Investigation of an introduced subtropical alga (*Lyngbya wollei*) in Whiteshell Provincial Park, Manitoba

by

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A Thesis
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In Partial Fulfillment of the Requirements
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Abstract

Nuisance growth of a filamentous cyanobacterium, *Lyngbya wollei*, was studied in lakes of Whiteshell Provincial Park in eastern Manitoba. Its increasing abundance in two lakes, White and Betula, over the last half dozen years has heightened awareness and concern by cottagers and recreational users that nearby lakes may become infested. *L. wollei* is typically found in the southeastern United States, and this is the only known occurrence in Canada. Desiccation experiments used to assess the ability of *L. wollei* to survive inter-lake transfer on recreational watercraft showed it can remain viable after short-term drying and stagnant conditions. Comparisons of lake basin morphology, land use, water and sediment chemistry of the infested lakes to those of other Whiteshell lakes showed that all lakes with shallow littoral areas and a photic depth greater than two and a half meters possess potential *L. wollei* habitat. Intensively used lakes such as Falcon, Caddy, Brereton, and Big Whiteshell are most susceptible to *L. wollei* inoculation. Principle Component Analysis based on water and sediment chemistry identified Jessica, Red Rock, Florence, and Madge Lakes as having the most similar conditions to the infested lakes. Consequently, these lakes may develop the greatest biomass and adverse effects of *L. wollei* growth. It is imperative that all clothing, footwear and recreational watercraft be cleaned thoroughly after being removed from infested lakes to prevent the further spread of *L. wollei* in the lakes of Whiteshell Provincial Park.

Chapter 1: Introduction

As humans become more mobile, moving efficiently around the globe, so do flora and fauna. Exotic species invade habitats where they do not naturally occur and often decrease both the abundance and diversity of native species in the invaded community (Buchan and Padilla 2000). This alters the system's natural biodiversity and community structure. Currently, exotic species constitute 10-30 % of the flora in most regions and, once established, are often impossible to eradicate (Buchan and Padilla 2000). As a result, inoculation must be minimized through the identification and protection of areas vulnerable to invasion.

L. wollei is a large, filamentous, mat forming cyanobacterium that has become common in lentic ecosystems in the Southeastern United States. At the time of this writing Lake Itasca in Minnesota is the most northerly known location of *L. wollei* in the United States. In Canada, *L. wollei* has been identified in two Whiteshell lakes, Betula and White. Presently, these infestations represent the only known occurrence of *L. wollei* in Canada. Recent *L. wollei* growth observed in the infested lakes and its occurrence around developed areas with cottages, resorts, campgrounds and public boat launches, suggest this is an exotic species introduced to the Whiteshell.

Like other exotic species, *L. wollei* is an opportunistic species out-competing most interspecific competitors once established in an aquatic system. Thick, dense mats proliferate on the bottom of littoral areas impeding swimming, boating and other recreational activities. Additionally the production of geosmin and neurotoxins analogous to those which cause paralytic shellfish poisoning may pose a health concern for all users (Carmichael *et al.* 1997). As a result, *L. wollei* infestations result in recreational, ecological and economic loss of affected lakes (Speziale *et al.* 1991).

Whiteshell Provincial Park encompasses 131 lakes (Schneider 2002). The Whiteshell has historically been an important recreational area facilitating activities such as swimming, boating and fishing. Betula and White Lakes have active water skiing clubs which were established in 1950 and 1963 respectively. These are the only two Whiteshell lakes with ski clubs. Historically boats used in water skiing competitions were moved around the continent for competitions. If *L. wollei* is transported between lakes by recreational watercrafts it is imperative that other Whiteshell lakes are protected from *L. wollei* inoculation.

This thesis marks the beginning of the investigation, identification and monitoring of *L. wollei* infestations in Whiteshell Provincial Park. The research presented here may be used to aid future research endeavors so that Whiteshell lakes may continue to provide recreational opportunities for future generations.

1.1 Objectives

1) The primary objective of this study was to examine the distribution and inoculation source of *L. wollei* in Whiteshell Provincial Park.

2) The second objective of this study was to investigate why Betula and White Lakes are the only known Whiteshell lakes with *L. wollei* infestations. The infested lakes were compared to other Whiteshell lakes based on land-use parameters, lake morphology, water and sediment chemistry.

1.2 Hypotheses

1) I hypothesize that recreational watercraft moved between infested water bodies in the United States and the Whiteshell resulted in the infestation of Betula and White Lakes. Current boat movement between these infested lakes and other Whiteshell lakes may put other waterbodies in the Whiteshell and throughout North America at high risk for infestation.

2) I hypothesize that Betula and White Lakes are unique from other Whiteshell lakes, with certain parameters which enable *L. wollei* to proliferate. Unique parameters may include high concentrations of calcium and phosphorus, which are known to be growth limiting nutrients. If Betula and White Lakes do not prove to be unique from other Whiteshell lakes based on land-use, lake morphology, water or sediment chemistry then we may use the data to predict other similar Whiteshell lakes which may be susceptible to *L. wollei* inoculation and infestation.

Chapter 2: Literature Review

2.1 Lyngbya wollei

2.11 Introduction

In the southeastern United States, a nuisance mat-forming cyanobacterium impedes the recreational, economic and aesthetic value of infested aquatic systems (Speziale *et al.* 1991). Recent taxonomic investigation by Speziale and Dyck (1992) classified the nuisance species as *Lyngbya wollei* Farlow ex Gomont comb. nov. Classification has enabled consistent communication and biological understanding of *L. wollei.* Investigation of its ecological and biochemical characteristic has resulted in a better understanding of this opportunistic species. *L. wollei* possesses both morphological and physiological characteristics, that give it a competitive advantage over other species. Consequently, aquatic systems can become dominated by *L. wollei* with associated biomass reaching as high as 1.0 – 1.5 kg dry weight m^{-2} (Beer *et al.* 1986). The nuisance potential of *L. wollei* makes it crucial to focus on management techniques so that this species no longer limits the use of the reservoirs, lakes and ponds which it currently infests.

2.12 Taxonomy

In the last three decades infestations of a recently described and exceptionally large filamentous cyanobacterium have become increasingly common in the Southeastern United States. Although there have been consistent descriptions of this organism it has been identified as six different species within three genera (Table 1) (Speziale and Dyck 1992). Proper identification of this nuisance organism is crucial for consistent communication and biological understanding. Traditionally cyanobacteria have been taxonomically classified by the International Code of Botanical Nomenclature ($ICBN_1$). This system is primarily used for eukaryotic organisms. Some researchers believe that cyanobacteria, with their prokaryotic habit, would be more accurately classified by the rules of the International Code of Bacteriological Nomenclature ($ICBN_2$) (Rippka *et al.* 1979). The discrepancies in the

Table 1: Inaccurate taxonomic classifications of *Lyngbya wollei* Farlow *ex* Gomont (Speziale and Dyck 1992).

Proposed Taxonomic Classification	Author(s) cited
Microcoleus lyngyaceus	(Kutzing) Crouan *sensu* Drouet
Plectonema wollei	Farlow *et* Gomont
Lyngbya magnifica	Gardner
Lyngbya majuscula	Harvey *ex* Gomont
Lyngbya birgei	Smith
Lyngbya latissima	Prescott

identification of this cyanobacterium appear to be the result of concurrent use of the two classification systems by different groups of researchers. Use of the $ICBN_2$ with cyanobacteria is based on a limited number of strains, and therefore receives limited support (Speziale and Dyck 1992).

The use of the $ICBN_1$ is also problematic. Grietler sub-divided the family Homogoneae into two sub-families using this system. Sub-division was based on the occurrence of heterocysts and presence of false branching (Speziale and Dyck 1992). The family Oscillatoriaceae is composed of taxa, that lack heterocysts and have simple filaments. *Lyngbya,* although occasionally having false branches, was placed in this family. *Plectonema* was placed in the sub-family Scytonemataceae due to characteristic false branching, even though it lacked heterocysts. Since both genera lack heterocysts the division was ultimately based on the occurrence of false branching. Speziale and Dyck (1992) proposed that false branching is a taxonomically invalid method of classification because it can result from environmental modification.

In contrast to *Plectonema, Lyngbya* does not put undo emphasis on the environmentally variable false branching characteristic. Therefore Speziale and Dyck (1992) has proposed that *Lyngbya* is the most accurate genus classification of the nuisance organism. Designation of the specific epithet was based on the elimination of previously applied taxonomic classifications. *Lyngbya birgei* is a planktonic species, which does not form floating masses. The nuisance organism differs from the marine species *Lyngbya majuscula* both in size and it has a limited halotolerance. *Lyngbya latissima* and *Lyngbya magnifica* are acknowledged synonyms for *Plectonema wollei. Plectonema wollei* is accurate in the description of the nuisance organism yet it puts strong emphasis on false branching. As a result, the nuisance organism has been classified as *Lyngbya wollei* Farlow ex Gomont comb. nov (Speziale and Dyck 1992).

2.13 Morphology

Speziale and Dyck (1992) identified a specimen type based on morphological variation found in *L. wollei* specimens. *L. wollei* cells are defined as discoid in shape having a diameter of 24-65mðm. Cells vary in length from 2-12 mm. The cells are arranged into uniseriate filaments, which are encased by a hyaline, lamellate sheath up to 12 mðm thick. The filaments are indeterminate in length and can exceed 40 cm in length. False branching may result from protrusion through lateral breaks in the sheath. These filaments produce an entangled mat of sparsely branched filaments. Mats are vertically stratified occurring throughout the water column in the summer (Speziale *et al.* 1991). The subsurface filaments are photosynthetically active, rich in phycobilin and as a result are blue black in color. Surface filaments are photosynthetically inactive and they are yellow – orange in colour, as a result of the high carotenoid content and bleached chlorophyll and phycobilin (Speziale and Dyck 1992). *L. wollei* is a perennial species, which overwinters as a benthic mat. *L. wollei* has no specialized reproductive or overwintering structures such as akinetes. All biomass produced throughout the water column accumulates as a benthic mat which functions as a base stock for re-infestation in the following growth season. Heterotrophic *L. wollei* filaments buried in the benthos are living and viable (Speziale *et al.* 1991). As a result these filaments may function as inoculum for subsequent growth (Head *et al.* 1999).

2.14 Ecological Adaptation

In any ecological system species assemblage is determined by the chemical and physical characteristics of the environment (Kohler and Hoeg 2000). In *L. wollei* dominated habitats these characteristics have been investigated to identify optimal growth conditions. Water conductivity and alkalinity were found to account for 55% of the variability in *L. wollei* biomass (Cowell and Botts 1994). Limited halotolerance suggests that *L. wollei* is a freshwater species. *L. wollei* is a stenohaline species with a strong preference for freshwater, showing negative growth at all salinities between 0 and 35 ppt by the loss of cells. At salinities of 17.5ppt and above, rapid death of the organism occurs (Cowell and Botts 1994). Optimal growth of *L. wollei* occurs in water of pH 8 (Cowell and Botts 1994). It may be concluded that *L. wollei* is sensitive to acidity and grows optimally in an alkaline environment. In contrast, at pH 4 there was negligible growth (Tubea *et al.* 1981). *L. wollei* has been identified most commonly in the southwestern United States in freshwater lentic ecosystems with these characteristics. Lakes, ponds and reservoirs may all be affected.

Alkalinity reflects the predominant form of inorganic carbon present in the water body and thus is an essential component in understanding the niche of *L. wollei.* Photosynthetic activity of *L. wollei* results in diel fluctuations in dissolved inorganic carbon (DIC) (Beer *et al.* 1990). In initial hours of photosynthesis, CO_2 concentrations are depleted to negligible levels. The water pH increases and consequently increases the bicarbonate concentration (Beer *et al.* 1986). At pH 8 bicarbonate is the predominant form of DIC. Beer *et al.* (1992) report that CO_2 concentrations within *L. wollei* mats are less than 1mðM suggesting bicarbonate is the main source of DIC available to *L. wollei* for photosynthesis and growth. Bicarbonate concentrations are as low as 0.15mM at midday as a result of increasing pH and yet photosynthesis still functions at 60% of its maximum productivity (Beer *et al.* 1986). Beer *et al.* (1986) results conclude efficient inorganic carbon uptake at low DIC levels maintains photosynthetic productivity.

L. wollei is able to efficiently utilize bicarbonate to supply cellular demands for inorganic carbon. This provides a competitive advantage to the species (Beer *et al.* 1986). Bicarbonate use results in an increase in carbon dioxide levels at the ribulose – 1,5-bisphosphate carboxylase oxygenase (RUBISCO) site. This is the same result achieved by plants employing the C4 mechanism (Beer *et al.* 1990). Beer *et al* (1992) conclude that there is no evidence supporting bicarbonate dehydration at the cell wall. Instead, *L. wollei* achieves saturating inorganic carbon concentrations through cellular uptake of bicarbonate. This conclusion is based on the absence of the enzyme carbonic anhydrase (CA) which intraconverts bicarbonate and carbon dioxide. In addition there is no evidence of a highly active carbon dioxide transport system and oxygen released originates internally. It is further suggested that the rate of photosynthesis evident in *L. wollei* could not be supported by an uncatalyzed dehydration of bicarbonate at the cell wall. Therefore cellular uptake of bicarbonate enables *L. wollei* to concentrate inorganic carbon at the RUBISCO site (Beer *et al.* 1992). After high DIC concentrations of bicarbonate are depleted oxygen is slowly released into the depleted DIC media. As a result, Beer *et al.* (1992) suggest a decarboxylation or refixation process may occur. At high DIC concentrations inorganic carbon may be fixed into an intermediate organic compound. This compound could be refixed when DIC concentrations are low. This carbon concentrating mechanism may give *L. wollei* a competitively advantage at low DIC concentrations while suppressing photorespiration.

L. wollei exhibits optimal productivity in a variety of DIC environments. Consequently, this species can optimize photosynthesis at varying oxygen levels. Photorespiration is suppressed and photosynthetic productivity is maintained in varying oxygen concentrations (Cowell and Botts 1994). Oxygen levels twice that of the atmospheric concentrations do not inhibit photosynthesis of *L. wollei* (Beer *et al.* 1986). Carbon dioxide released at 21% and 1% oxygen concentrations varied negligibly and thus it is concluded that photorespiration is unlikely the source of the released carbon dioxide (Beer *et al.* 1990). *L. wollei* insensitivity to oxygen concentrations is expressed throughout the year. The ability to maintain photosynthetic productivity at high oxygen concentrations gives *L. wollei* an advantage over competing species which photorespire. Optimal growth conditions may result with low DIC concentrations and high oxygen levels that inhibit the growth of other species (Beer *et al.* 1992).

Gas vesicles and ballast molecules are depth regulating apparatuses produced by photosynthesis in *L. wollei*. Gas vesicles and ballast molecules provide a competitive advantage to *L. wollei*. The energetically costly manufacture of these products results in depth regulating production (Klemer *et al.* 1995). *L. wollei* is a perennial mat, which overwinters as thick benthic mat. The buoyancy of *L. wollei* is regulated by the production of gas vesicles with positive buoyancy and ballast molecules with negative buoyancy. In the summer, a portion of the benthic mat floats to the surface buoyed by gas vesicles (Doyle and Smart 1998). As a result *L. wollei* representatives are found throughout the vertical water column as well as buried in the sediment (Speziale *et al.* 1991). The filaments found buried in the sediment are living and viable. They are also thought to be heterotrophic (Doyle and Smart 1998). The ability of *L. wollei* to inhabit areas with a wide variety of environmental variables is a competitive advantage.

The vertical stratification of *L. wollei* mats offers a competitive advantage for the acquisition of inorganic carbon. Both the atmosphere above and the water surrounding surface mats, contain usable sources of inorganic carbon. Ibelings and Maberly (1998) have determined that alkaline waters enhance the influx of atmospheric CO_2 in water. This increases the inorganic carbon available to *L. wollei* at the surface. Increased atmospheric carbon dioxide levels have been shown to increase productivity (Speziale *et al.* 1991). At the surface, photoinhibition may result from the high influx of light surface mats are exposed to. The resulting photodegradation of chlorophyll and phycobilin increases the carotenoid content of surface filaments. Consequently, surface filaments are photosynthetically inactive, but offer photoprotection to those below (Speziale *et al.* 1991).

L. wollei is vertically stratified and the physiological status of filaments throughout the bloom can be used to determine its optimal light regime (Brookes *et al.* 2000). Surface mats with reduced phycobilin pigments were unable to absorb visible light in the range of 550 -650nm (Speziale *et al.* 1991). Surface mats contain an increase in myxoxanthophyll, which results from the photodegradation of chlorophyll and phycobilin. Therefore yellow filaments containing few intact cells characterize surface mats. Subsurface mats are blue – black in colour corresponding with high chlorophyll$_a$ and phycobilin content. These subsurface mats are composed of orderly uniseriate filaments, which absorb photosynthetically active radiation (PAR) between 400 – 700 nm as a result of pigmentation composition (Speziale *et al.* 1991). Surface mats enable only 1-3% of PAR to reach the benthic mat. When shaded by vegetation, 1-5% PAR reaches the underlying benthic mat

(Doyle and Smart 1998b). As a result, the light compensation and saturation levels of *L. wollei* are low at 20 and 150 mδEm^{-2}s^{-1} respectively (Beer *et al.* 1986). Surface mats are subject to movement with wind and waves. This low compensation point shows adaptation to the low light benthic environment while the saturation level shows that *L. wollei* is adapted to short term, high intensity light flickers (Speziale *et al.* 1991). Mid-depth mats have the greatest photosynthetic potential, suggesting buoyancy regulation is a competitive advantage for *L. wollei* (Speziale *et al.* 1991).

Colonial cyanobacteria may have the ability to act as a single optical unit (Agusti and Philips 1992). Cyanobacteria cells absorbs less light than eukaryotic alga cells the same size due to a high pigment to chlorophyll$_a$ ratio. Colonial cyanobacteria are able to increase light absorption to levels beyond the sum of the total absorption by constituent cells. Increased absorption results from decreasing shelf shading within the colony by reducing the density of cells and pigments. Therefore in colonial cyanobacteria chlorophyll$_a$ is unrelated to pigment density of the cell. It increases absorption efficiency and adaptive ability. This method also makes eukaryotic algae superior competitors to non-colonial forms of cyanobacteria (Agusti and Philips 1992).This process may be observed in subsurface mats of *L. wollei* that are composed of orderly filaments (Speziale *et al.* 1991).

It has been generalized that cyanobacteria inhabit water with N: P ratios less than 64:1. This statement also applies to cyanobacteria which are non-nitrogen fixing (Elser 1999). This may result from species such as *L. wollei* being able to fix nitrogen without heterocysts. *L. wollei* has been found to exhibit nitrogenase activity under suitable environmental conditions (Philips *et al.* 1992). This may occur in low light or dark anoxic environments, where inhibiting oxygen is absent. In these conditions an increase in glucose results in increased nitrogenase activity. Philips *et al.* (1992) hypothesize that *L. wollei* utilizes exogenous electron donors for nitrogenase activity in such light limited environments.

Consequently, the vertical distribution of *L. wollei* places it in a number of environmental light regimes. It may be that each vertically stratified layer of the mat has an associated function. It has been determined that surface mats offer photoprotection to subsurface filaments and are largely photosynthetically inactive. Mats at mid depth have the highest associated photosynthetic rates (Speziale *et al.* 1991). Benthic mats are typically found at depths of 0.2-1.5m have low ambient PAR (Philips *et al.* 1992). Doyle and Smart (1998) have determined that the benthic mat and organic sediment zone are the source of dissolved nitrogen and phosphorus for *L. wollei* growth. In another mat forming species, *Lyngbya aestuarii,* Paerl *et al.* (1991) report that nitrogenase activity occurs in terminal undifferentiated cells. *L. wollei* may function using a similar mechanism. Nuisance cyanobacteria such as *L. wollei* that have large filaments and which are highly vacuolated are known to be able to store and translocate nutrients vertically (Klemer *et al.* 1995). In *L. wollei* vertical stratification may enable optimized nitrogen utilization by the entire infestation throughout the water column.

Doyle and Smart (1998) suggest that phosphorus is the growth limiting nutrient of *L. wollei.* Total phosphorus (TP) is thought to be a more accurate predictor of total algal biomass than total nitrogen (TN) or the ratio of TN: TP (Timbee and Prepas 1987). Mineralization of organic matter results in the availability of nutrients such as phosphorus at the sediment water interface. Caraco *et al.* (1993) suggest that anthropogenic sources of sulfate cause a change in aquatic sulfur cycles indirectly affecting the phosphorus availability of the system. Sulfate increases decomposition in anoxic conditions while reducing the binding potential of the sediment which inhibits phosphorus diffusion into the water above. An increase of sulfate from 70 – 120mmm has been determined to increase phosphorus release by the sediment by as much as 58%. Fe (III) binds phosphorus in the sediment. The oxidation of sulfide to sulfate results in the reduction of Fe (III) to Fe (II). This decrease in Fe (III) results in an increase in phosphorus available for uptake. Sulfate reduction is also an alkalinity generating process (Caraco *et al.* 1993). These processes create an optimal environment for *L. wollei* growth and development.

Phosphorus profiles show that there is strong phosphorus depletion throughout the benthic mats and in the underlying sediment (Doyle and Smart 1998). In *Aphanizomenon*, another nuisance cyanobacterium, phosphate is stored as polyphosphate (Klemer *et al.* 1995). *L. wollei* may store phosphate in a similar manner and is also able to store and fix nitrogen. Consequently, Cowell and Botts (1994) suggest that nitrogen and phosphorous increases do not result in increased colony growth. Instead increases in other nutrients, such as calcium, may have a more significant effect on growth.

The filament sheaths of *L. wollei* are composed primarily of calcium carbonate ($CaCO_3$) (Doyle and Smart 1998). Doyle and Smart (1998) suggest that the constituent $CaCO_3$ results in the characteristic strength of the mat. Cowell and Botts (1994) show calcium additions increased *L. wollei* growth. As a result, aquatic systems with calcareous sources, such as limestone, may facilitate increased growth of *L. wollei*. Calcium is known to be important for physiological processes in cyanobacteria. Calcium is also thought to enable *L. wollei* to tolerate increased nitrogen and phosphorous levels where cyanobacteria are usually at a competitive disadvantage. Calcium can also increase the utilization of phosphorus (Carmichael *et al.* 1997). Clearly, calcium is a crucial element for *L. wollei* growth. This is supported by Speziale and Dyck (1992) who found *L. wollei* infestations corresponded with sediment relatively high in calcium and phosphorus.

L. wollei produces toxins. These may confound the problem of aesthetically unpleasant infestations in the lakes, ponds and reservoirs where they are found. Paralytic shellfish poisoning (PSP) is a human poisoning syndrome which is caused by the potent neurotoxin saxitoxin (STX) and its analogues. Two species *Anabaena circinalis* and *Aphanizomenon flos-aquae* are known to produce PSPs. Carmichael *et al.* (1997) report that *L. wollei* is a third PSP producer. It is seven times less toxic than *Anabaena circinalis* . High performance liquid chromatography results show the presence of decarbamoylgonyautoxin-2 (dcGTX2), decarbamoylgonyautoxin-3 (dcGTX3), decarbamoylsaxitoxin (dcSTX) as well as six unidentified peaks. The dcGTX2, dcGTX3 and DCSTX are saxitoxin analogues (Onodera *et al.* 1997). The dcGTX2 and dcGTX3 are considered a minor component of the total toxicity *of L. wollei*(Yin *et al.* 1997). Six unidentified peaks revealed by HPLC, represent new saxitoxin analogues, which are under further investigation. Quantitative but not qualitative changes in the toxins produced differ under environmental variables including temperature, irradiance and nutrient concentrations of nitrogen, phosphate and calcium. Yin *et al.* (1997) report that the isolation of some samples leads to non-toxic results, suggests that there are both nontoxic and toxic filaments present in *L. wollei* mats. Toxicity may be a further competitive adaptation of *L. wollei.* In single species cultures the amount of toxin produced by *L. wollei* is significantly decreased, suggesting that toxin production is induced by interspecific competition (Yin *et al.* 1997). *L. wollei* infestations are also found to emit odorous compounds such as geosmin (Martin *et al.* 1987).

2.15 Management Techniques

In recent years, research has focused on the management and control of this nuisance species. *L. wollei* has proved to be resistant to current herbicides. The copper triethanolamine chelate *Cutrine-Plus* is used for the control of many types of algae. This chemical inhibits growth by binding to the chloroplast membrane, inhibiting the electron transport chain. Unfortunately, with the addition 1ppm, the maximum recommended concentration, growth of *L. wollei* was only inhibited by 50%. *Cide-Kick II* is an effective controller of aquatic weeds. Hallingse and Philips (1996) suggested that its use in combination with *Cutrine-Plus* may enhance effectiveness against *L. wollei*, but when applied it enhanced algal uptake of nutrients and increased mat growth. Chemical control is thought to have little effect on *L. wollei* because of its vertical distribution and the thickness of its mats. The algaecide *Diquat*, with a viscous settling agent, has been associated with moderate success in *L. wollei* control (Speziale *et al.* 1991). The limited success of chemical treatments has lead to the pursuit of alternate control methods.

Biological control using cyanophages has been investigated. Cyanophages occur naturally within the environment and are viruses which infect target cyanobacteria and lyse constituent cells (Philips *et al.*1990). Viruses of the LPP group infect members of the cyanobacteria genera *Lyngbya, Phormidium and Plectonema* (Monegue and Philips 1991). Thus cyanophages offer an alternative to chemicals which are non-toxic to other organisms and which are relatively target specific. Cyanophage LW 1was found to be able to suppress growth of *L. wollei* by 80-95%. The effectiveness of cyanophage control depended on the physiological stage of the *L. wollei.* LW1 was found to be most effective when applied to cyanobacteria before it was well established. *L. wollei* ,in contrast to other test species, *Anabaena flos-aquae* and *Anabaena circinalis,* did not show an accelerated decline in well established standing crops with the addition of cyanophages. Consequently, this technique is of little use in the control of established *L. wollei* infestations (Monegue and Philips 1991).

Other management methods have also proved ineffective. Commercial dyes such as *Rose Bengal* and *Methylene Blue* were found to moderately reduce *L. wollei.* High costs and the large scale of infestations make this removal technique impractical (Martin et al. 1987). Physical removal of surface mats has also proven to be a costly and temporary solution to the persistent nuisance organism (Tyler 1994). No known herbivores preferentially consume *L. wollei.* Grass carp (*Ctenopharyngodon idella)*, which have been found to consume *L. wollei,* prefer other algal species. Even at densities of 200 fish/acre, Carp do not consume enough *L. wollei* to significantly alter growth rates making this form of biological control ineffective (Dyck 1994).

The most recent management strategies have focused on the use of native emergent and submerged macrophytes. Initially, Doyle and Smart (1994a) determined that these species could reduce the negative impact of the nuisance *L. wollei.* In subsequent studies Doyle and Smart (1994b) reported that macrophyte growth could shade out *L. wollei.* They also suggested that macrophytes may reduce the amount of nitrogen and phosphorus available at the sediment water interface for uptake by the nuisance species (Doyle and Smart 1998). A number of species including *Pontederia cordata* and *Vallisneria americana* were found to almost completely eliminate surface mats. Doyle and Smart (1998) concluded that *P. cordata* resulted in the reduction of both benthic and surface mats. *P. cordata,* a rooted emergent macrophyte, decreased levels of dissolved nutrients available to *L. wollei. P. cordata* roots may have also increased degradation of *L. wollei* benthic mats through the release of O_2 and H^+. The release of oxygen is hypothesized to decrease the half-life of *L. wollei* from twenty to six months. Acidification by H^+ release may promote the degradation of *L. wollei's* $CaCO_3^-$ sheaths. This process may accelerate the loss of biomass and lead to significant mat degradation.

The University of Florida is currently pursuing further research into the effectiveness of native species on the reduction of *L. wollei* infestations. The Kings Bay *Vallisneria* Project focuses on the removal of *L. wollei* and revegetation of Crystal River and Kings Bay. The project will investigate how ecological factors influence revegetation in these areas. *Vallisneria* commonly known as tape grass is native to Florida. It provides food and habitat for aquatic organisms and may be an effective management tool. The initial pilot project started in July 2000 intends to determine the amount of *Vallisneria* needed to survive and compete in *L. wollei* dominated environments (Southwest Florida Water Management District 2000).

2.16 Summary

The opportunistic *L. wollei* inhabits alkaline freshwater lentic ecosystems. As a result *L wollei* is able to efficiently use bicarbonate as its DIC source. *L. wollei* also depresses photorespiration at high O_2 concentrations. These are important characteristics that increase the competitive advantage of this species. Vertical stratification of *L. wollei* mats may enable each layer of the infestation to have a unique function. This may also increase *L. wollei*'s competitive abilities. Surface mats use the atmosphere to increase usable inorganic carbon. Surface mats also become photosynthetically inactive due to high light influxes and resulting photoinhibition. Benthic mats have decreased photosynthetic potential as a result of low ambient PAR. Benthic mats have a crucial function in the production of nitrogen and translocation of nutrients throughout the infestation. Mid depth mats have the highest associated photosynthetic potential. By producing geosmin and PSPs *L. wollei* may further reduce the competitive capabilities of other species. *L. wollei* is an opportunistic and dominating species. It can out compete most interspecific competitors once established in an aquatic system. Many management techniques that have been explored have proven ineffective. Recent research suggests that native macrophytes may be the most effective control of this nuisance organism. Macrophytes take up nutrients and consequently release H^+. This process increases water acidity and decreases nutrient availability for *L. wollei.* Native emergents such as *Vallisneria* might shade out *L. wollei* mats. In the future, the dominance of *L. wollei* may be addressed by changing the environment of the many aquatic systems it inhabits.

