposition in the area was not significantly affecting the water chemistry, mainly because this area of Newfoundland is sufficiently removed from the sources of acid emissions. However, even with low deposition, it is important to monitor lake chemistry for signs of acid deposition impacts because the geology of the island is such that even with low deposition, the rock, with low amounts of alkaline chemicals and poor acid buffering capacities, is extremely sensitive to any acidic precipitation and along with resulting decreased pH, acid deposition results in the leaching of cations (Clair et al., 1997).

The above section describes, in brief, the disturbance history for Terra Nova National Park as well as providing some background information on the establishment of this area as a national park.

1.3 Thematic Cohesiveness of Papers

The following chapters present the two parts of this overall study. The first part of the study (Chapter 2) looks at the short- and long-term effects of forest disturbances on water chemistry in forested watersheds while the second part (Chapter 3) studies the specific disturbance of moose browsing on soil solution chemistry. Chapter 4 provides an overall conclusion for the study as a whole.

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Chapter 2 Long- and Short-term Impacts of Forest Disturbance on Water Chemistry in Boreal Watersheds

2.1 Abstract

Forested watersheds may reflect past and present forest conditions, including the effects of disturbances, in the chemistry of their surface waters. Questions arise as to the degree of change that will occur in ionic concentrations and the length of time after the event that these changes will remain detectable.

Terra Nova National Park, Newfoundland, Canada, was the location for a study of both short- and long-term effects of forest disturbance on water chemistry. A recent fire in the park made it possible to study the short-term effects of fire on stream and soil solution chemistry. The long-term study made use of previously collected data gathered from many sources and included disturbance history of the park and water chemistry data for 13 lakes and two streams representing forested watersheds within the park boundaries.

It was expected that the effects of the recent forest fire would be reflected in water chemistry but that water chemistry data available for areas having experienced past disturbances would not be distinguishable from water chemistry data available for areas having no record of any significant past disturbances.

On the short-term, it appeared that the disturbance of fire did cause differences in chemistry between burned and non-burned areas, with soil solution in burned areas having greater concentrations of PO_4^{2-}, SO_4^{2-}, K^+, Na^+, Cl^-, and conductivity than non-burned areas. The long-term effects of fire as well as the disturbance of logging, however, were not distinguishable in the water chemistry.

Possible explanations for this lack of difference could relate to the characteristics of the disturbance (size and magnitude), the time elapsed since the disturbance, resilience of the area or that any change was masked due to natural succession of forests resulting in natural chemistry changes.

2.2 Introduction

Terra Nova National Park, located in eastern Newfoundland, is at the easternmost limit of the Canadian boreal ecoregion. The park occupies an area of 400 km^2 and consists mainly of boreal forest landscapes that have been subject to a variety of disturbances. The park's numerous forested watersheds provide a good location to study disturbances by means of hydrogeochemical methods.

The purpose of this study was to determine if forest disturbances, mainly fire and logging, affect the water and soil solution chemistry of forests, on both the short-term (a few years to several decades) and long-term (multi-decadal to a century or more). It was expected that on the short-term, water chemistry differences would be observed. However, it was not expected that disturbances of the past would be detectable in available water chemistry data.

2.3 Forest Disturbance and Nutrients

In forested watersheds, disturbances are a major determining factor in forest composition and diversity and are defined as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resource pools, substrate availability, or the physical environment" (White and Pickett, 1985). For aquatic and terrestrial ecosystems, disturbances alter nutrient concentrations in the watershed and threaten the existence of these systems in their current form (Chanasyk et al., 2003).

Disturbances can create environments different from those that existed prior to the event. In order to better understand how disturbances can alter this environment, simplified models of a forest that has not been disturbed and a forest following a disturbance can be compared. In the absence of a disturbance a portion of the incoming radiation and precipitation is intercepted by vegetation, while some reaches the ground directly (Figure 2.1). Intercepted precipitation can be used by vegetation, lost through evapotranspiration, or passed to the ground via stemflow or throughfall. Once it reaches the ground, it can drain to nearby streams and lakes as overland flow or become subsurface flow and percolate into the ground. The portion that percolates into the ground can be taken up by root systems or microorganisms or leached down through the soil column, eventually becoming incorporated into groundwater (Church, 1997). Nutrients are added to the forest from the atmosphere as solutes in precipitation, as well as through dry deposition, and combine with those already in the system. They are subsequently passed to the soil, where they can be taken up by root systems and organisms, exchanged on soil particles, or eventually leached downwards, contributing to groundwater and eventually streamwater concentrations (Figure 2.1).

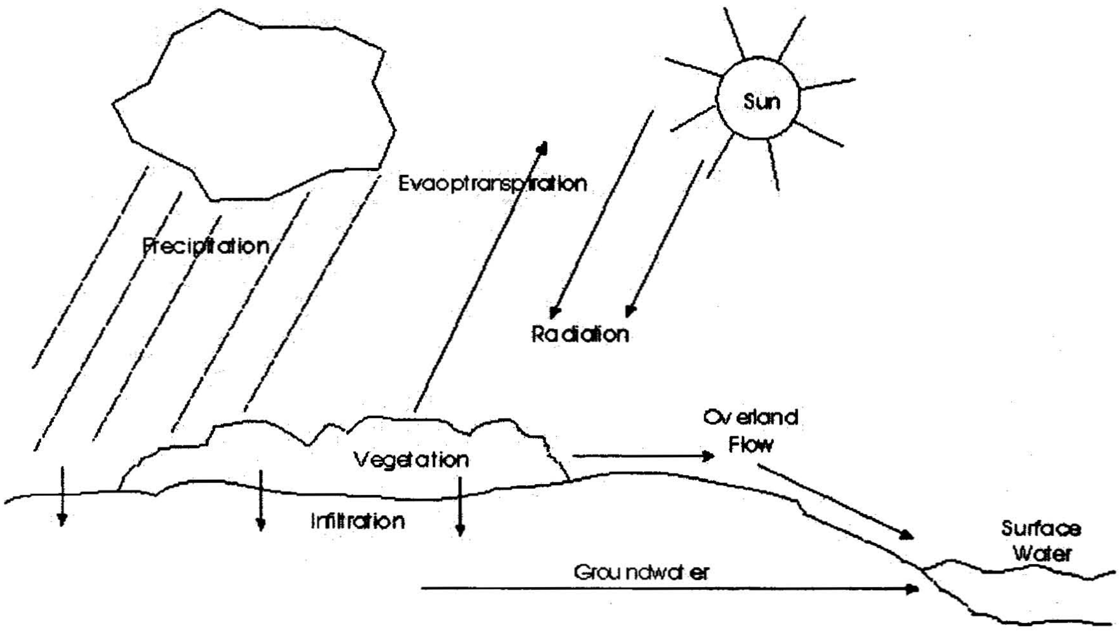

Figure 2.1 Natural processes in an undisturbed forest

A disturbance that results in the removal of crown cover and vegetation increases the direct radiation and precipitation to the ground, causing increased ground temperature and soil moisture (Keenan and Kimmins, 1993). The removal of vegetation also has a major hydrological impact through reduced interception and evapotranspiration (Martin et al., 2000; Putz et al., 2003). This reduction in evapotranspiration contributes to increased soil moisture, but this effect may be slightly offset by greater evaporation from the ground due to increased radiation and greater wind movement over the soil surface (Chen and Popadiouk, 2002; Putz et al., 2003). Streamflow often increases, attributable to both greater overland flow and water movement through the soil column, and peak flows may also increase (Keenan and Kimmins, 1993; Putz et al., 2003). Disturbances can often result in greater nutrients available on the forest floor and the reduced vegetation cover means less nutrient uptake, both leading to increased nutrient concentrations in the soil and, if combined with increased water movement in the column, greater ion transport to nearby streams and lakes (Johnson, E., 1992; Keenan and Kimmins, 1993; Chanasyk et al., 2003). As well, the canopy is capable of altering the chemical composition of precipitation (Lovett and Lindberg, 1993); therefore, on its removal, the chemical composition of precipitation reaching the ground could be different than what it would be if the canopy was present.

Generally, the degree to which nutrient concentrations change is related to the area of watershed disturbed, the intensity of the disturbance, the age of the area, and the specific characteristics of the location (Pinel-Alloul et al., 2002; Putz et al., 2003).

The most common natural disturbances originally associated with the boreal forest are wildfire, forest harvesting, insect defoliation, disease, windthrow, and herbivory. Recently acid precipitation and climate change have been added to this list.

2.3.1 Wildfire

Fire is thought to be the most important disturbance with regards to stand and landscape dynamics in the boreal forest (Johnson, E., 1992; Payette, 1992). In general, disturbance by wildfire reduces the canopy cover, thereby increasing ground temperature through increased solar radiation. Nutrients may be either lost or gained, generally depending on the fire regime, consisting of fire frequency, size, intensity, type, depth of burn, and season, and on site characteristics (Weber and Flannigan, 1997; Chen and Popadiouk, 2002; Chanasyk et al., 2003).

Fire intensity is a major determining factor for changes in nutrient levels following fire. A higher intensity fire can result in nutrients lost to the atmosphere through volatilization, with lower concentrations remaining in the soil and in runoff to receiving streams and lakes (Ahlgren and Ahlgren, 1960). Alternatively, substantial amounts of nutrients may also be added to the soil and associated streams through leaching from the ash layer (Lynham et al., 1998). Increased leaching relates to direct nutrient mineralization and a heightened nutrient release from the burning of organic matter and ensuing decomposition (Bourgeau-Chavez et al., 2000). In a low intensity fire, with a third or less of the organic soil layer burnt, changes in carbon (C), nitrogen (N), phosphorus (P), and major cations are not expected in soil solution or stream water (Richter et al., 1982).

Fire intensity is also involved in determining which vegetation species will re-establish following fire. For example, in black spruce forest types in Newfoundland , *Kalmia* is the dominant form of vegetation following a low intensity fire with little reduction of surface organic layer (Mallik, 1993). Associated with a *Kalmia* dominated environment are low available nutrient concentrations, making it difficult for other forms of vegetation to become established (Damman, 1971; Titus et al., 1995; Wallstedt et al., 2002)

Studies have shown that concentration of nitrogen and phosphorus compounds increased in nearby lakes and streams following fire but began to return to pre-fire levels after several years (Schindler et al., 1980; Bayley et al., 1992; Carignan et al., 2000). Studies have shown that apparent nutrient increases were of short duration, returning to pre-fire levels within two years, although some have taken up to 10 years (MacLean and Wein, 1977; Lynham et al., 1998; Simard et al., 2001). Burnt lakes showed higher concentrations of potassium (K^+), chloride (Cl^-), calcium (Ca^{2+}), nitrate (NO_3^-), and sulphate (SO_4^{2-}) relative to reference lakes (Carignan et al., 2000). Soil pH and exchangeable cation concentrations in soil, including magnesium (Mg^{2+}), Ca^{2+}, and K^+, also increased, related to the ash contribution to the soil, which leached base cations (Woodmansee and Wallach, 1981; Lynham et al., 1998; Simard et al., 2001). With increased nutrient concentrations in the soil, site conditions improve, allowing vegetation to return quickly and take up these available nutrients, thereby reducing the overall concentration of nutrients over time (Simard et al., 2001). In the absence of additional disturbances, the concentrations and values of most studied parameters continue to decrease over time until they approach pre-fire levels (Brais et al., 1995).

2.3.2 Logging

Another major disturbance to the boreal forest is logging, or timber harvesting. As with fire, logging removes the canopy and produces elevated nutrient exports (Bayley et al., 1992; Jewett et al., 1995; Lamontagne et al., 2000). However, in terms of specific effects, site characteristics as well as the different approaches available for harvesting trees must be taken into consideration (Smith et al., 2003).

Most harvesting methods use either whole-tree harvesting (WTH), extracting the whole tree above the stump including all branches and needles, or conventional harvesting (CH), where only stems of a set diameter or greater are extracted. Options also exist for the disposal of the logging residue, or slash. It may be completely removed, burned on site, or left to decompose, the latter generally resulting in greater nutrients available to the soil from leaching and denitrification (Keenan and Kimmins, 1993). Although none of these methods is the same as practices used in the past, conventional techniques leaving slash to decompose on site bears the closest resemblance to past practice.

In comparing these different harvesting methods, WTH appeared to remove greater amounts of nutrients from biomass than CH (Timmer et al., 1983; Maliondo, 1988; Titus et al., 1997, 1998). However, nutrient losses in soil solution were greater following CH (Titus et al., 1997, 1998). Greater nutrient losses following CH were related to the addition of slash, which can trigger increased decomposition and leaching of nutrients, increased mineralization, and delayed regrowth of vegetation, which would normally act as a nutrient sink (Titus et al., 1997, 1998); these effects lasted no more than 3 years (Titus et al., 1997).

Logging has resulted in increased concentrations of ammonium (NH_4^+), phosphate (PO_4^{2-}), NO_3^-, and K^+ in streams, but consumption of organic material by aquatic organisms helped to regulate such increases (Keenan and Kimmins, 1993). Lakes in cut regions have shown increased concentrations of total phosphorus, total organic nitrogen, K^+, Cl^-, and Ca^{2+} (Carignan et al., 2000). In hardwood forests, harvesting resulted in increased Ca^{2+}, K^+, NO_3^-, and H^+ concentrations and decreased SO_4^{2-} concentration in streamwater, with concentrations returning to preharvest levels within 3 to 5 years (Martin et al., 2000).

Both increases and decreases in decomposition have been reported following harvesting experiments. The differences in decomposition appear to be related to soil moisture, where increased decomposition was related to higher temperatures and soil moisture content (e.g., Keenan and Kimmins, 1993; Prescott et al., 1993), while greater evaporation following harvesting resulted in drier soils, and therefore decreased decomposition (e.g., Cortina and Vallejo, 1994).

An increase in decomposition results in increased amounts of nutrients in the soil. However with the removal of vegetation there are fewer plants to take up these nutrients; therefore, losses via leaching will appear to increase almost immediately (Keenan and Kimmins, 1993).

Both harvesting and fire result in the removal of the canopy and ground vegetation and an increase in nutrients leached from the ground to nearby lakes and streams. Although they both result in initial losses of nutrients, these disturbances are not identical in their impacts. Lakes in harvested regions showed higher sodium (Na^+) concentrations and dissolved organic carbon (DOC), while concentrations of Ca^{2+}, Mg^{2+}, NO_3^-, and SO_4^{2-} were higher in burnt lakes (Carignan et al., 2000). Similar patterns were noted for elemental loss rates (Lamontagne et al., 2000; Garcia and Carignan, 1999). For the forest floor, burned regions had lower mass of organic carbon, higher pH, and higher concentrations of total and available nutrients than cut regions, whereas cut regions had greater mass of organic matter and mass of total nutrients, related to increased biomass inputs, as well as higher levels of potentially mineralizable N (Simard et al., 2001).

While fire is considered to be the most important disturbance in the boreal forest (Payette, 1992), studies of stand and landscape dynamics indicate that in eastern boreal forest, fire intervals are increasing (e.g. Bergeron and Archambault, 1993) and as a result, a greater proportion of old-growth forest occurs where harvesting does not take place (Kneeshaw and Bergeron, 1998; Kneeshaw and Gauthier, 2003). These forests are more susceptible to small-scale disturbances, such as insect outbreaks and windthrow, and accordingly small-scale disturbances are becoming the controlling forces of stand dynamics for older forests (Kneeshaw and Bergeron, 1998; D'Aoust et al., 2004; Pham et al., 2004).

2.3.3 Insect Herbivory

Insects affect forest productivity, tree mortality rates, and nutrient and biogeochemical cycles. If insect populations become very large, they can suppress vegetation growth and cause widespread mortality, either directly through feeding activity or indirectly through the transmission of diseases (Schowalter, 1985). Such extreme outbreaks are seen to create patches in the forest, whereas individual events generally create gaps (McCarthy, 2001). Tree mortality opens up the canopy and increases litter accumulation on the forest floor, which results in increased nutrient availability through increased decomposition and mineralization (Schowalter, 1985). Alternatively, when insect populations are not at such extreme levels, they are thought to be beneficial to forests and an important regeneration mechanism, allowing balsam fir to return by killing many adult trees and thereby reducing the overstory (Baskerville, 1975; MacLean, 1984; Morin, 1994).

Forests are often at risk to outbreaks if they have been previously weakened by a disturbance, such as fire or drought (Oliver and Larson, 1990). Conversely, forests which have been weakened by insects and disease are more susceptible to other disturbances (Schowalter, 1985). For example, in areas of recent insect outbreaks, forest fire hazard increases due to an increase in dead and dry material available for burning (Stocks, 1985).

The native spruce budworm (*Choristoneura fumiferana* (Clem.)) is the most common insect to affect the boreal forest in Newfoundland, preferring balsam fir but also capable of feeding on spruce trees. Normally, outbreaks do not result in composition changes of balsam fir forests, as stands are able to regenerate; however, outbreaks do create oscillations in the age-class distribution of balsam fir (Blais, 1985). Other common insects to the boreal forest include the hemlock looper (*Lambdina fiscellaria fiscellaria* (Guen.)) and the larch sawfly (*Pristiphora erichsonii* (Htg.)).

Outbreaks of the spruce budworm, and their associated effects on the canopy, are not well understood in mixed boreal forests due to lower mortality of hosts compared with pure fir forests (D'Aoust et al., 2004). It is thought that outbreaks in mixed forests will result in changes in forest composition and eventually alter other forms of vegetation in the area (D'Aoust et al., 2004). Canopy openness is often assessed when studying outbreaks however, as it can take several years for mortality to occur as well as for trees to fall, this must be carried out over a significant amount of time in order to account for the dynamic state of such a disturbance (Nealis and Ortiz, 1996; Tanaka and Nakashizuka, 1997; Kneeshaw et al., 1998; Chen and Popadiouk, 2002).

A recent concern is how climate change will affect spruce budworm outbreaks. The frequency of outbreaks in both eastern and western forest regions of North America has increased in the 20^{th} century (Perry and Amaranthus, 1997) and results from modelling experiments have shown that with warm, dry conditions would increase yearly growth rates in a given area relative to the current population levels, resulting in more insects in that area (Fleming and Volney, 1995).

2.3.4 Windthrow

Windthrow is another disturbance common to the boreal forest. It has the potential to add litter to the forest floor, acting as a nutrient source, but in doing so creates an environment more prone to other disturbances, such as fire (Paine et al., 1998).

In general, windstorms can cause mortality and canopy disruption and reduce tree density and size structure as well as alter local environmental conditions (Dale et al., 2001); specific impacts depend on the characteristics of the storm, the stand-site, and the individual trees (Everham and Brokaw, 1996; Cooper-Ellis et al., 1999; Ostertag et al., 2003). The complexity of these characteristics all working together has resulted in a lack of predictions for the possible damage associated with windstorms (Ostertag et al., 2003; Peterson, 2004). Another problem adding to the lack of information on wind effects on forests is that the full effects of wind are often not felt for several years following the event, as post-windstorm mortality often takes several years to become evident, and long-term assessments of environmental, vegetation, and ecosystem response to these intense storms is complicated by the infrequent and unanticipated nature of these storms (Cooper-Ellis et al., 1999).