2.2 Whiteshell Provincial Park

2.21 Geography & Geology

Whiteshell Provincial Park, located approximately 140 km east of Winnipeg, encompasses 2 719 km^2 of southeastern Manitoba (Figure 1) (Schneider 2002). The park boundary corresponds with the Whiteshell River to the North and the Ontario border to the East. The park is located in the Precambrian Boreal Forest region of Manitoba (Jones *et al.* 1980). In this area the Precambrian Shield and Boreal Forest overlap (Whitesel 2001). The Whiteshell topography is characterized by rolling to hilly relief, rock outcrops, variable amounts of glacial drift, bogs and eskers (Barto and Vogel 1978). Four surface deposits persist in Whiteshell Provincial Park: lacustrine sediments, moraine deposits, glaciofluvial outwash and organic deposits (Forrester 1978). Isostatic rebound helped to produce the drainage basins of Whiteshell Provincial Park. Lakes occupy the majority of glacially excavated depressions in the area and fault basins (Moenig et al 1978). There are 131 lakes in the Whiteshell ranging in depth from 1 to 115 meters (Schneider 2002). Today, bogs and lakes cover 40-60 % of the surface of this region (Forrester 1978).

At the beginning of the twentieth century, gold was discovered across the border near the town of Keewatin, Ontario. As a result, prospectors flocked to the Whiteshell area.

Some of the earliest mining claims made in Manitoba were in the Falcon-West Hawk-Star Lake district in 1901 (Whitesel 2001). 'Patent Mining Claims' purchased before 1914 enabled owners to construct homes on their plot. This initiated colonization of the area by Europeans. A few patent mining claims, which could not be bought by the government, constitute the only privately owned land in the park today. In 1907, James Westropp Brereton established the first homestead on Crown land at Cross Lake. Homesteads were also established in the area surrounding Brereton Lake after 1907, with the completion of the CNR through the area. Following World War I, 400 ha of Crown land within the George Lake district was distributed as 'soldier grants' to returning soldiers interested in farming (Suggett 1984). This area was not a profitable agricultural area due to thin, undesirable soils. As a result, most of the land was returned to the Crown (Suggett 1984). The fuel division of the Arctic Ice Company had a logging camp located at Florence Lake in the 1920s. The camp was complete with stables to accommodate seven teams of horses, a blacksmith shop, oil shed and a twenty-five ton capacity ice house (Zimmerman 1991). In 1929, the Arctic Ice Company ceased production at Florence Lake and cottage development commenced.

By the 1920s the recreational potential of the Whiteshell area had been recognized and the Crown set aside land around a few lakes for recreational purposes. As a result, summer resort lots were surveyed in areas around Brereton, Nora, Florence, West Hawk and Falcon Lakes, which were accessible by railroad. This would mark the beginning of recreational users in the Whiteshell area.

2.22 Whiteshell Development

All land clearing and road construction initiated in the 1930s was completed by the Single Unemployed Men's Relief Commission, as overseen by the Forest Service. In 1939, portages were cleared and docks built to make the Whiteshell River more desirable to canoe enthusiasts. Since that time fire-pits have been installed in back-country campsites, portages have been cut and maintained between lakes and canoe routes have been mapped throughout the park (Anonymous 1978). Today there is an extensive network of canoe routes through intensive, extensive, backcountry and wilderness areas of the Whiteshell, which attracts visitors from around the globe.

Since the 1970s interpretative programs have been used to enhance the enjoyment of visitors to the Whiteshell. Through education interpreters improve visitor knowledge and appreciation of the park and its resources. Hiking trails, amphitheater programs and guided walks are used to educate visitors on important park features which may enhance their recreational experiences (Jones *et al.* 1980). There are numerous self-guiding trails throughout the park. These provide thoughtful information on the trail and park. There are four outdoor amphitheaters throughout the park, which facilitate summer evening interpretive programs. Amphitheaters are located at Nutimik, Big Whiteshell, West Hawk and Falcon Lakes. Evening programs provide family entertainment and information on the park. Visitors may also explore Whiteshell history at the Whiteshell Natural History Museum, West Hawk Geology and Mining Museum and the Whiteshell Trapper's Museum (Schneider 2002). The Alfred Hole Goose Sanctuary in Rennie is another important tourist attraction for visitors interested in learning more about the park and its wildlife. Interpretive programs and facilities throughout the park enhance visitor understanding and appreciation of Whiteshell Provincial Park. Appendix A: Supplementary Whiteshell material provides further detail on Whiteshell histroy and use.

2.23 Current Whiteshell

Manitoba has 95 Provincial Parks. Whiteshell Provincial Park is one of sixteen Natural Parks dedicated to preserving natural areas while accommodating recreational activities and resource use (Schneider 2002). Whiteshell Provincial Park is divided into four districts: Falcon, West Hawk, Seven Sisters and Rennie. As a result, visitor use may be broken down by district (Table 2). Forty percent of Whiteshell visitors entered the Park at Falcon Lake in 2003. Summary Table 1 shows that the Falcon District has the most visitors, followed by West Hawk, Seven Sisters and Rennie Districts respectively. Whiteshell Provincial Park use may also be understood by examining the number of cottages and campsites located

Table 2: District vehicle entry between May and September 2003. Number of annual and casual Provincial Park Passes sold in each district.

District	Vehicle Entry	Annual Permits	Casual Permits
Falcon	140 818	4 100	9 438
Rennie	61 526	2 847	4 343
Seven Sisters	74 514	3 761	6 048
West Hawk	78 697	2 830	4 828

Table 3: Number of cottages, seasonal and transient campsites on 12 Whiteshell lakes.

Lake	Cottage	Basic	Electrical	Basic	Electrical
Barren	23	0	0	0	0
Betula	170	27	0	17	0
Big Whiteshell	181	112	0	42	36
Brereton	348	25	36	18	8
Caddy	151	5	17	26	0
Falcon	813	0	164	242	155
Green	3	0	0	0	0
Hunt	8	0	0	0	0
Jessica	102	0	0	0	0
Red Rock	123	0	0	0	0
Star	129	0	0	0	0
White	83	25	6	29	0

Table 4: Summary of public beach and boat launch facilities on 12 Whiteshell lakes. Maximum number of visitors, unknown visitor numbers (-) and lakes with no public beaches (n/a) were recorded.

Public Beach	Max No. Visitors	Boat Launches
Barren Lake	n/a	1
Betula Lake		1
Betula Lake Campground Beach	70	1
Betula Lake Block 5,6,7 Beach	50	
Big Whiteshell Lake		2
Big Whiteshell North Shore	50	
Big Whiteshell South Shore	200	
Brereton Lake		3
Brereton Block 9	15	
Brereton Campground	110	
Brereton South Shore	300	
Caddy Lake	50	1
Falcon Lake		4
Main Beach (townsite)	500	
Lakeshore (campground)	-	
Faloma	100	
Toniata	75	
Block 10 A (Main Beach)	75	
Block 10 B	-	
Block 11	-	
Block 13 A	-	
Block 13 B	-	
Block 9	-	
Block 12	15	
Green Lake	n/a	1
Hunt Lake	n/a	1
Jessica Lake	n/a	1
Red Rock Lake	n/a	0
Star Lake	300	1
White Lake	100-150	1

Table 5: Historic waste disposal sites throughout the Whiteshell, most of which are presently inactive (Karp 1987).

Lake	Classification	Location (Section)	Registered by Parks Branch	Sites Active in 2003
Active Disposal Sites in 1987				
Falcon	Waste Disposal Grounds	NW 35-8-16E	Yes	No
	Brush Dump	NW 35-8-16E	Yes	No
Jessica	Waste Disposal Grounds	SE 9-12-15E	No	Yes
Betula	Brush Dump	SE 11-13-14E	Yes	Yes
Star Lake	Brush Dump	SW 18-9-17E	No	No
Inactive Disposal Sites closed prior to 1987			*Approx. Year Closed*	
Green Lake	Waste Disposal	NE 18-13-16E	1985	No
Brereton Lake	Waste Disposal	SW 5-12-15	1977	No
Dorothy Lake	Waste Disposal	SW 4-14-13E	1977	No
Nutimik Lake	Waste Disposal	NE 29-13-14E	1982	No
Nutimik Lake	Waste Disposal	SW 31-13-14E	1985	No
Pointe Du Bois	Waste Disposal	NW 26-15-14E	1985	No
Star Lake	Waste Disposal	SW 18-9-17E	1985	No

throughout the park (Table 3). Falcon Lake has 813 cottages, 164 seasonal campsites and 397 transient campsites making it the most intensively used lake in the park (Table 3 & 4). Historically, there have been waste disposal sites throughout the Whiteshell (Table 5). Presently there are four transfer stations, one for each district and a number of brush dumps located in the Whiteshell. It is evident from these statistics that Whiteshell Provincial Park is an important recreational area under intensive use.

2.24 Economic Resources

The Whiteshell Master Plan (Jones *et al.* 1980), states that "the use of park resources for commercial purposes, though clearly secondary (to recreational activities), is nonetheless important". Whiteshell economic resources include mining, hydro-electric power, forestry, wild rice (*Zizania aquatica*), and sport fishing. Presently, commercial exploitation of Whiteshell resources continues. Staked in 1912, one of the original patent gold mining claims located at Star Lake, remains active but has ceased production (Suggett 1984). Most mining done in the park today is granite quarrying used in construction of roads in Winnipeg (Schneider 2002). There are three hydroelectric generating stations in the northern region of Whiteshell Provincial Park. These three hydroelectric run-of-the-river generating stations along the Winnipeg River, are located at Pointe du Bois, Slave Falls and Seven Sisters. The generating stations are owned and operated by Manitoba Hydro (Schneider 2002). Managed forestry operations are used to suppress wildfires within the Whiteshell. There are 12 forestry operators currently harvesting from the Whiteshell area. Selective harvesting since the mid 1930s include Jack Pine (*Pinus banksiana*), White and Black Spruce (*Picea glauca, Picea mariana*), Balsam Fir (*Abies balsamea*), Tamarack (*Larix laricina*), Aspen (*Populus tremuloides*) and Birch (*Betula papyrifera*) which are used to produce pulpwood, lumber, fence posts and fuelwood. Aboriginal people traditionally used wild rice as a dietary staple, reseeding lakes with wild rice and introduced it to lakes without growth. Today it is harvested in the park by mechanical harvesting or handpicking with two poles and a canoe. The harvested rice is sold to processors. Another important resource is the sport fishery which attracts many visitors to the Whiteshell. The importance of the recreational fishing was acknowledged in the early 1940s with the development of the summer resorts and canoe routes through the Whiteshell. Consequently, a fish hatchery was established at the north end of West Hawk Lake in 1943. This was the first fish hatchery in the province and was employed to keep Whiteshell lakes well stocked with game fish, in particular rainbow and lake trout. The Whiteshell Fish Hatchery still stocks Whiteshell lakes with game fish species (Appendix A). As a result, economic resources were fundamental in the initial development of Whiteshell Provincial Park as a Forest Reserve and remain important today.

Natural Parks such as the Whiteshell facilitate a liaison between nature and outdoor enthusiasts. In order to understand and preserve this natural landscape rich with natural and cultural history, numerous studies have been undertaken in the Whiteshell. The majority of published studies were conducted between 1965 and 1975 (Appendix A). These studies attempted to characterize the park so that it could be developed and used to its fullest recreational potential. A Master Plan was developed in 1980 to define the role of Manitoba's Provincial Parks system and direct its development, management and operation. The primary objective of resource management stipulated by the Whiteshell Master Plan was "to establish water-quality guidelines and to manage the park's watershed to ensure that recreational values are maintained" (Jones *et al.* 1980). As a result, water quality testing initiated in the 1970s continues today administered by the Water Quality section of Manitoba Conservation.

2.25 Infestation Related Practices in Whiteshell Provincial Park

Since 1996, Betula Lake cottage owners have been working with the Water Quality Division of Manitoba Conservation to limit the spread and density of the *L. wollei* infestation. Initially mesh nets were given to interested cottage owners to harvest *L. wollei* mats from their shoreline. *L. wollei* mats were extremely heavy and this method proved impractical (Personal Communication). Parks supplied cottagers with buoys in 1997 which have been used annually to prohibit motor boats from entering Block 2, near shore areas at high speeds. The buoys have been anchored approximately 60 feet offshore and protect the area between

Block 2, Lot 6 and the campground. Block 2 cottagers with motor boats idle out beyond the buoys before beginning recreational activities. It was hypothesized that these approaches would limit the fragmentation of *L. wollei* filaments minimizing direct anthropogenic density enhancement.

In 1950, the Betula Lake Ski Bees, a water skiing club still active today was established. The White Lake Ski Club was formed in the early 1960s. Today the Freeriders Club operates wakeboarding clinics on numerous Whiteshell lakes, but Betula and White Lakes remain the only Whiteshell lakes with established water skiing clubs. Many Betula and White Lake clubs member have been distinguished Manitoba water skiers. As a result, these lakes have held competitions at the provincial and national levels. Today both Betula and White Lakes have a ski jump and slalom course for training. The original Betula Lake ski jump was moved to White Lake in the early 1970s. At this time the pier at the Betula Lake main beach was removed and the boat launch was moved to Block 5. Approximately four years ago Betula Lake acquired a new ski jump which was placed in the north-western basin away from cottage development and the *L. wollei* infestation. Historically water skiing activities were concentrated in the now infested south-western basin (personnel observation).

Concerned cottagers prompted a study conducted by Wendy Ralley from Manitoba Conservation, in 1997, comparing water quality in high and low intensity boating areas. Based on the parameters measured, high intensity boating did not have a significant effect on water quality. While recreational boating may not significantly alter water quality in a specific area, it may alter *L. wollei* density. Fragmentation of *L. wollei* filaments by motorized watercraft may result in increased density and biomass. At White Lake, the *L. wollei* infestation was concentrated in the areas surrounding the public beach. Consequently, *L. wollei* was found in thick mats near shore were people pull up their boats and around the White Lake water skiing dock. This may be evidence to suggest *L. wollei* biomass is affected by motorized watercraft disturbance.

At Betula Lake the campground beach area was dredged during the summer months, by Seven Sisters District personnel. Within the sectioned off swimming area a metal bar was dragged behind a motor boat along the sediment surface, tearing apart *L. wollei* mats. The fragmented mats were then manually raked from the swimming area. This practice may fragment *L. wollei* filaments. Each fragment may then grow to increase *L. wollei* total density. Personal observations further indicated that *L. wollei* mats quickly redistributed to cover the dredged area.

Betula Lake has an active and energetic community which is taking thoughtful action to impede the development of *L. wollei* infestations. Many residents have spent most of their lives on the lake and provide invaluable help and resources. The White Lake community is less aware of the *L. wollei* infestation in their lake and consequently less involved in current remediation strategies.

2.3 Paleolimnology

2.31 Introduction

Paleolimnology is defined as the study of lake history. Past environmental conditions are examined using chemical, biological and physical parameters within sedimentary profiles (Smol and Glew 1992). Paleolimnology may provide information on past conditions, productivity, and changes in parameters regulating lake productivity. This information may then be used to predict environmental conditions and future levels of productivity (Wetzel 2001). Paleolimnology is an invaluable tool when examining the past and preparing for the future.

2.32 Sediment sources

Lakes are natural sediment sinks. Lake sediment may be produced within the lake, or may be deposited from an external source (Wetzel 2001). Allochthonous material is deposited in the lake from the surrounding area and airshed. Autochthonous sediment material is the result of biological production and chemical precipitation (Smol and Glew 1992). Drainage basin morphology, type and distribution of its vegetation determine inorganic inputs.

Autotrophic productivity within the drainage basin and lake determine the organic matter content of the sediment (Smol and Glew 1992). Lake chemistry is dependent on atmospheric fallout, precipitation, evaporation, drainage basin lithology and the influence of soil on water inputs (Smol and Glew 1992).

2.33 Sediment composition & deposition

Paleolimnology enables examination of post glacial vegetation succession, climate changes, and anthropogenically induced changes in lakes and their watersheds (Smol and Glew 1992, Fisher *et al.* 1992). Multiple sediment parameters are examined providing lines of stratigraphic evidence for paleoecological reconstruction. Parameters include: water content, organic matter and carbonate mineral content, mineralogy, inorganic chemistry, pigments, pollen, algal and animal microfossils (Fisher *et al.* 1992). Sediment dating techniques enable detailed paleolimnological analysis.

With a half-life of 22.26 years, 210Pb is used to date lake sediments deposited over the last 150 years (Wetzel 2001). Lead-210 enters lakes via precipitation and catchment erosion accumulating in the sediment. This form of 210Pb is termed "unsupported" because it is produced from the decay of radium in the atmosphere or catchment and then transported into the lake (Wetzel 2001). To calculate the age of the sediment at a specific depth the activity of unsupported 210Pb is compared to the activity in the surface sediment. Lead-210 decreases with sediment depth as a result of radioactive decay. With a known half-life of 22.26 years, the magnitude of decay may be used to calculate the age of the sediment. The constant flux model assumes a constant flux of ^{210}Pb to the sediment and changing sedimentation rates (Haworth and Lund 1984).

The distribution of ^{137}Cs is another method used to examine lake sediment deposited within the last 50 years. Cesium-137 has been present in the atmosphere since 1954 as a result of atomic bomb testing. Cesium-137 typically show a sharp peak in sedimentary records correlated to the atmospheric test ban treaty of 1963 (Wetzel 2001). Consequently, 210Pb and 137Cs dating may be used in combination to date recently deposited sediments assuming migration within the sediment was negligible (Wetzel 2001).

Organic matter, carbonate minerals and non-carbonate clastic material are the three main components of lake sediment (Dean 1974). Sediment water content is indicative of the compactness of the sediment. Abrupt changes in the water content profile of a core may indicate a change in sediment composition. Sediment with high clay content is tightly packed with poor water-holding properties. In contrast, sediment water content increases with increased organic matter content (Warwick 1980). Characteristic signatures occur within the sediment. The productivity of the lake and drainage basin, driven by seasonal parameters, influences the rate and nature of sedimentary deposition (Smol and Glew 1992).

2.34 Lake productivity

Stratigraphic organic matter content is indicative of past levels of productivity. Organic matter dictates the rates and concentrations of organic micronutrients, bacteria, turnover rates, and dissolved organic compounds. High organic matter content increases these parameters resulting in high productivity in the system. In contrast low organic matter may limit the productivity of a system (Wetzel 2001). It is assumed that most organic matter is autochthonous in origin and that diagenesis rates may be assumed constant or may be estimated (Wetzel 2001). Increases in organic matter, nutrients and sediments within the lake basin may be an indication of anthropogenic eutrophication (Reavie *et al.* 2000).

Photosynthesis is the main source of carbonate precipitation within freshwater lakes (Reeves 1968). There are two main sources of carbon dioxide input: atmospheric solution along with sheetwash and tributary inflow (Reeves 1968, Wetzel 2001). Inorganic carbon in aquatic systems forms a complex equilibrium between carbon dioxide (CO_2), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). In water, CO_2 is very soluble and quickly forms carbonic acid, which dissociates to HCO_3^- and CO_3^{2-}. Water is buffered by the dynamic equilibrium of these inorganic forms of carbon (Wetzel 2001). When CO_2 is used by autotrophs the equilibrium shifts and bicarbonate and calcium, the predominant anion and cation in the system are precipitated as calcium carbonate (marl). Marl is produced until the equilibrium is reestablished. High concentrations of carbonate minerals are indicative of high levels of photosynthetic productivity. Carbonate mineral content indicates historical levels of productivity (Wetzel 2001).

Radiocarbon dating enables the calculation of past sedimentation rates. Erosion deposition may be inferred using clastic mineral stratigraphic components such as magnesium, sodium and potassium. Stratigraphic clastic mineral components are proportional to the drainage system erosion at the time of deposition. This provides a stratigraphic index of terrestrial input (Hickman *et al.* 1984).

Fossil pigments contained within the sediment function as biogeochemical markers. Photosynthetic pigments and their derivatives produce numerous paleolimnological indicator groups which may be used as a reliable record of historical productivity levels and algal species abundance (Smol and Glew 1992). Carotenoid and chlorophyll pigments have been used consistently as indicators of algal and bacteria populations (Leavitt 1993). Primary productivity has been correlated to pigment sedimentation rates and abundance in surface sediments (Leavitt and Carpenter 1990). Chlorophyll derivatives are indicators of gross shifts in algal abundance. Carotenoids are used as indicators of specific algal and cyanobacteria populations (Smol and Glew 1992).

Fossil pigments are subject to degradation. Sedimentary chlorophyll is degraded to the pheopigments: pheophytin and pheophorbide (Swain 1985). Pheopigments are produced through chlorophyll photo-oxidation, digestion by zooplankton or benthic detritivores, enzyme metabolism during senescence, and chemical or microbial mediated oxidation (Leavitt 1993). Microbial mediated degradation may be pigment or alga specific (Leavitt and Carpenter 1990). Carotenoid pigments remain metabolically active after assimilation by aquatic invertebrates. Chlorophyll pigments do not remain metabolically active and are not assimilated by aquatic invertebrates (Leavitt 1993). Pigment degradation is also influenced by three environmental parameters: oxygen, temperature and light (Wetzel 1970). Chlorophyll degradation is reduced in dark, less oxygenated and cooler hypolimnetic waters (Swain 1985). As a result, pigment stratigraphy is only an outline of the many processes which produce and preserve plant pigments (Swain 1985). Pigment concentrations expressed relative to organic matter provide the most accurate stratigraphic trends. When expressed per unit dry matter, dilution due to mineral soil erosion or carbonate precipitate may result in misleading pigment concentrations (Swain 1985). Individual pigment stratigraphy may be examined independently and concentrations may be compared to historical maximum values (Leavitt and Carpenter 1990).

Organic matter, carbonate content and total chlorophyll concentration may be used in combination to examine historic lake productivity. As indicators of historic lake productivity it was hypothesized that all three profiles follow similar patterns within a core.

The loss on ignition method determines the total carbonate content but does not indicate which carbonate minerals are present. If sediment is low in carbonate with a significant amount of clay this method may give inaccurate results. Between 550-1000°C the lattice OH water is removed from clay. As a result, sediment containing no carbonate with high clay content would exhibit a 3-4% loss on ignition (Dean 1974). The sediment collected in this study is highly organic in nature with an unknown amount of clay. Paleolimnological studies identify iron sulfides in the sediment based on dark coloured sediment or high concentrations of iron and sulfur within the core (Haworth and Lund 1984). The sediment collected was a dark brown in colour with a high concentration of iron. As a result, minerals within the sediment such as iron sulfides, feldspar and other minerals may account for the small loss on ignition between 550-1000°C. Dean (1974) states that the ignition loss method was determined to have a precision of 3.07 % for samples containing little or no clay. Consequently, the carbonate content may not be an appropriate method to measure of historic productivity.

An increase in organic matter content signals an increase in productivity. Allochthonous inputs may result in an inaccurate representation of productivity. As a result, organic matter content and total chlorophyll may be examined together to infer past productivity levels. Allochthonous organic matter is pigment poor, in senescent deciduous tree leaves 90-98 % of all chlorophyll is destroyed in 7 to 15 days. (Leavitt 1993). Total chlorophyll was expressed as a concentration of organic matter which is considered the most reliable index with limited bias by differential rates of inorganic sediment (Wetzel 1970). As a result, organic matter content and total chlorophyll concentrations together may be considered the most effective indicator of past autochthonous productivity.

2.35 Whiteshell Sediment Geochemistry

Sediment geochemistry is another important method for examining lake productivity as a result of anthropogenic and natural disturbances. Sediment cores represent a temporal scale where historic sediment concentrations located at the base of the core may be compared to current concentrations at the top of the core. This temporal scale may be used to differentiate natural eutrophic conditions from cultural eutrophication. Cultural eutrophication conditions are indicated by an accelerated increase in organic matter, nutrient and heavy metal concentrations from anthropogenic impacts (Reavie *et al.* 2000). Select nutrient and heavy metal concentration profiles may be examined as indicators of cultural eutrophication.

Macronutrient concentrations limit algal growth, while micronutrient concentrations affect species growth rates (Hyenstrand *et al.* 2001). Nitrogen is an important macronutrient required by autogenic organisms to produce amino acids, nucleic acids, chlorophyll and other nitrogen containing compounds (Graham and Wilcox 2000). Total kjeldahl nitrogen is a measure of total organic nitrogen and ammonia as a percent of sediment dry weight used for the purposes of this study. Nitrogen is more abundant than phosphorus but its high demand makes it the second most important limiting nutrient in freshwater aquatic systems.

Phosphorus is essential to biological metabolism with relatively small amounts available in the hydrosphere. Consequently, it is the primary growth limiting nutrient in freshwater aquatic ecosystems. Phosphorus in atmospheric precipitation originated from fine particles of rock and soil, living and dead organisms, volatile compounds released from plants, natural fires and fossil fuel combustion. Atmospheric precipitation may account for 40% or more of the annual phosphorus loading within a lake (Wetzel 2001). Haworth and Lund (1984) state that in numerous studies anthropogenic enrichment of lakes by sewage discharge was sufficiently dramatic to leave conclusive evidence of phosphorus enrichment.

Manganese and iron are essential for nitrate assimilation, nitrogen fixation, photosynthesis and catalyze numerous algal enzyme systems (Wetzel 2001). Deposition of phosphorus into lake sediment results from the co-precipitation of phosphorus with iron and manganese oxides and hydroxides (Wetzel 2001, Pardo *et al.* 2003). Manganese also adsorbs to iron oxides and coprecipitates with ferric hydroxide. Phosphorus complexes with iron and manganese are important in controlling sedimentary phosphorus concentrations. The oxidized sediment-water interface traps iron, manganese and consequently phosphorus within the sediment. As the redox potential decreases the release of iron, manganese and phosphorus increases. Manganese has a higher redox potential than iron. Consequently, manganese is released from the sediment prior to iron (Wetzel 2001). If iron and manganese concentrations remained constant for the length of the core then increasing phosphorus concentration profiles would indicate increased phosphorus inputs (Wetzel 2001). Correlated concentrations profiles indicate sediment was affected by redox conditions. As sediment redox potentials decrease iron, manganese and phosphorus complexes move up through the sediment until immobilized again by redox conditions (Wetzel 2001). Consequently, phosphorus concentrations may be concentrated at the sediment surface. Correlated iron, manganese and phosphorus concentrations increasing up the sediment core may be the result of this natural process and not indicative of cultural eutrophication.

Cyanobacteria require calcium for photosystem II activity, nitrogen fixation and phosphate uptake (El-Zahraa and Zaki 1999). Calcium can also increase the utilization of phosphorus (Carmichael *et al.* 1997). Boron is required to maintain algal growth under calcium limiting conditions (Bonilla *et al.* 1995). Boron functions in cell-wall synthesis and structure as well as membrane structure and function (El-Zahraa and Zaki 1999). Research indicated boron has an integral role in protecting heterocysts from oxygen. It is thought that boron stabilizes the heterocyst envelope inhibiting oxygen diffusion which would prohibit nitrogen fixation. Boron may also maintain the Ca-pectin association in cell walls, repair heterocyst damage caused by calcium deficiency, and facilitate calcium uptake (Bonilla *et al.* 1995).

Over 80 minerals contain boron. Weathering of igneous and sedimentary rock and soil leaching are sources of boron (CCME 1987). Boron concentrations may also be supplemented by anthropogenic practices. The major compound, borax, is used as a cleaning compound and may occur in domestic sewage. Whiteshell Provincial Park is located on the Precambrian Shield. It may be expected that most Shield lakes would experience similar natural boron concentrations. Consequently, increased boron concentrations may be the result of anthropogenic activity in the surrounding watershed.

Four heavy metals, arsenic, cadmium, lead and mercury, may be used to examine anthropogenic lake contamination. The Canadian Sediment Quality Guidelines for the protection of Aquatic Life summarize the interim freshwater sediment quality guidelines (ISQG) and probable effect levels (PEL) for these heavy metals. Sedimentary arsenic concentrations depend on geochemistry, anthropogenic and industrial activity. Arsenic is more common in the earths crust than other common elements such as mercury and cadmium. Weathering of arsenic containing rocks is an important natural source of arsenic. Arsenic is also released into the atmosphere by combustion of fossil fuels and is a component of leaded gasoline, laundry and other household products (CCME 1987). Cadmium is toxic to aquatic organisms at very low concentrations (Wetzel 2001). Sources include industrial emissions, fertilizers and pesticides containing cadmium and burning fossil fuels (CCME 1987). Lead is used primarily in the production of acid-storage batteries and chemical compounds such as alkyl lead additives including tetramethyl- and tetraethyllead (CCME 1987). Beginning in 1923, anti-knock lead alkyls, tetraethyl and tetramethyl lead were incorporated into gasoline at a concentrations of 2 - 4 g/gal (Silver and Wozniak 2001). Fifty years later in 1973, the combustion of leaded gasoline peaked accounting for 70 % of total Canadian lead emissions to the atmosphere (McCallum and Hall 1998). Research has shown a consistent increase in lead levels in lake sediments since lead was added to gasoline. As a result, by 1990 all lead additives were removed from Canadian gasoline (McCallum and Hall 1998). Mercury is used in pulp and paper manufacture, gold extraction, batteries, mercury based pesticides among other. As a result, these heavy metals may provide valuable information on the land-use practices in Whiteshell Provincial Park.

Chapter 3: Methods and Materials

3.1 Lyngbya wollei

3.11 Study Area

Whiteshell Provincial Park is located in the south-eastern corner of Manitoba, Canada (Figure 1). The Park is divided into four land use zones: wilderness, backcountry, extensive and intensive (Figure 1A-1E, Table 6). These land use zones form a continuum of land use throughout the park (Hegenson and O'Connor 1978). The use of motorized vehicles is prohibited in the wilderness zone. This reserves the Mantario Lake Wilderness area for canoeing and hiking adventures, which have minimal impact on the environment. In contrast, intensive use zones have been developed to support summer homes and recreational activities. These areas are important to tourism in Manitoba and support seasonal recreational activities such as boating and snowmobiling.

3.12 Study Organism

*Lyngbya wollei (*Farlow ex Gomont) comb. nov., is a member of the family Oscillatoriaceae and division Cyanophyta (Speziale and Dyck 1992). Farlow first reported this species in 1877, from its occurrence in a pond near Boston, Massachusetts. *L. wollei* trichomes are composed of discoid cells 24-65 and 2-12 μm in diameter and length, respectively. End cells are rounded and acalyptate (Speziale and Dyck 1992). The sheath surrounding each trichome is up to 12 μm thick, hyaline and lamellate. Individual filaments are indeterminant in length, sparsely false-branched and form entangled mats. Healthy trichomes are blue-black and become green to yellow in colour when photooxidized (Speziale and Dyck 1992).

Since 1877, this alga has been given six different taxonomic identities (Table 1). Speziale and Dyck (1992) conclude the most accurate taxonomic identity of this alga is *Lyngbya wollei* (Farlow ex Gomont) comb. nov. Although most botanical taxonomic systems identify this alga as *Plectonema wollei*, Speziale and Dyck (1992) feel this puts undue

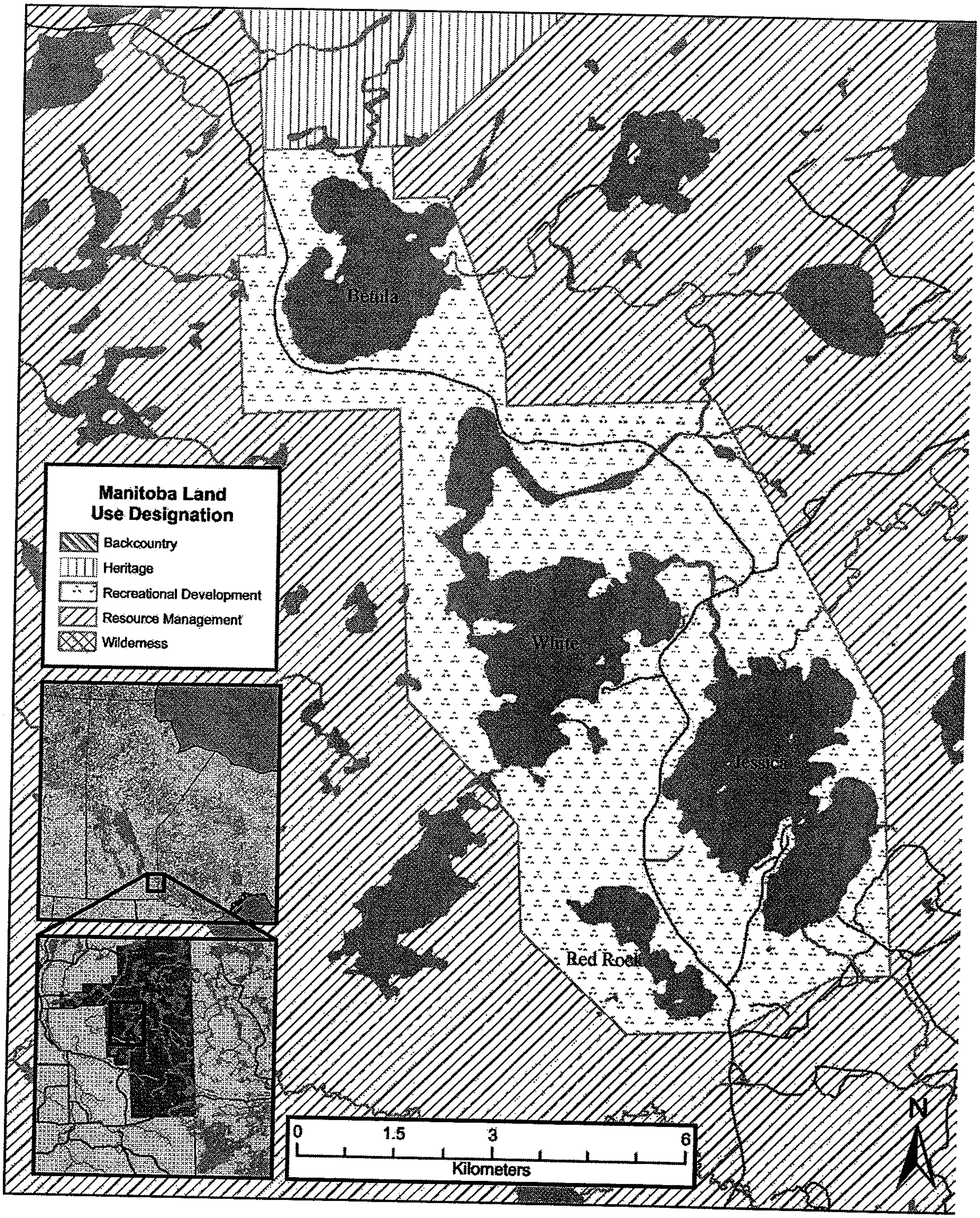

Figure 1A: Whiteshell Provincial Park map showing Betula, White, Jessica, and Red Rock Lakes. Labeled lakes were sampled monthly in 2002.

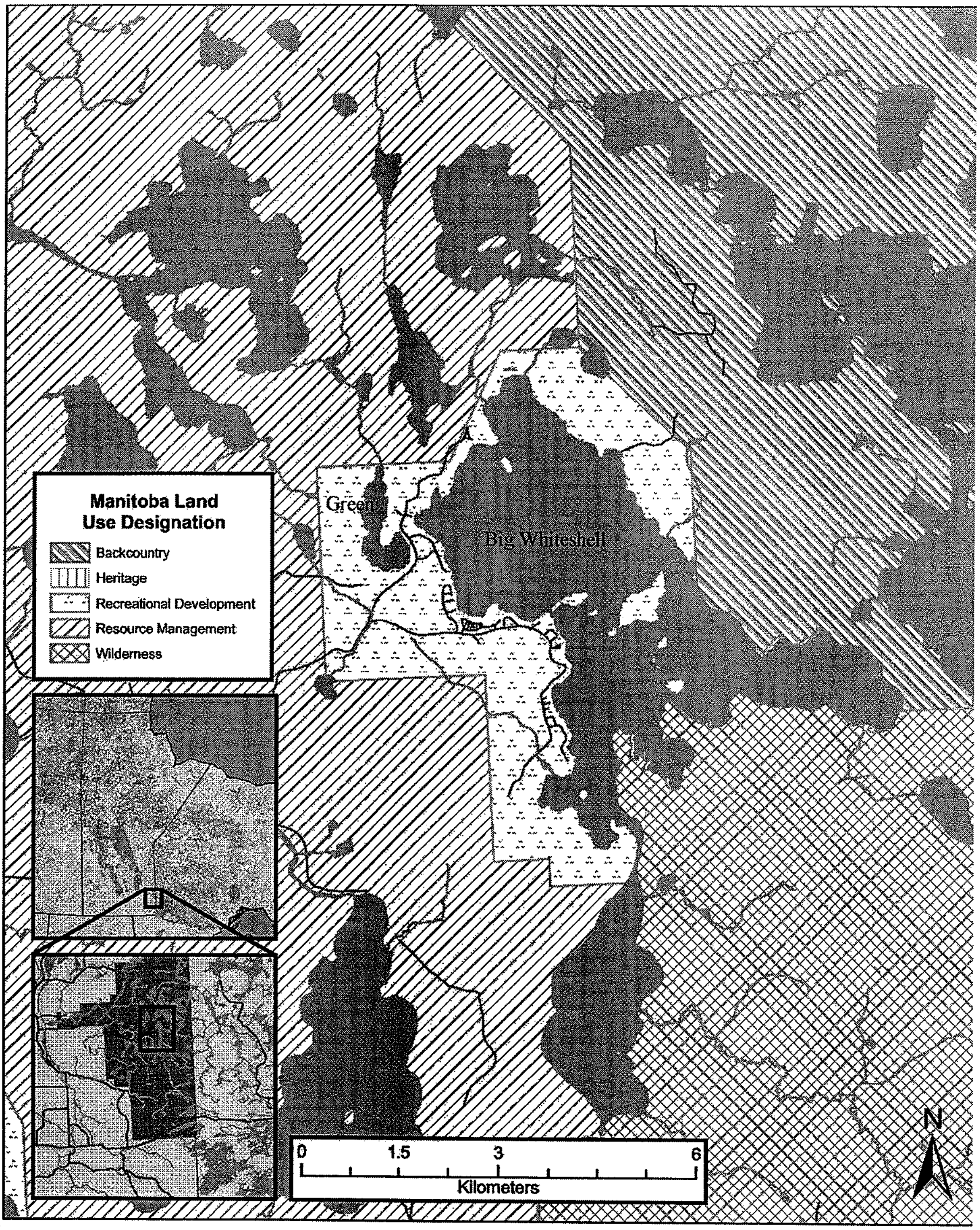

Figure 1B: Whiteshell Provincial Park map showing Big Whiteshell and Green Lakes. Labeled lakes were sampled monthly in 2002.

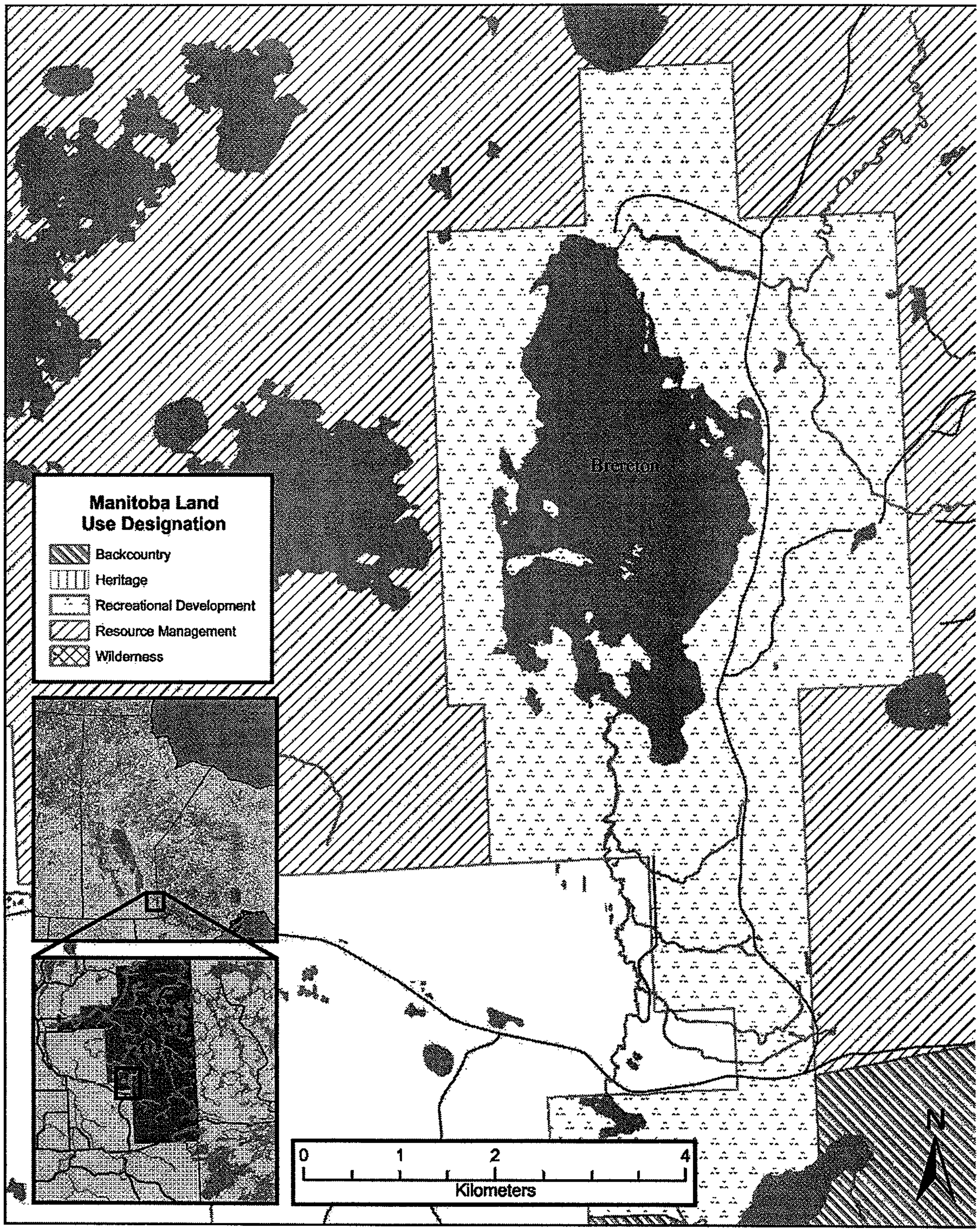

Figure 1C: Whiteshell Provincial Park map showing Brereton Lake. Labeled lake was sampled monthly in 2002.

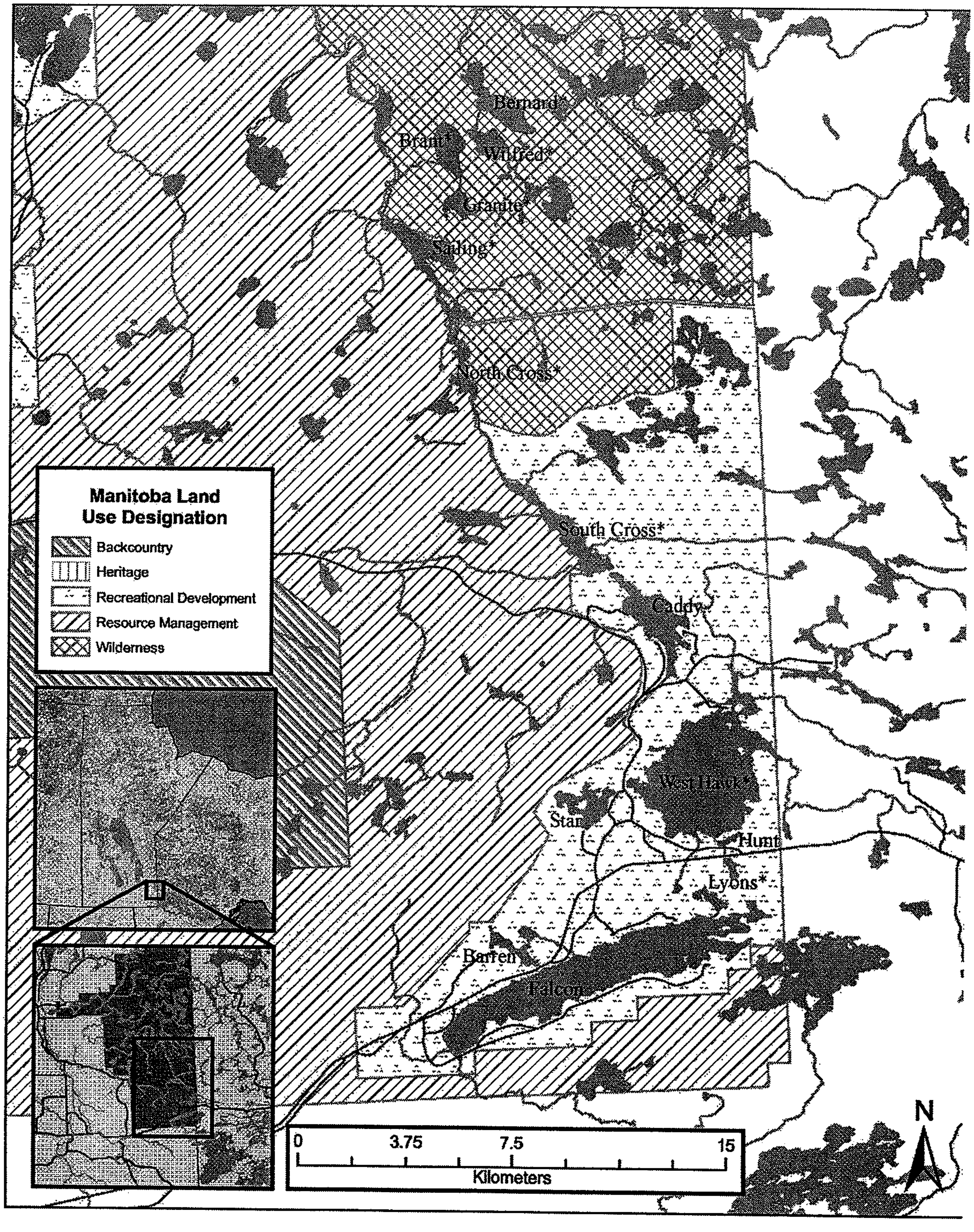

Figure 1D: Whiteshell Provincial Park map showing intensive-use and backcountry lakes. Labeled lakes were sampled monthly or in July (*) 2002.

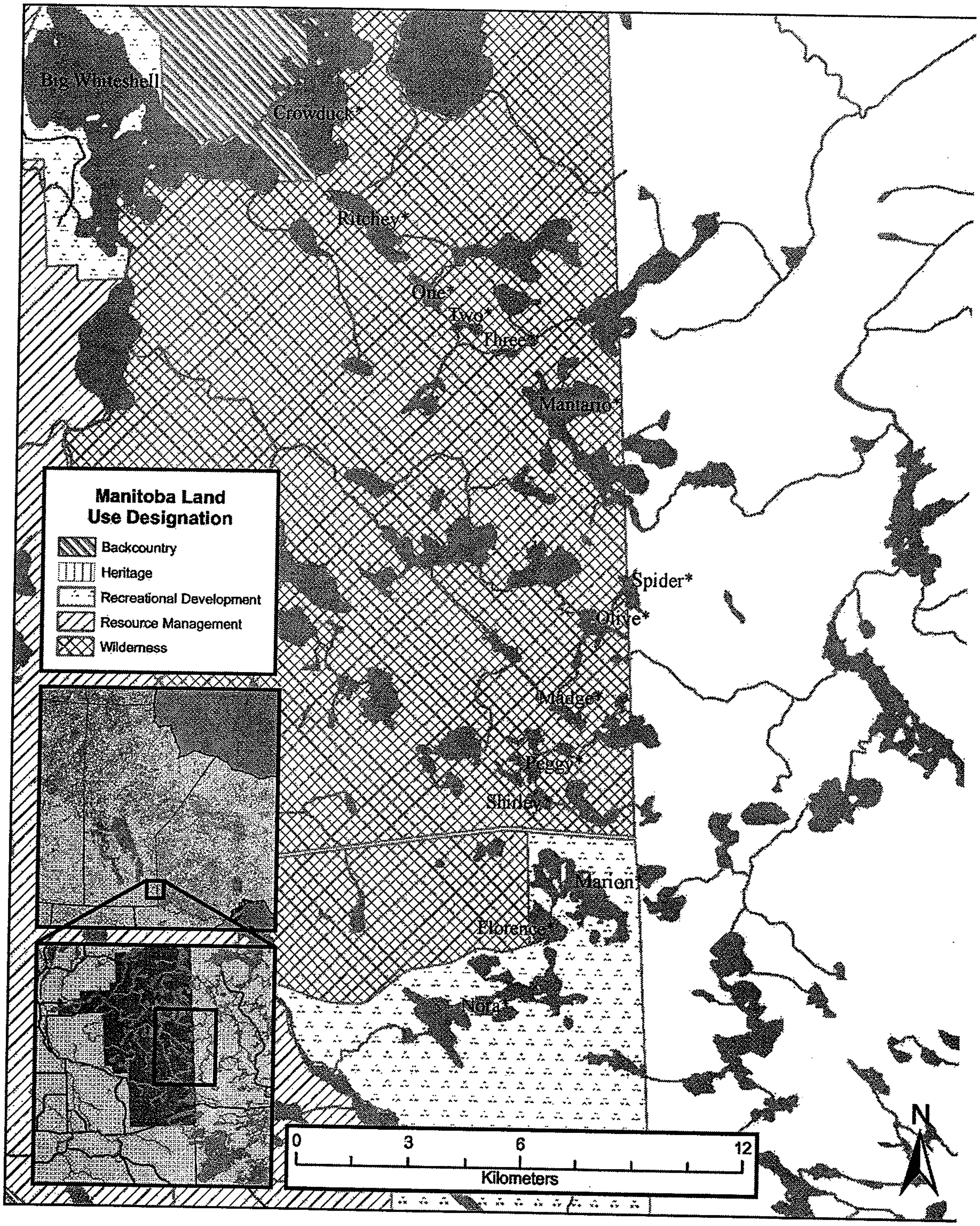

Figure 1E: Whiteshell Provincial Park map showing the Mantario Wilderness Area. Labeled lakes were sampled monthly or in July (*) of 2002.

Table 6: Whiteshell Provincial Park land use zones and recreational activities permitted (Y) or prohibited (N) (The Whiteshell Master Plan: Summary Report August 1983).

Zone	Area (km^2)	Percent Park Area	Cottages	Recreational Vehicles	Roads	Fishing	Hunting	Forestry	Mining
Mantario Wilderness	320	12	N	N	N	Y	N	N	N
Backcountry Recreation	420	15	Y	Y	N	Y	Y	Y	Y
Extensive Recreation	1 701	62	Y	Y	Y	Y	Y	Y	Y
Intensive Recreation	303	10	Y	Y	Y	Y	Y	Y	Y

emphasis on the environmentally induced false branching characteristic. In 1999, Manitoba Conservation personnel collected algal samples from Betula and White Lakes in Whiteshell Provincial Park. Hedy Kling of the Freshwater Institute, Department of Fisheries and Oceans, identified these algal specimens as *Plectonema wollei*. For consistency with current literature this alga will be referred to as *Lyngbya wollei* for the purposes of this project.

3.13 *Lyngbya wollei* Distribution

In 1999, Manitoba Conservation personnel identified *L. wollei* in Betula and White Lakes (Figure 1A). For the reconnaissance survey conducted in 2002, 35 Whiteshell lakes were searched for the occurrence of *L. wollei* (Table 7). For the twelve intensively studied lakes, two investigations were undertaken during the summer of 2002. Public boat launches were investigated for the presence of *L. wollei*. The perimeter of the lake was then toured by canoe or motorboat to examine nearshore areas for the presence *L. wollei* mats. Rakes were used in an attempt to comb the bottom of the lakes in nearshore areas. This technique proved ineffective. In nearshore areas the bottom was either clearly seen or the bottom was too deep to be reached by a rake. As a result, this time consuming method was abandoned. Consequently, the search for the presence of *L. wollei* involved visual observation of the nearshore areas of each lake. *L. wollei* was not found in any other lakes in Whiteshell Provincial Park. During the summer of 2003, four lakes: Betula, White, Jessica and Caddy Lake were searched monthly from May to August for the occurrence of *L. wollei*. A large fishing spoon weighted with a rock, attached to a rope was lowered through the water column to the sediment surface. The barbed hooks grasped algae off the lake bottom, which enabled it to be retrieved at the lake surface. The perimeter of the lake was toured dropping the fishing spoon approximately every 2 m to determine the presence or absence of *L. wollei*. When algae samples were retrieved that were morphologically similar to *L. wollei*, the UTM coordinates of the sampling site were recorded (Garmin 12XL) and the sample was put in a jar and labeled. Samples were preserved with Lugols iodine solution and were later identified in the laboratory using a compound microscope. In Betula and White Lakes where *L. wollei*

Table 7: Inventory of lakes sampled in 2002, monthly (M) or in July (J).

Lake	Sampling Regime	Land Use Zone
Barren	M	Intensive
Betula	M	Intensive
Big Whiteshell	M	Intensive
Brereton	M	Intensive
Caddy	M	Intensive
Falcon	M	Intensive
Green	M	Intensive
Hunt	M	Intensive
Jessica	M	Intensive
Red Rock	M	Intensive
Star	M	Intensive
White	M	Intensive
Lyons	J	Intensive
West Hawk	J	Intensive
Florence	J	Extensive
Nora	J	Extensive
South Cross	J	Extensive
Crowduck	J	Backcountry
Bernard	J	Wilderness
Brant	J	Wilderness
Granite	J	Wilderness
Madge	J	Wilderness
Mantario	J	Wilderness
Marion	J	Wilderness
North Cross	J	Wilderness
Olive	J	Wilderness
One	J	Wilderness
Peggy	J	Wilderness
Ritchey	J	Wilderness
Sailing	J	Wilderness
Shirley	J	Wilderness
Spider	J	Wilderness
Three	J	Wilderness
Two	J	Wilderness
Wilfred	J	Wilderness

was identified, a transect was canoed perpendicular to the shoreline to determine the area of infestation in each lake.

In 2002, a survey of backcountry lakes was conducted to search for the occurrence of *L. wollei* and collect water samples. The first day or two of each canoe trip was dedicated to the search for *L. wollei* in back country lakes. Due to time constraints it was not possible to search the entire perimeter of every backcountry lake for the occurrence of *L. wollei*. As a result, canoe launches, campsites and other easily accessible nearshore areas were searched. *L. wollei* was not found in any backcountry lake.

3.14 *Lyngbya wollei* Biomass

SCUBA divers were employed to estimate *L. wollei* biomass in infested lakes. On July 30, 2003 SCUBA divers used 0.46 m^2 quadrats to harvest portions of *L. wollei* mats from Betula and White Lakes. Quadrats were constructed using copper pipe and ninety degree copper elbow joints. Holes were drilled into the pipe to enable the quadrat to sink and remain on the sediment. A Lucky Strike rubber replacement fishing net 23 inches deep was fastened around the quadrat using flare tape and wire. A slit was cut through the top of the net to enable the diver to extract the vegetation within the quadrat without losing any biomass. The diver pushed the quadrat into the substratum, reached through the slit in the top of the net and retrieved all biomass from within the quadrat. The harvested biomass extracted by the diver was placed in a drawstring mesh bag. A small hand held garden hoe was used to churn up the sediment to ensure all vegetative biomass was retrieved from the quadrat. The mesh bag filled with the harvested vegetation was brought to the surface by the diver were it was emptied into a labeled plastic bag. Two quadrats were harvested at 10 m and 20 m along a transect perpendicular to the shore. Harvesting methods were similar to those employed by Cowell and Botts (1994).

The samples of *L. wollei* mats were then taken back to the University of Manitoba. Mats were rinsed to remove sediment following similar methods to those described by Speziale *et al.* (1991). Once the harvested mats had been rinsed of sediment they where laid out on drying racks in the Buller Building rooftop greenhouse. Drying racks were constructed using two inch pine timbers. Each drying rack was rectangular in shape, three feet long and two feet wide with a central supporting cross piece. Window screen was fastened to the top of the wooden frame with nails. The harvested *L. wollei* mats were laid out on the screen allowing air to flow below and above drying samples. Mats were allowed to dry for three weeks at 30 to 50°C. The harvested mat from each quadrat was then weighed (Table 20). As a result, biomass of *L. wollei* mats in Betula and White Lakes was estimated.

3.15 *Lyngbya wollei* Desiccation Experiments

Two desiccation experiments were conducted during the summer of 2003. The objective of these experiments was to examine the oxygen production or consumption of *L. wollei* samples after various drying times. This experiment examined the ability of *L. wollei* to survive varying periods of desiccation and subsequently its potential for surviving inter-lake transfer. *L. wollei* samples were collected from Betula Lake for drying. Initially a sample of *L. wollei* was collected on June 23 and small clumps appearing approximately the same size were laid out on a drying rack in the University of Manitoba greenhouse. The temperature in the greenhouse fluctuated between 15 and 35 °C. As a result, *L. wollei* samples were dried under natural daily light and temperature fluctuations. The greenhouse protected the samples from moisture and wind. Another sample of *L. wollei* was collected from Betula Lake on July 18, 2003. Small clumps appearing approximately the same size were spread out on the drying rack at the same time daily from July 19 to July 21, 2003. A portion of the sample collected on July 18 was kept in a container in relative darkness until the experiment was conducted on July 23, 2003, representing a stagnant sample. As a result, the experiment included *L. wollei* samples that had been dried for one month, 4 days, 3 days, 2 days and a stagnant sample.

The July 23, 2003 desiccation experiment was conducted at the Betula Lake campground beach. Clear plastic jars with white plastic lids and a volume of 503 ml were used to conduct these experiments. One piece of dried *L. wollei* from each date was placed in a labeled jar with lake water for half an hour, prior to the experiment. This rewetted the *L. wollei* samples and decreased the amount of air bubbles retained within the sample. The jars were then emptied and refilled with the sample retained inside the jar. Each jar was sealed under water in order to exclude air bubbles from the sample. Once filled the jar was inverted to ensure there were no large air bubbles trapped within the jar. There were a total of eight treatment jars. The dried and stagnant samples constituted five treatments. A fresh sample of *L. wollei* was collected, providing a fresh treatment. Two control treatments, a light and dark bottle filled with lake water were used. The dark bottle was painted black and covered with black electrical tape to exclude light. In contrast, the light bottle was the same as the other treatments but only contained lake water with no *L. wollei*. The two controls enabled the determination of oxygen evolution by phytoplankton in the water.

A strip of Duct Tape one centimeter wide was tied immediately below the lid of each jar. Each jar was then inverted and two pieces of 15 cm long wire were folded in half and inserted around the Duct Tape strip on both sides of the jar. The jar was then placed on a wire shelf. The wire was then twisted around the wire shelf securing the jar to the shelf. The shelf with eight jars secured lid down was placed in water 0.5 m deep. The jars were removed after 45 minutes and a 200 mL sample of water was collected from each jar. The oxygen concentration (mg/L) was then measured using the Winkler titration method (APHA #199). The experiment was repeated successively for a total of three trials. This experiment was conducted between 11 am and 2 pm, corresponding to the period of maximal daily sunshine.

The experiment conducted in August followed the same methodology as outlined for the July experiment with the exception of the drying procedures. The samples collected from Betula Lake were dried in the greenhouse located on the roof of the Buller Building at the University of Manitoba. There was a considerable increase in drying temperature and light exposure at this location. Drying temperatures were typically between 40 and 50 °C. The stagnant sample was left out with the drying algae in full sunlight. Due to the warm temperatures water evaporated from the container. As a result, to keep the sample from drying up, minimal lake water was added periodically to keep the sample wet. The jars were left in the water for 40 minutes with three replicate trials on August 18, 2003.

The *L. wollei* samples from each treatment and trial were collected following each experiment and placed in a labeled bag. These samples were taken back to the University of Manitoba and spread out on the drying racks. In July the samples were dried for two weeks in the greenhouse, then placed in a drying oven at 40°C for 10 hours and 45 minutes and weighed to obtain a dry weight for each treatment sample. The August samples were dried in the Buller building roof top greenhouse for 22 days and then weighed.

The oxygen concentrations in each treatment bottle were compared to that in the light bottle. Treatment concentration was determined by subtracting the oxygen concentration in each treatment jar from the light bottle concentration from each respective trial. This enabled the determination of oxygen evolution or consumption by the *L. wollei* sample, which was then divided by the dry weight of the *L. wollei* sample. As a result, the production or consumption of oxygen per milligram *L. wollei* was calculated (Table 21A & 22A). Using JMP IN, Analysis of Variance (ANOVA) was used to determine if desiccation treatments had significantly different oxygen concentrations per milligram *L. wollei* dry weight. The Tukey-Kramer method was used to make individual pairwise comparisons between treatments.