Studies of large-scale windstorms have shown that nutrient cycles are affected through the input of significant amount of litter to the ground (Ostertag et al., 2003). This additional litter has generally not undergone any form of transformation, as often occurs with fire, and therefore has the potential of adding greater amounts of nutrients, altering rates of litter decomposition and mineralization (Sanford et al., 1991), and affecting nutrient cycling and exports in stream water (Schaefer et al., 2000). In cases where no previous disturbance weakened the forest it appeared that nutrient changes were not long-term (Bowden et al., 1993; Ostertag et al., 2003).

In a temperate forest a large-scale experimental windstorm did not change nutrient retention rates, in fact, little change in the soil environment occurred (Bowden et al., 1993). It appeared that the forest was extremely resilient to the storm, with biotic controls able to keep ecosystem processes relatively unchanged (Bowden et al., 1993). This minimized response following such a disturbance was related to the reestablishment of vegetation near the forest floor (Cooper-Ellis et al., 1999), which reduces the effects on biogeochemical cycles (Carlton and Bazzaz, 1998). The long-term impacts and the associated recovery following such a disturbance depend on the repair mechanisms during the reorganization stage of the forests (Ostertag et al., 2003).

2.3.5 Acid Deposition

Another disturbance of significant concern today is acid deposition. Generally, this disturbance varies with location, with greater environmental impacts experienced in areas closest to pollution sources. However, due to long-range transport of atmospheric pollutants and different geological resistance, even areas at greater distances from the sources are potentially at risk.

Acid deposition creates acidic conditions in soils if the proportion of ionic exchange sites occupied by acidic cations increases; however, this can also occur naturally as experienced with decomposition of organic matter (Binkley, 1992). When exchange sites are occupied by these acidic cations, H^+ is released and results in a net H^+ load to the system (Binkley, 1992).

Soil studies have shown that soils exposed to SO_4^{2-} levels greater than background levels resulted in accelerated leaching of cations (Harrison and Johnson, 1992). However, with reduced air pollution, inputs and deposition of SO_4^{2-} decrease and can potentially result in the release of SO_4^{2-} previously stored in the soil. This potential release of SO_4^{2-} from soil storage can in turn accelerate the leaching rate of cations, altering associated stream and soil solution chemistry (Lindberg and Garten, 1988). Reductions in SO_4^{2-} concentrations in precipitation have resulted in reduced SO_4^{2-} concentrations at watershed outlets; yet, changes did not occur in pH and losses of Ca^{2+} and Mg^{2+} remained relatively high (Houle et al., 1997).

Research on acid deposition has also been focussed on nitrogen saturation, when nitrogen inputs to the soil from mineralization and the atmosphere exceed retention capacity (Aber et al., 1989). With increased NO_3^- production and concentrations, NO_3^- begins leaching out of the system, which can result in accelerated leaching rates of cations, having been displaced from exchange complexes (Cole, 1992). Eventual nutrient deficiencies for the soil and associated vegetation can arise (Van Miegroet et al., 1992).

Base cations (Ca^{2+}, K^+, Mg^{2+}, and Na^+) are very sensitive to acid deposition and the introduction of H^+ promotes their loss through cation exchange or weathering processes and may result in soil and foliar leaching (Johnson, D., 1992; Church, 1997).

Sulphur emissions and concentrations of sulphur acidifying substances in precipitation in eastern Canada have decreased since the 1970s, while nitric acid and base cation emissions remain elevated (Clair et al., 1997). These additional emissions could be the explanation for altered pH and base cation concentrations in many lakes (Houle et al., 1997). Although sulphur emissions may be reduced, the presence of such additional emissions requires that forests continue to be monitored in order to determine if these emissions are causing any changes in forest dynamics.

2.3.6 Climate Change

In the next 100 years, it is expected that the boreal forests will experience the largest temperature increases of all forest types (WCMC, 2004). Direct impacts to the forest include changes in tree species distribution, growth rates, and nutrient cycling (Peng and Apps, 1998). Indirectly, climate change will affect other forms of disturbances, such as fire regimes (e.g. Bergeron and Flannigan, 1995; Weber and Flannigan, 1997; Bergeron et al. 2001) and insect outbreaks (e.g. Fleming and Volney, 1995).

In efforts to determine how boreal forests will respond to climate change, most studies apply models of potential climate change scenarios. The most common scenarios, determined by Global Circulation Models, are changes in temperature and precipitation, a doubling of ambient carbon dioxide (CO_2) levels, and a combination of these two, temperature and precipitation changes and a doubling CO_2. In all three scenarios, net primary production and total biomass were shown to increase, but only the combination of climate change and CO_2 doubling caused increased decomposition and net N mineralization rates (Peng and Apps, 1998).

Forest composition and species distribution will also be affected by climate change. Studies have attempted to determine how climates in certain areas will change and what tree species will survive. For many boreal species, it appears that expected climate change trends would result in a northward migration of the boreal forest (Burton and Cumming, 1995; Hogg and Hurdle, 1995; Sykes and Prentice, 1995; C-CIARN, 2002; WCMC, 2004). Eventually, new species would dominate the vacated areas and would provide different quality of litter to those areas, thereby altering rates of decomposition and mineralization and ultimately changing the overall chemistry of the area (Weber and Flannigan, 1997).

Another important aspect of climate change is its impact on disturbance regimes (Dale et al., 2000). Fire frequency of the eastern boreal forest is expected to decrease with a changing climate (Bergeron and Flannigan, 1995; Bergeron et al., 2001; Flannigan et al., 2001). This decrease in fire interval is suggested to be related to increased precipitation and relative humidity, while elsewhere in Canada the risk of forest fire is expected to increase when precipitation and relative humidity decrease (Bergeron and Flannigan, 1995; Flannigan et al., 2001).

Climate change could also affect other disturbances, such as insect outbreaks. A decrease in the frequency of late spring frosts and an increase in the frequency of droughts could cause the population density of the spruce budworm to increase and enable it to remain elevated for a longer period of time (Fleming and Volney, 1995). This possible increase in insect defoliation would add dead, dry litter to the forest, potentially making them more susceptible to fire (Fleming and Candau, 1998).

2.3.7 Forest Succession

As already mentioned, disturbances can trigger changes in forest composition, and therefore forest type. However, forests can also undergo such changes even in the absence of disturbances, a process known as succession. No matter what the stimulus, succession results in changes in chemical characteristics of the area due to changes in forest species composition.

Succession is a natural part in a forest's lifecycle. As forests grow, different vegetation forms become more dominant and thus others decline, causing a shift in vegetation. Such changes in forest composition result in changes in the chemical make up of the soil and surrounding area, similar to the effects of disturbance induced shifts in vegetation and forest structure. These changes will eventually be expressed in water and soil solution chemistry.

This natural progression of forests, and the associated chemistry changes, can complicate studies which attempt to determine if disturbances are responsible for any observed chemical composition changes in forests.

This study looks at the extent to which the disturbance history of a boreal forest in Newfoundland is reflected in the water chemistry. The short-term effects of a recent forest fire on stream and soil solution chemistry were studied, as were the long-term effects of past disturbances on available water chemistry. It is expected that the effects of the recent forest fire will be reflected in water chemistry, due to the initial impacts to the area, and that nutrients in stream and soil solution will increase in the burned region. Based on other long-term studies, which have shown that most detectable water chemistry changes following a disturbance return to normal levels after 10 years ((MacLean and Wein, 1977; Gordon and Van Cleve, 1983; Lynham et al., 1998; MacEachern et al., 2000; Martin et al., 2000; Simard et al., 2001), it is not expected that water chemistry data available for areas having experienced past disturbances will be distinguishable from water chemistry data available for areas having no record of any significant past disturbances.

2.4 Study Area

In Newfoundland and Labrador, 60.5% of the land area is forested (Natural Resources Canada, 2003) with the boreal forest being the dominant forest type. Newfoundland's history is closely tied to its forest resources, seen as an important economic commodity. As such, they have been continuously harvested, however, these forests have also had to experience other disturbances, mainly fire, windthrow, insect and disease outbreaks, as well as the effects of climate change and acid deposition.

Terra Nova National Park, designated in 1957, typifies the eastern boreal forest of Newfoundland. The park is situated at 54° 00'W, 48° 30'N on the east coast of Newfoundland and covers an area of approximately 400 km^2 (Figure 2.2). The vegetation is characteristic of the eastern boreal forest: black spruce (*Picea mariana* (Mill.) BSP) and balsam fir (*Abies balsamea* (L.) Mill) are the dominant tree species, with some eastern larch (*Larix laricina*) and minor remnants of eastern white pine (*Pinus strobus* L.) (Power, 2000). White spruce (*Picea glauca* (Moench) Voss)) is rare and balsam poplar (*Populus balsamifera* L.) absent due to nutrient poor soils (Power, 2000). Sheep laurel (*Kalmia angustifolia)* is the dominant shrub, and co-occurs with a number of different species of flora, moss, and lichen (Power, 2000).

Figure 2.2 Location of study area - Terra Nova National Park, Newfoundland

Forest communities, classified by Damman (1964), take vegetation, soil moisture, nutrient status, and topographic position into consideration. A more recent park biophysical classification system (Gauthier et al., 1977) is based on site conditions and past disturbances. Using the Damman forest communities, black spruce (including scrub spruce) and balsam fir communities together make up greater than 70% of the parks total area (Power, 2000). Each forest community is characterized by a dominant type of disturbance, for black spruce this is fire whereas while balsam fir do experience fire, the most common disturbance is insect outbreaks (McCarthy, 2001).

The soils in Newfoundland have developed since the last glaciation and are generally acidic in nature. Although the total nutrient content in the soils may be high, the low pH makes these nutrients unavailable for vegetation and therefore they are classified as nutrient poor (Roberts, 1983). In Terra Nova National Park soils are primarily podzols with a bleached grey A horizon over a brown to reddish-brown B horizon. The sharp colour contrast of these horizons is related to the leaching of minerals from the A to the B horizon.

The climate of Newfoundland is related to the northern hemisphere mid-latitude atmospheric circulation, the proximity to mainland Canada, and, perhaps most importantly for the east coast, the influence of the cold ocean surface, primarily the Labrador Current (Banfield, 1983). For the park area, summers are cool and short with a mean summer (May-Sept) temperature of 12.6°C and mean summer rainfall of 448.9 mm; average summer relative humidity is 68%. The majority (75%) of the 1184.3mm of total annual precipitation falls as rain. Winds are predominantly from the south-southwest and summer winds average 20.6 km/hr (Power, 2000).

2.4.1 Disturbance History

The 2002 Wildfire Event

Terra Nova National Park, like most boreal forests, has a history of disturbance events. However, due to efficient fire suppression no large-scale fires, required for stand-renewal, have recently occurred in the park. Consequently, fire management has been outlined as one of the vegetation management issues for Terra Nova National Park (Power, 2000). It has also been recommended that prescribed burns be used in order "to restore and to maintain natural vegetation patterns and processes in the Terra Nova forest landscape", mainly for black spruce forests (Power, 2000).

On June 13, 2002 while preparations were being made for a prescribed burn in the Rocky Pond access road area, a fire ignited and burned an area of 98 ha (Figure 2.3). Examination of burned trees showed two different zones of intensity, a high intensity burn characterized by scorched trees where no needles remained, and a lower intensity burn, where some needles remained on trees.

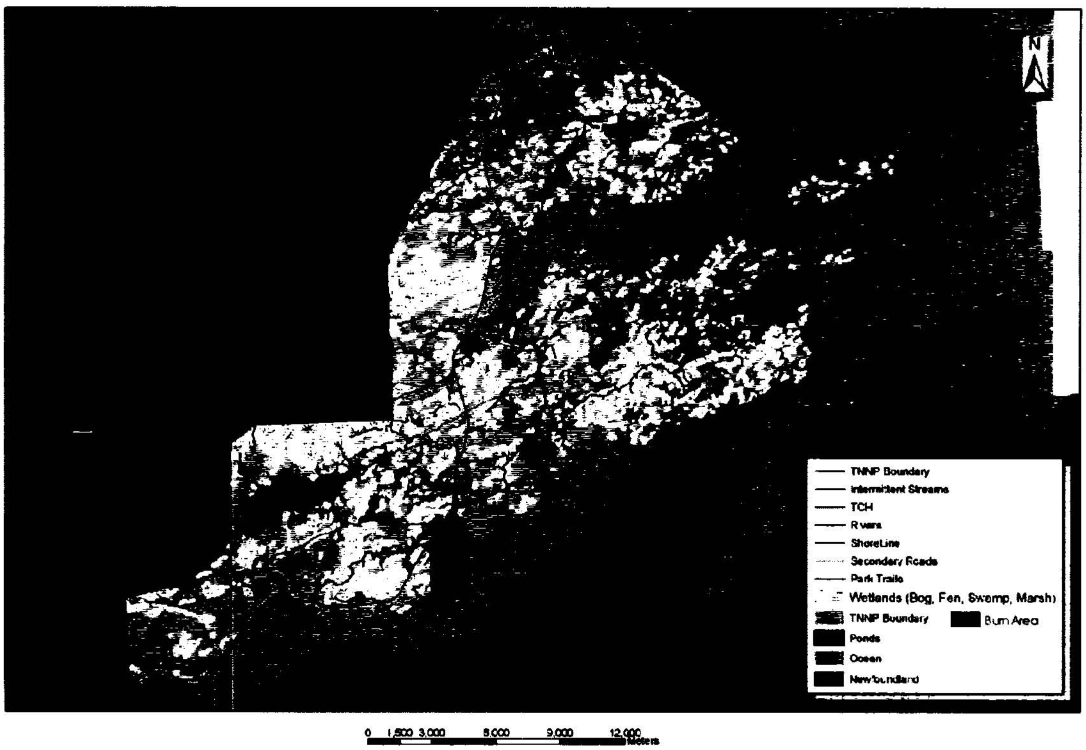

Figure 2.3 Location of burn area in Terra Nova National Park

Vegetation in the Rocky Pond Road area is characterized by reindeer lichen (*Cladonia rangiferina*), sheep laurel, and black spruce; the Damman forest type is

Cladonia-Kalmia-Black Spruce (SKc #21) (Meades and Moores, 1989). The Canadian Forest Fire Behaviour Prediction system (Forestry Canada Fire Danger Group, 1992) divided black spruce communities into two fuel types: 1) spruce-lichen woodland types, with open stands and well-drained uplands with continuous mats of lichen ground cover and 2) boreal spruce types, with a more closed canopy black spruce stand with a carpet of feather and sphagnum mosses (Johnson, E., 1992). The Rocky Pond burn area falls into the first group, spruce-lichen woodland, which is much more flammable than the second, due to the more open canopy which allows for direct insolation and drying of the lichen forest. Soils in this area are mainly podzols and are very sandy. From field work, the Ae (6cm deep), Bf1 (19cm deep), Bf2 (31cm deep), and C horizons were distinguished and an iron pan was encountered approximately 25 cm below the ground cover (Power, pers. comm.). Because of this iron pan, tree roots are found at shallow depths (Power, 2000).

The difference in soil type, and associated processes, in this forest community and fuel type results in a different hydrology, and can result in different chemical characteristics. While the chemistry might be different, it is not expected that the effects of fire in this forest type would be different than in other forest types. Regardless of location, a forest fire burns forest material and releases nutrients to the soil and the surrounding environment. Such releases affect the concentrations of nutrients in the water chemistry.

Historical Events

As expected, the disturbance history of Terra Nova National Park includes more than just fire. From the late 1800s until the creation of the park in 1957, forest harvesting played a prominent role in the area, with wood supplying many local sawmill and woodcutting operations (Major, 1983; Munro, 2001). Normally, logging is not permitted in the national parks of Canada but cutting did occur in Terra Nova National Park for several years following its establishment, although no records account for the magnitude of this activity (MacEachern, 2001). Wood was reported to have been taken for the construction of infrastructure in the park as well as being offered to local residents to harvest for personal purposes (MacEachern, 2001). This history of logging undoubtedly resulted in disturbance to the forest. The location and timing of the logging activities can be seen in Appendix 2-1.

The park also has a history of wildfire. Although fire has occurred in the past, the rate at which it currently occurs has decreased greatly over the last 70 years or so (Power, 1996). From records of fires in Newfoundland (Wilton and Evans, 1974) and from the park and surrounding area (Power, 1996, 2000), a list of fires having directly affected Terra Nova National Park was compiled; see Appendix 2-2.

Significant spruce budworm outbreaks did not occur in Newfoundland until the 1970s, with a major outbreak lasting from 1972-1984 (Canadian Council of Forest Ministers, 2003). Currently in Terra Nova National Park, there is concern about the combination of insect defoliation and mammalian herbivory, specifically moose, and the possible resulting ecological problems (Power, 2000), as herbivores are known to have a strong impact on succession after outbreaks and blowdowns (Peterson and Pickett, 1995).

Although insect outbreaks and wind are disturbances that affect the park, they generally occur at non-epidemic levels and much of the wind damage is not distinguishable from trees which fell following insect disturbance (Power, pers.comm.).

As well, following insect outbreaks trees die slowly over a number of years (Baskerville and MacLean, 1979; Nealis and Ortiz, 1996) and post-windstorm mortality takes several years to become evident (Cooper-Ellis et al., 1999). Therefore, the low levels of these disturbances in the park combined with the time requirement for the effects to transpire makes studying them in the context of the watershed chemistry extremely difficult.

In terms of acid deposition, Clair et al. (1997) reported a lack of acidification related trends in lake data from Terra Nova National Park. It was suggested that this indicated that the low acid deposition in the area was not significantly affecting the water chemistry, mainly because this area of Newfoundland is sufficiently removed from sources of acid emissions.

The above section has provided a very brief history of known disturbance in Terra Nova National Park but does illustrate those disturbances which are more relevant to the area. It is expected that given the disturbance history of the park, the disturbances of fire and logging would be more significant in terms of lasting effects than the other disturbances known to have occurred.

2.5 Methodology

There were two components to this study: one using data collected through field work and the second using previously collected data.

2.5.1 Field Methods

Soil Solution Sampling

Tray lysimeters (zero-tension lysimeters) were used to sample shallow soil solution following a design of B. Roberts of Forestry Canada (Roberts, pers. comm.). The lysimeters were made of plastic containers, approximately (L) 40 cm x (W) 28 cm x (D) 14.5 cm, with plastic grids placed in the bottom of them. Fittings were secured in a drilled hole in each lysimeter, which allowed for tubing to be attached, connecting the lysimeter to a collecting bucket (Appendix 2-3). Six lysimeters were placed in the area on August 28, 2002: two in an unburned area located adjacent to the burned area, two in the high intensity burn area, and two in the lower intensity burn area.

Approximately 10 cm depth of forest floor material (duff) was placed in the trays on site. Collecting buckets were located downslope from the lysimeters. Samples were pumped from these buckets into sterile plastic Nalgene® bottles using hand pumps. After each sampling, buckets were completely emptied by continuous pumping. See Appendix 2-4 for a complete list of sample dates and the number of samples from each visit. The volume of water pumped out at each visit, representing the approximate volume of water collected in each bucket between sampling visits, was recorded. The samples were analyzed for pH, conductivity, and colour prior to further chemical analysis. All lysimeters but one in the unburned area were left in place over the winter (Nov. 2002 – May 2003); they were all subsequently removed in July 2003.