3.16 *Lyngbya wollei* Toxicology

L. wollei samples were collected from Betula and White Lakes during the summer of 2002 and 2003, to be tested to production of the neurotoxin saxitoxin and its analogues. Crayfish and water samples were also collected from infested areas to test for the presence of saxitoxin contamination. Analysis is ongoing at the Freshwater Institute, Winnipeg, Manitoba. Select samples have been sent from the Freshwater Institute to associated laboratories in Germany and New York for toxin analysis. The results of these analyses will not be included in this study.

3.2 Water Sampling

3.21 Water Sampling 2002

In 2002, surface water samples were collected monthly from May to August from twelve lakes throughout the Whiteshell (Table 7 & Figure 2-13). The lakes chosen were easily accessible and formed a continuum with respect to size, recreational use, and watershed activity. Water samples were collected from water quality stations designated as sampling sites by Manitoba Conservation. Water samples have historically been collected from these sites. As a result, data collected for the purposes of this project contribute to the long term monitoring of Manitoba lakes. Green and Hunt Lakes did not have provincially-designated water quality stations. At Green Lake water samples were collected from the middle of the largest basin, as the bathymetry for this lake was unknown. In contrast, Hunt Lake samples were collected from the middle of the lake, which had the greatest depth, identified using a bathymetric map. Water samples were analyzed by CanTest Laboratories located in Winnipeg, MB and Vancouver, B.C. Conventional parameters were measured in Winnipeg and nutrient and metal concentrations were determined by the laboratory in Vancouver. Chlorophyll analysis was conducted at the University of Manitoba.

In May, June and August, water samples were collected from all twelve lakes. Bottles were rinsed twice in the lake before collecting water samples from the surface. At each site the date, time, GPS coordinates, cloud cover, wind speed, water and air temperature were measured. The photic zone depth was estimated from the Secchi depth. At each site the Secchi disk was lowered down on the shaded side of the boat until it disappeared from sight. It was then retracted until it could be seen again, at which time the rope was marked off. The Secchi depth was recorded as the mean of the two depths.

Four bottles were filled at each site, comprising one sample. The first sample was used to measure pH, conductivity, hardness and other conventional parameters (Table 8). H_2SO_4 was added to the second sample to preserve it for nutrient concentration analysis. HNO_3 was added to the third sample so that it could be analyzed for metal concentrations

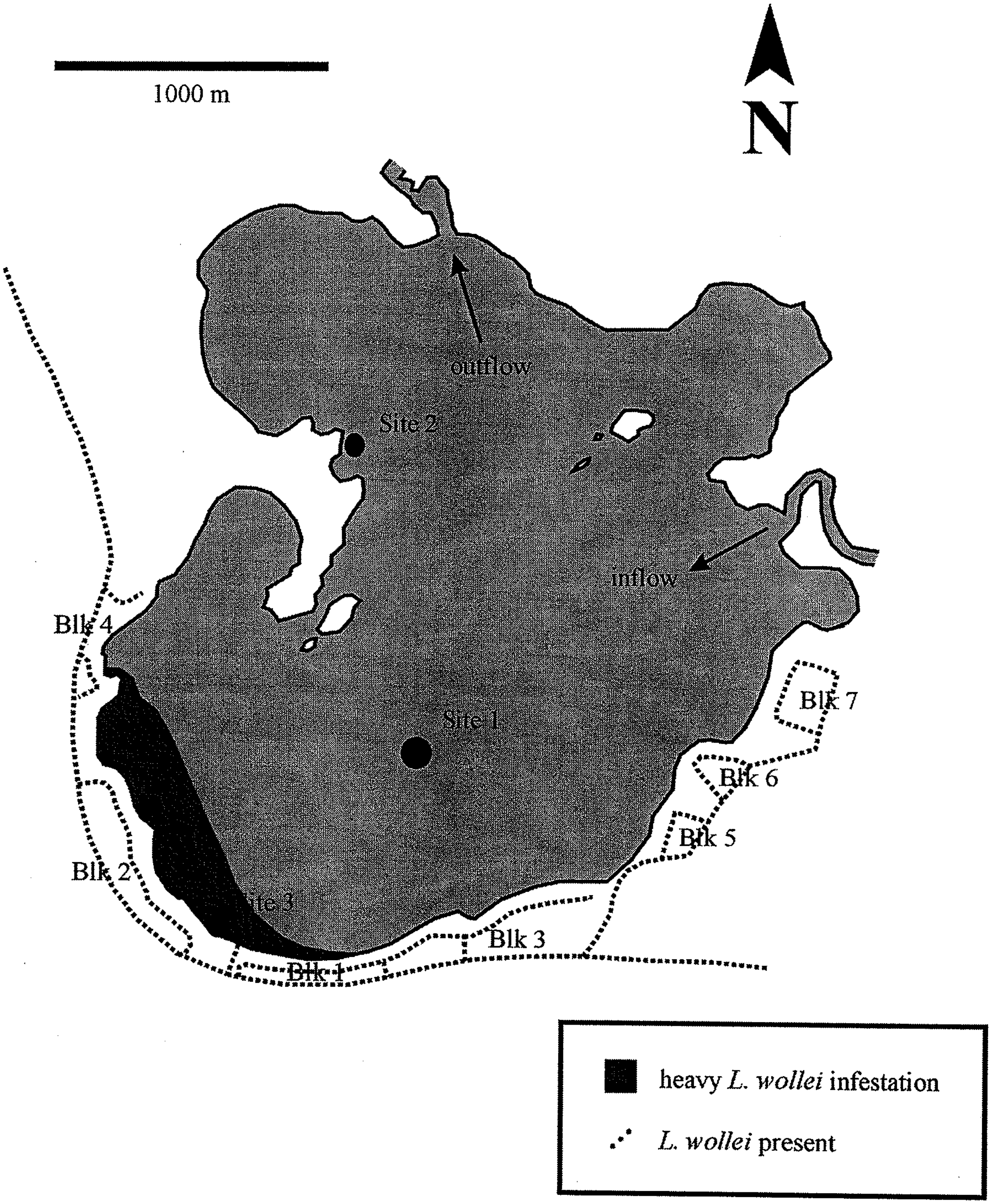

Figure 2: Betula Lake water sampling sites and *L. wollei* distribution.

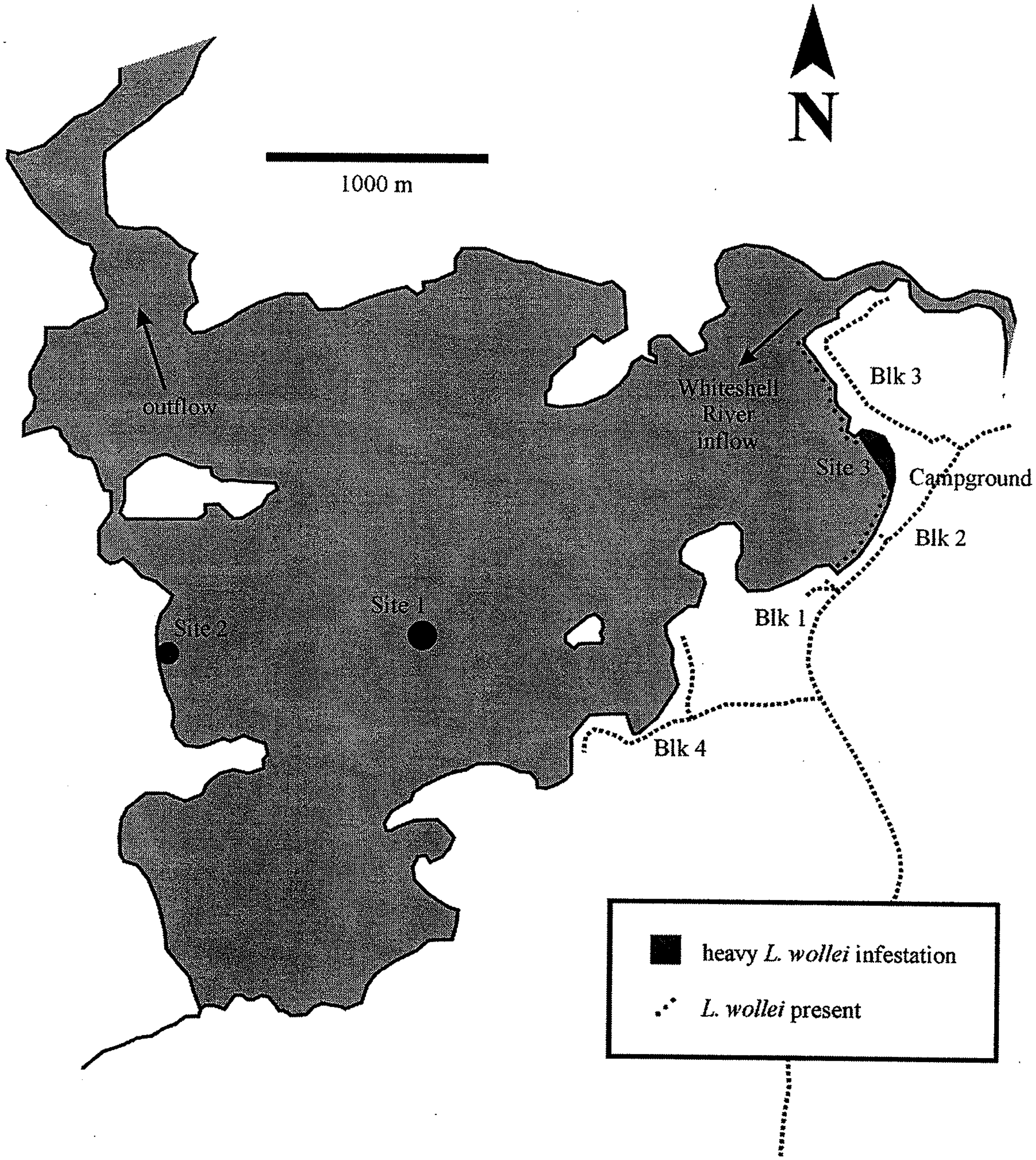

Figure 3: White Lake water sampling sites and *L. wollei* distribution.

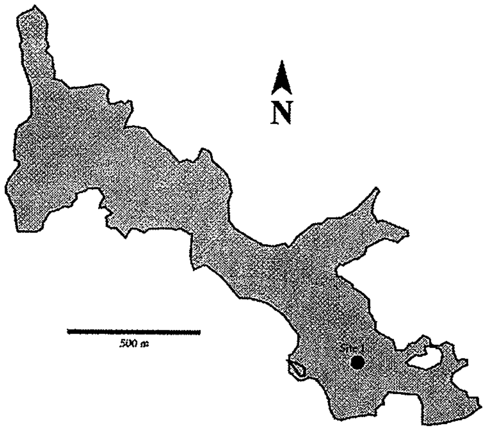

Figure 4: Barren Lake water sampling site.

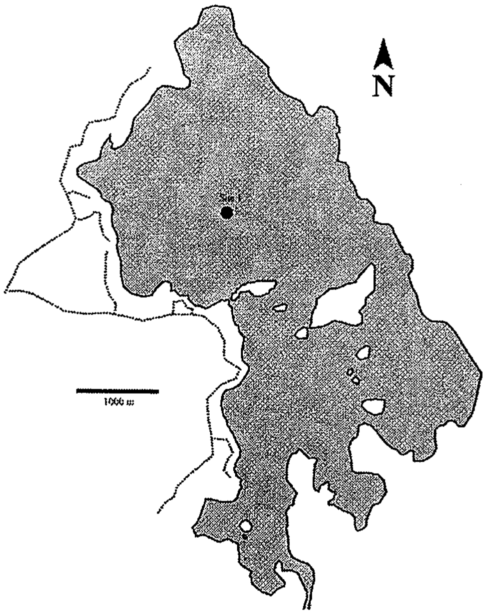

Figure 5: Big Whiteshell Lake water sampling site.

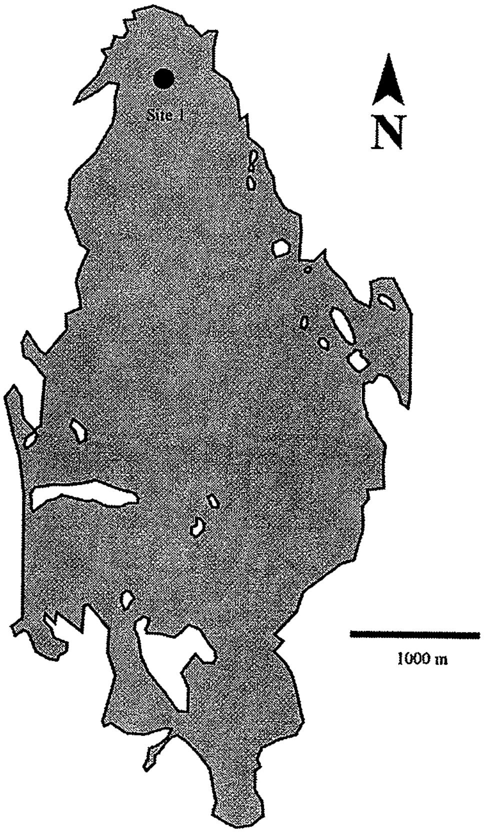

Figure 6: Brereton Lake water sampling site.

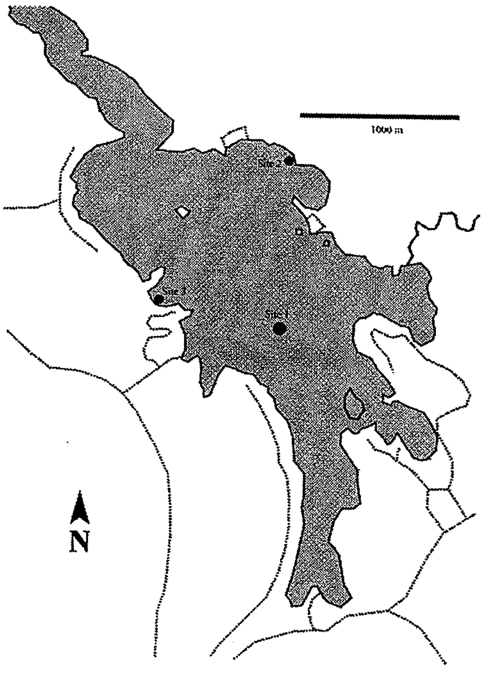

Figure 7: Caddy Lake water sampling sites.

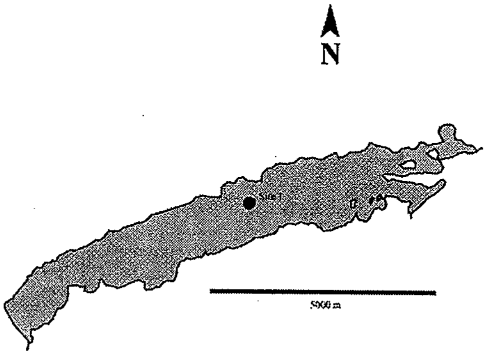

Figure 8: Falcon Lake water sampling site.

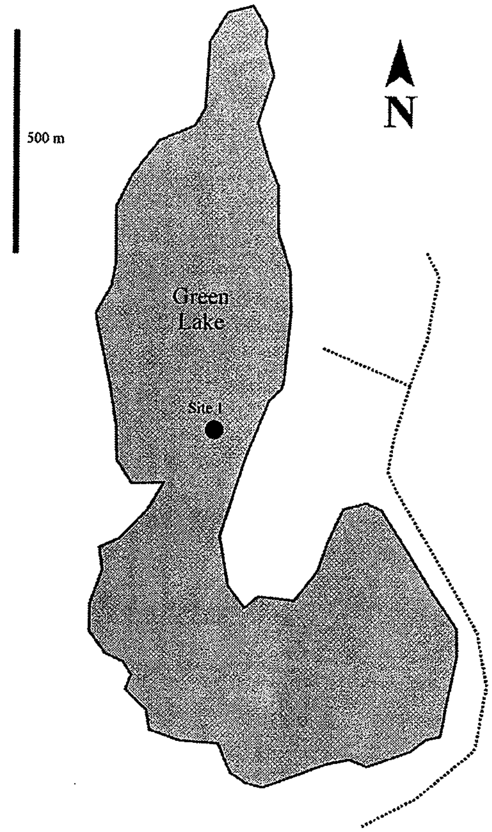

Figure 9: Green Lake water sampling site.

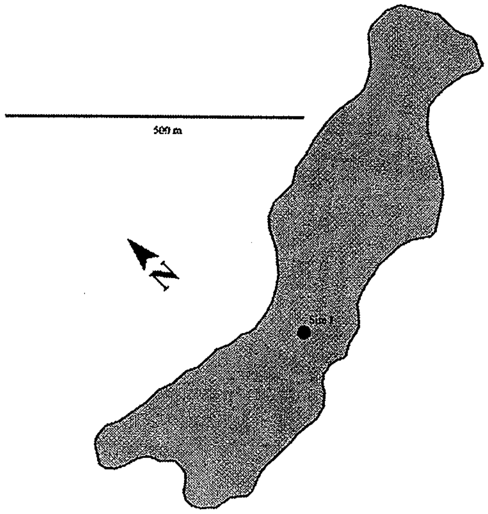

Figure 10: Hunt Lake water sampling site.

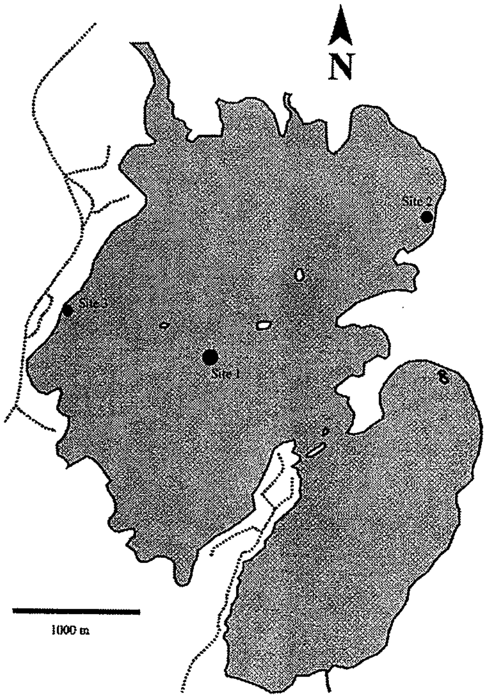

Figure 11: Jessica Lake water sampling sites.

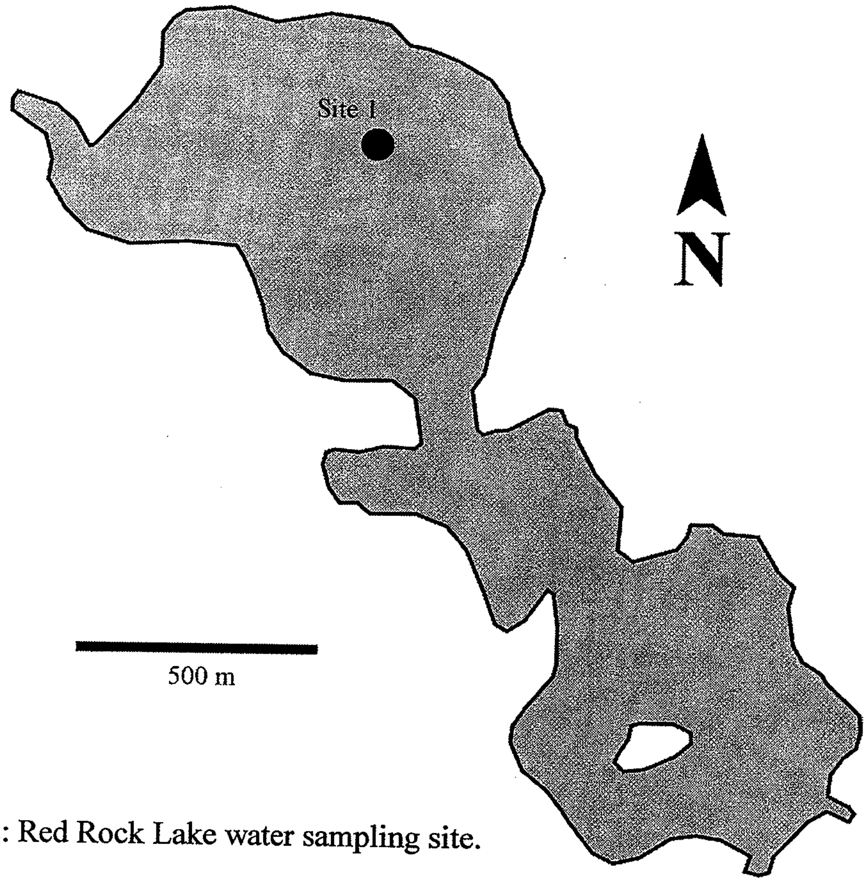

Figure 12: Red Rock Lake water sampling site.

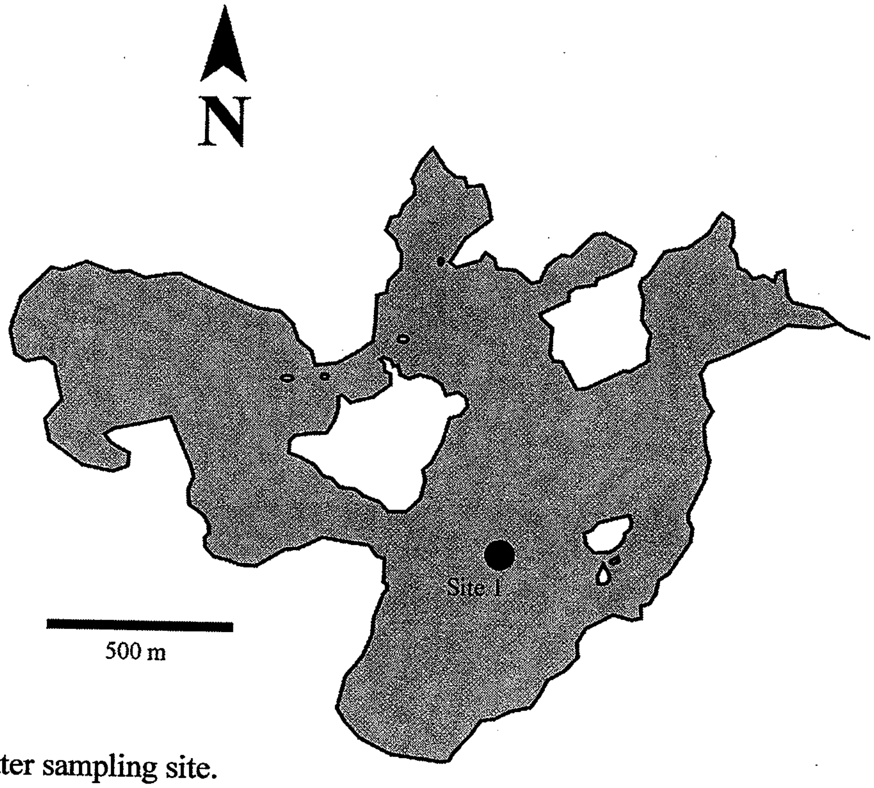

Figure 13: Star Lake water sampling site.

(Table 8). All these samples were analyzed by CanTest. A liter of water was collected from each site for chlorophyll a analysis. A known volume of this sample was filtered (Whatman GF/C) under mild vacuum. These filters were frozen until analyzed, when each filter was placed in a glass vial and 5 mL of 90% methanol to extract algal pigments. Samples were processed following the methods outlined for sediment chlorophyll analysis (section 3.36 Chlorophyll analysis).

In July 2002, a water quality survey of 35 lakes was conducted. This survey examined 21 backcountry and 14 intensively used lakes (Table 7). Twelve of the 14 intensively used lakes were those sampled monthly throughout the summer. All samples were collected using a canoe to access the sampling sites. Canoes were borrowed from residents and resorts on intensively used lakes so that boats were not moved between lakes. Manitoba Conservation supplied a canoe to be used on Hunt and Green Lakes where they could not be borrowed.

Three canoe trips through the wilderness area allowed the sampling of 21 lakes, the first time that data has ever been collected from remote lakes in Whiteshell Provincial Park (Figure 1). The furthest lake on each trip was reached in one or two days. All sampling was done on the return trip in a single day. Sampling sites were located at the center of the lake or at the center of the largest bay the canoe route passed through. At each lake, for consistency, one person recorded site descriptions and environmental conditions while the second took surface water samples. Coolers were used to carry water samples. Ice delivered by a second team on the last day of the trip was used to keep the samples cool. Samples were then driven into Winnipeg where they were analyzed by CanTest. July water samples were measured for conventional parameters and nutrient concentrations (Table 8B).

3.22 Water Sampling 2003

In 2003, water sampling was conducted on four Whiteshell Lakes: Betula, White, Jessica and Caddy. Two lakes, Betula and White had *L. wollei* infestations. In contrast, Jessica and Caddy Lakes did not have known *L. wollei* infestation. Sampling was conducted biweekly from late May until the end of August. Surface water samples were collected from

Table 8A: Water sampling parameters for 2002.

Sample	Parameter	Units
2002 Monthly		
Conventional Parameters	pH, Laboratory	pH units
	Conductivity	µS/cm
	Total Alkalinity $CaCO_3$	mg/L
	Bicarbonate Alkalinity HCO_3	mg/L
	Carbonate Alkalinity CO_3	mg/L
	Hydroxide Alkalinity OH	mg/L
	Dissolved Oxygen, Winkler	mg/L
	True Color	CU
	Turbidity	NTU
	Hardness (Total) $CaCO_3$	mg/L
Nutrient Analysis	Dissolved Chloride Cl	mg/L
	Nitrate and Nitrite N	mg/L
	Dissolved Sulphate SO_4	mg/L
	Ammonia Nitrogen N	mg/L
	Total Kjeldahl Nitrogen N	mg/L
	Total Phosphorus P	mg/L as P
	Total Particulate Phosphorus P	mg/L as P
	Total Soluble Phosphorus P	mg/L as P
	Soluble Reactive Silica SiO_2	mg/L
Metal Analysis	Total Calcium Ca	mg/L
	Total Iron Fe	mg/L
	Total Magnesium Mg	mg/L
	Total Manganese Mn	mg/L
	Total Potassium K	mg/L
	Total Sodium Na	mg/L
2002 July Survey		
Conventional Parameters	pH, Laboratory	pH units
	Conductivity	µS/cm
	Total Dissolved Solids	mg/L
	Total Suspended Solids	mg/L
Nutrient Analysis	Total Phosphorus P	mg/L as P
	Total Particulate Phosphorus P	mg/L as P
	Total Soluble Phosphorus P	mg/L as P
	Nitrate and Nitrite N	mg/L
	Ammonia Nitrogen N	mg/L
	Total Kjeldahl Nitrogen N	mg/L

Table 8B: Water sampling parameters for 2003.

2003 Biweekly		
Conventional Parameters	pH, Laboratory	pH units
	Conductivity	µS/cm
	Total Dissolved Solids	mg/L
	Total Suspended Solids	mg/L
	Total Phosphorus P	mg/L as P
	Total Particulate Phosphorus P	mg/L as P
	Total Soluble Phosphorus P	mg/L as P

three sites on each lake (Figure 3,6,10,13). For consistency water samples were collected from these same Manitoba water quality sites sampled in 2002, at the center of each lake, site 1. The second site was located in a sandy littoral area at a depth of 0.5 m. This site was relatively uninhabited, lacking cottages, roads or other recreational facilities. In contrast, the third site was located at the main beach area with a high cottage density and many recreational facilities. This sampling method enabled the comparison of water quality between sites within each lakes. At each site, water collected was analyzed for conventional parameters, nutrients and chlorophyll a (Table 8). Water sampling methods were consistent with those used in 2002. JMP IN was used to conduct ANOVA to determine whether the water quality parameters were significantly different between sites on each respective lake.

Vertical attenuation of photosynthetically active radiation (PAR) in the water column was measured using a LI-COR spherical sensor and a flat terrestrial sensor connected to a LI-1000 data logger. Readings were taken by the spherical sensor above and below the water surface and then at 0.5 m depths to the bottom of the lake. Simultaneous readings were recorded from the terrestrial sensor, to correct underwater reading for variation in surface irradiance due to cloud cover. Light measurements were recorded biweekly when water samples were collected. Mean photic depth was calculated for all four lakes using biweekly measurements (Table 18).

In July 2003, I conducted a survey of all twelve lakes sampled in 2002. At each site the Secchi depth, light penetration and a water sample was collected. Photic depths for each lake were calculated using light meter measurements (Table 18). Water samples collected were analyzed for chlorophyll a.

3.3 Sediment Core Collection

3.31 Coring and Core Processing

Sediment cores were extracted from thirteen Whiteshell Lakes during February and March of 2002 and 2003, respectively. Sediment core analysis was used to examine changes in nutrient and metal concentrations over time. In 2003, sediment cores were extracted from three lakes in the wilderness zone and two in the extensive recreation zone (Table 9). The remaining eight lakes sampled are located in intensive recreational areas (Table 9). The lakes formed a continuum with respect to recreational access and human land use. Sediment cores were extracted from water quality sites used historically by Manitoba Conservation. For lakes which did not have pre-existing water quality sites bathymetric maps provided by the government were used to take samples from the deepest area of the lake. For lakes without bathymetric maps, samples were typically taken from the center of the largest basin.

3.32 Core Collection

The location of each water quality station was estimated using a bathymetric map supplied by Manitoba Conservation. The date and time of sampling was recorded at each site. A Garmin GPS 12XL GPS receiver was used to record UTM coordinates of each sample site. At each site, an ice auger was used to drill four holes, each approximately 20 cm in diameter. The ice thickness, total water depth and snow depth were measured using one hole. The second hole was used to take water samples from the surface water filling the hole. The two remaining holes were used for collecting the sediment core(s) from the site. Special care was taken to prevent the flocculent sediment being disturbed by the coring device. If the sediment was disturbed before the core was extracted then the remaining fourth hole was used in a second attempt. A modified mini Kajak-Brinkhurst gravity corer (Figure 14) was used to extract all sediment cores. This gravity corer was lowered through the ice hole, down through the water column and into the sediment to a depth of about 40 cm. Inertial force pushed the core tube into the sediment. Once the core tube had settled into the sediment a guided brass weight was sent down the rope by the operator to trigger the rubber plunger. The plunger created suction in the core barrel, which enabled the operator to recover the column of sediment within the tube undisturbed.

Two people were required to retrieve the sediment core from the water. One person held the weighted head of the corer while the second person fitted a rubber stopper into the end of the core tube. The stopper was put in place before the tube was removed from the

Table 9A: Summary information on sediment cores extracted from 5 Whiteshell lakes. Sediment cores dated (*) are indicated.

Lake	Sample ID	Lake Type	Date	Time	Recreation Zone	Core Length (cm)	Sediment Core Intervals (cm)	Latitude Longitude
Jessica	JS 1	1	31/1/2002	14:30	Intensive	32	2	N 50 00 08.0 W 95 28 58.3
Jessica	JS 2	1	31/1/2002	16:00	Intensive	32	2	N 50 00 35.8 W 95 29 52.2
Jessica	JS 3	1	1/2/02	9:30	Intensive	30	5	N 50 01 11.3 W 95 29 47.2
White	WH 1	1	1/2/02	11:00	Intensive	34	2	N 50 02 02.3 W 95 31 10.7
White*	WH 2*	1	1/2/02	13:00	Intensive	34	2	N 50 02 03.7 W 95 33 20.7
White	WH 3	1	1/2/02	14:00	Intensive	30	5	N 50 01 05.2 W 95 32 43.6
Betula	BT 1	1	1/2/02	15:30	Intensive	28	2	N 50 04 12.8 W 95 35 30.0
Betula	BT 2	1	1/2/02	16:30	Intensive	30	5	N 50 04 42.8 W 95 35 29.9
Betula*	BT 3*	1	2/2/02	9:55	Intensive	32	2	N 50 05 24.1 W 95 34 55.1
Brereton	BR 2	2	2/2/02	14:00	Intensive	30	2	N 49 54 23.8 W 95 32 33.3
Brereton	BR 3	2	2/2/02	14:45	Intensive	15	5	N 49 55 30.8 W 95 32 53.0
Red Rock	RR 1	3	2/2/02	14:05	Intensive	30	2	N 49 59 29.5 W 95 31 50.8
Red Rock	RR 2	3	2/2/02	14:05	Intensive	30	5	N 49 59 29.5 W 95 31 50.8

Lake Type: 1 = Part of Whiteshell River, 2 = Part of Rennie River, 3 = Other

Table 9B: Summary information on sediment cores extracted from 4 Whiteshell lakes. Sediment cores dated (*) are indicated.

Lake	Sample ID	Lake Type	Date	Time	Recreation Zone	Core Length (cm)	Sediment Core Intervals	Latitude Longitude
Barren	BA 1	3	14/3/2003	13:30	Intensive	48	2	N 49.70583867 W 95.2783119
Barren	BA 2	3	14/3/2003	13:30	Intensive	45	5	N 49.70583867 W 95.2783119
Star	ST 1	3	14/3/2003	15:00	Intensive	50	2	N 49.75131649 W 95.24721883
Star	ST 2	3	14/3/2003	15:00	Intensive	40	5	N 49.75131649 W 95.24721883
Caddy	CDY 1	1	15/3/2003	14:35	Intensive	24	2	N 49.80834239 W 95.20917387
Caddy	CDY 2	1	15/3/2003	14:35	Intensive	25	5	N 49.80834239 W 95.20917387
Hunt	HT 1	3	15/3/2003	15:45	Intensive	48	2	N 49.73979759 W 95.17921417
Hunt	HT 2	3	15/3/2003	15:45	Intensive	40	5	N 49.73979759 W 95.17921417

Lake Type: 1 = Part of Whiteshell River, 2 = Part of Rennie River, 3 = Other

Table 9C: Summary information on sediment cores extracted from 4 Whiteshell lakes. Sediment cores dated (*) are indicated.

Lake	Sample ID	Lake Type	Date	Time	Recreation Zone	Core Length	Sediment Core Intervals (cm)	Latitude Longitude
Florence	FLO 1	3	15/3/2003	12:00	Extensive	42	2	N 49.88723975 W 95.18790864
Florence	FLO 1	3	15/3/2003	12:00	Extensive	45	5	N 49.88723975 W 95.18790864
Madge*	MA 1*	3	16/3/2003	11:00	Wilderness	36	2	N 49.93816853 W 95.18136491
Madge	MA 2	3	16/3/2003	11:00	Wilderness	35	5	N 49.93816853 W 95.18136491
Shirley	SH 1	3	16/3/2003	13:30	Wilderness	34	2	N 49.91734066 W 95.18920138
Shirley	SH 2	3	16/3/2003	13:30	Wilderness	30	5	N 49.91734066 W 95.18920138
Marion	MR 1	3	16/3/2003	15:00	Wilderness	26	2	N 49.90189739 W 95.18529897
Marion	MR 2	3	16/3/2003	15:00	Wilderness	30	5	N 49.90189739 W 95.18529897

Lake Type: 1 = Part of Whiteshell River, 2 = Part of Rennie River, 3 = Other

water. The core tube was then placed upright on the ice surface. The clamps on the core barrel were then loosened and the weighted corer head was removed. The core tube was held upright and the outside rinsed carefully to remove excess sediment. The core was then examined to ensure the sediment had not been disturbed during extraction. If the core was deemed acceptable, it was taken to a heated tent nearby for extrusion.

3.33 Core Subsampling

The core tube was fastened onto an extruding stand. The extruding device enabled the sediment core to be pushed up the core tube sequentially. The core was then extruded in 2 or 5 cm strata. Each stratum was scrapped from the extruding platform into a labeled plastic bag. These samples were retained for in-house analysis. One core from each lake was extruded at 5 cm increments for gross nutrient and metal analysis. These latter samples were placed into glass containers, which were labeled according to their lake, site, interval and sent to CanTest in Vancouver, B.C. Any observations made about the cores were recorded on site. All samples were kept in a cooler or refrigerator at approximately 4°C until analyzed.

3.34 Sediment Geochemistry

Sediment geochemistry was analyzed by CanTest Ltd. Each 5 cm subsample was analyzed for more than 28 element concentrations (Table 10). Analytical methods employed follow CanTest Ltd. 2002 - 2003, laboratory methods for Manitoba Conservation, Winnipeg. Using JMP IN, ANOVA was used to examine the mean concentration differences for each element from all 13 sediment cores. Pairwise comparison was done using Tukey-Kramer to identify lakes which had significantly different mean element concentrations from Betula Lake (Table 30). Principal component analysis was used to examine current and mean sediment conditions in all 13 Whiteshell lakes sampled. See statistical analysis section below for further detail.

3.35 Water, Organic Matter & Carbonate Content

One core from each lake was analyzed for water, organic matter and carbonate content. The methods followed Dean (1974). A 1.9 cm^3 sample of sediment was collected using an

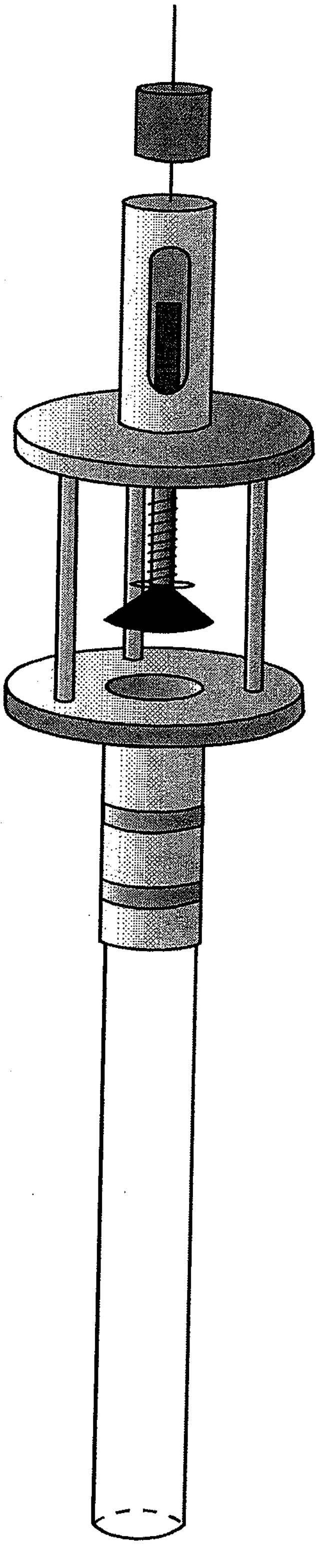

Figure 14: Schematic diagram of a modified Kajak-Brinkhurst miniature gravity coring sytem.

open-ended 5 cc syringe from each interval of the core. Each 1.9 cm^3 sediment sample was then placed into an oven-dried, pre-weighed ceramic crucible. The crucible was then immediately reweighed to obtain the wet weight of the sample. The crucibles were then placed in an oven for 24 hours at 104°C. The crucibles were then re-weighed and the dry mass was recorded. These data were used to determine water content as a percent of total wet weight. The samples were then placed in a muffle furnace at 550°C for 1 hour then reweighed. Organic matter is known to ignite between 200 and 500°C. This process enabled organic matter content to be calculated as a percent of dry weight. Finally, the samples were incinerated at a temperature of 950°C for three hours, then reweighed. The weight loss represents the amount of carbon dioxide evolved from carbonate minerals. This enabled the calculation of carbonate mineral content of the sample as a percent of the dry weight.

3.36 Chlorophyll Analysis

Chlorophyll was extracted from wet sediment using 90% methanol following Swain (1985). An open-ended 5 cc syringe was used to collect 1.9 cm^3 of sediment from each sample, which was then placed in 10 mL of 90% methanol. The sample was inverted several times to mix the sediment thoroughly with the solvent. The tubes were allowed to stand in the dark at room temperature for 24 hours. This ensured all pigments in the sediment were extracted then the samples were centrifuged at 500 rpm for 15 minutes to remove suspended particulates. Absorbance readings from 400nm to 1000nm at 0.5nm intervals of each sample were taken using an Ultrospec 4000 UV/Visible Spectrophotometer. Then 0.1 ml of 0.04M hydrochloric acid was added to each sample, which were then left in the dark for 1 hour. The acidification of the samples converted the chlorophyll a in the sample into pheophytin. This procedure enabled chlorophyll a and pheopigments to be used to determine the total chlorophyll a concentration within each sample (Lorenzen 1967). After an hour the samples were placed back into the spectrophotometer and remeasured using the same parameters as initially described. Readings taken at 665nm and 750nm pre and post acidification were

Table 10: Sediment chemistry parameters measured (µg/g) in sediment cores collected in 2002 and 2003.

Total Organic Carbon
Total Inorganic Carbon
Total Kjeldahl Nitrogen
Arsenic
Barium
Cadmium
Chromium
Cobalt
Copper
Lead
Mercury
Nickel
Selenium
Thallium
Vanadium
Zinc
Aluminum
Boron
Calcium
Iron
Magnesium
Manganese
Phosphorus
Potassium
Sodium
Strontium
Titanium
Zirconium
Available Phosphorus

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then used to determine the concentrations of chlorophyll, pheophytin and total chlorophyll in each sample following monochromatic calculation formulae of Marker *et al.* (1980).

3.37 Sediment Dating

Three sediment cores collected from Betula, White and Madge Lakes were dated using ^{210}Pb and ^{137}Cs. Each core was subsampled at 2 cm intervals. Lead-210 was measured using Alpha Spectroscopy. Cesium-137 was measured using Gamma-ray Spectroscopy. Based on ^{210}Pb measurements the constant flux model (CRS model) was used to calculate the date of the sediment cores. This model assumed a constant flux of ^{210}Pb to the sediment and changing sedimentation rates. Cesium-137 profiles may be used to verify the sediment chronology measured. Prior to 1954, 137Cs deposition from nuclear fallout was nonexistent or insignificant. Cesium-137 deposition continued to increase until the Test Ban Treaty of 1963. As a result, the onset and peak concentration of 137Cs may be used to identify the 1954 to 1964 peak. The ^{137}Cs peak was obscured in two cores and consequently, ^{210}Pb dates were used. In order to determine if the sediment core was collected from a depositional area a focus factor was calculated by dividing the excess ^{210}Pb flux measured for each core, by 170 Bq/m^2/yr, the expected atmospheric input of excess ^{210}Pb measured at the Experiment Lakes Area in Ontario. A focus factor greater than one indicates the core was collected from a depositional area. A value less than one indicated sediment loss from the area.

3.4 Whiteshell Environmental Quality

3.41 Whiteshell Resident Survey 2002

Whiteshell residents were surveyed in 2002 on their perceptions of environmental quality in the Park. Property owners in Whiteshell Provincial Park where asked questions pertaining to their water use, boating frequency, and shoreline activities (Appendix C). The Whiteshell survey was created by Gordon Goldsborough and Karen Lind following a similar format to that used by Sasha Brown at Delta, Manitoba (Brown 2002). The surveys were distributed with the 50th anniversary edition of the Whiteshell Echo, the local newspaper, to all property owners in the park about 3800 in total. There was a 20% response rate with 776 surveys returned by mail, fax, email or delivery to drop-off boxes at sites in the park. Surveys were then sorted by the lake identified as closest to the respondent's residence. The response rate from each lake was determine by dividing the number surveys submitted from the specific lake by the total number of residences on the lake. To determine the percent response by lake to various questions the chosen response was divided by the total number of responses for the respective lake. Using survey results a mean average weight was determine for months of cottage use and sewage handling systems. These parameters were then incorporated into Correspondence Analysis of land use intensity.

3.42 Enumeration of Whiteshell Development

Physical enumeration was also employed to investigate Whiteshell environmental quality. Campgrounds associated with our 12 intensively studied lakes were toured to document washroom, grey water and sewage facilities (Table 11). For each campground the number of non-modern, modern washroom and shower building buildings present were recorded. Non-modern washroom facilities were outhouses with no sinks or running water available. Modern washroom facilities were those which had running water with flushing toilets and sinks. Each washroom building represented a source of sewage in the campground. Grey water facilities were provided for dumping waste and sewage produced by campers. Trailer sanitary disposal stations enabled recreational vehicles to dump holding tanks. In the intensity of use data matrices grey water and trailer sanitary disposal stations were grouped together. These important facilities provided a responsible, designated area for waste disposal which otherwise may have been disposed of in an inappropriate or environmentally harmful way.

The Parks and Natural Areas Branch of Manitoba Conservation supplied current data on cottage density, number of seasonal and transient campsites, number of public beaches and boat launches for all lakes examined in the 2002 reconnaissance survey (Table 3 & 4). Morphological parameters of these 12 lakes were investigated using bathymetric maps and orthophotographs (Table 12). Angling bathymetric maps produced by Manitoba Conservation were used to determine the maximum lake depth. A planimeter was used to determine the volume of each lake. The Land Navigator orthophotos from July 1999, were opened in ArcView were the perimeter of each lake was traced and the perimeter and surface area were determined. This method was also used to determine the fetch across each lake from a SW direct, as this is the predominant wind direction in the park . Mean lake depth was then determined by dividing the lake volume by the surface area. The shoreline development index (D_L) and volume development index (D_V) were calculated based on there respective formula (Table 12) (Wetzel 2001). The number of resort units located directly adjacent to a lake and resort boat rentals were determined from the Manitoba 2003 Accommodations & Campgrounds guide provided by Travel Manitoba. The Whiteshell Interpretive Park Map was used to record the number of facilities and recreational activities associated with our 12 intensive use lakes including: marina/gas stations, groceries, distance to closest town, waterfalls, biking, hiking, self-guiding and Mantario trails and major canoe routes (Table 13).

3.43 Recreational Boating

Recreational boating is an important Whiteshell tourist attraction. As a result, it was my objective to examine the boat use on Betula, White, Jessica and Caddy Lakes. Two methods were employed to monitor the movement of boats between these and other lakes in the park and elsewhere. In 2002, journals were placed in campground offices at Betula, White, and Brereton Lakes. Visitors to these campgrounds with a recreational watercraft filled out the journal stating where they had traveled from, which lakes they would be using their watercraft on and type of watercraft (Table 14).

The 2002 Whiteshell Resident survey asked property owners: how many boats they owned, boat type, what lakes their boats are operated on and whether visitors to their residence brought boats and from where. As a result, the movement of boats within the park by visitors and residents was described. These surveys enable the number of motorized and non-motorized boats to be extrapolated for each lake based on the number of responses and total

Table 11: Number of campsites, washroom and sewage facilities at campgrounds located at 12 intensively studied lakes current to 2003. Some lakes without campground facilities (–).

Lake	Seasonal Electrical	Seasonal Basic	Transient Electrical	Transient Basic	Washroom Buildings		Buildings with		Grey water disposal site	Trailer sanitary station
					Non-modern	Modern	Sinks	Showers		
Barren	–	–	–	–	–	–	–	–	–	–
Betula	–	27	–	17	3	0	0	0	1	0
Big Whiteshell	–	112	36	42	1	2	2	1	4	1
Brereton	36	25	8	18	2	2	2	0	1	1
Caddy	17	5	0	26	2	1	1	0	0	1
Falcon	164	–	155	242	0	10	10	3	0	0
Green	–	–	–	–	–	–	–	–	–	–
Hunt	–	–	–	–	–	–	–	–	–	–
Jessica	–	–	–	–	–	–	–	–	–	–
Red Rock	–	–	–	–	–	–	–	–	–	–
Star	–	–	–	–	–	–	–	–	–	–
White	6	25	–	29	3	2	2	1	1	0

number of cottages. This method was employed to estimate the number of boats on each of the 12 lakes examined (Table 15). To further understand the use of these lakes as recreational boating areas, a boating survey was conducted on August 2, 2003. This day was the Saturday of the August long-weekend, so as such, it was considered a high use day. The number of boats launched at the boat launches on Betula, White, Jessica and Caddy Lakes between 8 am and 6 pm were recorded (Table 16). As a result, insight was gained into recreational boating activity on these lakes.

3.5 Statistic Analysis

3.51 Univariate Statistical Analysis

Analysis of Variance (ANOVA) was used to investigate the significance of differences among means of several populations, based on samples (Townend 2002). JMP IN was used to conduct ANOVA on three data matrices. Data collected from *L. wollei* desiccation experiments, 2003 water chemistry and sedimentary element concentrations were examined using ANOVA. As a result, ANOVA was used to examine data matrices based on individual parameters. In order to compare lakes based on numerous parameters Multivariate statistical methods including: Principal Component Analysis (PCA) and Component Analysis (CA) were employed.

3.52 Multivariate Statistical Analysis

Multivariate statistical analysis was used to examine two separate groups of Whiteshell lakes composed of twelve and thirteen lakes, referred to as Group 12 and Group 13 hence forth (Table 17). All of the data sets were modified so they could undergo multivariate statistical analysis. The concentration of some sedimentary nutrients and metal concentrations were below the laboratory detection limits and given a less than value. For data analysis these value were changed to zero and data were log(x+1) transformed. Adding one to low concentrations resulted in a non-linear relationship. As a result, variables with concentration values less than two were multiplied by a factor of one hundred or one thousand.

Table 12: Morphological parameters and shoreline (D_L) and volume (D_V) development indexes for 12 intensively studied Whiteshell lakes.

Lake	Surface Area (km^2)	Perimeter (km)	Fetch (km)	Mean Depth (m)	Max. Depth (m)	D_L	D_V	Photic Depth (m)
Barren	0.72	8.11	0.63	3.12	6	2.7	1.56	7.34
Betula	5.21	13.13	3.10	1.78	6	1.62	0.89	3.87
Big Whiteshell	17.44	35.22	3.41	4.43	7.5	2.38	1.77	6.41
Brereton	8.89	20.83	3.56	3.81	6	1.97	1.91	2.87
Caddy	3.08	15.81	1.28	2.91	6	2.54	1.46	6.15
Falcon	15.50	38.28	9.93	10.17	21	2.74	1.45	9.64
Green	0.63	5.21	0.77	1	1	1.85	3.00	5.92
Hunt	0.18	2.59	0.94	6.38	12	1.72	1.60	8.41
Jessica	8.61	21.48	3.54	1.92	4.5	2.06	1.28	4.10
Red Rock	1.51	9.64	0.82	1.69	3	2.21	1.69	15.25
Star	1.51	9.90	1.37	3.33	6	2.27	1.67	5.44
White	6.38	17.60	3.54	2.09	7	1.97	0.90	4.03

Table 13: Inventory of recreational activities for 12 intensively studied Whiteshell lakes. Boat rental shops located on respective lakes denoted by yes (Y) and no (N).

Lake	Distance to closest town (km)	Boat Rental	Marina/ Gas Station	Grocery	Public Beaches	Public Boat Launch	Water skiing Clubs	Hiking Trails
Barren	2	N	0	0	1	1	0	1
Betula	32	Y	1	1	2	1	1	2
Big Whiteshell	36	Y	2	2	2	2	0	2
Brereton	8	Y	1	1	3	3	0	1
Caddy	8	Y	1	2	1	1	0	3
Falcon	2	Y	2	2	11	4	0	0
Green	38	N	0	0	0	1	0	0
Hunt	4	N	0	0	0	1	0	1
Jessica	20	Y	0	0	0	1	0	1
Red Rock	18	N	0	0	0	0	0	1
Star	0	N	0	0	1	1	0	2
White	23	N	1	1	1	1	1	1

Table 14: Survey of origin, destination and type of watercraft brought to the Whiteshell by visitors camping at Betula, White and Brereton lakes. Unknown parameters were designated not applicable (n/a).

Campground	Origin	Destination Lake(s)	Motor Boat Type	Horsepower	Hull (ft)
Betula Lake	Morris	Betula Lake	Fishing	20	14
	Winnipeg	Betula Lake	Fishing	40	16
	Beausejour	Betula Lake	Fishing	20	14
	Steinbach	Betula Lake	Ski	n/a	n/a
	Grunthal	Betula Lake	Fishing	n/a	n/a
	St. Pierre	Betula Lake	Fishing	n/a	n/a
	Winnipeg	Betula Lake	Fishing	n/a	n/a
White Lake	Altona	White	Ski	125	n/a
	Winnipeg	Big Whiteshell	Fishing	35	18
	Blumenort	White	Fishing	65	16
	Winnipeg	White	Fishing	40	16
	Winnipeg	White	Ski	75	16
	Winnipeg	White	Fishing	40	18
	Ste. Anne	White	Fishing	60	18
	Winnipeg	White	Ski	115	16.5
	Carman	White	Fishing	40	14
Brereton Lake	Caddy Lake	Brereton	Fishing	115	n/a
	Brereton	Brereton	Fishing	25	14
	Lake of the Woods	Brereton	Fishing	75	16.5
	Lake of the Woods	Brereton	Fishing	70	16
	Lockport	Brereton	Fishing	25	14
	Bird Lake	Brereton	Fishing	30	16
	Bird Lake	Brereton	Fishing	20	15

All data were log transformed, with the exception of the pH variable. The SYNTAX 2000 statistical package was used for multivariate statistical analysis.

Ordination analytical methods represent data structure in a lower dimensional space (Kenkel 2001). PCA is used to analyze linear data, summarizing linear trends of variation. In contrast, CA may be used to analyze non-linear data, because data is standardized by both variables and objects. Variable component scores are computed directly and indirectly for CA and PCA respectively. Intensity of use and lake morphology data matrices had numerous zero values. This non-linear data was analyzed using CA. Water and sediment chemistry data had few zero values and PCA was used. When Group 12 was examined based on parameters measured including: intensity of use, lake morphology and mean 2002 water chemistry CA was used to analyze the data because of its non-linear nature. In contrast, PCA was used to analyze Group 13 based on measured variables including: July 2002 water chemistry, winter water chemistry and current sediment chemistry.

Chapter 4: Results

4.1 Lyngbya wollei

4.11 Distribution

Presently, *L. wollei* growth has been identified in Betula and White Lakes. In Betula Lake, *L. wollei* mats were found in the south-western bay throughout the littoral area between Blocks 1 and 4 (Figure 2). Mats were raked off the bottom at depths up to two and a half meters. The highest *L. wollei* density was in the Betula Lake campground area. In White Lake, *L. wollei* was found in the north-eastern bay (Figure 3). *L. wollei* was found to occur sporadically along the Block 1, 2 and 3 shorelines. The highest density of *L. wollei* growth occurred between Blocks 2 and 3 where the White Lake campground is located. Infestations were found in areas under intensive use with road access, cottages, resorts and recreational facilities.

Table 15: Estimated number of motorized and non-motorized watercraft extrapolated from the Whiteshell resident survey. Percent of survey respondents with visitors who bring boats to the Whiteshell and there origin.

Lake	Cottages	Response	Response (%)	Estimated No. Recreational Watercraft on Lake		Visitors Boating		Other
				Motorized	Non-motor	None (%)	MB (%)	
Barren	23	7	30	20	46	100	0	–
Betula	170	47	28	184	174	79	15	Alberta
Big Whiteshell	181	54	30	188	238	80	13	North Dakota
Brereton	348	81	23	417	318	84	15	Minnesota
Caddy	151	41	27	199	149	71	17	Saskatchewan (SK)
Falcon	813	164	20	848	823	88	7	SK and Nebraska
Florence	30	8	27	53	72	100	0	–
Green	3	2	67	3	5	100	0	–
Hunt	8	3	38	0	16	100	0	–
Jessica	102	29	28	151	158	79	21	–
Nora	20	8	40	30	23	100	0	–
Red Rock	123	30	24	152	144	80	10	–
Star	129	35	26	133	151	71	9	Alberta
White	83	23	28	79	123	83	0	Indiana

Table 16: Number of boats launched or returned at public boat launches between 8 am and 6 pm on August 2, 2003.

	Returned			Launched		
Lake	Motorized	Non-Motorized	Total	Motorized	Non-Motorized	Total
Betula	0	0	0	16	3	19
White	1	0	1	11	4	15
Jessica	3	0	3	12	1	13
Caddy	2	0	2	26	11	37

Betula and White Lakes are shallow. In areas where *L. wollei* proliferates, the maximum depth in Betula and White Lakes are 2.5 and 2.75 meters, respectively. The mean photic depth of Betula and White Lakes are 3.87 and 4.03 meters respectively (Table 18). Consequently, >1% light may reach the sediment in the infested bays. Infested areas of Betula and White Lakes have similar morphology and light penetration but distinct *L. wollei* distribution.

The Whiteshell Resident Survey asked cottagers if they had ever seen *L. wollei* in their lake. Twenty-eight percent of property owners from White and Betula Lake responded to the survey. Only 17 % of White Lake respondents had seen *L. wollei* in their lake. In contrast, 60 % of Betula Lake respondents had observed *L. wollei* in their lake. One respondent from each lake indicated they had first seen *L. wollei* in their lake in the 1960s. The majority of people had only noticed *L. wollei* infestations in the last 5 years. The White Lake infestation was patchy with minimal impact on recreational users. The beach had minimal *L. wollei* growth and mats were not readily observed from the beach. In contrast, the Betula Lake infestation was distributed evenly over the infested area impacting recreational use of the lake. The beach area had a dense proliferation of *L. wollei*. Large amounts of *L. wollei* biomass were observed washed up on shore and floating in the water. As a result, the Betula Lake infestation had a greater impact on recreational lake users. Algae species collected from various Whiteshell lakes, which appeared morphologically similar to *L. wollei* were identified to genus (Table 19). *Lyngbya* genera found were not *Lyngbya wollei* species.

4.12 Biomass

SCUBA divers were employed to examine the distribution of *L. wollei* biomass along a 20 meter transects originating from the shoreline in the campground areas of Betula and White Lakes. Ten meters offshore *L. wollei* had a mean dry biomass of 254 g/m^2 in Betula Lake. White Lake yielded three times the mass found in Betula Lake with 642 g/m^2 dry weight (Table 20). In contrast, at twenty meters offshore *L. wollei* mean dry weight from

Table 17: Summary of lakes included in Group 12 and Group 13.

Group 12	Group 13
Barren	Barren
Betula	Betula
Big Whiteshell	Brereton
Brereton	Caddy
Caddy	Florence
Falcon	Hunt
Green	Madge
Jessica	Marion
Red Rock	Red Rock
Star	Shirley
White	Star
	White

Betula Lake was ten times higher than White Lake with 271 and 26 g/m^2 respectively (Table 20).

4.13 Desiccation Experiments

July Desiccation Experiment

The mean oxygen concentration for each treatment was calculated from three trials. Analysis of variance concluded that treatment mean oxygen concentrations were significantly different, $p = 0.031$ (Table 21A). The fresh, stagnant and two day treatments evolved more than 1.0 μg O_2 /mg DW. In contrast, the one month, three and four day treatments produced less than 1.0 μg O_2 /mg DW. All treatments with the exception of the 3 day treatment had a positive net oxygen production (Table 21B, Figure 15). The 3 day treatment consumed 1.41 μg O_2 /mg DW. The ANOVA output showed that the fresh and stagnant treatments had mean concentrations higher than the other treatments. The Tukey-Kramer test concluded only the fresh and 3 day treatment had significant concentration differences.

August Desiccation Experiment

Results from the August desiccation experiment showed that mean oxygen evolution was significantly different between treatments, $p = < 0.0001$ (Table 22A). The fresh and stagnant treatments evolved more than 6.0 μg O_2 /mg DW. In contrast, all remaining treatments with the exception of the five day treatment consumed oxygen (Table 22B, Figure 16). The Tukey- Kramer test confirmed that oxygen concentrations for dried *L. wollei* treatments were significantly different from fresh and stagnant *L. wollei* treatments.

4.2 Water Chemistry 2003

In 2003, water samples were collected biweekly from three sites on Betula, White, Jessica and Caddy Lakes. Analysis of Variance determined that the three samples sites on Betula, Jessica and Caddy Lakes were not significantly different ($p > 0.05$) based on investigated water chemistry parameters. ANOVA determined White Lake total phosphorus concentrations were significantly different between sample sites ($p = 0.0303$). The remaining parameters for White Lake showed no significant difference between sites. Tukey-Kramer

Table 18: Photic depth of 12 Whiteshell lakes measured between July 15 - 22, 2003.