Stream Sampling

Stream samples were collected from Terra Nova Brook, which flowed through the burn area. Three sampling locations were used, one from within the burned area and two locations upstream of the burn. Two locations were sampled upstream of the burn due to the placement of a highway culvert at the time of sampling. The construction could have disturbed the water in the stream, therefore samples were taken from both upstream and downstream of the culvert.

Water samples were collected in 250 mL and 500 mL sterile Nalgene® bottles and underwent the same analysis procedures as soil solution samples.

In addition to water samples, conductivity and oxygen saturation readings were taken at all stream locations, using the Exatech 470303 or WTW conductivity meter and LF 318 and Orion Dissolved Oxygen Meter model 810 Aplus respectively.

Water Chemistry

Soil solution and stream samples were analyzed for pH (using Orion portable pH meter model 230 Aplus), conductivity (using either the Exatech 470303 or WTW conductivity meter LF 318 respectively), and colour (using an Aquaquant 14421 colour comparator). The soil solutions were then passed through a 45 μm filter prior to further analysis.

Ion chromatography (IC) was used for the chemical analysis of cations (Na^+, K^+, Mg^{2+}, Ca^{2+}, NH_4^+-N) and anions (Cl^-, NO_3^-, SO_4^{2-}, PO_4^{2-}-P). The ion chromatograph (Dionex DX-100) was located at Memorial University of Newfoundland. Details of this chemistry procedure can be found in Appendix 2-5.

2.5.2 Disturbance History and Database Search/Lake and Stream Water Chemistry

In order to obtain a thorough history of disturbance in Terra Nova National Park, extensive searches were conducted and information collected on the type, timing, and location of each disturbance. Ultimately, only the forest harvesting and wildfire were included in this study. Insect outbreaks, windthrow, and acid deposition were excluded based upon the lack of precision in identifying timing of these disturbances or the apparent lack of significant effects in the area. It is also important to consider that in general, fire is the most common disturbance in black spruce forests and insect outbreaks are the most common disturbance in balsam fir forests (McCarthy, 2001).

A search was conducted in order to compile any existing water chemistry data for lakes in Terra Nova National Park. Water chemistry data was found to be available for a limited number of lakes for 1965 (Deichmann and Bradshaw, 1984) and 1969 (Kerekes, 1974). The main source of data came from Environment Canada (ENVIRODAT) and the Acid Precipitation Monitoring Network in Atlantic Canada (Clair, 2001). Ultimately, sufficient data existed for only 13 lakes to be analyzed statistically, see Appendix 2-6.

Water chemistry was available for four streams in the park; however only two of these streams provided enough data to be explored, these being Bread Cove Brook and Southwest Brook (Appendix 2-6).

The locations where logging and fire were known to have occurred were overlaid with the locations for which water chemistry was available. Those watersheds that overlapped could be used as indicators of disturbance. Overall, seven areas were deemed to have sufficient chemistry data and also have endured a recent disturbance. These overlaps can be seen in Table 2.1.

Table 2.1: Areas in Terra Nova with known disturbance and available water chemistry

Disturbed Area	Type	Time	Lakes/Streams
Bread Cove	Logging	1920-1950	Bread Cove Brook
Minchin Cove	Logging	1925-1950	Minchin Pond
			Big Pond
Charlottetown	Logging	1940-50s	Yudle Pond
	Fire	1957	
		1974	
		1986	
		1982	other side-no pond
Fox Pond	Fire	1970	Ochre Hill Pond N
Blue Hill West	Fire	1986	Pine Hill Pond
No known disturbance			Long Waters Pond S
			Shallow Pond #3
			Rattle Pond
			Chatman Pond W
			Nameless Pond #2
			Bog Pond
			Jay Pond
			Moses Cove Pond

2.5.3 Statistical Methods

Park Lakes and Streams

Basic exploratory statistics were carried out on the accumulated water chemistry data, after grouping by year, including descriptive statistics, normality tests, homogeneity of variance tests, and difference plots, using SPSS Version 10.0. Confidence intervals at the 95% confidence level were calculated from the median in order to determine which lakes, if any, had similar chemical profiles. Multivariate ANOVA was also done for the park lakes (using the full-factorial model and calculating the sums of squares of an effect as the sums of squares adjusted for any other effects that do not contain it and orthogonal to any effects (if any) that contain it). Residual tests included residual plots and residual sum-of-squares and cross-product matrix (SSCP).

Rocky Pond Road Area Samples

Similar statistics were used for water samples from the burn area, including basic exploratory statistics and confidence intervals.

2.6 Results

2.6.1 Rocky Pond Road Area Fire

Terra Nova Brook

Terra Nova Brook was initially sampled at three locations but early results showed that there was no detectable difference in concentrations between the samples taken above and below the culvert, therefore sampling was reduced to one location, below the culvert (on the east side of the Trans-Canada Highway).

Ammonium and phosphate concentrations were found to be negligible and were excluded from further analysis. The 95% confidence intervals (Appendix 2-7: Terra Nova Brook) and boxplots (Appendix 2-8: Terra Nova Brook) for the remaining 10 variables (pH, conductivity-field, conductivity-lab, Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, and Ca^{2+}) revealed that the medians of samples from the burn region were higher than those upstream, except for pH. This trend was also noticeable in the time-series plots (e.g., Cl^-

in Figure 2.4; Appendix 2-9: Terra Nova Brook). However, although differences were noted, these differences were not significantly different.

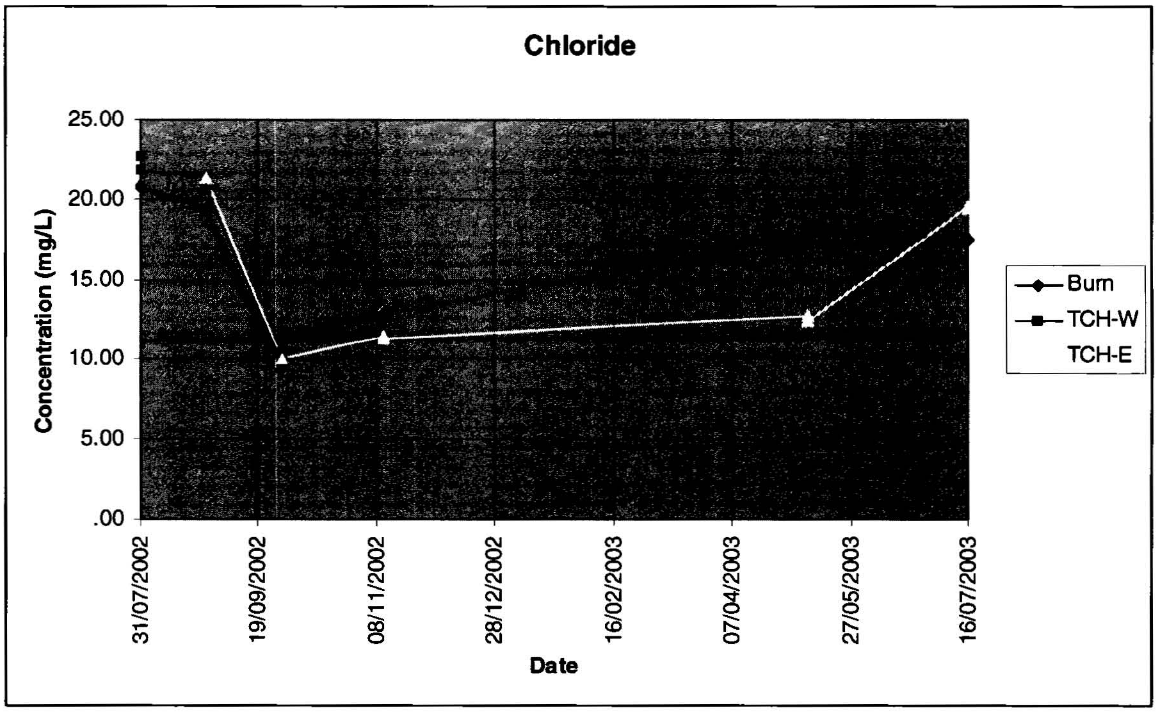

Figure 2.4 Chloride concentrations from samples in and upstream of burn area

Over the course of sampling, the two locations showed similar trends for all but one studied variable. Initially, nitrate appeared to be relatively high in the burn area, compared to upstream, but concentrations began to decrease gradually. Following the 2003 winter, the upstream location increased in nitrate concentration while in the burn, concentrations fluctuated.

Lysimeters

Nitrate and ammonium concentrations were low or non-existent for all locations at all times, and they were not included in the analysis. The confidence intervals (Table 2.2; Appendix 2-7: Rocky Pond Road lysimeters) and boxplots (Appendix 2-8: Rocky Pond

Road lysimeters) for the remaining 9 variables (conductivity, pH, Cl^-, PO_4^{2-}, SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+}) showed that conductivity, PO_4^{2-} (Figure 2.5), SO_4^{2-}, and K^+ in the unburned region were lower than in both the burned regions and Cl^- and Na^+ in the unburned region were lower than in the high intensity burn area. There was a minor overlap in pH, with the unburned region being slightly higher than both burned regions. Mg^{2+} and Ca^{2+} did not differ among the three cases. However, overall, the high intensity burn results were not distinguishable from the low intensity burn.

Table 2.2: 95% Confidence intervals for Rocky Pond Road lysimeters

	Cond.	pH	Cl	NO 3	PO4	SO4	Na	NH 4	K	Mg	Ca
Unburn	18.88 - 22.52	3.90 - 4.03	1.43 - 2.08	0	0.00	0.63 - 1.01	0.85 - 1.29	0	0.36 - 0.46	0.16 - 0.19	0.12 - 0.37
Low	43.95 - 51.05	3.61 - 3.97	1.66 - 4.10	0	1.32 - 3.28	1.10 - 1.62	1.24 - 1.89	0	2.78 - 3.41	0.19 - 0.26	0.15 - 0.42
High	45.86 - 63.04	3.59 - 3.90	2.93 - 5.17	0	3.00 - 4.96	1.16 - 2.11	1.42 - 2.40	0	2.49 - 3.74	0.15 - 0.33	0.16 - 0.33

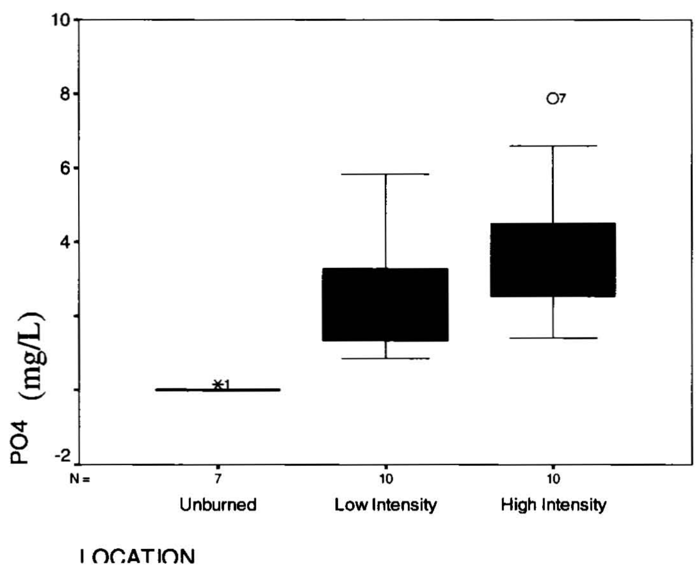

Figure 2.5: Boxplot of phosphate from Rocky Pond Road lysimeters

The time-series plots of the lysimeters by location (Appendix 2-9: Rocky Pond Road lysimeters) also indicate consistently higher conductivity, Cl^-, NO_3^-, SO_4^{2-}, Na^+, and Mg^{2+} concentrations in the burned regions; pH (Figure 2.6) was higher for the unburned while no pattern was seen in Ca^{2+}. Conductivity, Cl^-, PO_4^{2-}, Na^+, and Mg^{2+} were consistently greater in the higher intensity burn area than in the lower intensity burn area, however these differences were not significantly different.

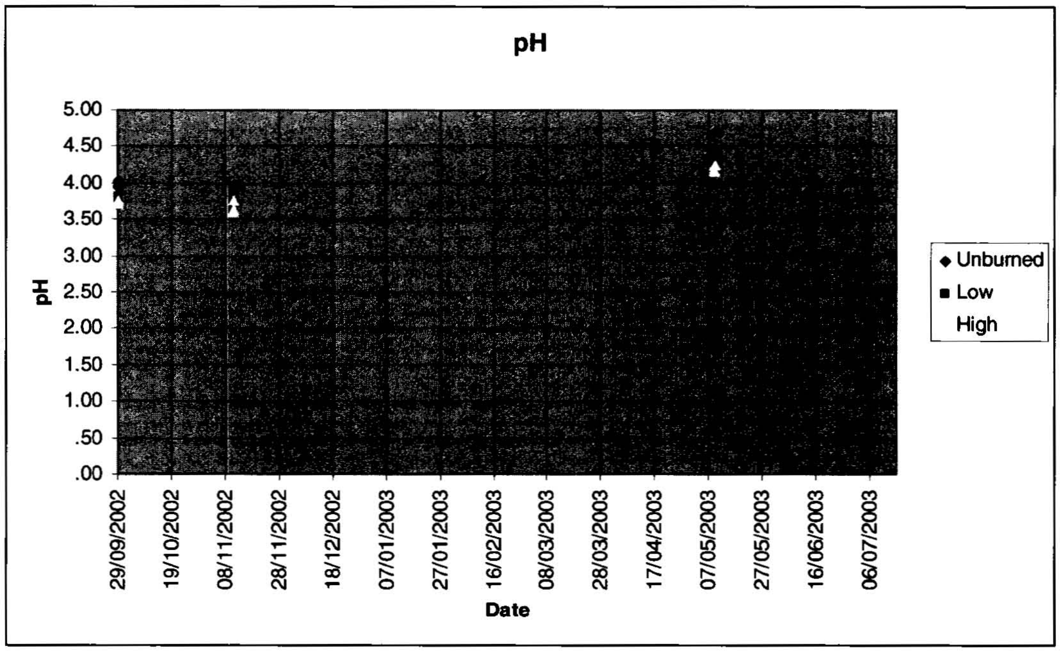

Figure 2.6: pH plot from Rocky Pond Road lysimeters

2.6.2 Surface Water Chemistry

Lakes

Data from 13 lakes with sufficient chemistry data, whether associated with a recent disturbance or not, were analyzed with respect to 11 variables (alkalinity, conductivity, colour, pH, DOC, Ca^+, Mg^+, Na^+, K^+, Cl^-, SO_4^{2-}). The greatest number of samples available for the lakes (summarized by year) was slightly over 30, with some lakes having only 15 or 20 samples.

The mulivariate ANOVA showed that the lakes were significantly different one from another based on the studied variables. Values for one lake, Pine Hill Pond, appeared anomolous. Two separate mulivariate ANOVAs were calculated, one including Pine Hill Pond and one excluding it. As seen in Table 2.3, even with the exclusion of Pine Hill Pond, the remaining lakes remained significantly different from each other with respect to water chemistry. Residual tests confirmed that there was no relationship between the variables.

Table 2.3: ANOVA results without Pine Hill Pond

	F	df	P-value
Alkalinity	42.558	11	< 0.0001
Conductivity	88.903	11	< 0.0001
Colour	34.24	11	< 0.0001
pH	22.787	11	< 0.0001
DOC	16.966	11	< 0.0001
Ca	78.055	11	< 0.0001
Mg	37.963	11	< 0.0001
Na	106.535	11	< 0.0001
K	6.21	11	< 0.0001
Cl	84.008	11	< 0.0001
SO4	14.025	11	< 0.0001

From the confidence intervals, Shallow Pond and Rattle Pond appeared similar, overlapping for all 11 variables, while Chatman Pond West overlapped with Ochre Hill Pond for 8 variables, and with Jay Pond for 7 variables (Table 2.4; Appendix 2-7: Park lakes and streams). In terms of calculated medians (Table 2.5), Bog Pond and Pine Hill Pond were the most different from the others, with Bog Pond having the lowest medians (for 8 of the 11 variables) and Pine Hill Pond the highest medians (for 9 of 11). Pine Hill

Pond had an extreme range of values for many variables, including conductivity, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and SO_4^{2-}.

Table 2.4: 95% confidence intervals of water chemistry variables for park lakes and streams

Ponds	Alkalinity (mg/L)	Cond. (µS/cm)	Colour (rel units)	pH	DOC (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)
Long Waters S	1.76 - 2.24	18.36 - 19.94	38.51 - 51.49	6.02 - 6.18	6.43 - 7.77	1.25 - 1.35	0.29 - 0.33	1.61 - 1.79	0.14 - 0.18	2.36 - 2.60	0.84 - 1.10
Ochre Hill N	1.09 - 1.55	18.87 - 21.13	89.61 - 110.39	5.50 - 5.70	8.14 - 9.76	0.91 - 1.07	0.34 - 0.40	2.02 - 2.18	0.17 - 0.21	2.51 - 2.71	0.92 - 1.08
Shallow #3	2.02 - 2.48	23.03 - 24.97	34.80 - 45.20	6.12 - 6.28	6.59 - 7.41	1.22 - 1.38	0.38 - 0.42	2.41 - 2.59	0.20 - 0.22	3.37 - 3.63	1.05 - 1.35
Rattle	2.04 - 2.56	23.24 - 25.36	28.37 - 38.63	6.22 - 6.38	5.97 - 6.73	1.22 - 1.36	0.38 - 0.43	2.50 - 2.70	0.21 - 0.23	3.48 - 3.92	1.13 - 1.38
Chatman W	2.37 - 3.25	20.54 - 23.46	82.10 - 97.90	6.04 - 6.26	8.47 - 10.63	1.30 - 1.70	0.37 - 0.47	2.04 - 2.36	0.15 - 0.22	2.43 - 2.73	0.88 - 1.11
Nameless #2	3.17 - 3.98	26.35 - 29.65	39.23 - 52.77	6.22 - 6.38	6.37 - 8.23	1.65 - 1.92	0.49 - 0.57	2.69 - 2.91	0.22 - 0.25	3.68 - 4.11	1.44 - 1.96
Bog	1.19 - 1.51	13.52 - 16.48	24.73 - 35.27	5.82 - 5.98	4.57 - 5.93	0.61 - 0.76	0.21 - 0.26	1.42 - 1.74	0.18 - 0.22	1.66 - 1.95	0.72 - 1.14
Jay	2.47 - 3.13	27.00 - 31.00	75.91 - 104.09	5.90 - 6.10	10.57 - 13.43	1.82 - 2.24	0.44 - 0.56	2.52 - 2.85	0.21 - 0.25	3.32 - 3.85	0.89 - 1.11
Moses Cove	1.46 - 1.74	35.20 - 36.80	20.86 - 29.14	5.95 - 6.05	5.55 - 6.25	1.07 - 1.13	0.55 - 0.59	4.28 - 4.52	0.30 - 0.34	6.80 - 7.12	2.02 - 2.18
Yudle	4.30 - 6.50	37.11 - 54.89	24.05 - 40.95	6.52 - 6.88	7.72 - 12.28	2.95 - 3.55	0.45 - 0.50	3.47 - 5.33	0.20 - 0.20	3.75 - 8.15	1.94 - 2.36
Minchin	2.87 - 5.58	26.77 - 31.83	35.16 - 44.84	6.32 - 6.58	7.67 - 9.33	1.84 - 2.06	0.49 - 0.53	2.73 - 2.97	0.20 - 0.27	3.50 - 4.20	1.08 - 1.81
Big	3.12 - 5.58	20.97 - 27.03	45.62 - 54.38	6.04 - 6.56		1.50 - 2.10	0.45 - 0.48	2.35 - 2.55	0.21 - 0.24	3.31 - 3.47	1.27 - 1.36
Pine Hill	8.37 - 10.03	145.16 - 197.84	9.23 - 20.77	6.80 - 7.10	5.79 - 8.21	6.27 - 7.53	0.94 - 1.06	17.62 - 30.38	0.42 - 0.58	27.64 - 51.36	3.76 - 4.64
Bread Cove Brook	2.38 - 2.82	24.44 - 26.36	37.85 - 42.15	6.21 - 6.31	5.64 - 6.16	1.40 - 1.54	0.38 - 0.42	2.42 - 2.62	0.19 - 0.21	3.34 - 3.72	2.18 - 2.42
South-West Brook	3.49 - 4.30	31.39 - 33.91	97.13 - 102.87	6.16 - 6.30	9.71 - 10.69	1.99 - 2.21	0.52 - 0.56	3.33 - 3.59	0.29 - 0.31	4.52 - 4.86	4.30 - 4.70