Lake	Photic Depth (m)
Red Rock	15.25
Falcon	9.64
Hunt	8.41
Barren	7.34
Big Whiteshell	6.41
Green	5.92
Star	5.44
Caddy	4.53
Jessica	4.04
White	4.04
Betula	3.57
Brereton	2.87

pairwise comparison indicated a significant difference between sites with a positive value. Based on the Tukey-Kramer pairwise comparison the high and low anthropogenic impact littoral sites did not have significantly different total phosphorus concentrations. Water chemistry parameters measured in boating lanes with high and low intensity of traffic also showed no significant difference between water chemistry parameters (Appendix). Consequently, with the exception of White Lake total phosphorus, water chemistry variables were not significantly different between the three sites investigated within each respective lake.

4.21 Photosynthetically Active Radiation

Photic depth is the depth to which one percent of surface PAR penetrates through the water column. The mean photic depth for Betula, White, Jessica and Caddy Lakes were calculated based on biweekly measurements recorded from May to August 2003 (Table 18). Light measurements were collected in July 2003, from the remaining eight lakes in Group 12 (Table 18). Red Rock Lake had the greatest photic depth at 15.25 meters. Betula Lake had the second smallest photic depth after Brereton Lake at 3.57 meters.

4.3 Statistical Analysis of Group 12

4.31 Intensity of Land Use

Correspondence Analysis, was used to compare Group 12 based on intensity of use variables (Figure 17, Table 23). The eigenvalues for axis one and two were 65 % and 11.99 % respectively, accounting for 77 % of the variability in the data. Axis one was highly correlated with intensity of use variables, while axis two was best correlated with distance of the lake from the closest town. Groups of lakes which experienced similar intensity of use regimes were identified. Betula, White, Brereton, Big Whiteshell and Caddy Lakes formed one group. This group was positively correlated with axis one. All of these lakes had a campground and numerous other recreational facilities but were a moderate distance from the closest town (Table 13). Falcon Lake was distinct from all other lakes positively correlated with both axis one and two. The town of Falcon is located adjacent to the lake. As a result,

Table 19: Filamentous algae genera collected from four Whiteshell lakes, which appear morphologically similar to *Lyngbya wollei.*

Big Whiteshell Lake	Caddy Lake	Jessica Lake	White Lake
Scytonema	*Anabaena*	*Bennothrix*	*Lyngbya**
	Cladophora	*Mougeotia*	*Mougeotia*
	*Lyngbya**	*Oedogonium*	*Scytonema,*
	Mougeotia	*Scytonema*	*Spirogyra*
	Scytonema	*Spirogyra*	*Tolypothrix*
	Vaucheria	*Tolypothrix*	
	Zygnema	*Zygnema*	

* *Lyngbya* included are not *Lyngbya wollei.*

Table 20: *L. wollei* dry weight (g/m^2) harvested by SCUBA divers with 0.46 m^2 quadrats along transects at 10 and 20 meters on July 30, 2003.

Lake	UTM Zone 13	Quadrat 1 10 m	Quadrat 2 10m	Average DW 10 m	Quadrat 1 20 m	Quadrat 2 20 m	Average DW 20 m
Betula	N 5549269 E 0314599	230	278	254	348	193	271
White	N 5549269 E 0314599	591	693	642	52	0	26

Table 21A: July Desiccation experiment ANOVA table.

	df	SS	MS	F	P-value
Treatment	5	92.26623	18.4532	3.6384	0.031
Error	12	60.86213	5.0718		
Total	17	153.12836			

Table 21B: July 23, 2003 Desiccation Experiment treatment oxygen evolution.

Treatment	Trial 1 Evolved O_2 μg O_2 /mg DW	Trial 2 Evolved O_2 μg O_2 /mg DW	Trial 3 Evolved O_2 μg O_2 /mg DW	Mean Evolved O_2 μg O_2 /mg DW
Fresh	4.29	6.44	5.19	5.31
Stagnant	3.40	6.29	3.33	4.34
1 month	-0.43	0.41	2.65	0.88
4 days	-1.28	0.84	2.79	0.78
3 days	-6.12	0.92	0.98	-1.41
2 days	0.96	4.02	1.01	2.00

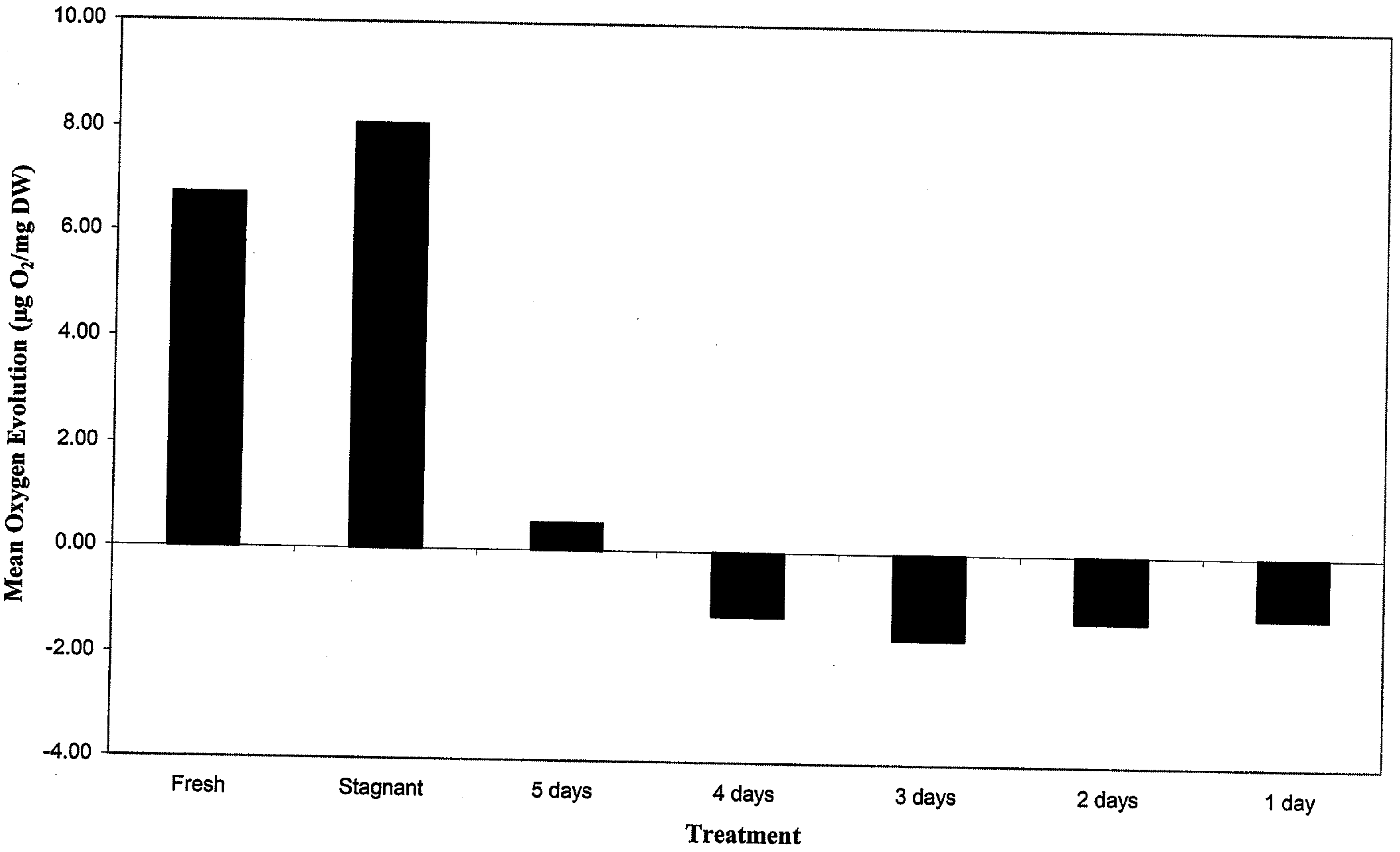

Figure 15: Mean oxygen evolution by *L. wollei* treatments in July desiccation experiment.

Table 22A: August 18, 2003 Desiccation Experiment ANOVA table.

	df	SS	MS	F	P-value
Treatment	6	310.28885	51.7148	23.5665	< 0.0001
Error	13	28.52745	2.1944		
Total	19	338.8163			

Table 22B: August 18, 2003 Desiccation Experiment treatment oxygen evolution.

Treatment	Trial 1 Evolved O_2 µg O_2 /mg DW	Trial 2 Evolved O_2 µg O_2 /mg DW	Trial 3 Evolved O_2 µg O_2 /mg DW	Mean Evolved O_2 µg O_2 /mg DW
Fresh	5.81	6.35	8.08	6.75
Stagnant	5.98	9.04	9.26	8.09
5 days	0.45	0	1.12	0.52
4 days	-2.56	-1.27	0.23	-1.20
3 days	-2.02	0	-2.81	-1.61
2 days	-3.46	n/a	-0.27	-1.24
1 day	-1.45	-2.57	0.6	-1.14

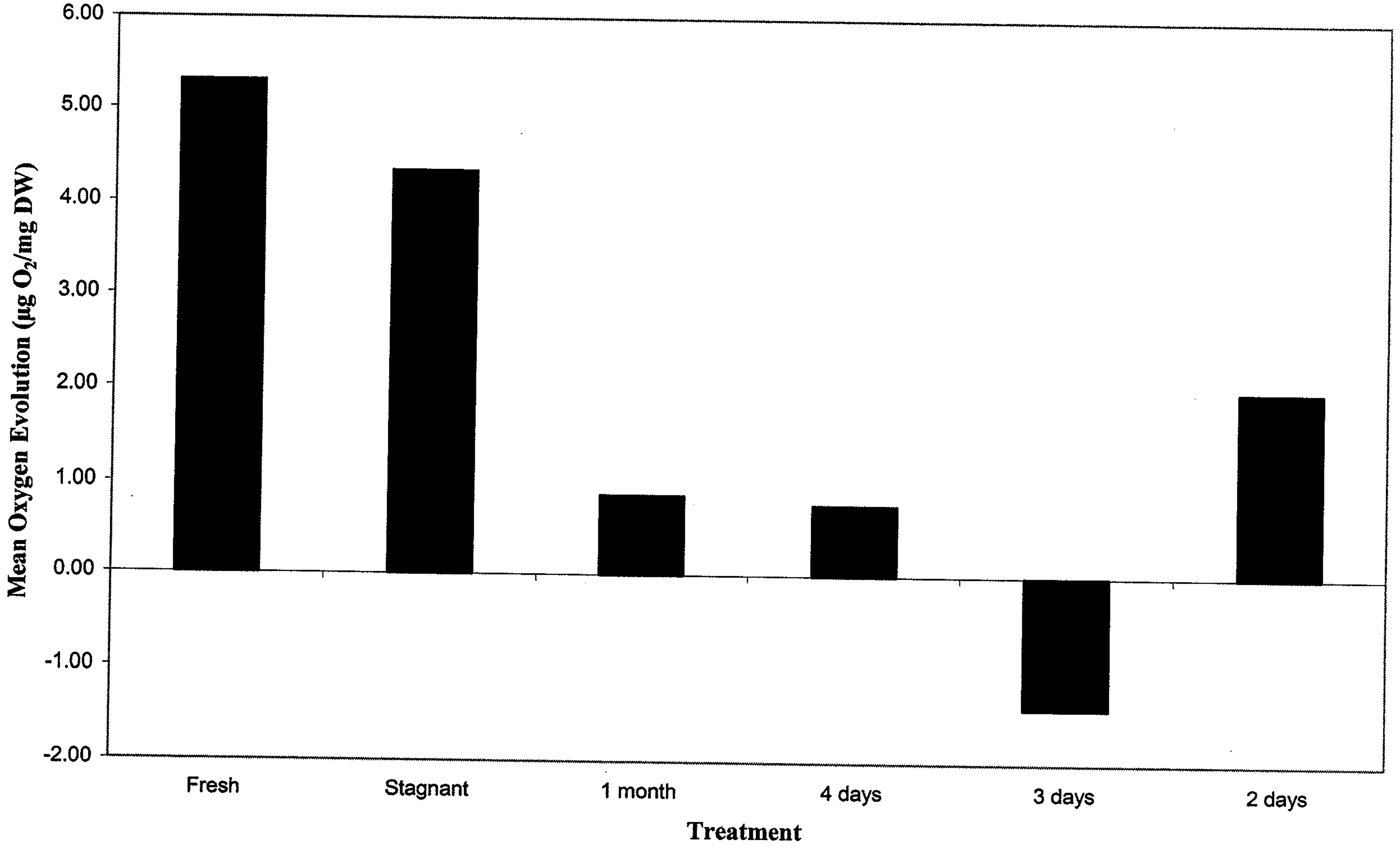

Figure 16: Mean oxygen evolution by *L. wollei* in August desiccation experiment.

Falcon Lake had the most modern and numerous campground and recreational facilities of all twelve lakes examined. In contrast, Green Lake was negatively correlated with axis one and two. Green Lake was the furthest of all Group 12 lakes from the closest town with only a few cottages and no recreational facilities. The remaining five lakes: Jessica, Red Rock, Star, Barren and Hunt experienced moderate to low intensity of use respectively. Red Rock, Star and Barren formed a second group with relatively low intensity of use but were distinguished by lake distance from the closest town. Jessica Lake was positioned between group one and two, with moderately intensity of use. Hunt Lake had the second lowest intensity of use after Green Lake. Consequently, Figure 17 created a continuum for intensity of use, in the positive direction along axis one.

4.32 Lake Morphology

Correspondence Analysis differentiated Group 12 based on morphological parameters. The cumulative eigenvalue percentage for axis one and two was 89.43 %, at 66.77 and 22.66 % respectively (Figure 18). Axis one was positively correlated with lake surface area and fetch. Mean and maximum depths were positively correlated with axis two. Group one was composed of Betula, White, Brereton, Big Whiteshell and Jessica Lakes. These lakes had large surface areas and fetch with moderate depths. In contrast to the intensity CA, Caddy Lake was replaced by Jessica Lake in group one. Consistent with the intensity CA group two included: Red Rock, Star and Barren Lakes. Caddy Lake was positioned between group one and two with moderately high surface area and fetch. Falcon, Hunt and Green Lakes remained outliers. Falcon Lake is deep with a large surface area and fetch, positively correlated with both axis one and two. Green Lake is small and shallow, while Hunt Lake is a small deep lake. As a result, CA identified similar groups and outliers based on morphological and intensity of use variables.

4.33 Water Chemistry: Summer 2002

Principal component analysis was used to examine Group 12 based on mean water chemistry variables from monthly sampling in 2002 (Figure 19). Axes one and two had eigenvalues of 42.94 and 21.35 % respectively. Five of the twelve lakes were identified as outliers with unique water chemistry characteristics. Brereton Lake was distinguished by high iron concentrations. Green lake was correlated with high concentrations of total kjeldahl nitrogen, manganese, chlorophyll a and turbidity. Falcon and Hunt Lakes had relatively high conductivity, alkalinity and potassium. Big Whiteshell was positively correlated with axis two and had the highest mean pH. The remaining lakes had similar water chemistry characteristics positioned in the center of the PCA, have similar chemical composition.

4.34 Group 12 Summary

When all three data matrices: intensity of use, lake morphology and water chemistry variables for Group 12 were combined CA and the same groups and outliers were identified as those produced by intensity of use variables. Group one included: Betula, White, Brereton, Big Whiteshell and Caddy Lakes. Group two was composed of Red Rock, Star and Barren Lakes. Jessica Lake lay between the two groups. Falcon, Green and Hunt Lakes were outliers.

4.4 Statistical Analysis of Group 13

4.41 Water Chemistry: July 2002

Principal component analysis distinguished Group 13 based on July 2002 water chemistry (Figure 20). It was determined Betula, White and Jessica Lakes had high concentrations of chlorophyll a, total particulate phosphorus, total phosphorus and total suspended solids forming Group A. The "backcountry" lakes: Florence, Madge, Marion and Shirley all had low water chemistry parameters forming Group B. Group A and B had distinct July water chemistry characteristics located at opposite ends of axis one with an eigenvalue of 51.18 %. Red Rock, Caddy and Brereton Lakes formed a third group which are most similar to Group A. Star and Barren lakes formed the fourth group which was most similar to Group B water chemistry. Hunt Lake was identified as an outlier with extremely high conductivity.

Table 23: Intensity of land-use parameters used to examine Group 12 using Correspondence Analysis. Variables were counted or calculated based on Whiteshell Resident 2002 Survey(*).

Intensity parameters
Distance of lake from closest town
Number of Cottages
Number of Resort Units
Number of Seasonal Campsites
Number of Transient Campsites
Number of Services at Lake
Number of Recreation Facilities
Number of Beaches
Number of Boat Launch
Number of Non-Modern Washroom Buildings
Number of Modern Washroom Buildings
Number of Shower Buildings
Number of designated grey water and trailer sanitary stations
Mean weighted average of monthly lake use reported by residents in Whiteshell Survey
Mean weighted average for type of sewage handling system)
Extrapolated number of motorized watercraft*
Extrapolated number of non-motorized watercraft*

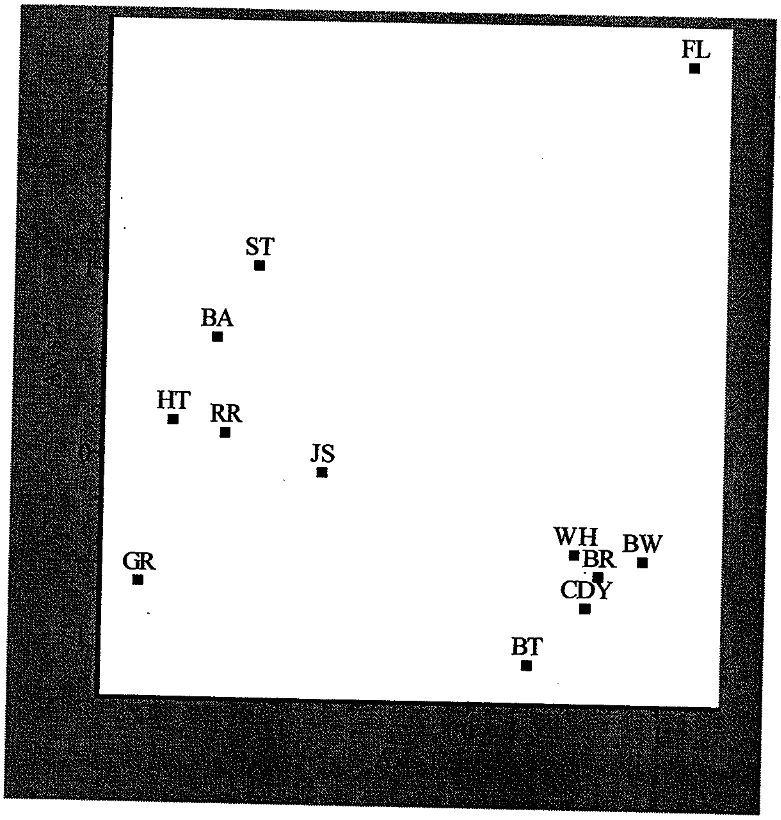

Figure 17: Correspondence analysis ordination biplot showing lake associations based on intensity of land-use variables. The eigen values for Axis 1 and 2 are 65 and 12% respectively. Lake codes: Barren (BA), Betula (BT), Big Whiteshell (BW), Brereton (BR), Caddy (CDY), Falcon (FL), Green (GR), Hunt (HT), Jessica (JS), Red Rock (RR), Star (ST), and White (WH).

4.42 Water Chemistry: Winter 2002 – 2003

When PCA was preformed using winter water chemistry parameters Groups A and B found in the July PCA were again identified at opposite ends of axis one (Figure 21). Group A had high water chemistry parameters such as nitrite, nitrate, chlorophyll a and total particulate phosphorus. Group B maintained low concentrations of water chemistry parameters, with the exception of total kjeldahl nitrogen. Star and Red Rock Lakes had water chemistry very similar to Group A. Caddy, Barren and Brereton had moderate water chemistry parameters correlated with axis one but were distinguished by axis two. Brereton Lake was positively correlated with axis two with elevated colour and iron concentrations. As a result, Group A and B remained distinct but the remaining lakes were repositioned based on unique chemical characteristics.

4.43 Sediment Chemistry

The top five centimeter subsample from each sediment core was used to represent current sediment chemistry conditions. PCA was used to identified Group 13 lakes with similar current sediment chemistry (Figure 22). Betula, White and Jessica Lakes all had relatively low element concentrations, with the exception of phosphorus and boron. In contrast, Caddy, Barren, Star, Shirley and Brereton Lakes had high element concentrations. Madge, Red Rock and Florence Lakes had moderate element concentrations. Red Rock and Florence Lakes were pulled down axis two by relatively high phosphorus concentrations. This group of lakes had the closest sediment chemistry to Betula, White and Jessica Lakes. Marion Lake was an outlier with very low concentrations of all sedimentary elements.

The concentration of sedimentary elements changed throughout the length of the each core. The mean concentration of each element was calculated to compare overall sediment chemistry for each lake. Groups of lakes identified with similar sediment chemistry were similar to those produced by the current sediment PCA. The eigenvalues for axis 1 and 2 were 47.83 and 23.04 %, respectively. Group one included Betula, White, Jessica and Red Rock Lakes. These lakes are negatively correlated with axis 1. Consequently, these lakes

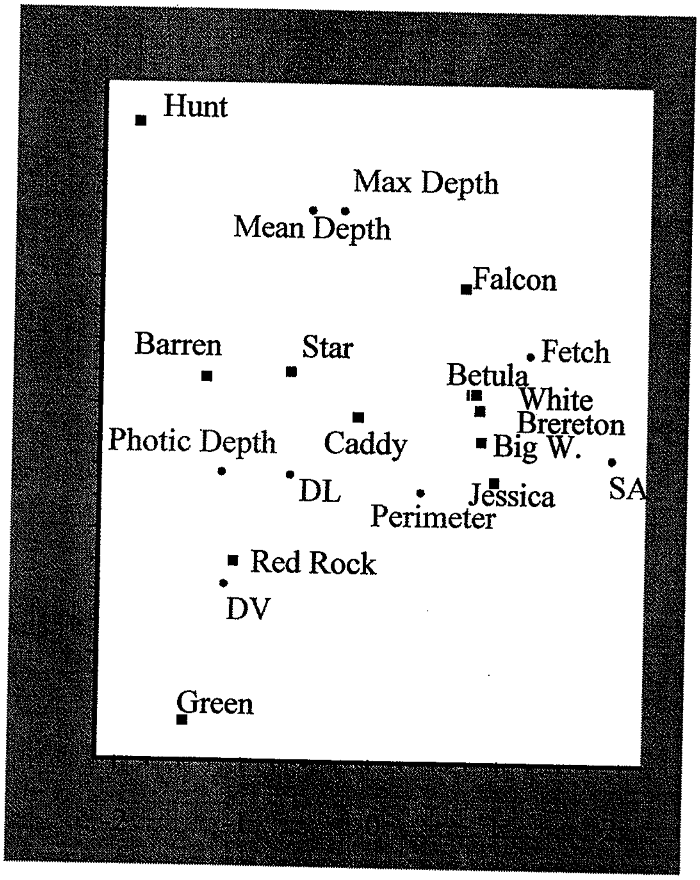

Figure 18: Correspondence analysis ordination biplot of lake morphology parameters. The eigen values for Axis 1 and 2 are 66.77 and 22.66%, respectively. Lake morphology variables: maximum lake depth (max depth), mean lake depth (mean depth), shoreline development index (DL), volume development index (DV), lake surface area (SA), lake perimeter (perimeter), mean lake photic depth (photic depth), largest lake fetch (fetch).

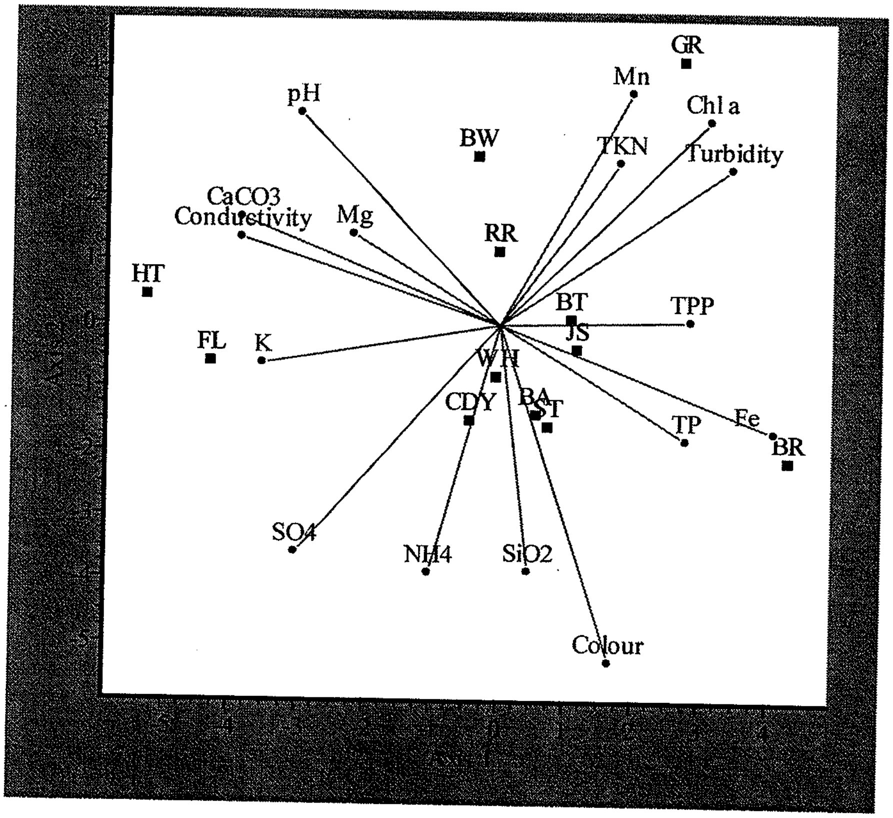

Figure 19: Principal component analysis ordination biplot of mean monthly water chemistry from 2002. The eigen values for Axis 1 and 2 are 42.94 and 21.35 % respectively. Lake codes: Barren (BA), Betula (BT), Big Whiteshell (BW), Brereton (BR), Caddy (CDY), Falcon (FL), Green (GR), Hunt (HT), Jessica (JS), Red Rock (RR), Star (ST), and White (WH).

have relatively high concentrations of boron. Group two included Madge, Florence and Brereton Lakes with moderate nutrient concentrations. Florence Lake was pulled up axis 2 because it had the highest mean TKN concentration. Star and Barren Lakes formed group three which was correlated with both axis 1 and 2 with relatively high nutrient concentrations, in particular copper and nickel. Shirley and Caddy Lakes formed group four with high nutrient concentrations. Sediment cores from these lakes were nutrient rich, with the second highest magnesium concentrations after Marion Lake. Hunt and Marion Lakes formed groups onto themselves. These outliers both had high nutrient concentrations correlated with axis 1 but were distinguished by axis 2. Hunt Lake had high concentrations of selenium, copper and iron. In contrast, Marion Lake had high concentrations of magnesium and potassium. As a result, groups one to six formed a continuum with respect to sediment nutrient enrichment. Group one lakes had relatively low mean nutrient concentrations with the exception of boron. In contrast, group's four to six had relatively high mean concentrations, distinguished by elements correlated with axis 2.

Principal component analyses of mean heavy metal concentrations distinguished relatively pristine and contaminated lakes. The eigenvalues for axis 1 and 2 were 58.47 and 22.51 %, respectively. Brereton, Star and Hunt Lakes formed a group with high mean concentrations of mercury and arsenic. Red Rock, Shirley, Florence, Caddy and Madge Lakes had relatively high cadmium and lead concentrations. Barren, White and Betula lakes had relatively low heavy metals concentrations. Barren had a higher mean arsenic concentration than Betula and White Lakes. Jessica and Marion Lakes had the lowest heavy metal concentrations.

4.44 Group 13 Summary

Principal component analysis was used to examine Group 13 based on the three data matrices combined: July 2002 water chemistry, winter water chemistry and current sediment chemistry. The first two axes had a cumulative eigenvalue of 50.85 %. The lake groups produced were most similar to those produced by the current sediment PCA. Betula, White,

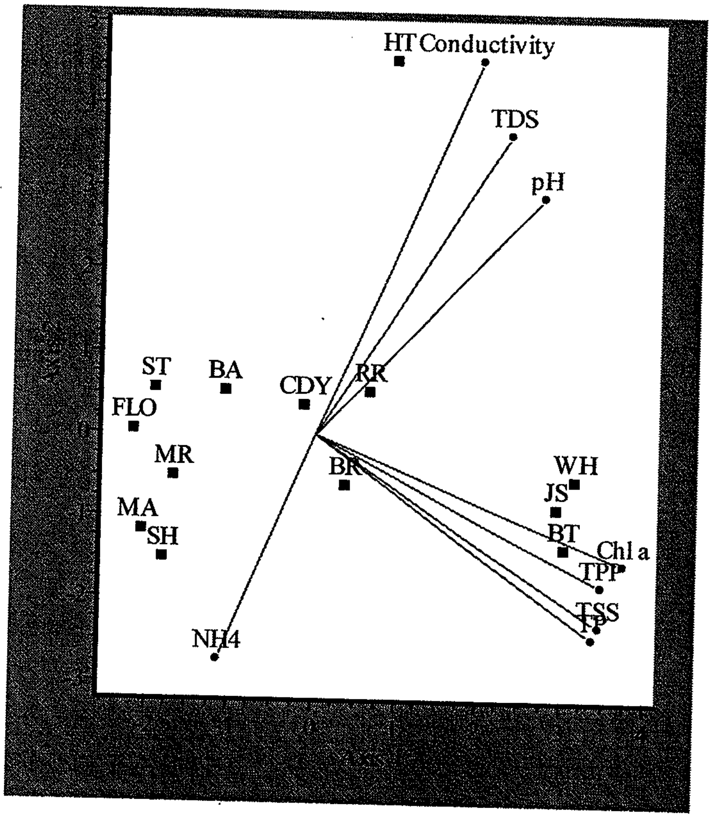

Figure 20: Principal component analysis ordination biplot of July 2002 water chemistry. The eigen values for Axis 1 and 2 are 51.18 and 30.12 % respectively. Lake codes: Barren (BA), Betula (BT), Brereton (BR), Caddy (CDY), Florence (FLO), Hunt (HT), Jessica (JS), Madge (MA), Marion (MR), Red Rock (RR), Shirley (SH), Star (ST), and White (WH).