Table 2.5: Median ion concentrations of water chemistry variables park lakes and streams

Ponds	Alkalinity (mg/L)	Conductivity (µS/cm)	Colour (rel units)	pH	DOC (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO4 (mg/L)
Long Waters S	2.00	19.2	45	6.10	7.1	1.300	0.310	1.700	0.160	2.480	0.970
Ochre Hill N	1.32	20.0	100	5.60	9.0	0.990	0.370	2.100	0.190	2.610	1.000
Shallow #3	2.25	24.0	40	6.20	7.0	1.300	0.400	2.500	0.210	3.500	1.200
Rattle	2.30	24.3	34	6.30	6.4	1.290	0.405	2.600	0.220	3.700	1.255
Chatman W	2.81	22.0	90	6.15	9.6	1.500	0.420	2.200	0.185	2.580	0.995
Nameless #2	3.58	28.0	46	6.30	7.3	1.785	0.530	2.800	0.235	3.895	1.700
Bog	1.35	15.0	30	5.90	5.3	0.685	0.235	1.580	0.200	1.805	0.930
Jay	2.80	29.0	90	6.00	12.0	2.030	0.500	2.685	0.230	3.585	1.000
Moses Cove	1.60	36.0	25	6.00	5.9	1.100	0.570	4.400	0.320	6.960	2.100
Yudle	5.40	46.0	33	6.70	10.0	3.250	0.475	4.400	0.200	5.950	2.150
Minchin	3.60	29.3	40	6.45	8.5	1.949	0.512	2.850	0.236	3.846	1.445
Big	4.35	24.0	50	6.30		1.800	0.467	2.453	0.225	3.394	1.311
Pine Hill	9.20	171.5	15	6.95	7.0	6.900	1.000	24.000	0.500	39.500	4.200
Bread Cove Brook	2.60	25.4	40	6.26	5.9	1.470	0.400	2.520	0.200	3.530	2.300
South-West Brook	3.90	32.7	100	6.23	10.2	2.100	0.540	3.460	0.300	4.690	4.500

From the time-series plots of the lakes, it was possible to see how each lake's chemical composition changed over time. As well, the plots revealed if any of the lakes demonstrated unusual composition at a certain time, possibly a consequence of a disturbance. All time-series plots can be seen in Appendix 2-9: Park lakes.

Shallow Pond (Figure 2.7) and Rattle Pond (Figure 2.8) changed similarly, with similar trends for all variables. Chatman Pond West and Ochre Hill Pond also changed similarly for most variables.

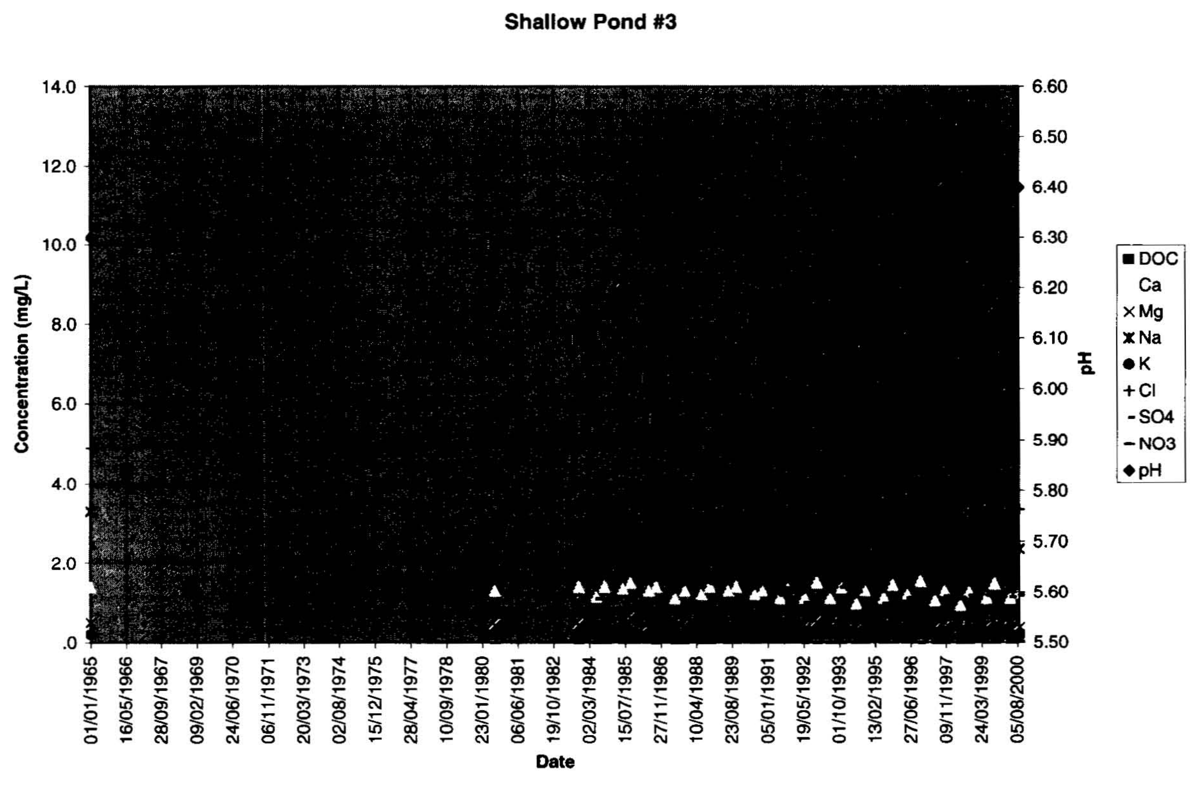

Figure 2.7: Water chemistry for Shallow Pond #3

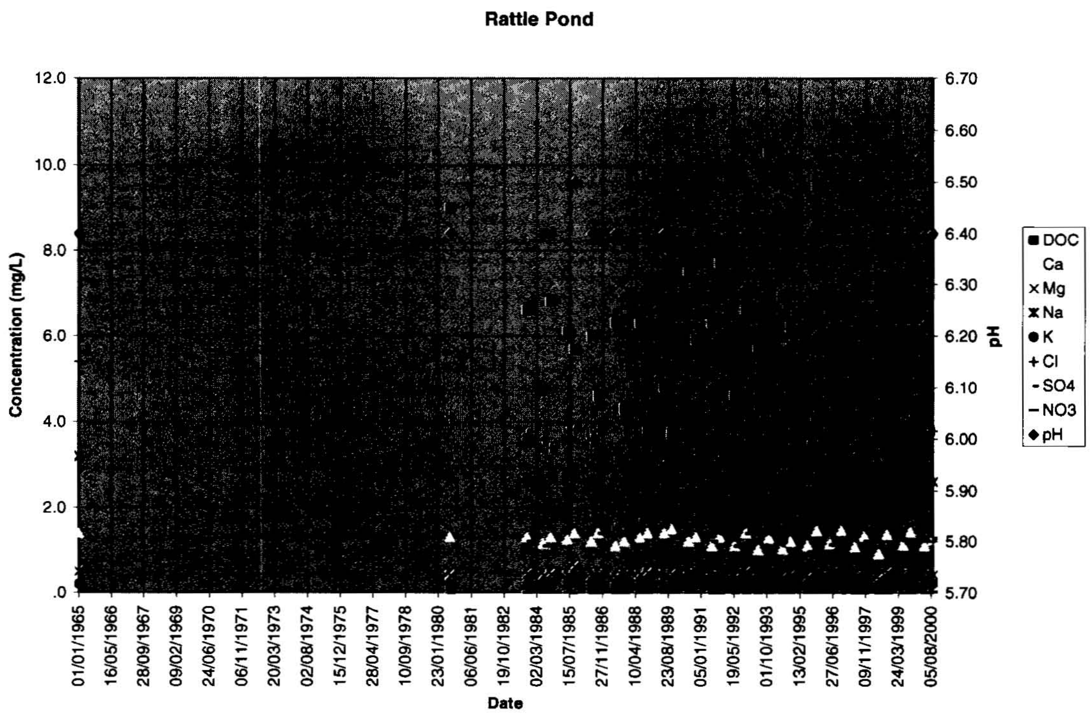

Figure 2.8: Water chemistry for Rattle Pond

When changes at Pine Hill Pond were plotted relative to the other lakes, its unique chemical composition was again apparent. Although data were not continuous over the approximately 20 years of sampling, enough data were available to reveal the unique behaviour of the lake for all variables but colour and DOC. Data from 1965 and 1969 show similar values but in 1983 all measures decreased considerably and then increased soon after. Sampling in 1990 showed that values for some parameters had once again dropped but by 1991 had risen considerably and returned to levels comparable to earlier years. Samples taken in 2000 revealed that the variables appeared to have stabilized somewhat at higher values.

Streams

Confidence intervals (Appendix 2-7: Park lakes and streams) and boxplots (Appendix 2-8: Park streams) for the two streams overlapped for pH and alkalinity. However, the streams were distinguishable from each other in all other variables. The medians for Southwest Brook for all variables but pH were greater than those for Bread Cove Brook (Table 2.5).

Looking at the time-series plots of the two streams for the 11 variables (Appendix 2-9: Park streams), it was possible to visually compare the trends of the streams. While the records showed similar patterns at times, there were other times when only one stream seemed to exhibit any change, such as peaks for Mg^{2+} in Bread Cove Brook in 1990 and for conductivity, Na^+, and Cl^- in 1995; Southwest Brook had peaks in 1989 for conductivity, Na^+, and Cl^-. When comparing the general oscillating trends of the two lakes, it appeared that Southwest Brook was more variable than Bread Cove Brook.

Bread Cove Brook was plotted on its own for all available variables in order to better determine whether any past disturbance had any affect on the streams chemical signature (Appendix 2-9: Bread Cove Brook).

2.7 Discussion

2.7.1 Rocky Pond Road Area

While water samples from Terra Nova Brook near the burned region had consistently higher concentrations of nutrients than those taken upstream, the results were not statistically distinguishable. It is likely that the expected nutrient increases in the receiving waters were offset by vegetation uptake, as the fire occurred during a time of vegetation growth (Bayley, et al., 1992).

In terms of soil solution, the results of chemical comparisons at the Rocky Pond Road area are in agreement with what would be expected in a burn area. The burning of organic matter results in direct nutrient mineralization and a heightened nutrient release ultimately to be leached into the soil (Bourgeau-Chavez et al., 2000). The differences in PO_4^{2-} concentrations between the unburned region, which recorded negligible concentrations, and the burned regions agree with other studies which reported increased phosphorus compounds following a burn (Schindler et al., 1980; Bayley et al., 1992; McEachern et al., 2000).

The time-series plots did suggest a difference in nutrient concentrations between the two burn intensities. Previous studies have shown that in a higher-intensity burn, soil nutrient concentrations may be less than in a lower-intensity burn, due to increased volatilization (Lynham et al., 1998). However, it has also been suggested that a greater ash layer on the surface may supply greater concentrations of nutrients leached into the soil. In this study, although a visual vegetation difference was noted between the high and low intensity burn areas, no significant chemical difference could be determined.

2.7.2 Park Lakes and Disturbance Events

Although a number of lakes were distinguishable for certain variables based on graphs and box plots, these differences bore no relationship to the watershed forest disturbance history.

Because of the time gap between the end of the logging activity in the mid-1950s and the first recorded sample in 1965, it is likely that any effects on water chemistry had been mitigated and the chemistry had reached a state of equilibrium. The lack of water data prior to harvesting meant it was not possible to determine if the lakes in the harvested regions had reached a new equilibrium or had returned to levels which existed prior to the disturbance.

The Minchin Pond-Big Pond area was logged between 1925 and1950 and possibly late into the 1950's. From the available data, it appears that both Minchin Pond and Big Pond had recovered from any effects of this activity by 1965, when samples were first taken. In Big Pond, differences in certain ion concentrations between 1965 and 1980 did not relate to any disturbance during that time and no such differences could be seen in the Minchin Pond data. Similarly, as expected, the water chemistry data available for Bread Cove Brook from 1980-1995 did reflect the earlier logging disturbance, which occurred until the mid 1900s.

As with logging activities in the park, the outbreaks of fire were not reflected in the water chemistry. Yudle Pond had the most recent record, with fires nearby in Charlottetown in 1957, 1974, and 1986, as well logging which occurred in this region during the 1940's and 1950's. Although differences in nutrient concentrations were evident from the time-series plot, they did not seem to coincide with any of the known disturbances.

A fire occurred in the Ochre Hill Pond N watershed in 1970 and although small changes in ions were noted between 1965 and 1980, it appeared that most parameters remained near the 1980 values for the remainder of the sampling period. If the changes between 1965 and 1980 stemmed from the fire, it is expected that with time the values would have begun to drop back to pre-fire levels, but this did not occur.

The fire at Blue Hill West occurred in the Pine Hill Pond watershed; however, due to the anomalous behaviour of the Pine Hill Pond record, as discussed below, it was not possible to determine if the fire had had any impact on the chemistry.

A change in vegetation density as well as species composition has been reported following harvesting (Power, 1996). Dense stands of black spruce-moss forests which were present prior to harvesting did not regenerate (Damman, 1964; Power, 1996). Pine was a preferred wood for harvesting but the rate of harvesting was not sustainable for this species, resulting in very little pine occurrence today (Power, 2000). In general, once harvesting operations cease, forest communities that regenerate are not necessarily the same as those that were present prior to harvesting (see Meades and Moores, 1989 for specific forest regeneration successions). If a shift in vegetation occurs, changes in nutrient levels of the soils, soil solution, and nearby streams would subsequently change. However, this would require pre-harvest data as well as a long-term post-harvest study in order to capture such changes.

Power (2000) reported that following the fires in Newman Sound, Charlottetown, and Blue Hill West, *Kalmia* was the dominant species, while spruce regeneration, having dominated the areas prior to the fires, was suppressed. Because *Kalmia* reduces available nutrients (Damman, 1971; Titus et al., 1995; Wallstedt et al., 2002), it is expected that nutrient levels at those sites would be lower than they were prior to the fires. This nutrient change would not be seen immediately but should occur in the years following the fires, with the regeneration of vegetation. Unfortunately the records that exist for the lakes are not sufficient to determine if such a vegetation change has affected water chemistry. No long-term water chemistry data exist for lakes on Newman Sound, data available for the Charlottetown area do not extend far enough to enable vegetation change following the fire to be observed, and the data available for Pine Hill Pond (near the Blue Hill West fire) is extremely erratic. Whether water chemistry changes will ensue due to this shift in vegetation, and how long it will take for such chemical changes to be seen, depends on many factors associated with the transport of water through these systems.

Vegetation shifts, such as those which can occur after fire and logging, can also occur in the absence of disturbances. Forests go through natural succession resulting in forest composition and structure changes, and therefore changes in chemical composition. Because these changes occur without any preceding disturbance event, they may complicate attempts to determine how a disturbance event affects forest structure and associated characteristics.

The general lack of discernable differences in the water chemistry of lakes in watersheds that have experienced disturbances could perhaps be best explained by one or a combination of the following: 1) the period of time between the disturbance events and sampling was great enough that any effect had been reduced making its detection impossible; 2) the water renewal times of the lakes might be sufficiently long, thus any increase in nutrient levels were mitigated by the time water reached the lakes (Schindler et al., 1980; Bayley et al., 1992; Pinel-Alloul et al., 2002; Allen et al., 2003); 3) the disturbance might not have been of sufficient magnitude to bring about any detectable change, relative to the watershed area or lake volume (Smith et al., 2003); 4) the timing of the disturbances was such that rapid recovery of vegetation limited nutrient losses

(McColl and Grigal, 1975; Schindler et al., 1980; Chanasyk et al., 2003); or 5) external disturbances, such as acid deposition, climate change, or insects, could have contributed to the variation in lake chemistry to an extent that any effects produced by fire or logging are undetectable (Bergeron et al., 2001; Foster et al., 1997).

This explanation of external disturbances being responsible for the lack of changes seen in the chemistry of the lakes is unlikely. All the lakes in the park are exposed to the same climate and thus similar weather events and precipitation chemistry; no one lake is climatically different from another in any significant way.

It is also doubtful that the effects of acid deposition are masking the effects of other disturbances. As previously discussed, Clair et al. (1997) suggested that this area of Newfoundland is far enough removed from acid emission sources and therefore there is little impact of acid deposition on lake chemistry.

From examination of the general trends seen in the time-series plots of the lakes, slight but not statistically significant increases were noted over the sampling period in colour, DOC, and K^+ and a decrease in pH and SO_4^{2-}. A decrease in SO_4^{2-} would be in agreement with reports of decreased atmospheric SO_4^{2-} deposition in Terra Nova National Park and Newfoundland (NEPMoN; Clair et al., 2002) and in lakes and streams in the Atlantic Canada region (Summers, 1995; Stoddard et al., 1999; Clair et al., 2002). The slight decrease in pH and increase in DOC suggests that recovery of lakes has not occurred (Houle et al., 1997; Stoddard et al., 1999). However, only 3 of 63 tests on lake chemistry data in the park for 1983 to 1994 showed significant trends and these were thought to be spurious, implying that lake chemistry did not change in the area (Clair et al., 1997). From an extended time series for the same lakes (1983-1997), a general decreasing trend in lake SO_4^{2-} concentration, increase in H^+ in several lakes, and little change in base cation concentrations were seen (Clair et al., 2002) and it is believed that critical acid loads for Newfoundland lakes may be close to background states (Clair et al., 2002).

It could, therefore, be that the park lakes were resilient to their respective disturbances, either due to one or a combination of the factors already suggested, such as disturbance size or water renewal time. The one lake that proved to be continuously variable was Pine Hill Pond. Sediment cores were taken from this lake in 1991 in order to determine previous vegetation communities and climate trends (Anderson and Macpherson, 1994; Wolfe and Butler, 1994; Macpherson, 1995). The top of this core (0-132cm) revealed a large amount of wood chips (Macpherson, pers. comm.) which was originally thought to have been related to past logging activities; however, no mention of significant logging in this area was found. Minshall et al. (1997) reported that following fire, there was a substantial increase in pieces of wood in receiving water bodies. Pine Hill Pond did experience a fire in 1986 but this would not explain why its chemical composition prior to 1986 was so different from other lakes in the park. Two other possible explanations exist: 1) the proximity of the lake to the Trans-Canada Highway and 2) the presence of beavers (*Castor canadensis caecutor* Bangs).

The Trans-Canada Highway bisects the catchment area of Pine Hill Pond and was constructed between 1958 and 1960, with upgrades done in 1995 (Power, pers. comm.). Park authorities are responsible for the highway through the park, including maintenance and salt application. As is expected for any water body located near a salted highway, some amount of road salt will enter the water and is capable of affecting the natural concentrations of nutrients. Kerekes (1974) related results of elevated salinity, Na^+ and Cl^- for Pine Hill Pond, to the additional salts this lake received due to road maintenance. From the data for Pine Hill Pond in this study, concentrations of Na^+ and Cl^- are both much greater than for other lakes and seem to be highly variable. This erratic behaviour of Na^+ and Cl^- could be due to the application of road salt, as amounts and timing applied depend on current conditions. As well, salinity data for the lake from 1970 to present showed a clearly increasing trend, while no such trend was apparent for other park lakes, see Figure 2.9 (Note: salinity was estimated from conductivity in 2001 and 2002 by multiplying it by 0.51, as suggested by J. Kerekes).

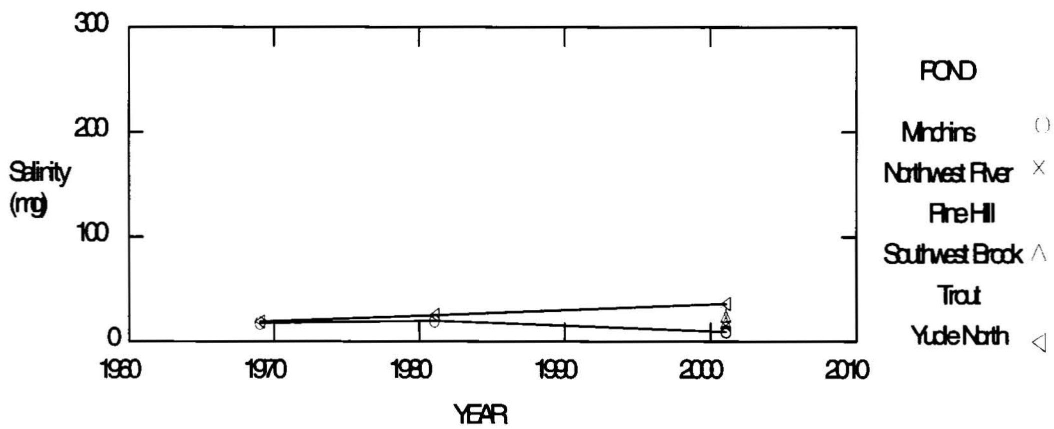

Figure 2.9 Salinity value for selected lakes in Terra Nova National Park (Coté, pers. comm.)

Beavers are also capable of altering stream and lake conditions through cutting of trees and flooding of streams and rivers. Beavers are able to modify channel geomorphology and hydrology, increase retention of sediment and organic matter, create and maintain wetlands, modify current nutrient cycling and decomposition dynamics, modify the riparian zone, influence the character or water and materials transported downstream, and modify habitat, which influences community composition and diversity (Naiman et al., 1986). In streams, beaver activity results in changes in absolute amounts of carbon inputs, standing stocks, and outputs (Naiman et al., 1988). For nitrogen, the flooding of surrounding soil can lead to increases in the amount of reduced nitrogen and available forms of N in soil solution (Naiman et al., 1988).

Areas most suitable for beavers are those which have been recently disturbed and thus provide the preferred habitat of beavers, that being early successional forest; for Terra Nova National Park, this includes areas near the highway and campgrounds (Power, 2000). Pine Hill Pond, being near the highway and having experienced disturbances, is therefore a suitable area for beaver activity. It is known that beavers were present in the area between 1967 and 1971 (Kerekes, pers. comm.) and there appears to be an abandoned beaver dam still present on the lake. It is not known exactly how much of an influence beavers are having on this area today.

It is likely that both of these factors, proximity to the Trans-Canada Highway and beaver activity, are affecting the water chemistry at Pine Hill Pond. The individual contribution of each of these factors is unknown.

2.8 Conclusion

The recent fire in the Rocky Pond Road area did result in differences in soil solution chemistry between unburned and burned regions, but no significant difference was found between a high intensity burn area and a low intensity burn area. Greater soil solution concentrations of PO_4^{2-}, SO_4^{2-}, K^+, Na^+, Cl^- and conductivity in the burned region were as expected due to burning of organic matter and subsequent nutrient release.

Based on water chemistry, it was not possible to distinguish lakes in watersheds which had experienced disturbances from lakes where no disturbance was known to have occurred. All lakes had unique chemical signatures and no specific changes were noted at the times of known disturbance events. There are several possible explanations for this result, with the most probable being length of time since the disturbance, the relative size and magnitude of the disturbance, resilience of the areas, and the complicating factor of natural succession of forests and associated changes in chemical properties.

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Chapter 3 Water Chemistry for a Boreal Watershed and the Impacts of Moose Herbivory on Soil Solution Chemistry

3.1 Abstract

A boreal watershed in Terra Nova National Park, Newfoundland, was used as the basis for several studies. The Big Pond-Minchin Brook system has been monitored since 2000 in order to determine its chemical signature and to see how the water chemistry compares with that of other boreal forest watersheds. This same area was used as a study on how a local disturbance, moose presence and browsing behaviour, affected soil solution chemistry. Any effects on the chemistry of soil solution from this local disturbance would eventually be reflected in the stream chemistry of the Big Pond-Minchin Brook watershed.

Ion chromatography was used to analyze the chemistry of both the surface water and soil solution samples. There was little difference in the water chemistry among the three locations and results were in agreement with those published for other boreal streams. In the absence of recent logging or fire, herbivory by moose was considered the principal form of disturbance. Potential effects of moose on soil nutrient concentrations were investigated using tray lysimeters inside and outside a 0.12-ha fenced exclosure. Significant differences in concentrations of NH_4^+ and PO_4^{2-} in soil solution were measured, with greater concentrations outside the exclosure. These differences are presumably related to moose excretions. Experimental decomposition bags placed inside and outside the moose exclosure indicated greater decomposition rates in the unbrowsed area.

3.2 Introduction

Water plays an important role in forested watersheds. From its initial contact with the canopy and foliage to interactions with the forest floor and subsequent pathways, water transports and transforms nutrients throughout the hydrologic cycle (Church, 1997). Disturbances in watersheds, both natural and anthropogenic, result in marked changes in the system and disrupt the components of the hydrologic cycle, thereby altering nutrient flows and concentrations. While on the large scale the effects of disturbances are complex to study, research at the local scale proves valuable in understanding how disturbances alter nutrients and their cycling in water (Putz et al., 2003). Studies of streamwater chemistry can advance understanding of biogeochemical processes and overall watershed functioning (Church, 1997; Martin et al., 2000).

In Newfoundland, the boreal forest is the dominant forest type and Terra Nova National Park provides an excellent location to study boreal forest watersheds. One such study is the Big Pond-Minchin Brook watershed study, which was initiated in 2000 to determine the chemical signature of the system (e.g., Bonnell, 2002; Golletz, 2002).

Interdisciplinary watershed studies, such as the Hubbard Brook Ecosystem Study (Likens and Bormann, 1995) and the Coweeta Hydrological Laboratory (Swank and Crossley, 1988), have been carried out in attempts to determine the structure and functioning of watersheds and to monitor the effects of acid precipitation upon them. Many of these watershed studies have included experimental forest disturbances as a means of better understanding how the system reacts to external stress, such as logging and fire.

Although logging and fire are part of Terra Nova National Park's history, and fire continues to be a factor in forest dynamics, it is the disturbance created by herbivores that has become a major concern (Power, 2000). Through grazing and browsing, herbivores are capable of altering forest structure, biomass, production, and species composition, potentially changing nutrient cycling in the system (McInnes et al., 1992). These potential changes to the surrounding environment are the reasons why herbivores have become a potential concern in Terra Nova National Park.

In Newfoundland, moose (*Alces alces* L.) are a prominent herbivore, browsing primarily on balsam fir (*Abies balsamea* (L.) Mill) and hardwoods. Moose are not native to Newfoundland but were introduced from Nova Scotia in 1878, with additional moose transported from New Brunswick in 1904 (Dodds, 1983). Since their introduction, moose have thrived on the island and while some see them as a benefit to tourism and sport and subsistence hunting, they also have a major impact on forest composition and structure. It is generally their overabundance that classifies moose as a disturbance to the boreal forest, as at low numbers they are often considered part of the dynamic system (McLaren, pers. comm.).

Moose browsing shifts forest community composition from a mixture of fir, spruce and hardwoods such as birch toward one dominated by black spruce (*Picea mariana* (Mill.) BSP), which is not a preferred browse species. This shift results in reduced soil nutrient availability due to spruce's slower growth rates, high leaf-retention rates (resulting in low litterfall), lower quality litter, and slower litter decomposition rates

(Pastor et al., 1988; McInnes et al., 1992; Pastor et al., 1993). For nitrogen (N) specifically, greater spruce dominance results in depressed cycling, because spruce trees have slower growth rates and slower N uptake than fir and hardwoods. Therefore, a shift to spruce weakens the plant sink for N and leads to increased leaching of N (Pastor et al., 1993). These shifts in forest composition have many implications to the surrounding environment.

Much of the information on the effects of moose on boreal forests has come from studies conducted in Isle Royale National Park, Michigan, where four moose exclosures were erected between 1948 and 1950. These fenced areas enabled researchers to observe by comparison exactly how moose browsing can change forest composition (McInnes et al., 1992). Microbial activity was reported to be greater inside the fenced area than outside and the exclosures had higher soil concentrations of sodium (Na^{+}), potassium (K^{+}), magnesium (Mg^{2+}), calcium (Ca^{2+}), and cation exchange capacity than soil sampled outside the exclosures (Pastor et al., 1993).

Moose also affect the environment through their excretions, which become incorporated into the ground and can potentially alter soil nutrient chemistry and biological activity. In their study of moose effects in Isle Royale National Park, Pastor et al. (1993) looked at the addition of moose pellets to determine if there was any increase in nutrient availability through increased N mineralization, associated with moose manuring. They found that the chemical properties of pellets were significantly different from those of humus alone. The pellets had a greater carbon (C) content, greater N content in late summer, greater C:N ratio in early summer, and mineralized less N but more C than soil (Pastor et al., 1993). When added together, soil and pellets appeared to stimulate C and N mineralization, but overall this was not enough to combat the negative effect of nitrogen depression from increased spruce dominance (Pastor et al., 1993).

During the 1960s a browse survey was conducted in central Newfoundland in response to a concern that forest regeneration following logging was being affected by moose browsing (Bergerud and Manuel, 1968). Bergerud and Manuel (1968) made four predictions on the long-term effects of moose browsing on balsam fir and white birch: (i) white spruce would become the dominant tree species; (ii) white birch would be excluded from the canopy; (iii) the commercial value of the forest would be reduced or eliminated in its second rotation; and (iv) the carrying capacity of the area for moose would be reduced.

Thompson and Curran (1993) re-examined Bergerud and Manuel's study area and found a significant positive relationship between the density of conifer trees and browsing damage to balsam fir recorded as severe or dead. They also reviewed Bergerud and Manuel's (1968) four predictions regarding future forest condition and found evidence to support two of the original four predictions: moose have substantially altered forest structure through suppression and killing of balsam fir and birch saplings were in poor condition due to browsing. The prediction that the current forest would not be economically useful was not supported and no conclusion was reached in regards to the fourth prediction regarding carrying capacity, although it was suggested that carrying capacity had not experienced a substantial decline (Thompson and Curran, 1993). Overall, moose browsing is unlikely to result in balsam fir being eliminated from future forests, as balsam fir remains a common species in the overstorey and understorey of many areas of Newfoundland, however balsam fir as the dominant forest cover could be affected. It was suggested that long-term effects might be felt in the soil, competing plants, and local moose density (Thomspon and Curran, 1993).

Although moose browsing might not completely eliminate balsam fir from the boreal forests of Newfoundland, it proves to be a primary limitation factor in the regeneration and succession of balsam fir (Power, 2000). With a low abundance of fir and poor seed supply due to moose browsing, a birch-aspen forest is predicted to develop (Meades and Moores, 1989). In Terra Nova National Park, approximately 13 km^2 of forest once classified as balsam fir is now birch-aspen (Power, 2000). As well, in some balsam fir forests, the moose induced lack of advanced balsam fir regeneration may encourage the growth of the shrub *Kalmia* (Thompson and Mallik, 1989) An increase in *Kalmia* leads to lower nutrient concentrations and creates an environment less able to support the original forest communities (Damman, 1971; Titus et al., 1995; Wallstedt et al., 2002).

There are also questions about the effect of moose browsing on forests previously affected by other disturbances, such as fire and insect defoliation. Insects create oscillations in the age-class distribution of balsam fir forests (Blais, 1985), which, in turn, provides moose with their preferred forage. If the combination of disturbances, alternating between insects, fire and moose, continues in Terra Nova National Park, the forests will be primarily in an early successional structure (Power, 2000).

The effects of moose browsing in Terra Nova National Park are at present serious enough to make moose one of the vegetation management issues for the park (Power, 2000). Research on the effects of moose on the environment will help in the establishment of an effective moose management strategy (Power, 2000).

There were two components to this study. The first involved monitoring the hydrology and surface water chemistry in a boreal watershed in Terra Nova National Park. Monitoring watersheds is important in understanding catchment behaviour and testing hypotheses as well as in understanding how these systems change with perturbations (Church, 1997). Through hydrochemical monitoring, watershed functions over the long- and short-term can be observed and factors such as geology, soil and vegetation type, climate, age, and history, can be studied in order to better understand their effects on biogeochemistry (Church, 1997). One of Parks Canada's key priorities is maintaining natural settings and ecological integrity (Parks Canada, 2003). In order to accomplish this goal, studies of natural environments, such as this watershed study in Terra Nova National Park, need to be conducted.

The second part of this study focused on the effects of moose on soil solution chemistry by observing an area with moose and an area where moose have been excluded. The disturbance created by moose has the ability to affect processes both above and below ground, including soil solution (Jewett et al., 1995). Natural factors and processes connected to the chemistry of soil solution include soil weathering, litterfall and mineralization, NO_3^- uptake through vegetation growth, inputs of water to the soil causing decreased concentrations, increased evapotranspiration causing increased concentrations, mineral fixation, or physical soil disruption, which promotes ion exchange and displaces ions leading to increased soil solution concentrations (Jewett et al., 1995). All these factors can alter the chemical composition of water. Any event capable of disrupting any of these factors will, therefore, result in changes in solution chemistry. Studying soil solution allows the more immediate effects of moose on water chemistry to be observed prior to any biogeochemical transformations which could occur as water continues to infiltrate deeper into the soil column (Church, 1997).

It is expected that the monitoring of the boreal watershed will provide useful information for the park on the functioning of boreal watersheds within its boundaries as well as helping to gain a better understanding of the chemical signature of such systems. In terms of the moose experiment, it is expected that there will be a difference in the chemistry of soil solution between an area where moose are present and where they are excluded. Soil solution samples inside the exclosure are expected to have higher concentrations of ions than samples taken from outside the exclosure. This relates to vegetation growth, as moose browsing can shift forest composition and promote the growth of less nutritious vegetation species, which results in reduced soil nutrient availability (Pastor et al., 1988; McInnes et al., 1992; Pastor et al., 1993).

3.3 Study Area

3.3.1 Big Pond-Minchin Brook Watershed

The Big Pond-Minchin Brook watershed is located in Terra Nova National Park (54° 00'W, 48° 30'N), see Figure 3.1. Several small streams empty into Big Pond, which is drained by Minchin Brook into Minchin Pond and Minchin Cove, Newman Sound, and eventually the Atlantic Ocean. The geology of the area is primarily Precambrian bedrock, with soils being mainly podzols with a bleached grey A horizon over a brown to reddish-brown B horizon. The sharp colour contrast of these horizons is related to the leaching of minerals from the A to the B horizon (Bourgeau-Chavez et al., 2000); regosols, gleysols, and organic soils are also present. Soils in Newfoundland have developed since the last glaciation and are generally acidic in nature. While the total nutrient content in the soils may be quite high, the low pH makes nutrients unavailable for vegetation and for this reason soils are considered nutrient poor (Roberts, 1983).

Figure 3.1 Location of study area – Terra Nova National Park

The Minchin Brook watershed is dominated by black spruce and balsam fir, which are typical of 70% of the forest communities found in the park (Power, 2000). Damman (1983) classified land by ecoregions, each having distinct ecological responses to climate as expressed by the development of soils and vegetation (Power, 2000). Terra Nova National Park falls into two of these ecoregions: Central Newfoundland Ecoregion (Northcentral Subregion) and North Shore Ecoregion (Damman, 1983). The Big Pond-

Minchin Brook watershed is located in the North Shore ecoregion, characterized by cooler temperatures along the coast than inland but with a longer frost free period, poor growing conditions due to colder soils, strong winds, and salt effects. As well, quality of tree growth generally diminishes with proximity to the coast (Power, 2000).

The climate of Newfoundland is related to the northern hemisphere mid-latitude atmospheric circulation, the proximity to mainland Canada, and, perhaps most importantly for the east coast, the influence of the cold ocean surface, primarily the Labrador Current (Banfield, 1983). For the park area, summers are cool and short with a mean summer (May-Sept) temperature of 12.6 ^{o}C and mean summer rainfall of 448.9 mm; average summer relative humidity is 68 %. The majority (75%) of the 1184.3 mm of total annual precipitation falls as rain. Winds are predominantly from the south-southwest and summer winds average 20.6 km/hr (Power, 2000).

3.3.2 Minchin Cove

The forest type at Minchin Cove is Hylocomium-Balsam Fir (Fh#9) (Meades and Moores, 1989). Balsam fir and black spruce are the dominant tree species in the area, but white birch and trembling aspen can also be found. The moss carpet is dominated by feathermoss, made up of *Hylocomium splendens, Pleurozium schreberi, Ptillium crista-castrensis,* and *Rhytidiadelphus triquetrus.* The soils associated with this forest type are orthic gleysol, orthic humic gleysol, rego gleysol, and podzol (Meades and Moores, 1989).

As determined from field observations, the organic layer extends to a depth of approximately 13 cm, followed by the A horizon, approximately 9cm deep, and then the

B horizon. Using the Munsell Colour system (Munsell Soil Color Charts 1994), the colour of the A horizon was determined to be 5YR7/1 and the B was 5YR 4/4.