Jessica and Red Rock Lakes formed one group. Group two consisted of: Caddy, Star and Barren Lakes. The third group was composed of backcountry lakes: Shirley, Madge and Florence. Brereton Lake was positioned between all three groups. Marion and Hunt Lakes were outliers.

4.5 Sediment Geochemistry

4.51 Description of Whiteshell Cores

Sediment cores were collected from a total of 13 Whiteshell Lakes. Sediment cores varied from 15 to 50 cm in length (Table 9). The cores had no perceptible smell. Red Rock Lake sediment was soft and flocculent. Hunt Lake sediment had a distinct granular texture. Cores extracted from Marion Lake exhibited a colour change. The top half of the core was brown in colour similar to other Whiteshell cores. In contrast, the bottom half of the Marion Lake cores were very firm grey clay with large pieces of fibrous plant material throughout. All remaining cores had a homogenous texture and brown colour. A filamentous black alga was observed at the surface and within sediment core BT1 collected from Betula Lake (Table 9). Due to the nature of the lake bottom a sediment core could not be collected from site BR1 on Brereton Lake (Table 9). The range in water content, organic matter content, carbonate content and total chlorophyll concentrations have been recorded in Table 24. A detailed summary of sediment composition as a function of depth is provided below.

4.52 Sediment Composition

4.52-1 Barren Lake

The water content profile showed a typical increase up the core from a basal 89 % to 95.2 % sediment wet weight (Figure 23). The organic matter content constituted approximately 36 – 37 % sediment dry weight with four distinct fluctuations at 6, 18, 30 and 38 cm. There were three decreases in organic matter content experienced at 6, 30 and 38 cm. The minimum organic matter content value was 34.9 % at 38 cm. In contrast, at 18 cm the profile showed a distinct peak, to a maximum value of 41.3 % organic matter content. Total chlorophyll had a maximum concentration of 105.9 μg/g at the top of the core. Total

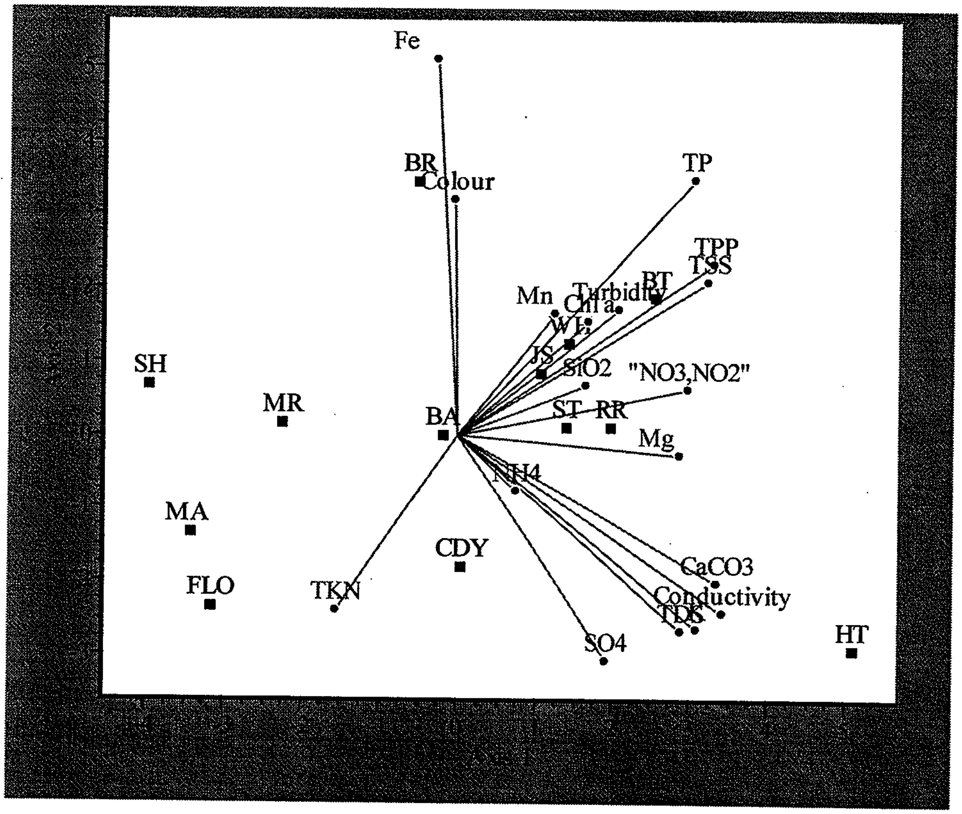

Figure 21: Principal component analysis ordination biplot of winter water chemistry. The eigen values for Axis 1 and 2 are 38.93 and 17.24 % respectively. Lake codes: Barren (BA), Betula (BT), Brereton (BR), Caddy (CDY), Florence (FLO), Hunt (HT), Jessica (JS), Madge (MA), Marion (MR), Red Rock (RR), Shirley (SH), Star (ST), and White (WH).

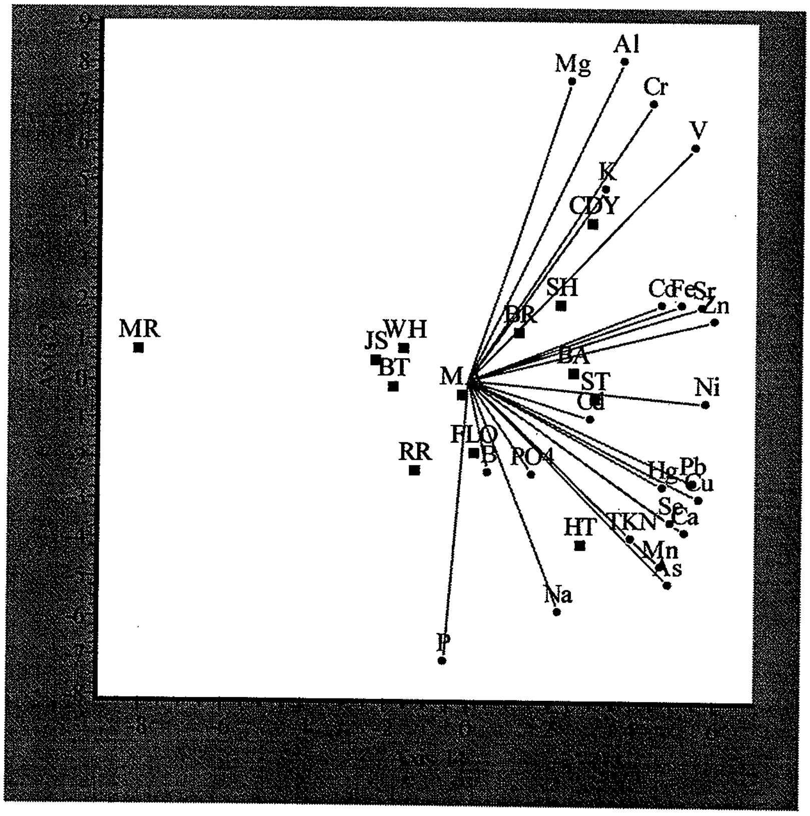

Figure 22: Principal component analysis ordination biplot of current sediment chemistry. The eigen values for Axis 1 and 2 are 47.83 and 23.04% respectively. Lake codes: Barren (BA), Betula (BT), Brereton (BR), Caddy (CDY), Florence (FLO), Hunt (HT), Jessica (JS), Madge (MA), Marion (MR), Red Rock (RR), Shirley (SH), Star (ST), and White (WH).

chlorophyll showed four fluctuations correlated with those described for organic matter content. At 6 and 30 cm depths organic matter content and total chlorophyll both decreased. In contrast, when the organic matter content peaked at 18 cm the total chlorophyll concentration decreased sharply to its second lowest concentration of 26 µg/g. The lowest concentration of total chlorophyll 15.5 µg/g was found at 40 cm, 2 cm below the minimum organic matter content value. Carbonate content ranged between 1.1 and 2.9 % and fluctuations appeared to be unrelated to those observed in the other water content, organic matter and total chlorophyll profiles (Table 24).

4.52-2 Betula Lake

Betula Lake water content obtained a maximum value of 93.4 % sediment wet weight at the top of the core and decreased to 87.8 % at the base (Figure 24). Fluctuations observed in the water content profile are relatively small and were not correlated to changes in organic matter or carbonate content profiles. At the top of the core organic matter constituted 35.8 % dry weight decreasing to 34.2 % at 14 cm. Below 16 cm organic matter content was maintained above 36.7 % reaching a maximum of 38.1 % at 24 cm. Total chlorophyll had a maximum value of 463.7 µg/g at the top of the core. Total chlorophyll decreased steadily down the core with a single peak to 110.1µg/g at 14 cm. Carbonate content ranged between 1.1 and 1.9 % dry weight with a single minimum value of 1.1 % occurring at 24 cm.

4.52-3 Brereton Lake

The Brereton Lake water content profile showed numerous fluctuations throughout the length of the core. These fluctuations were relatively small, with a range of only 4.3 % (Figure 25). Water content fluctuated between 87.2 % and 91.5 % (Table 24). Fluctuations were not correlated with other organic matter, carbonate content fluctuations. Organic matter content is maintained at approximately 30 % throughout the core. Total chlorophyll is relatively consistent throughout the length of the core. Total chlorophyll had a maximum peak of 100.6 µg/g at the top of the core, drastically dropped to 25.2µg/g at 2 cm, and continued to steadily decrease with depth. Brereton Lake had the lowest maximum total chlorophyll concentration of all cores. Carbonate content ranged between 1.0 and 1.5 % sediment dry weight.

4.52-4 Caddy Lake

Water content, organic matter content and total chlorophyll profiles from Caddy Lake were relatively consistent lacking large fluctuations experienced by other cores. Water content ranged from 83.3 % up the core to 92.5 % (Figure 26). Organic matter content was consistently low at approximately 17 % with a small increase at the base to 20.8 %. Caddy Lake maintained the second lowest organic matter content after Marion Lake. Total chlorophyll was 168.3 μg/g at the top of the core and decreased down the core to 28.3 μg/g. Carbonate content ranged between 0.8 and 2.2 % sediment dry weight.

4.52-5 Florence Lake

Water content ranged between 92.2 % and 97.6 % wet weight up the core. Relatively small fluctuations observed were not correlated to other profile fluctuations (Figure 27). Florence Lake experienced a decrease in organic matter content at 12 cm from 47.2 % to a low of 43.6 % at 22 cm with a final peak to 45.4 % at a depth of 28 cm. Total chlorophyll had a maximum value of 794.6 μg/g the second highest concentration after Hunt Lake. Total chlorophyll decreased to a minimum concentration of 102.8 μg/g at 20 cm, 2 cm above the observed organic matter minimum, but followed a pattern similar to the organic matter profile with a subsequent peak at 28 cm. Total chlorophyll experienced a substantial decrease at 6 cm correlated with a decrease in carbonate content. With the exception of this one correlation carbonate fluctuations were not correlated with other profiles and had a maximum content of 3.3 % dry weight.

4.52-6 Hunt Lake

The water and organic matter content profiles of Hunt Lake water content were very similar in shape. There were two pronounced fluctuations in the profiles (Figure 28). At a depth of 14 cm water content was relatively low and organic matter content reached its minimum value of 32.4 %. In contrast, at 28 and 30 cm respectively organic matter content was found to be maximal 47.4 % and water content showed a distinct peak. Both water content and organic matter decreased from 30 to 44 cm with a final basal peak at 46 cm. Hunt Lake had the highest total chlorophyll concentration at 1644.9 µg/g. Carbonate content and total chlorophyll concentration appeared to have similar profile trends. Both profiles experienced an initial decrease down the core with a large peak at 10 cm. Corresponding peaks were also observed at 20 and 30 cm. Carbonate content ranged between 1.3 and 4.1 % dry weight.

4.62-7 Jessica Lake

Jessica sedimentary water content increased up the core from 87.4 % to 94.4 % sedimentary wet weight. Organic matter was maintained at approximately 35 – 36 %, with two distinct fluctuations (Figure 29). At 20 cm the organic matter content decreased to a minimum 33.0 % and at 26 cm peaked at a maximum 36.7 % . Total chlorophyll decreased consistently down the length of the core with a single peak of 88.5 µg/g at 20 cm. This correlated with the organic matter profile fluctuation. The carbonate content ranged between 0.2 and 1.8 % with a substantial decrease to 0.9 % at 20 cm. As a result, organic matter, carbonate and total chlorophyll all showed a substantial fluctuation at 26 cm.

4.52-8 Madge Lake

Water content consistently increased up the core from 90.5 % to 95.7 % sedimentary wet weight (Figure 30). The organic matter profile showed three distinct peaks. Organic matter reached a maximum of 44.2 % at 12 cm and showed two smaller peaks at 18 and 30 cm. The maximum total chlorophyll concentration of 222.4 µg/g was located at a depth of 2 cm. Marion and Shirley Lakes also showed similar subsurface total chlorophyll maximum. Total chlorophyll decreased down core with two peaks at 12 and 20 cm. Carbonate content ranged between 0 and 3.2 %, decreasing sharply to zero at 12 cm. As a result, at 12 cm substantial fluctuations in organic matter, carbonate content and total chlorophyll concentration were recorded.

Table 24: Summary of Loss on Ignition parameters for 13 Whiteshell sediment cores.

	Water Content (%)		Organic Matter Content (%)		Carbonate Content (%)		Total Chlorophyll (μg/g OM)	
Lake	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Barren	89.0	95.2	34.9	41.3	1.1	2.9	15.5	105.9
Betula	87.8	93.4	33.9	38.1	1.1	1.9	39.1	463.7
Brereton	87.2	91.5	29.8	31.2	1.0	1.5	22.0	100.6
Caddy	83.3	92.5	16.6	20.8	0.8	2.2	17.6	168.3
Florence	92.2	97.6	42.8	52.1	0.7	3.3	102.8	794.6
Hunt	91.0	98.7	32.4	47.4	1.3	4.1	84.4	1644.9
Jessica	87.4	94.4	33.0	36.7	0.2	1.8	18.3	123.4
Madge	90.5	95.7	36.3	44.2	0.0	3.2	62.5	222.4
Marion	72.4	82.8	9.0	15.3	0.3	1.3	6.5	228.6
Red Rock	93.2	96.6	49.5	54.5	1.0	2.6	59.4	296.3
Shirley	90.5	95.3	36.2	41.4	1.8	4.1	91.4	298.6
Star	66.7	95.8	5.1	44.0	0.4	5.7	65.9	172.3
White	86.7	94.9	31.6	36.1	1.2	2.1	20.9	293.7

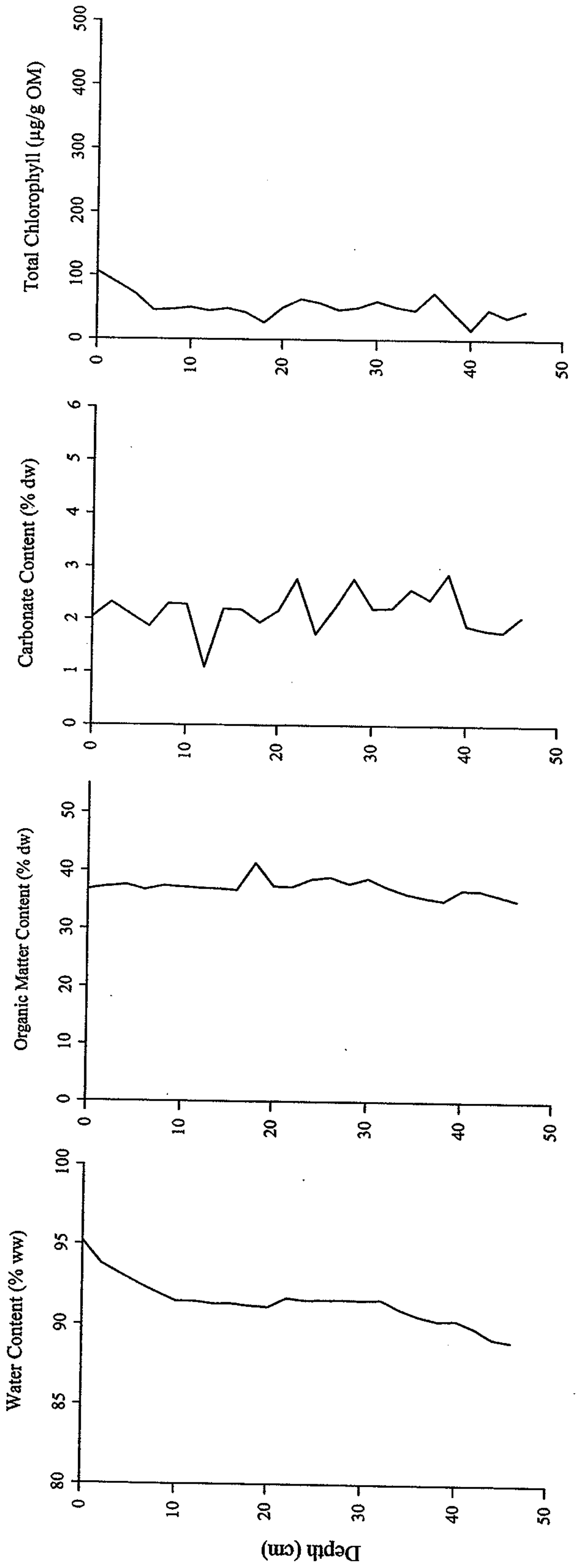

Figure 23: Loss on ignition of bulk sediment composition for Betula Lake.

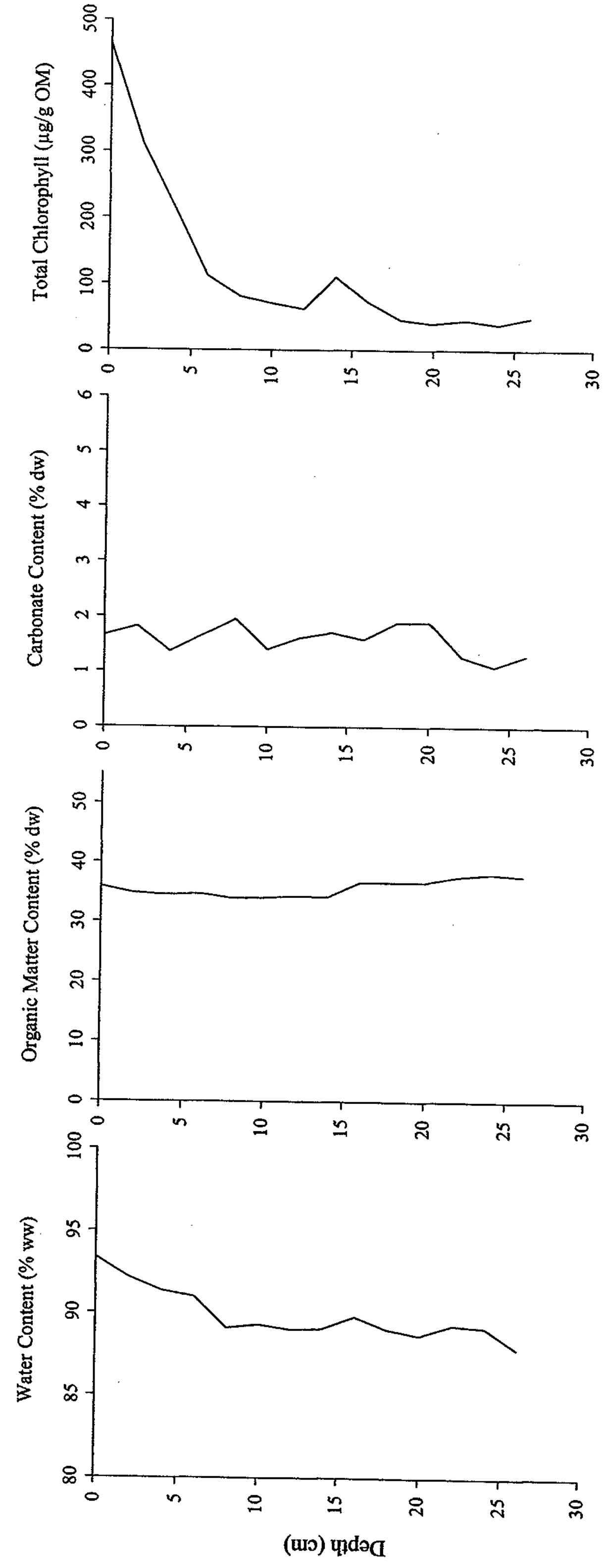

Figure 24: Loss on ignition of bulk sediment composition for Betula Lake.

4.52-9 Marion Lake

The Marion Lake sediment core maintained the lowest water content with minimum and maximum values of 72.4 % and 82.8 % respectively. The profile showed a sharp decrease in water content in the top 8 cm, a sharp increase to the 16 cm depth and subsequent decrease down the core (Figure 31). Water content and organic matter profiles were very similar in shape. The organic matter profile showed the same trend and at 16 cm peaked at the maximum 15.3 % organic matter content. In contrast, other Whiteshell cores had maximum organic matter content values between 30 and 55 %. Similar to Madge Lake the maximum total chlorophyll concentration 228.6 μg/g was found subsurface at 2 cm. The only other distinct total chlorophyll peak occurred at 10 cm where organic matter content fell to its lowest value of 9.0 %. Carbonate content ranged between 0.3 and 1.3 % fluctuations were not correlated with other sediment profiles.

4.52-10 Red Rock Lake

Red Rock Lake maintained the highest sedimentary water content with a range of 3.4 %. Minimum and maximum values were 93.2 % and 96.6 % respectively. Water content fluctuations were relatively small and were not correlated to other profile fluctuations (Figure 32). Organic matter content was 51.6 % dry weight at the top of the core and decreased down core with a basal peak of 53.2 to 54.5 % in the bottom 6 cm. Total chlorophyll was 207.7 μg/g at the top of the core and decreased down core. Two peaks in total chlorophyll were detected, 110.9 μg/g at 16 cm and a maximum peak value of 296.3 μg/g at 28 cm. Carbonate content ranged between 1.0 and 2.6 % dry weight with a relative peak between 24 – 28 cm.

4.52-11 Shirley Lake

Shirley Lake water content increased up the core from 90.5 % to 95.3 % sedimentary wet weight. A fluctuation is observed at 16 cm but relatively this is a small change less than one percent (Figure 33). Organic matter and total chlorophyll both peak with maximum values at 2 cm in depth. The next correlated fluctuation occurred at 14 cm where organic

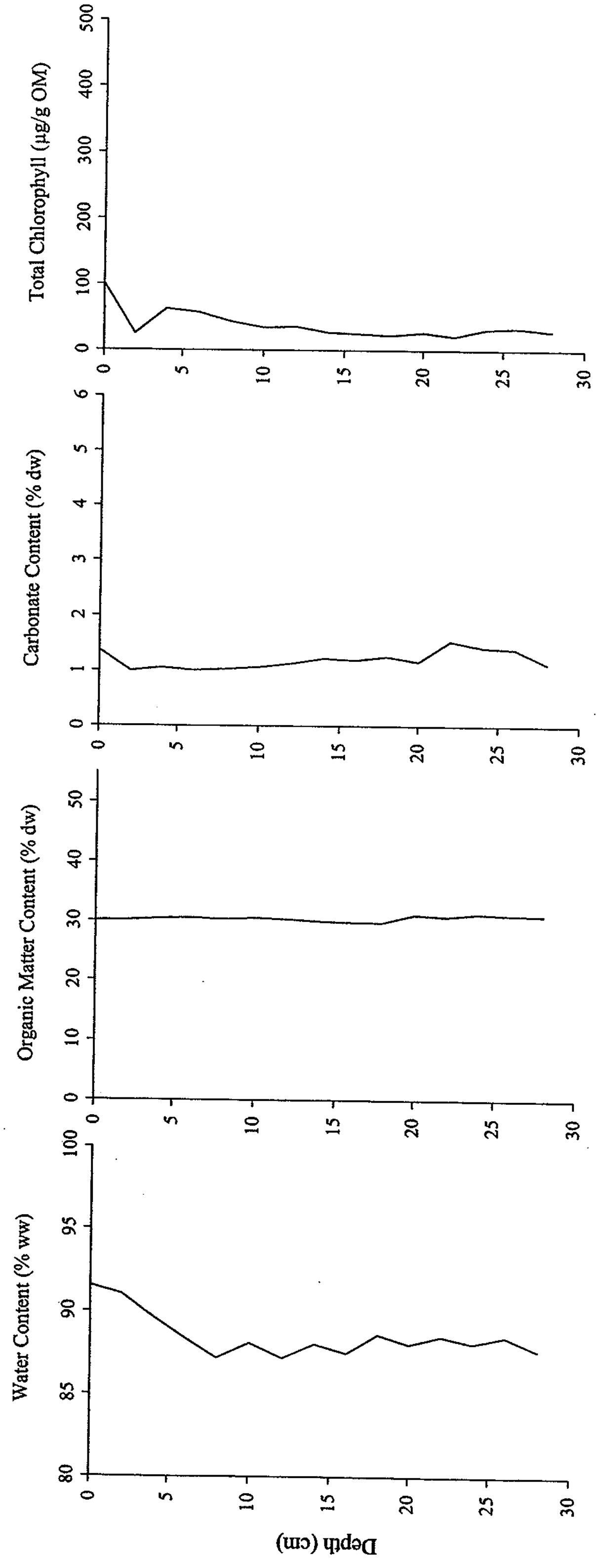

Figure 25: Loss on ignition of bulk sediment composition for Brereton Lake.

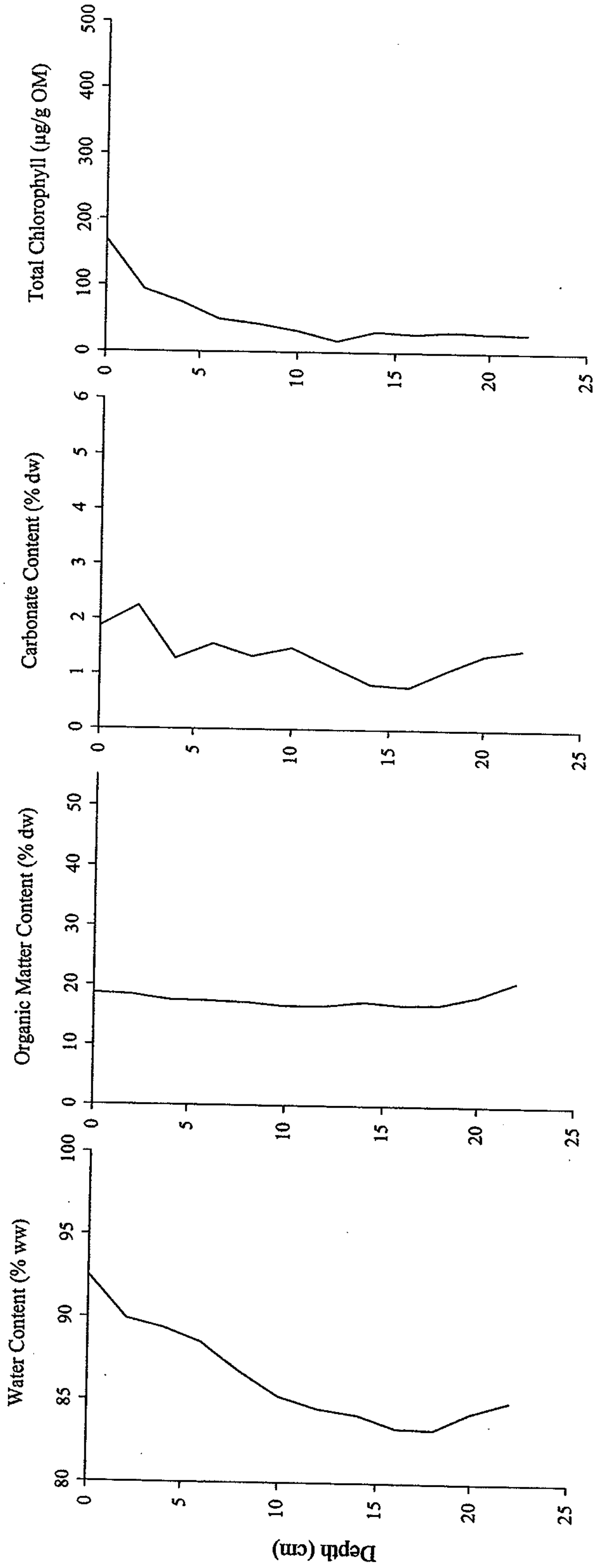

Figure 26: Loss on ignition of bulk sediment composition for Caddy Lake.