The history of Minchin Cove is marked with disturbance events, leading to the forest's present composition and distribution. Although there is no evidence of extensive clear-cutting, remains from logging activities are scattered along the shoreline and a graveyard of those families who participated in the logging of the area can still be found. This region, along with many other regions in the park and elsewhere across the island, was logged from the late 1800s until the mid-20th Century (Major, 1983; Munro, 2001), resulting in changes to the natural characteristics of the forest. Logging ceased soon after the establishment of the park in 1957.

A current disturbance affecting this region is herbivory, mainly moose and hare browsing (Power, 2000). Several moose exclosures have been constructed in Terra Nova National Park and outside the park's boundaries. There are two exclosures near Minchin Cove, the one used in this study is situated immediately adjacent to Minchin Brook. This exclosure was erected in 1999 and consists of a 35 m x 35 m (0.122 ha) area surrounded by a 2.5 m high coarse-mesh wire fence. A 5 x 5 m fine-mesh fenced area within the larger exclosure is designed to exclude snowshoe hare.

3.4 Methodology

3.4.1 Field Methods

Stream/Pond Sampling

Since 2000, water samples have been taken on a seasonal basis from three locations within the Big Pond-Minchin Brook watershed: at the outlet of Big Pond, the outlet of Minchin Pond, and from Minchin Brook. For the purposes of this study, samples were taken monthly from May 8, 2002 through November 12, 2002. Water samples were collected in 250 mL and 500 mL sterile Nalgene® bottles and returned to the laboratory for further analysis. When possible, conductivity (either Exatech 470303 or WTW conductivity meter LF 318) and oxygen saturation (Orion Dissolved Oxygen Meter model 810Aplus) readings were taken *in-situ*.

Soil Solution Sampling

Tray lysimeters (zero-tension lysimeters) were used to sample shallow soil solution following a design of B. Roberts of Forestry Canada (Roberts, pers. comm.). The lysimeters were made of plastic containers, approximately (L) 40 cm x (W) 28 cm x (D) 14.5 cm, with plastic grids placed in the bottom of them. Fittings were secured in a drilled hole in each lysimeter, which allowed for tubing to be attached, connecting the lysimeter to the collecting bucket (Appendix 3-1). Eight lysimeters were placed at the Minchin Cove site on June 8, 2002, four outside the moose exclosure (lysimeter #1-4) and four inside the moose exclosure (lysimeter #5-8) (Figure 3.2).

Approximately 10 cm depth of forest floor material (duff) was placed in the trays on site. Collecting buckets were located downslope from the lysimeters. Samples were pumped from these buckets into sterile plastic Nalgene® bottles using hand pumps. After each sampling, buckets were completely emptied by continuous pumping. See Appendix 3-2 for a complete list of sample dates and the number of samples from each visit. The volume of water pumped out at each visit, representing the approximate volume of water collected in each bucket between sampling visits, was recorded. The samples were analyzed for pH, conductivity, and colour prior to further chemical analysis. Sampling from the lysimeters commenced on July 13, 2002 and ended November 12, 2002.

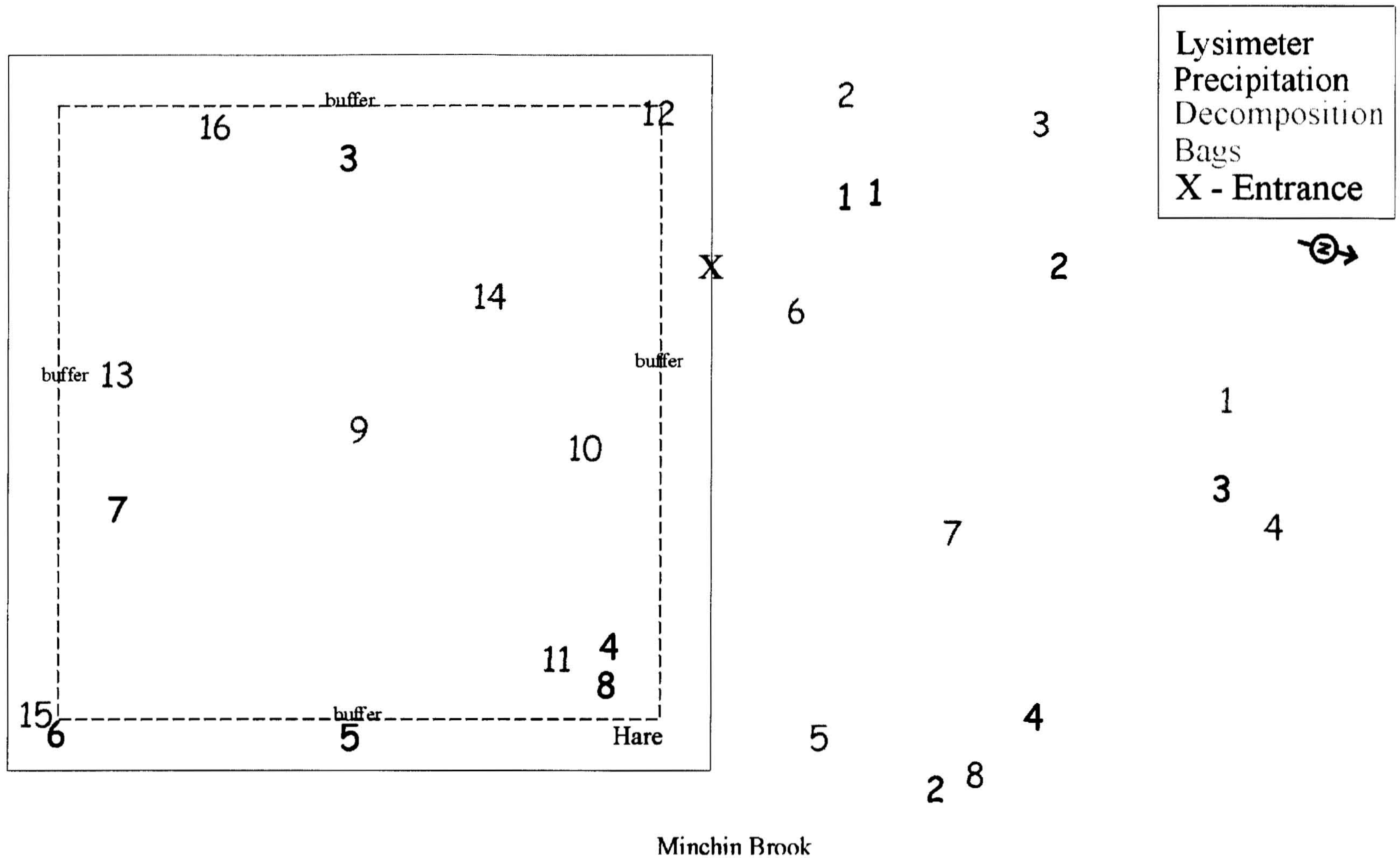

Figure 3.2 Minchin Cove study area – moose exclosure and area outside exclosure. The exclosure measures 35 m by 35 m.

Precipitation Samples

Four precipitation collectors were installed at the Minchin Cove study site, two outside the moose exclosure (numbers 1 and 2) and two inside the exclosure (numbers 3 and 4) (Figure 3.2). The purpose of this sampling was to determine the chemical composition of the precipitation reaching the forest floor. In each of the sampling areas one collector was located under closed canopy (2 and 4) while the other was under open conditions (1 and 3). These collectors caught mainly throughfall precipitation and canopy drip; that is, the portion of the total precipitation that fell through or was intercepted and released by the canopy. The specific design details of the precipitation collectors can be found in Appendix 3-3.

Analysis followed the same procedure used for the soil solution samples.

Decomposition Bags

Decomposition bags were used at the Minchin Cove site to determine whether there was a difference in litter decomposition rates between areas with and without moose presence. In total 16 decomposition bags were buried in the Minchin Cove area, eight were buried outside the exclosure (1-8) and eight inside (9-16) (Figure 3.2). The bags were made of window screening nylon mesh and sewn into 15 x 25-cm bags. Ground cover from the respective areas was collected on June 8, 2002 and dried separately at a low temperature (160 ^{o}C). Approximately 15 g of dried material from inside the exclosure was placed in each of the eight bags to be buried inside the exclosure. These bags were sewn closed and weighed, with each bag being numbered. The same procedure was followed for material from outside the exclosure (using litter from outside the exclosure to be buried outside the exclosure).

The bags were inserted just below the ground surface, in the feathermoss layer, on June 9, 2002, and were marked with flagging tape, indicating their number, and left undisturbed throughout the field season. On November 12, 2002, 15 of 16 bags were collected (number 6 outside the exclosure could not be located) and placed in ziplock bags to be transported back to the laboratory. The contents were emptied into aluminum pans and dried at a temperature of 160 °C for 24 hours. This remaining sample was then weighed and calculations were performed to determine the actual amount of sample remaining.

Soil Chemistry

Soil samples were taken on June 8, 2002 from each lysimeter location for both the A and B horizon. The samples were collected in plastic bags and transported to the Soil Plant and Feed Lab, Department of Forest Resources and Agrifoods, for chemical analysis.

The averages for the A and B horizons for samples from both inside and outside the exclosures were calculated from the values provided by the lab. The pH average was obtained by converting pH into hydrogen concentrations of which the average was calculated; this average was then converted back into a pH value.

Particle Size Analysis

A soil pit dug outside the moose exclosure on November 3, 2003 was used to determine colour and to obtain samples for grain size analysis. No soil pit was dug inside the exclosure in order to minimize the disruption to the developing ecosystem. It was not expected that there would be significant differences in grain size and colour between inside and outside the exclosure. Grain size analysis was performed at Memorial University of Newfoundland for soil samples from the A and B horizon while loss-on-ignition was performed for the duff layer. See Appendix 3-4 for further details of the method.

The calculated cumulative percent for each soil sample was plotted against grain diameter and the resulting distributions were compared.

Water Chemistry

Soil solution, stream samples, and precipitation samples were tested for pH (using Orion portable pH meter model 230 Aplus), conductivity (using either the Exatech 470303 or WTW conductivity meter LF 318 respectively), and colour (using an Aquaquant 14421 colour comparator). The soil solutions samples were then passed through a 45 μm filter prior to further analysis.

Ion chromatography (IC) was used for the chemical analysis of cations (Na^+, K^+, Mg^{2+}, Ca^{2+}, NH_4^+) and anions (Cl^-, NO_3^-, SO_4^{2-}, PO_4^{2-}). The ion chromatograph (Dionex DX-100) was located at Memorial University of Newfoundland. Details of this chemistry procedure can be found in Appendix 3-5.

3.4.2 Statistical Methods

Minchin Cove Exclosure

Basic exploratory statistics were performed on the accumulated data, including descriptive statistics, normality tests, homogeneity of variance tests, and different plots, all using SPSS Version 10.0. Confidence intervals were calculated from the median at the 95% confidence level. All data were grouped according to their location, inside versus outside the exclosure.

3.5 Results

3.5.1 Big Pond-Minchin Brook Watershed

The time-series plots for the three sampling locations within the Big Pond-Minchin Pond watershed were similar. Concentrations of all nutrients appeared to be slightly higher for Minchin Brook (Figure 3.3) than Big Pond (Figure 3.4) and Minchin Pond (Figure 3.5), where concentrations were almost identical.

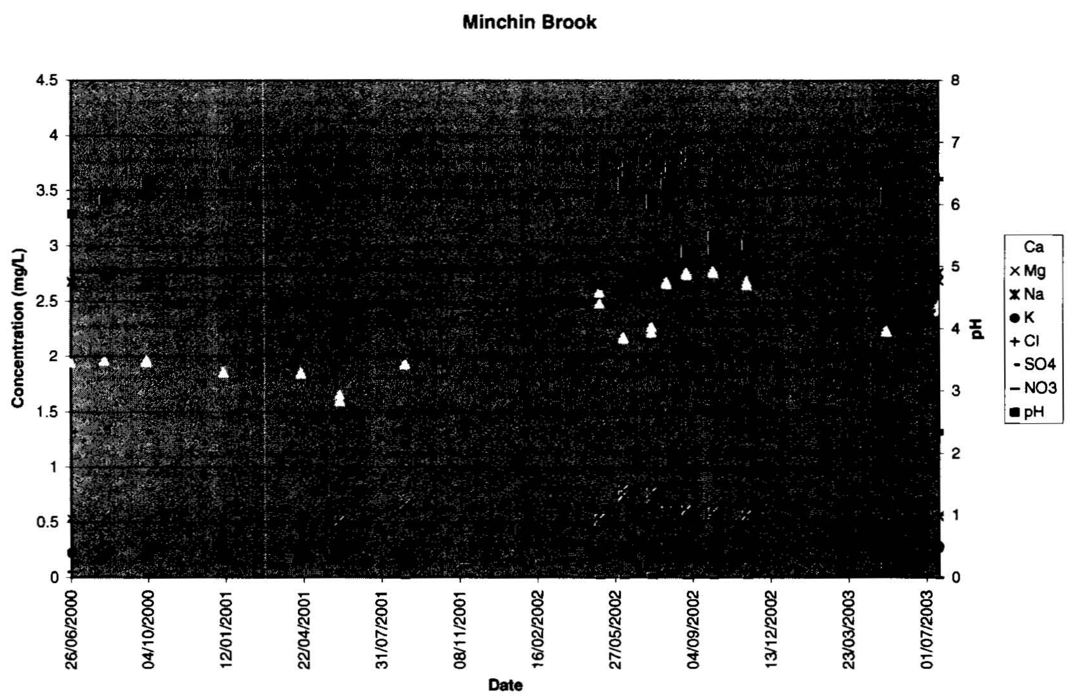

Figure 3.3 Water chemistry for Minchin Brook

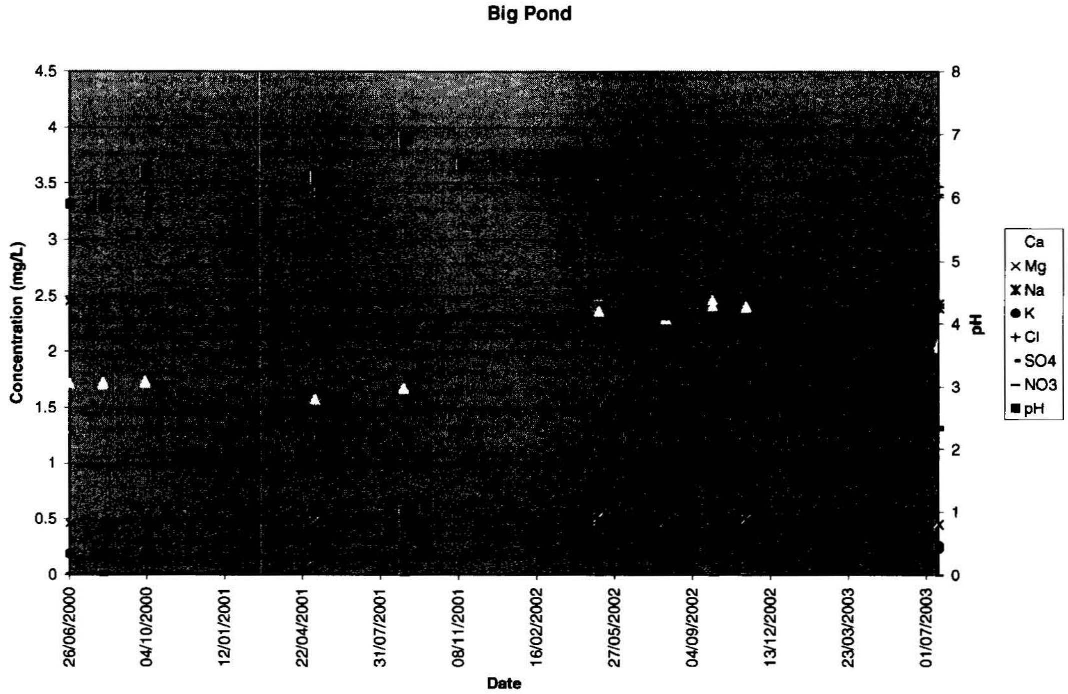

Figure 3.4 Water chemistry for Big Pond

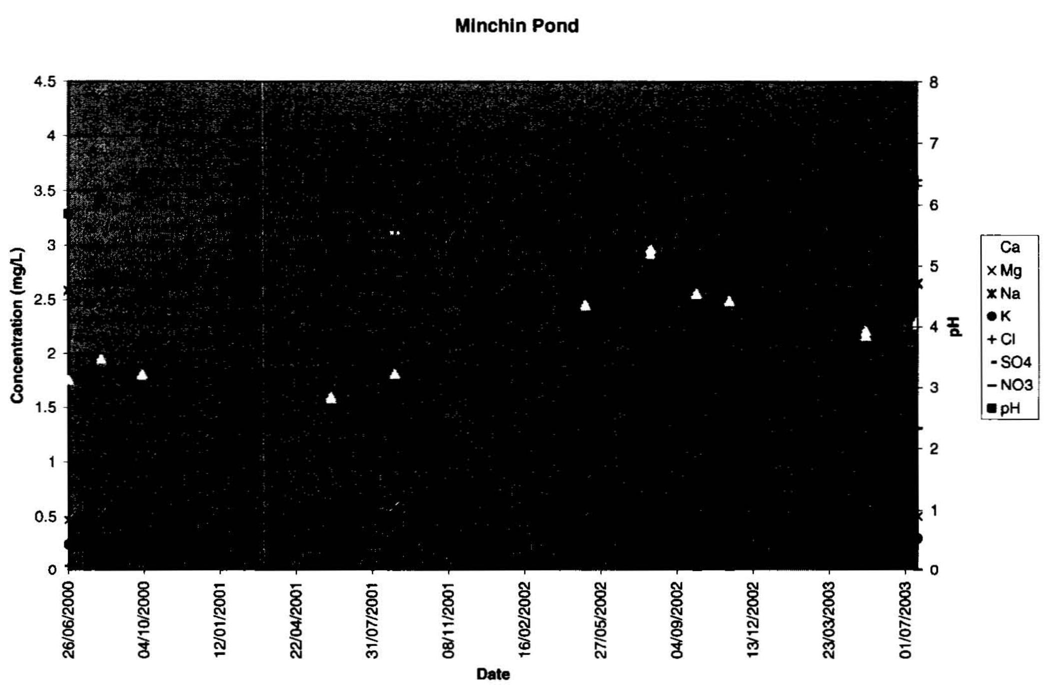

Figure 3.5 Water chemistry for Minchin Pond

Since the most recent regular sampling began in 2000, there has been little change in the two lakes and the brook, with only slight increases noted in concentrations of Ca^{2+} and Mg^{2+} for all three sampling locations in the spring and summer of 2002.

3.5.2 Minchin Cove Exclosure

Soil Solution

The boxplots (Appendix 3-6) and calculated intervals (Table 3.1) for soil solution chemistry revealed that samples from outside and inside the exclosure were not distinguishable for most studied parameters (conductivity, pH, Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+}). It was, however, possible to differentiate the two locations for PO_4^{2-} (Figure 3.6) and NH_4^+ (Figure 3.7) with greater concentrations in samples from outside the exclosure. The medians of conductivity, Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+} outside the exclosure were higher than inside; only Mg^{2+} and pH were higher inside the exclosure (Table 3.1).

Table 3.1: Confidence Intervals and Medians for Minchin Cove Lysimeter Samples

Variable	Outside Exclosure			Inside Exclosure		
	Median	95% C.I. for med (low)	95% C.I. for med (high)	Median	95% C.I. for med (low)	95% C.I. for med (high)
Conductivity	90.00	74.05	105.95	72.35	60.72	83.98
pH	3.84	3.70	3.98	4.04	3.84	4.24
Cl	6.85	5.01	8.68	6.02	5.12	6.93
NO3-N	0.06	0.04	0.09	0.05	0.03	0.07
PO4-P	0.36	0.05	0.66	0.00	/	/
SO4	3.92	2.78	5.05	3.35	2.99	3.70
Na	3.50	2.85	4.14	3.00	2.44	3.56
NH4-N	1.99	1.11	2.88	0.24	0	0.87
K	5.10	3.86	6.34	4.48	4.05	4.92
Mg	0.59	0.32	0.87	0.83	0.69	0.97
Ca	1.71	1.34	2.07	1.61	0.72	2.49

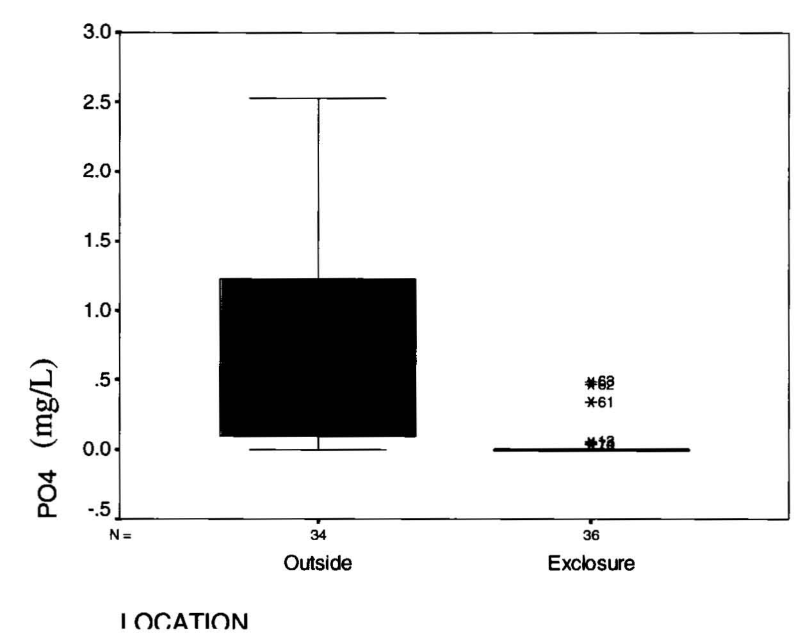

Figure 3.6: Boxplot for phosphate concentrations from Minchin Cove lysimeters

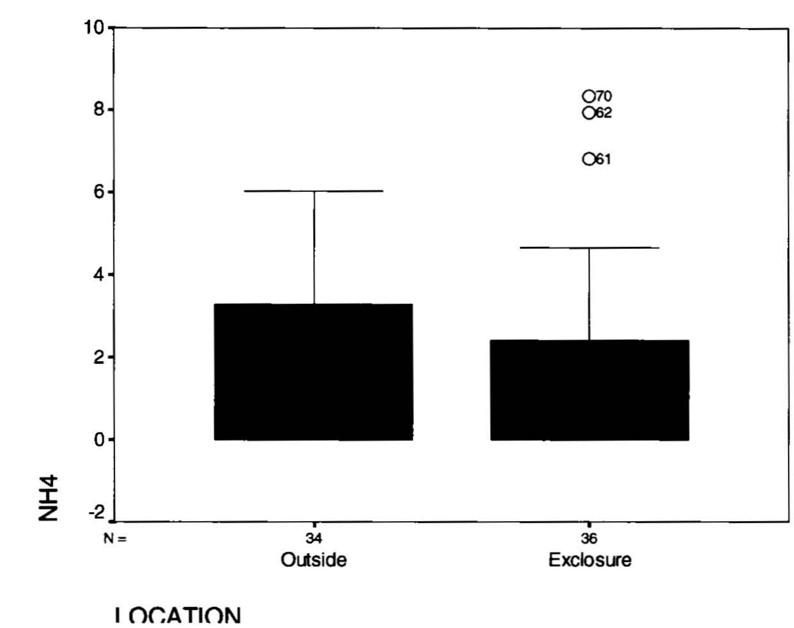

Figure 3.7: Boxplot for ammonium concentrations from Minchin Cove lysimeters

The time-series plots of the lysimeters (Appendix 3-7: Minchin Cove lysimeters) revealed that the lowest pH and the highest conductivity and concentrations for ions, except PO_4^{2-}, were reached in the late summer of 2002; the lowest conductivity and concentrations and highest pH came from the July 2003 samples. Lysimeter #1 and #3, both outside the exclosure, generally had the highest concentrations; however #7, located inside the exclosure, also appeared to have high values, especially when compared to the other lysimeters within the exclosure. As well, the July 2003 sample of lysimeter #7 showed major peaks in NO_3^- and NH_4^+.

The approximate volume of water pumped from the lysimeters increased steadily from the beginning of sampling until the end, (Figure 3.8). As well, lysimeters inside the exclosure had on average slightly more water than those outside, except for lysimeter #2 located outside the exclosure, which consistently had the most water.

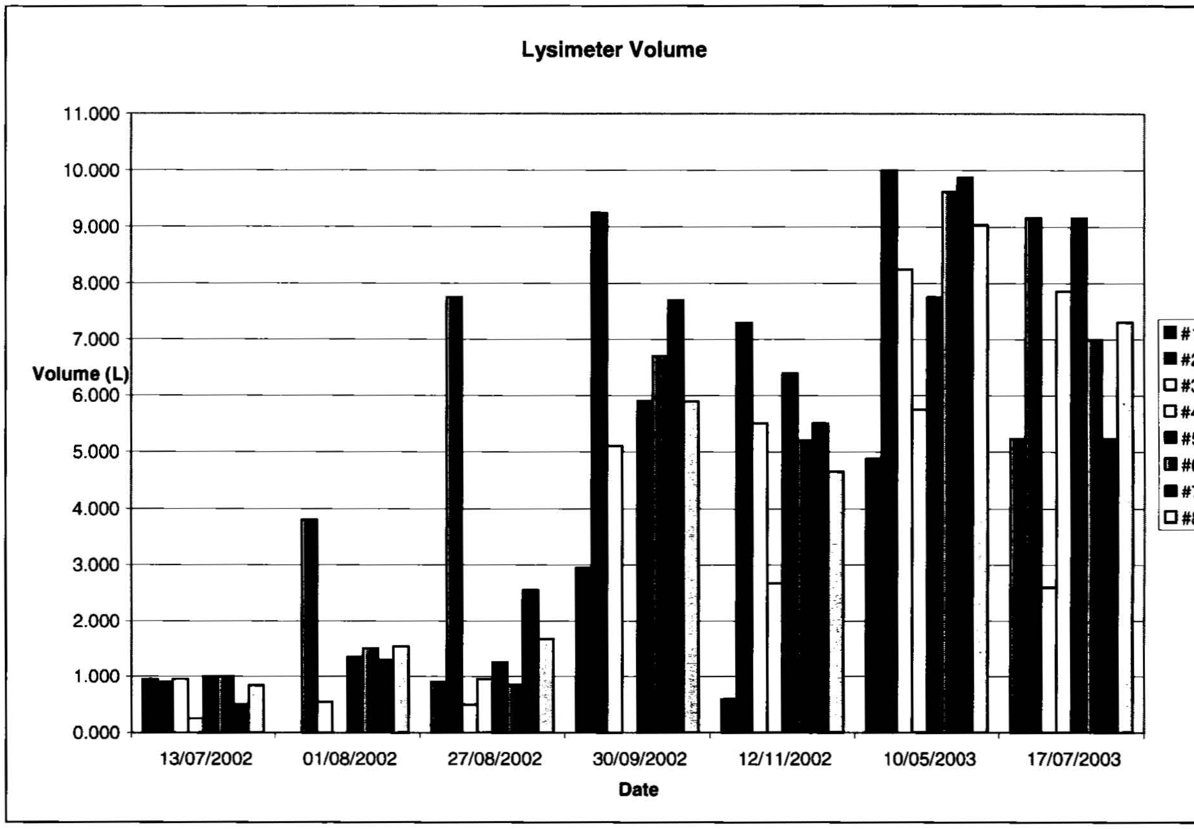

Figure 3.8 Volume of water pumped out of Minchin Cove lysimeters

Precipitation Samples

The time-series plots of sample results from the four precipitation collectors (Appendix 3-7: Precipitation collectors) showed that the concentrations of ions were variable over the sampling period. For most studied variables a slight decreasing trend was noticed, reaching minimums in September 2003 and then increasing slightly in November 2003. For all variables but NH_4^+ and NO_3^-, collector #4 recorded the highest concentrations and collector #3 the lowest (e.g., Figure 3.9); both of these collectors were located in the exclosure. The collectors that were placed below closed canopy cover, #2 and #4, had higher concentrations of Cl^{-}, PO_4^{2-}, SO_4^{2-}, Na^{+}, K^{+}, Mg^{2+}, and Ca^{2+} relative to the two placed under more open canopy conditions, #1 and #3.

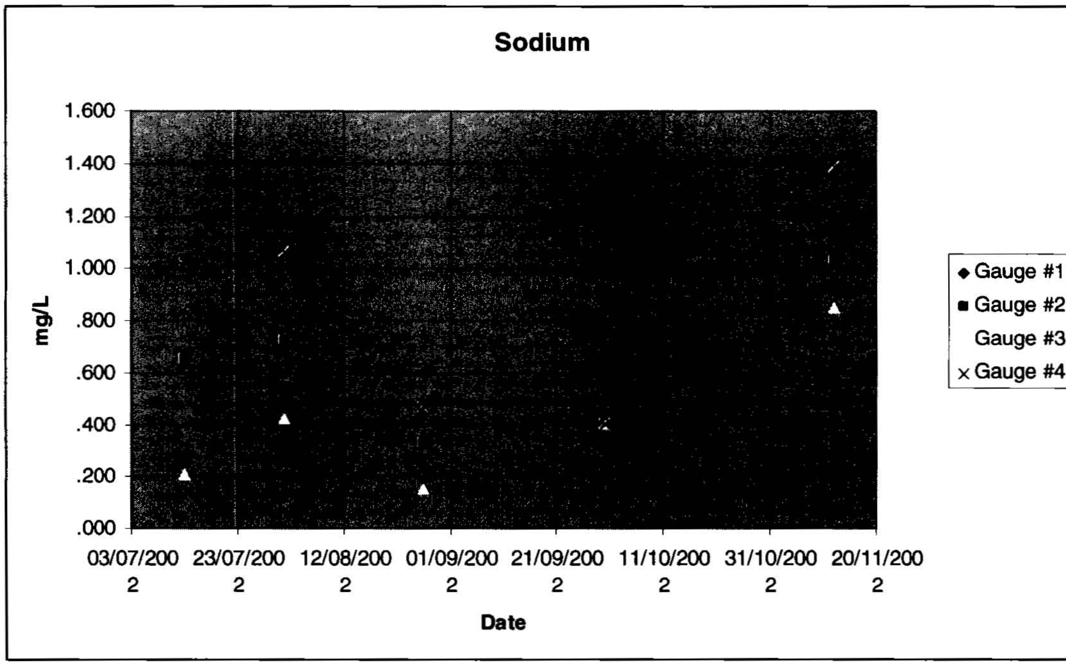

Figure 3.9: Sodium concentrations from precipitation samples

Decomposition Bags

The dry weights of the decomposition bags before being placed in the field and the dry weights following their collection can be found in Appendix 3-8; the weight and percent lost was calculated from these dry weights.

The decomposition bags buried inside the exclosure (#9-16) lost 50 % or more of their original material (median of weight lost was 8.8g), while the bags buried outside the exclosure lost much less (median of weight lost was 4.9g); this difference in loss is evident in (Figure 3.10).

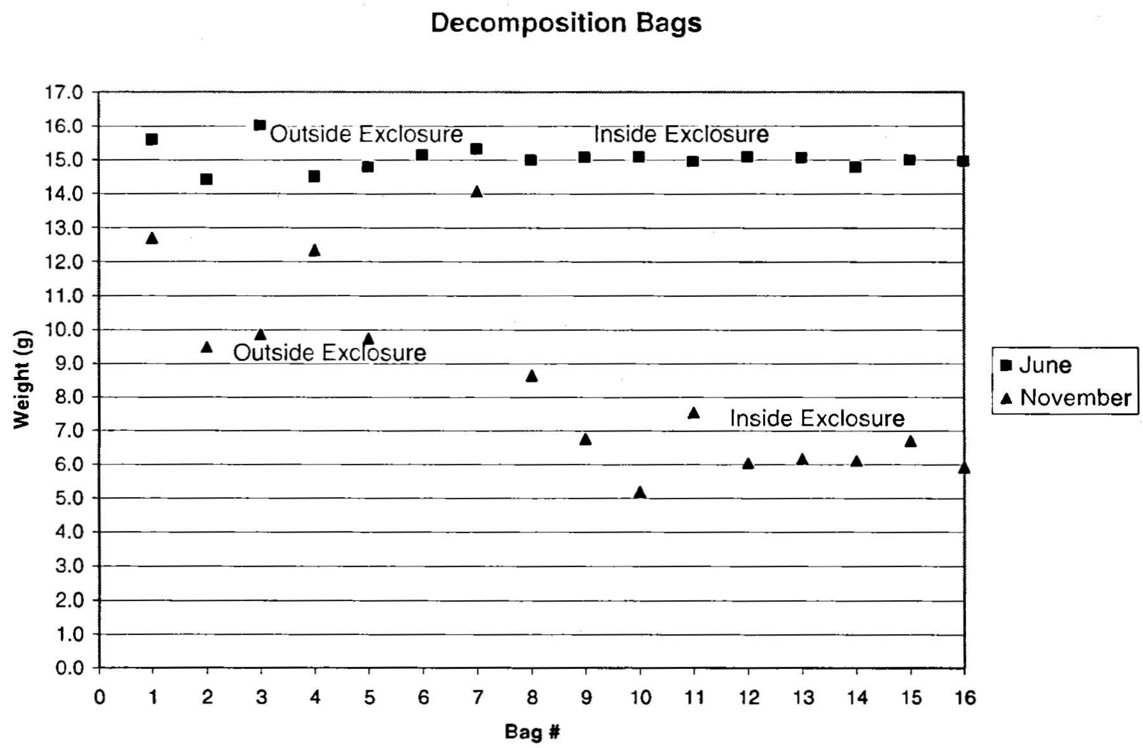

Figure 3.10 Weight differences for decomposition bags

Soil Chemistry

The results of analysis performed by the Soil Plant and Feed Lab, Department of Forest Resources and Agrifoods can be found in Appendix 3-9. The average pH values were re-calculated using the data provided by the lab; details on the calculation of the pH can be found in Appendix 3-9. The plots of the calculated averages revealed that there was little difference in soil concentrations and pH between the samples taken from inside and outside the exclosure

Particle Size Analysis

From the grain size distribution (Figure 3.11, Figure 3.12; Appendix 3-10), 66.4% of the A horizon sediment fell between 16 mm and 2 mm, while the sediment of the B horizon was much more evenly distributed, with 84.6% of the sample between 8 mm and 0.250 mm. Loss-on-ignition showed that organic matter made up just over 50% of the duff layer.

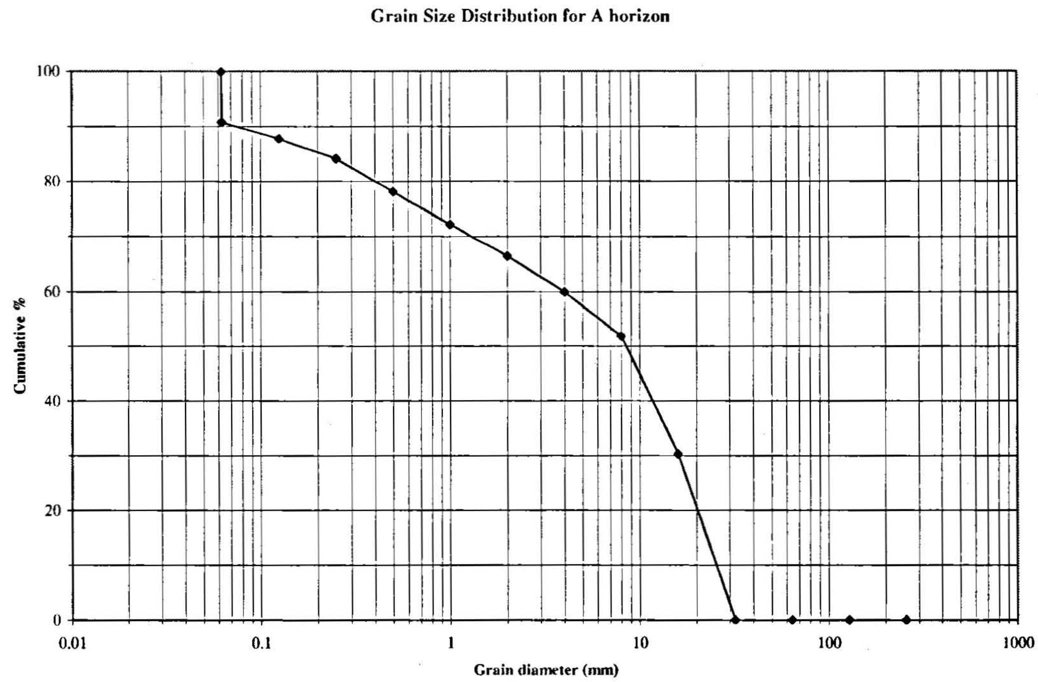

Figure 3.11 Grain size distribution for A horizon

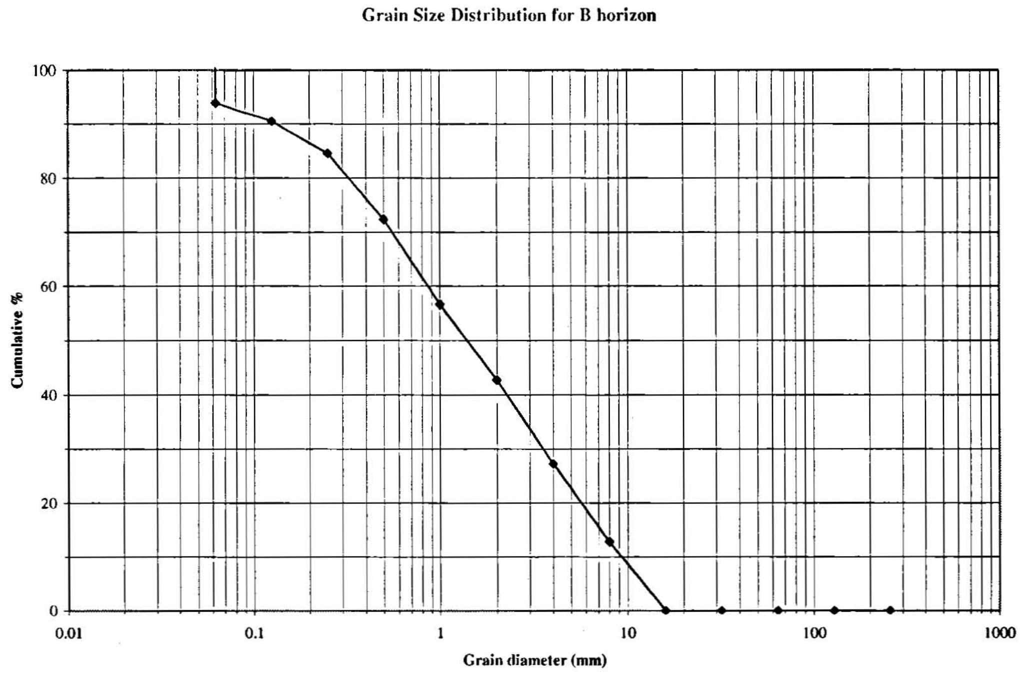

Figure 3.12 Grain size distribution for B horizon

3.6 Discussion

3.6.1 Big Pond-Minchin Brook Watershed

The chemical signatures of the sampled water bodies agree with reports from other boreal streams and lakes. Streams in coniferous forests in the United States were reported to have median NO_3^- concentrations of 0.03mg N/L, 0.01mg N/L of NH_4^+, and 0.004mg P/L of PO_4^{2-} (Binkley, 2001). Similar results were found for nitrogen in streams in spruce forests of Finland, 0.0313 mg/L for NO_3^- and 0.0137 mg/L NH_4^+ (Holopainen et al., 1991). Results for a control stream in a black spruce peatland area in Québec were also similar to the Minchin watershed results (Prévost et al. 1999).

Most ion concentrations in Minchin Brook were similar to two other streams in the park for which data exist, Bread Cove Brook and Southwest Brook. However, Minchin Brook had lower concentrations of SO_4^{2-} (Figure 3.13). The Minchin Brook values include data from a more recent sampling period, during which it has been observed that sulphur emissions have declined across eastern North America and some, though not all, study lakes in Atlantic Canada have experienced declining acidification (Jeffries, 1997).

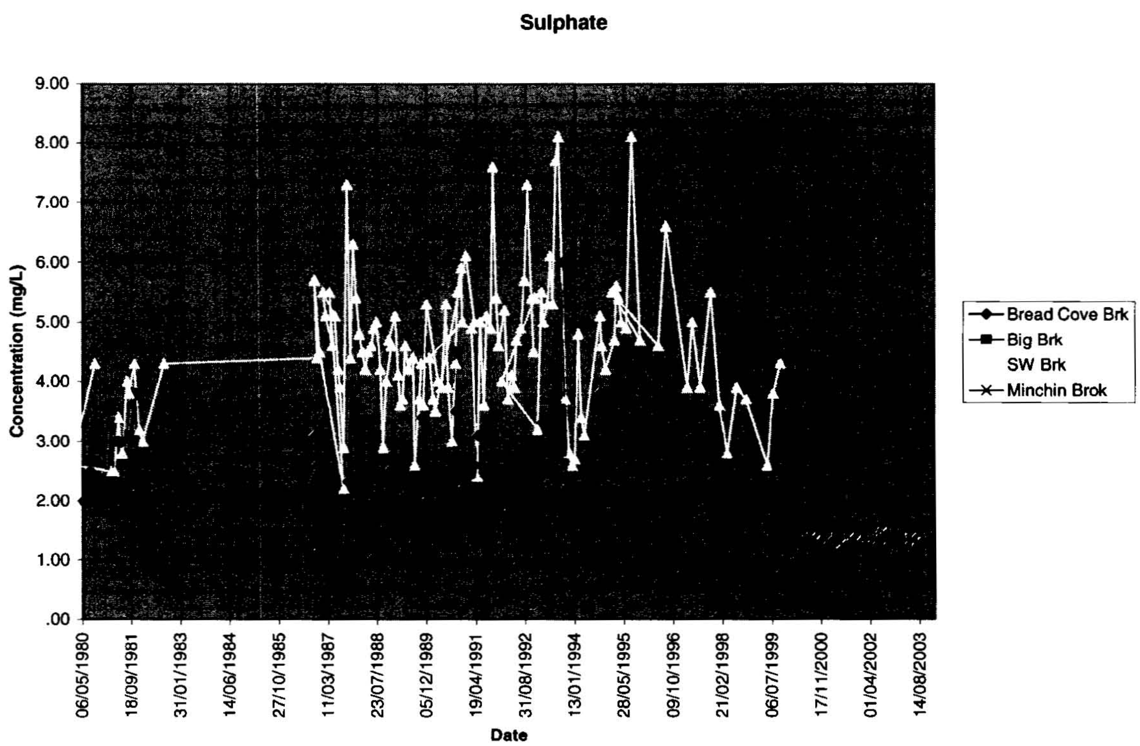

Figure 3.13 Sulphate concentrations for streams in Terra Nova National Park

3.6.2 Minchin Cove Exclosure

Chemistry

The overlap of the confidence intervals for most of the soil chemical variables indicates no difference outside the exclosure compared to inside the exclosure.

Furthermore, soil nutrient concentrations between the two locations for the A and B horizons were not distinguishable. These results do not agree with the expected results. The only variables which enabled distinction between the two locations at Minchin Cove were NH_4^+ and PO_4^{2-}, both being greater outside the exclosure.

Pastor et al. (1993) showed that soil taken from inside a moose exclosure on Isle Royale had significantly greater concentrations of exchangeable cations than did samples from outside the exclosure at the most heavily browsed site. Although he did not study soil solution directly, it was anticipated in this study that solution concentrations would be consistent with the bulk soil chemistry.

One possibility for why the data from Minchin Cove did not show greater concentrations inside the exclosure is that more water flowed through the lysimeters in the exclosure than through those outside, resulting in diluted concentrations in the exclosure. Although Pastor et al. (1993) found that soil moisture was not significantly different inside versus outside exclosures, at Minchin Cove the volume of water that passed through the lysimeters, as calculated from the amount of water pumped out of the collecting buckets at each visit, was slightly higher inside. This might mean that concentrations inside the exclosure were diluted. However, it is not believed that this is a primary cause for the lack of detectable difference between locations.

It is more likely that the similarity between soil solution concentrations outside and inside the exclosure relates to the younger age of the Minchin Cove exclosures, compared to the Isle Royale exclosures. The exclosures in Isle Royale National Park were sampled by McInnes et al. (1992) approximately four decades after their construction, providing time for vegetation changes and related effects to become more pronounced. At Minchin Cove, the exclosures were set up 1999, meaning that only 3 to 4 years had elapsed before sampling began.

McInnes et al. (1992) reported that absolute amounts of nutrients were significantly greater inside exclosures in Isle Royale National Park than outside, but that significant differences in mean nutrient concentrations were noted only for the most heavily browsed areas of the three studied exclosures (Pastor et al., 1993). Pastor et al. (1993) suggested that low soil nitrogen availability could result when moose browsing exceeds 2-4 $g \cdot m^{-2} \cdot yr^{-1}$ (Pastor et al., 1998). In 1997, the density of moose in Terra Nova National Park was 0.81 moose/km^2 (Murphy, 1997), which was below the calculated critical carrying capacity of 1.3 moose/km^2 (Oosenburg et al., 1991). It is therefore probable that browse consumption is not great enough to be causing any significant differences in soil and solution chemistry.

The absolute increase in nutrients inside the Isle Royale exclosures was related to the greater amount of litter produced by hardwood trees. For Minchin Cove, while there is a visual difference in ground vegetation between inside and outside the exclosure, new shrub and tree growth is still underway and it is likely that not enough time has elapsed for any significant increases in litter production or for the observed vegetation differences to result in soil chemical differences.

While both Isle Royale National Park and Terra Nova National Park are within the boreal forest biome, the composition of their forests differ. In Minchin Cove, the primary tree species are balsam fir and black spruce. These species are less nutritious and decay relatively slowly compared to the greater number of aspen and birch found in Isle Royale National Park.

Tree species and their associated litter have different nutrient availabilities (Prescott, 2002). Although a shift from balsam fir to black spruce, as is expected to occur at Minchin Cove, would change the chemistry, the litter from both these coniferous species requires a longer period of time to decompose and supply the ground with its nutrients, compared to hardwood species. Therefore, the predicted shift in nutrient concentration due to moose browsing might require a longer period of time to become evident for the tree species present at Minchin Cove than would be expected for a hardwood dominated forest, such as at Isle Royale.

As for the greater concentrations of NH_4^+ and PO_4^{2+} observed outside the exclosure, this difference is most likely related to animal excretions, which can add organic matter and nutrients from digested organic matter and plant litter to the soil (Pastor et al., 1988; McNaughton, 1990; Holland et al., 1992; McInnes et al., 1992; Pastor et al., 1993; Hobbs, 1996). In a study by Pastor et al. (1993), fecal pellets combined with soil were found to stimulate N mineralization above levels found for either fecal pellets or soil alone; it was suggested that urine deposition would have a similar effect. Their overall conclusion, however, was that moose manuring did not alter nutrient supplies (Pastor et al., 1993).

Another possible factor for increased NH_4^+ is nitrogen saturation, which could result in greater amounts of NH_4^+ in the ground (Church, 1997). Associated with increased NH_4^+ are increased levels of microbial nitrification in soil, resulting in increased levels of H^+ (and therefore lower pH) and increased nitrate concentrations in soil solution (Church, 1997; Currie et al., 1999). In this study lower pH in soil solution was noted outside the exclosure, where elevated NH_4^+ concentrations also occurred.

However, no changes in NO_3^- were seen, therefore nitrogen saturation is unlikely to be a factor at Minchin Cove.

Analysis of the precipitation samples revealed no significant difference in ion concentrations inside and outside the exclosure for most studied ions. Both the highest and lowest concentrations for most studied ions were obtained from the two gauges inside the exclosure. Only NH_4^+ concentrations were found to be higher outside the exclosure than inside. This is consistent with the higher concentrations of NH_4^+ in soil solution found in samples from this area. There was no clear explanation for this increased NH_4^+ in precipitation outside the exclosure, as the two sampling locations (inside and outside the exclosure) are in close proximity to each other. Phosphate concentrations outside the exclosure were not elevated in precipitation, therefore their greater concentration in soil solution outside the exclosure cannot be related to precipitation concentration. Interestingly, the gauges with the highest concentrations for most ions were the two placed under more closed canopies. It has been suggested that canopy interactions can alter the nutrient concentrations of incoming precipitation (Lovett and Lindberg, 1993; Church, 1997) and although only a small part of this study, the results obtained from these simple gauges agree with this work.

Decomposition

Results from the decomposition bags showed that bags from inside the exclosure had less mass remaining upon collection than did bags from outside the exclosure indicating faster rates of decomposition inside the exclosure than outside.

Decomposition activity relates to the temperature, soil moisture, the pH of the environment, and the chemical and physical nature of the litter (Walse et al., 1998; Prescott, 2002). In a review of the effects of temperature, moisture, and pH on decomposition, Walse et al. (1998) explained that for temperature, decreasing nutrient concentrations make the effect of temperature on decomposition stronger, and for moisture, decomposition rates increase with relative soil moisture saturation. The importance of pH is its ability to control survival of soil organisms. Fungi are capable of living in relatively acidic soils, with optimal conditions ranging between pH 3 to 7, and are generally responsible for decomposing more resistant material (Walse et al., 1998). Bacteria are more sensitive to lower pH, preferring a pH greater than 5, and are responsible for decomposing more easily decomposable material (Walse et al., 1998). A greater presence of fungi could be interpreted as less decomposition taking place due to the longer time required for decomposition of resistant material. The type of soil biota is also related to they type of litter present. Changes in vegetation will alter the amount, quality, and distribution of litter which will ultimately affect the soil biota. This, in turn, can have significant effects on ecosystem processes including changes in nutrient concentrations (Wolters et al., 2000). However, ecological changes due to vegetation changes are not expected unless there are significant changes in the litter quality (Wolters et al., 2000).

At Minchin Cove, temperature sensors were placed inside the exclosure at depths of 5 cm and 20 cm, however none were placed outside the exclosure. Because of this it is not possible to determine if there was a difference in temperature. This said, the proximity of the locations and the lack of apparent canopy difference make any significant soil temperature differences unlikely. No direct moisture readings were taken either inside or outside but as previously discussed, lysimeters placed inside the exclosure appeared to collect more water than those outside the exclosure. However, to conclude greater soil moisture from this observation might be extending the data too far. As for pH differences, it appeared that both soil and soil solution pH values were similar inside and outside the exclosure. Because of the similarity in pH it is unlikely that there was any significant difference in soil biota inside and outside the exclosure, therefore decomposition differences would not be associated with fungal versus bacterial presence.

It is possible that the greater concentrations of ammonium and/or phosphate, most likely from moose excretions, affected the rate of decomposition. Pastor et al. (1988) explained that excrement from herbivores contains digested organic matter and plant litter and provides organic matter and nutrients to the soil and that these could affect microbial processes. Pastor et al. (1993) also noted higher microbial activity inside exclosures, however no further study on decomposition was performed.

The most likely explanation for increased decomposition in the exclosure compared with outside is not any difference in the quality of the area or the type of soil organisms but instead in the quantity of decomposers. The observed greater decomposition from inside the exclosure could indicate that this environment supports a greater number of decomposers, therefore the mass of litter remaining after 5 months was considerably less in the exclosure due to more decomposers being available to decompose the material. The greater amount of ground vegetation with the exclusion of moose could offer habitats to a greater number of soil organisms and result in increased decomposition.

Because organic matter and litter quality relate to decomposition rates and soil organism activity (Keenan and Kimmins, 1993), it would have been interesting to have placed decomposition bags filled with litter from inside the exclosure in the area outside the exclosure and vice-versa. This would have provided useful information on whether it was the litter composition or the site activity that was responsible for the greater decomposition from inside the exclosure.

Overall, Naiman (1988) suggested that the long cycles of animal populations may make the study of their effects on ecosystems, biogeochemical cycles, and soil characteristics difficult in the short-term. Because of the relatively short time that the Minchin Cove exclosure had been in place, only three years at the time of this study, there is a good possibility that the exclusion of moose had not yet had an opportunity to generate the expected differences.

3.7 Conclusion

Monitoring of the Big Pond – Minchin Brook boreal watershed revealed that the three main components (Big Pond, Minchin Pond and Minchin Brook) had similar chemistries. Such monitoring projects are important in our understanding of the flows within systems and should be continued.

The second aspect of the study revealed that soil solution samples obtained from moose exclosures did not differ chemically from samples obtained in an area where moose are present. This lack of difference could be explained through one or a combination of factors including insufficient time for vegetation differences to result in chemical differences, low moose densities, low intensity of moose browsing, or increased water flow in the exclosure resulting in diluted soil concentrations. Surprisingly, a difference in decomposition was noted between outside and inside the exclosure; reasons for this are speculative. The most probable explanation, perhaps, is that the vegetation inside the exclosure supports a greater number of decomposers, resulting in more litter being decomposed over a set amount of time.

A logical follow-up to this study would be to repeat the experiment in several years, when the differences between the two areas have had a greater amount of time to become more pronounced.

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Chapter 4 Summary

4.1 Introduction

This chapter will unite the material presented in the individual manuscripts and provide overall conclusions and implications as well as make recommendations for future research.

4.2 General Conclusions and Implications

All forests are affected by disturbances, both natural and anthropogenic in origin. Boreal forests are an excellent example of a system where disturbances influence both the distribution and composition of the existing and future forest structure and dynamics.

The objectives of this project were to study a boreal forest with a history of disturbance events and to determine whether past and present disturbances have had any discernible impact on the chemistry of soil solution and nearby surface water.

The first part of the study had two components, first was a case study of a recent forest fire and its impacts on the local soil solution and brook water chemistry. The second component involved compiling the disturbance history of Terra Nova National Park and subsequently using existing water chemistry data to determine if these disturbance events caused any noticeable changes in the water chemistry.

As outlined in the conclusion of that chapter (2.8), the recent fire in one area of Terra Nova National Park did result in differences in soil solution chemistry between unburned and burned regions, although no difference was found between a high intensity burn area and a low intensity burn area. However, it was not possible to distinguish lakes in watersheds that had experienced known disturbances from those where none had occurred. Several reasons for the lack of difference in lake water chemistry between disturbed and undisturbed watersheds were suggested, such as length of time since the disturbance, size and magnitude of the disturbance, and resilience of the areas.

The second part of this project involved monitoring a boreal watershed in Terra Nova National Park and studying how a more recent disturbance, moose browsing, is affecting the chemistry of the soil solution in this region.

By monitoring such a boreal watershed, its chemical signature can be obtained which helps in our understanding of a catchment's profile and watershed functions over the long- and short-term (Church, 1997). Specifically, Parks Canada has outlined that one of their key priorities is maintaining natural settings and ecological integrity (Parks Canada, 2003) and in order to accomplish this, studies of natural environments, such as this watershed study in Terra Nova National Park, need to be conducted.

The impacts of moose browsing to the boreal forests of Terra Nova National Park have increased substantially in the century since moose were introduced to Newfoundland. Through browse preferences, moose are able to influence which form of vegetation will dominate, potentially altering the chemistry of the area.

The monitoring of the boreal watershed illustrated that the three studied components all had similar chemistries, which is significant when studying flows and cycles within watersheds.

Analysis of soil solution in areas of moose presence and absence revealed that excluding moose has not resulted in significant chemical differences. Suggestions for why no difference in soil solution chemistry was noted included insufficient time for vegetation differences to result in chemical differences, low moose densities, low intensity of moose browsing, or increased water flow in the exclosure resulting in diluted soil solution concentrations. Interestingly, a difference in litter decomposition rate was noted between an area where moose were present compared to where they were absent. It was suggested that this might have been related to the vegetation inside the exclosure supporting a greater number of decomposers, resulting in more litter being decomposed over a set amount of time.

Overall, this study provided information on how past and present forest disturbances such as fire and logging affect water chemistry in boreal forests. It appears that with moderate disturbance and given the sufficient time, forests are able to recover naturally and minimize any long-term effects to their environment, chemically speaking. Although the short-term study of a recent forest fire did yield results suggesting chemical differences in soil solution, it will be interesting to see if such differences are observed in subsequent years.

It is not yet possible to conclude whether the chemistry of surface and soil waters in this forest system will be significantly affected by the long-term impacts of herbivory, however. While no discernible effects have been noted on the short-term, the impacts on the long-term might prove to be different.

4.3 Future Research

There is much research still to be conducted on the effects of disturbances to the boreal forest. Specific to this study, there are many more aspects that should be looked at when determining the impacts of disturbances to the boreal forest of Terra Nova National Park.

In terms of water chemistry impacts, the area burned in 2002 should continue to be monitored to determine if the noted chemical differences persist. As well, the regions most prevalent to moose browsing should be monitored in order to determine if long-term browsing will affect the soil solution chemistry and in turn that of streams and lakes..

Determining the impacts of disturbances to water chemistry is only one aspect of the overall picture. Vegetation predominance, community structure, animal habitats, and biological productivity are just some of the other systems that are affected by forest disturbances. In order to fully understand the effects disturbances have had and continue to have on our forests, it is necessary to take all these factors into consideration.

4.4 References

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