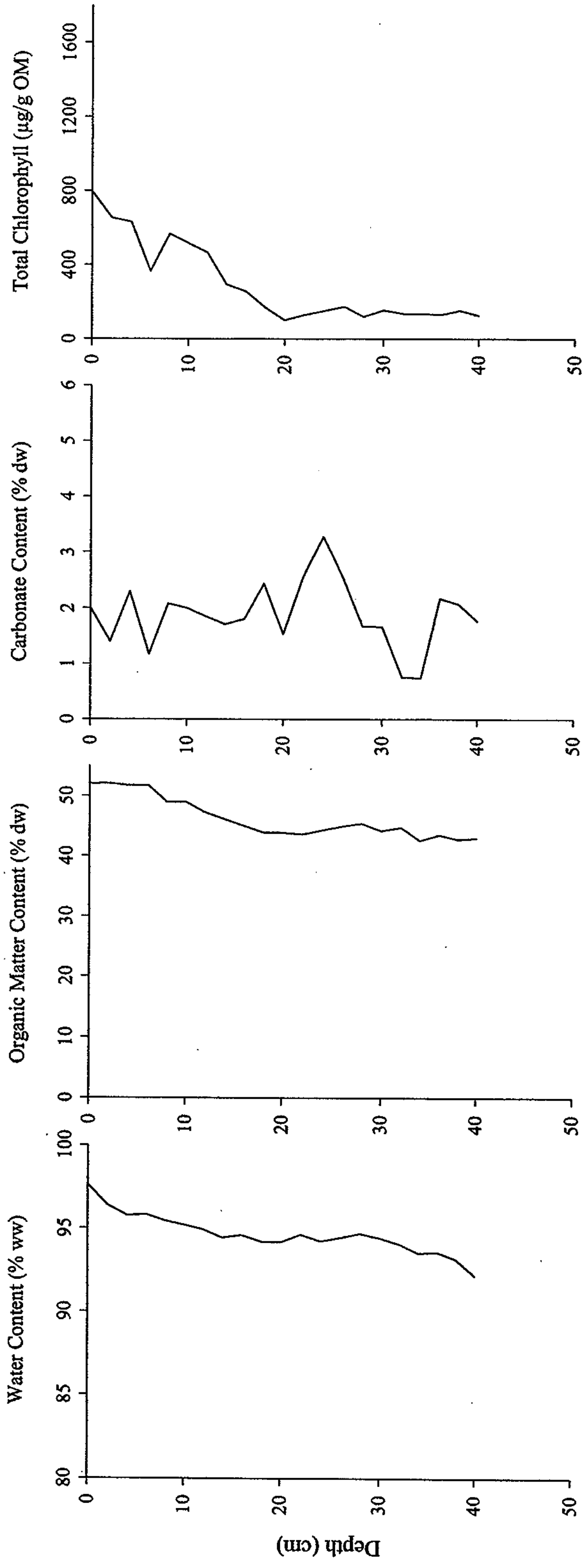

Figure 27: Loss on ignition of bulk sediment composition for Florence Lake.

matter hits a relative low while total chlorophyll peaks. The total chlorophyll profile also peaked at 18 and 24 cm depths. Carbonate content showed a peak at 24 cm correlated with total chlorophyll but the remaining peaks are uncorrelated to other profile fluctuations. Carbonate content ranged between 1.8 and 4.1 % dry weight.

4.52-12 Star Lake

Star Lake sediment showed a unique pattern when compared to all other sediment cores examined. Profiles showed consistent patterns of peaks in water, organic matter and carbonate content (Figure 34). All profiles showed five peaks up the core at 44 cm, 34 cm, 28 cm, 22 cm and 18 cm. The minimum water, organic matter and carbonate contents occurred at 36 cm. Carbonate content and total chlorophyll concentration were at maximum values of 5.7 % and 172.3 μg/g respectively at the sediment surface. Other total chlorophyll peaks are not correlated with the other profiles with peaks up the core at 40 cm, 32 cm, 20 cm. Carbonate content ranged from 0.4 to 5.7 % dry weight.

4.52-13 White Lake

Water content, organic matter content and total chlorophyll concentration decreased down the core (Figure 35). Water content decreased from a maximum of 94.9 % wet weight at the top of the core to 86.7 % at the base. Organic matter content decreased down the core from a maximum 36.1 % at the surface. At a depth of 18 cm organic matter content was low at 31. 8 %. Total chlorophyll decreased down the core from a maximum surface concentration of 293.7 μg/g. At 18 cm carbonate content peaked at 2.0 %. Carbonate content ranged between 1.2 and 2.1 % dry weight.

4.53 Sediment Dating

Sediment chronologies for Betula, White and Madge Lakes have been summarized in Tables 25-28. According to the median year of deposition, the sediment cores represented over 150 years of lake depositional history. Madge and White Lakes had a focus factor of one. In contrast, the Betula Lake focus factor was 0.7 based on a Pb-210 flux rate of 113 Bq/m^2/yr.

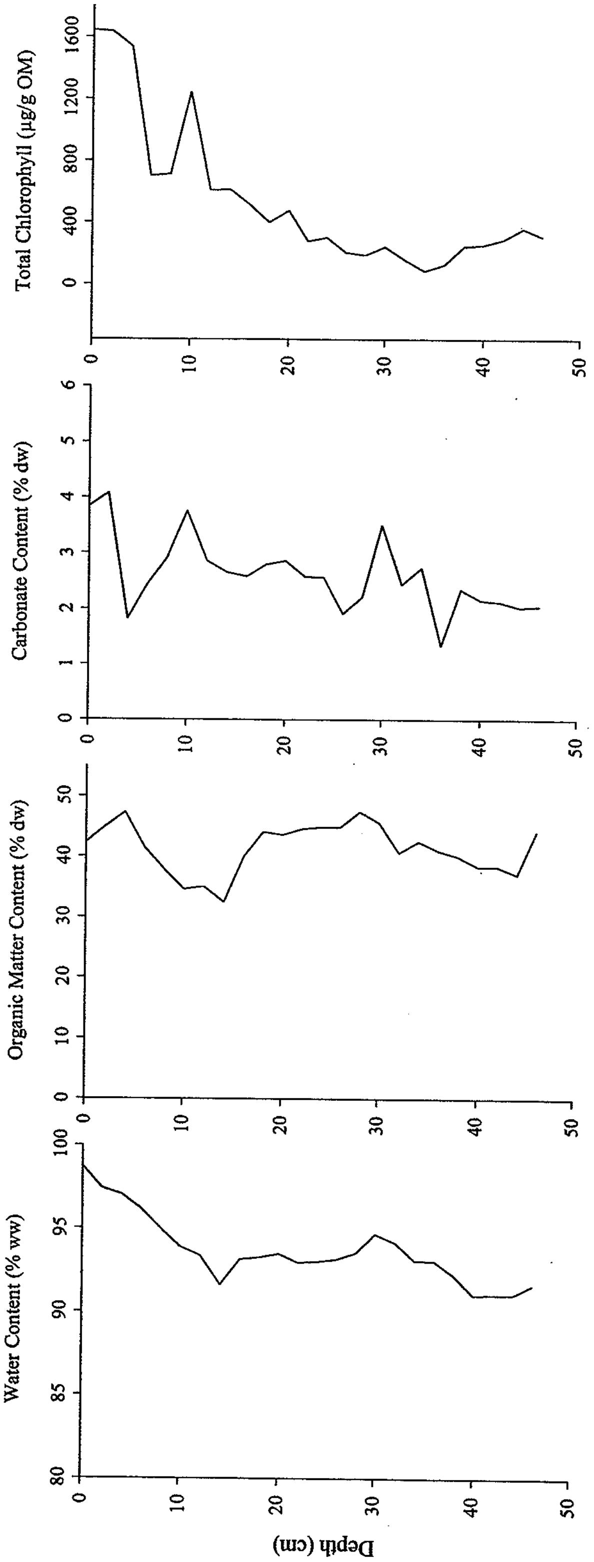

Figure 28: Loss on ignition of bulk sediment composition for Hunt Lake.

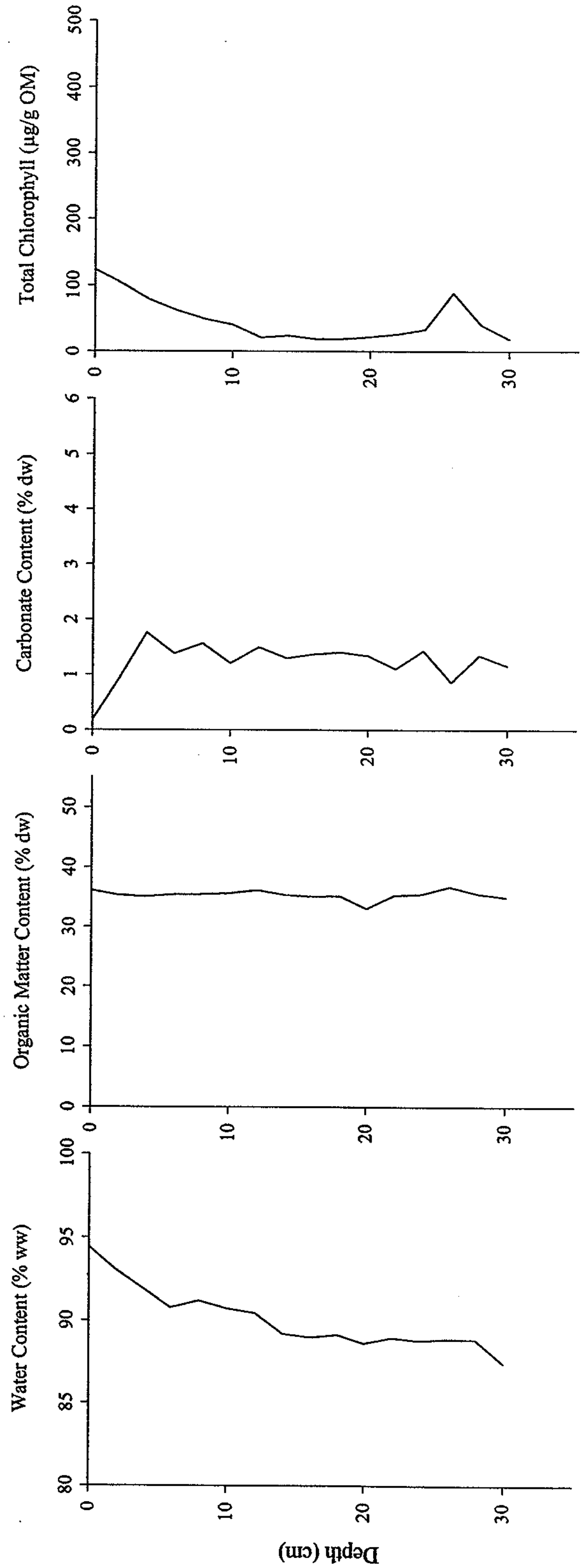

Figure 29: Loss on ignition of bulk sediment composition for Jessica Lake.

Sediment accumulation rates remained relatively constant for the length of the Betula and Madge sediment cores with a sharp increase at the bottom of the core (Figure 36). In contrast, sediment accumulation rate increased up the length of the White Lake sediment core (Figure 36). White Lake presently has a sediment accumulation rate of 329 $g/m^2/yr$ more than twice the rate found in Madge Lake. Betula and White Lake mean constant flux sedimentation rates were 213 $g/m^2/yr$. The Betula Lake mean constant flux sedimentation rate was heavily skewed by a single sedimentation rate of 781 $g/m^2/yr$ at the base of the core. The exclusion of this value decreased the Betula Lake mean constant flux sedimentation rate to 165 $g/m^2/yr$. Madge Lake has the lowest mean constant flux sedimentation rate of 141 $g/m^2/yr$.

4.54 Sediment Geochemistry Introduction

Sediment geochemistry is an effective tool for examining watershed land use histories. Select nutrients and heavy metal concentrations related to anthropogenic disturbance were graphed in concentration versus depth profiles to examine changes through time (Figures 37-47, Appendix). Table 29, provides a summary of sediment core means and ranges for all elements measured. Mean sediment concentrations significantly different from Betula Lake were recorded in Table 30.

4.55 Nutrients

4.55-1 Total Kjeldahl Nitrogen

Sediment concentration profiles of total kjeldahl nitrogen revealed small concentration increases up the core for Betula, Jessica, Red Rock and White Lakes. Profiles for the remaining lakes did not show a distinct trend, with small fluctuations in concentration up the length of the core (Figure 37). The maximum TKN concentration was observed at the top of the Red Rock Lake core with 2.81 % dry weight. Red Rock Lake had the highest mean TKN concentration at 2.56 % dry weight. In contrast, Marion Lake had the lowest TKN concentration of all 13 lakes at the top of the core with a value of < 0.2 % dry weight. Marion Lake also had the lowest mean TKN concentration of 0.09 % dry weight. Marion

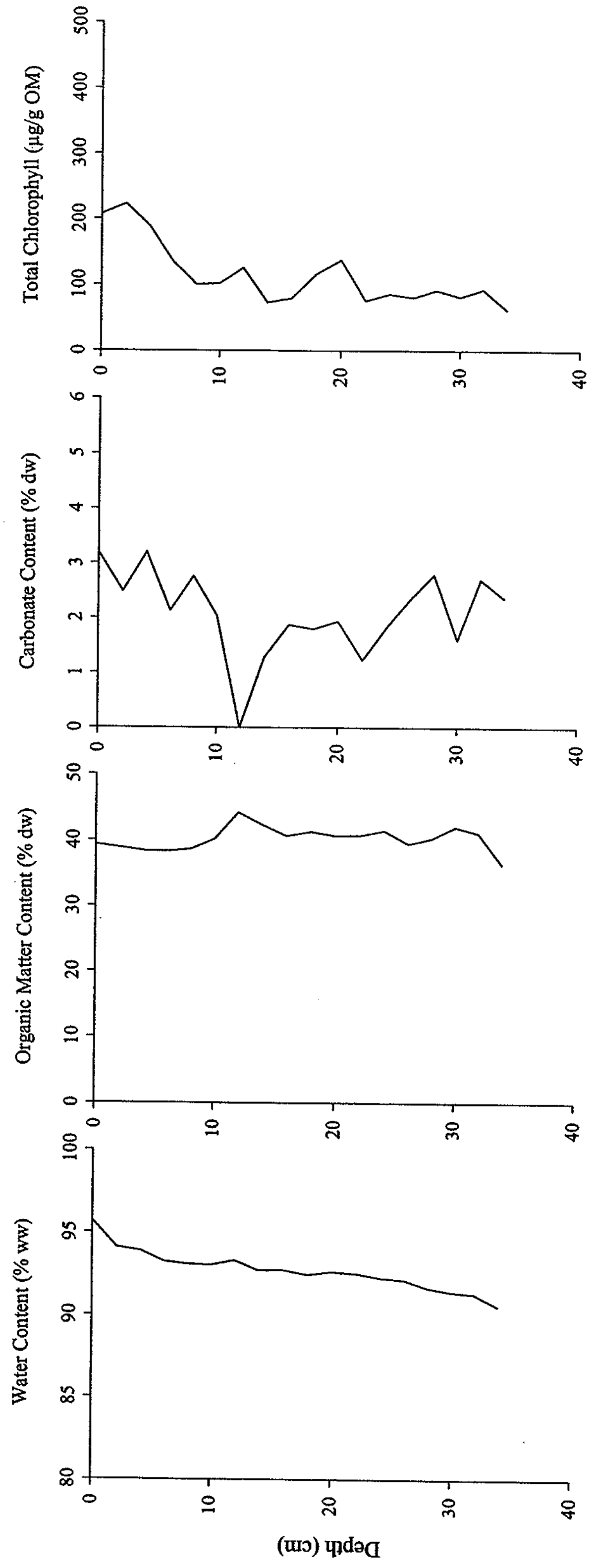

Figure 30: Loss on ignition of bulk sediment composition for Madge Lake.

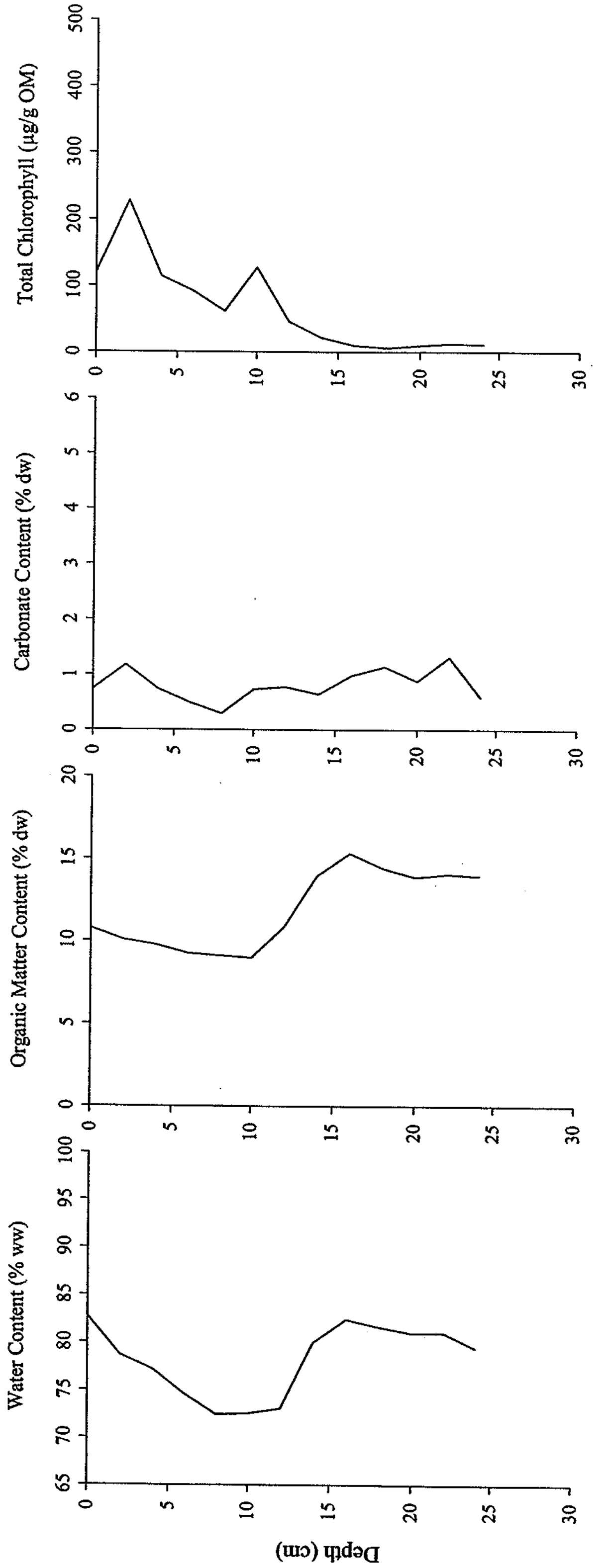

Figure 31: Loss on ignition of bulk sediment composition for Marion Lake.

Lake mean TKN concentration was significantly lower than the Betula Lake mean concentration (Table 30). Betula and White Lakes had the third and fourth highest mean TKN concentration at 1.8 and 1.67 % dry weight respectively.

4.54-2 Phosphorus

Phosphorus concentration profiles showed a generally increased up the sediment core (Figure 38, Table 29). Madge and Marion lakes were the exceptions with relatively constant concentrations down the core and basal peak concentration. Shirley Lake had the highest phosphorus concentration at 10 400 µg/g at the top of the core. Madge had the second highest phosphorus concentration of 9 300 µg/g at the base of the core. The lowest phosphorus concentrations occurred in Jessica and Caddy Lakes with value of 802 and 1180 µg/g. White and Betula had the third and fourth lowest mean phosphorus concentrations respectively. Madge and Shirley Lakes had significantly higher mean phosphorus concentrations than Betula Lake (Table 30).

4.55-3 Iron and Manganese

Seven of the thirteen lakes sampled showed distinct profile correlations between phosphorus, iron and manganese concentrations. Profiles showed an increase in concentrations up the core. In contrast, Madge and Marion Lakes iron and manganese profiles were correlated to each other but not with phosphorus concentrations. Marion Lake phosphorus concentrations peaked the interval below the iron and manganese peak. Red Rock Lake phosphorus concentration fluctuations were best correlated with the iron concentration profile. Florence, Hunt and Star Lake phosphorus concentrations were best correlated with manganese profiles, iron profiles diverged from the general trend upward increasing trend of these profiles.

4.55- 4 Iron

Shirley Lake had the highest concentration of iron at 30 400 µg/g at the top of the core (Figure 39, Table 29). Jessica Lake had the lowest concentration at 9 060 µg/g. The greatest mean iron concentration was 25 166 µg/g for the Brereton Lake core. Jessica Lake had the

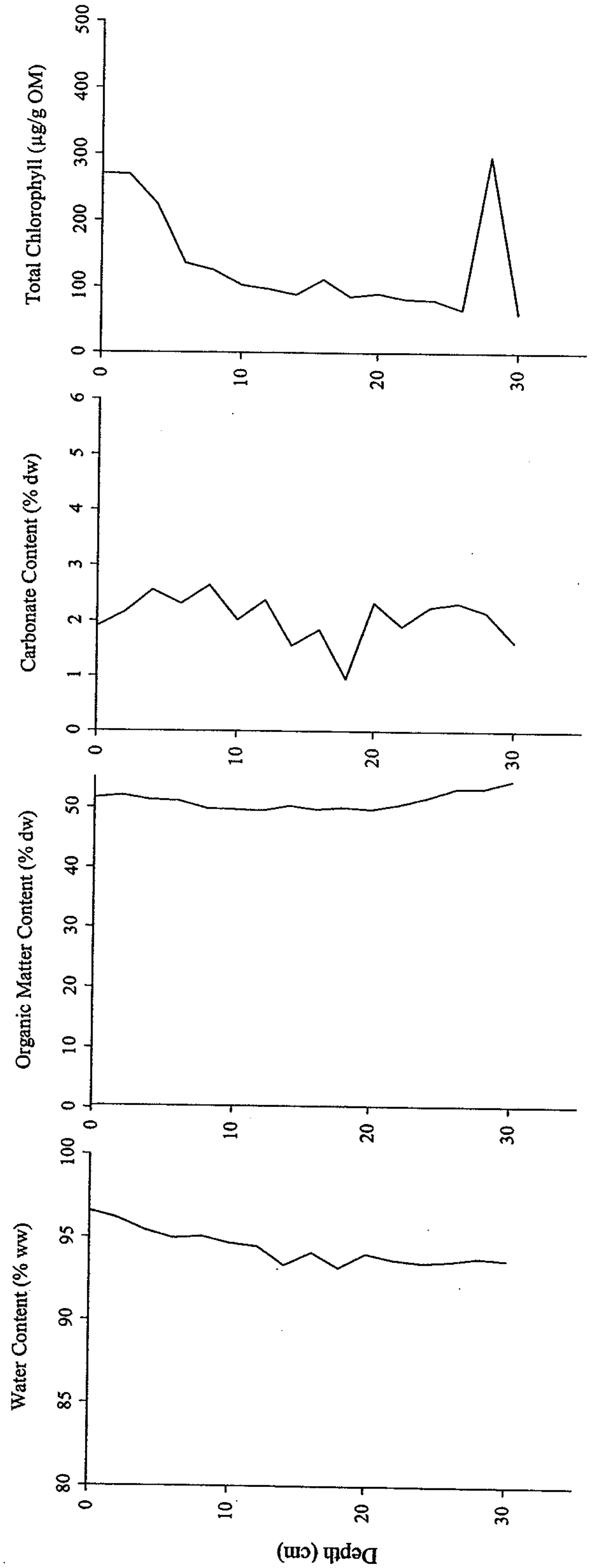

Figure 32: Loss on ignition of bulk sediment composition for Red Rock Lake.

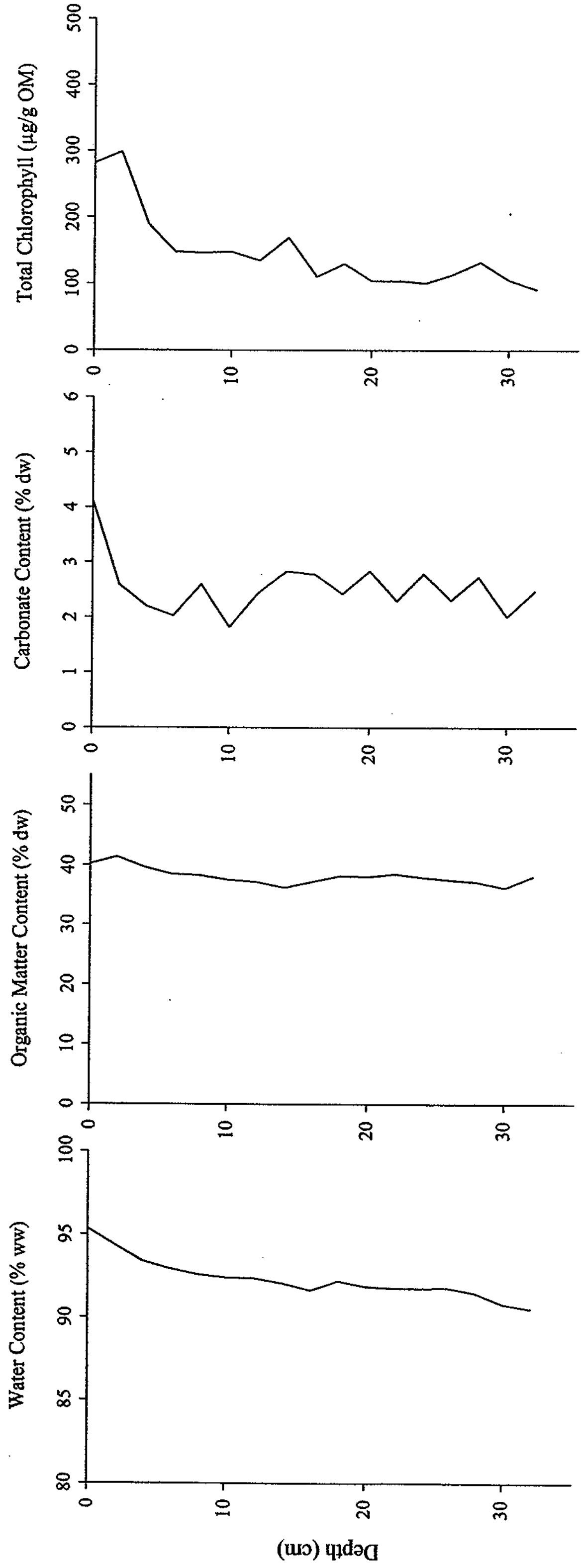

Figure 33: Loss on ignition of bulk sediment composition for Shirley Lake.

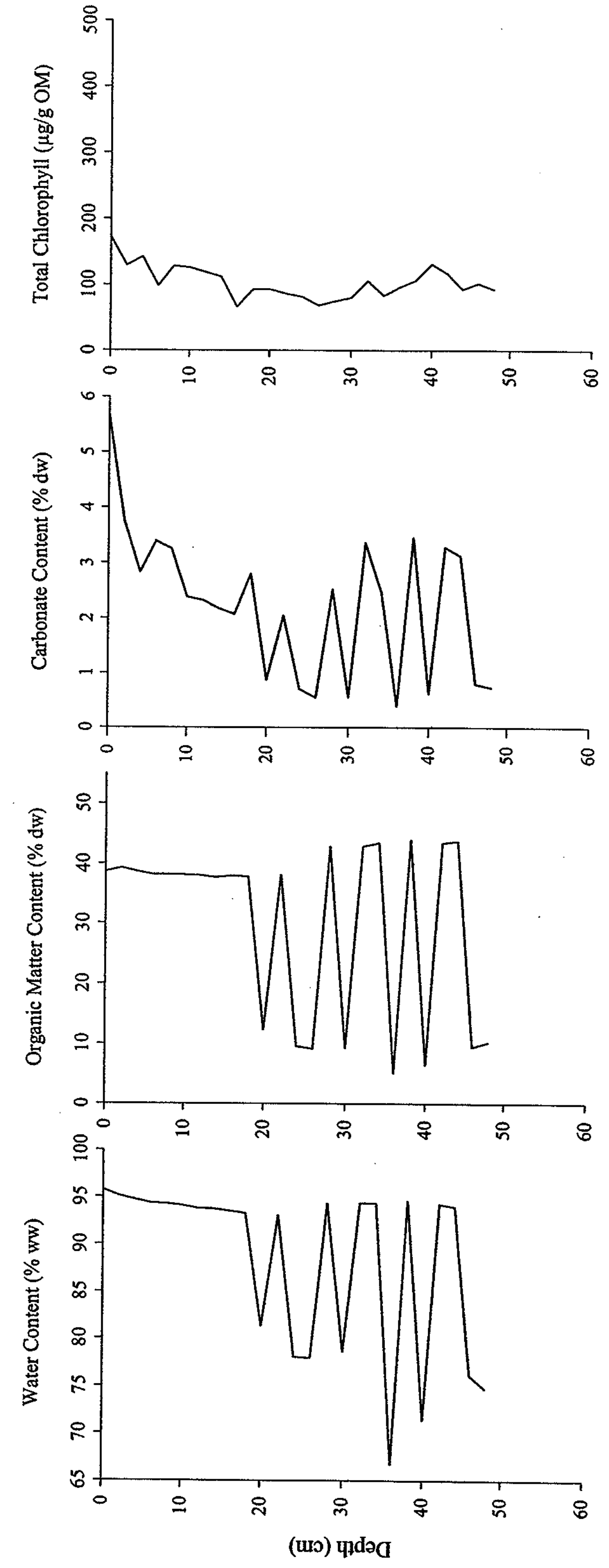

Figure 34: Loss on ignition of bulk sediment composition for Star Lake.

lowest mean iron concentration at 11 423 µg/g. Brereton, Caddy, Hunt, Shirley and Star Lakes all had significantly higher mean iron concentrations than Betula Lake (Table 30).

4.55-5 Manganese

Hunt Lake had the overall and highest mean manganese concentrations at 2 660 and 1 748 µg/g respectively (Figure 40, Table 29). The lowest manganese concentration of 176 µg/g was found in the Marion Lake core. Jessica Lake had the lowest mean manganese concentration of 242 µg/g. Hunt Lake was the only lake with a significantly higher mean manganese concentration than Betula Lake (Table 30).

4.55-6 Available Phosphorus

Maximum available phosphorus concentrations were found at the top of Betula, Caddy, Florence, Hunt, Jessica, Madge and Red Rock Lake cores (Figure 41). Florence Lake had the highest available phosphorus concentration of all cores at 74 µg/g. Caddy, Florence and Jessica Lakes showed a consistent concentration increase up the core to maximal values at the top. In contrast, Betula, Hunt, Madge and Red Rock Lakes concentrations fluctuated up the core to a final maximum peak at the top. Barren, Shirley, Star and White Lakes had available phosphorus concentration profiles that demonstrate a decrease in concentration up the sediment core. The profiles of Shirley, Star and White Lakes all showed maximum concentrations at the second last interval sampled (Figure 41). Florence Lake had the highest mean available phosphorus concentration at 40.1 µg/g. Caddy and Marion Lakes had the lowest mean available phosphorus concentrations at 7.16 and 7.25 µg/g respectively. Florence Lake's mean available phosphorus concentration was significantly higher than Betula Lake (Table 30).

4.55-7 Calcium

Calcium concentrations remained relatively consistent throughout the length of the cores. Only small fluctuations were observed (Figure 42, Table 29). Hunt Lake maintained the highest calcium concentrations throughout the length of the core. In contrast, Marion and Shirley Lakes show considerable fluctuation in calcium concentrations. These two lakes

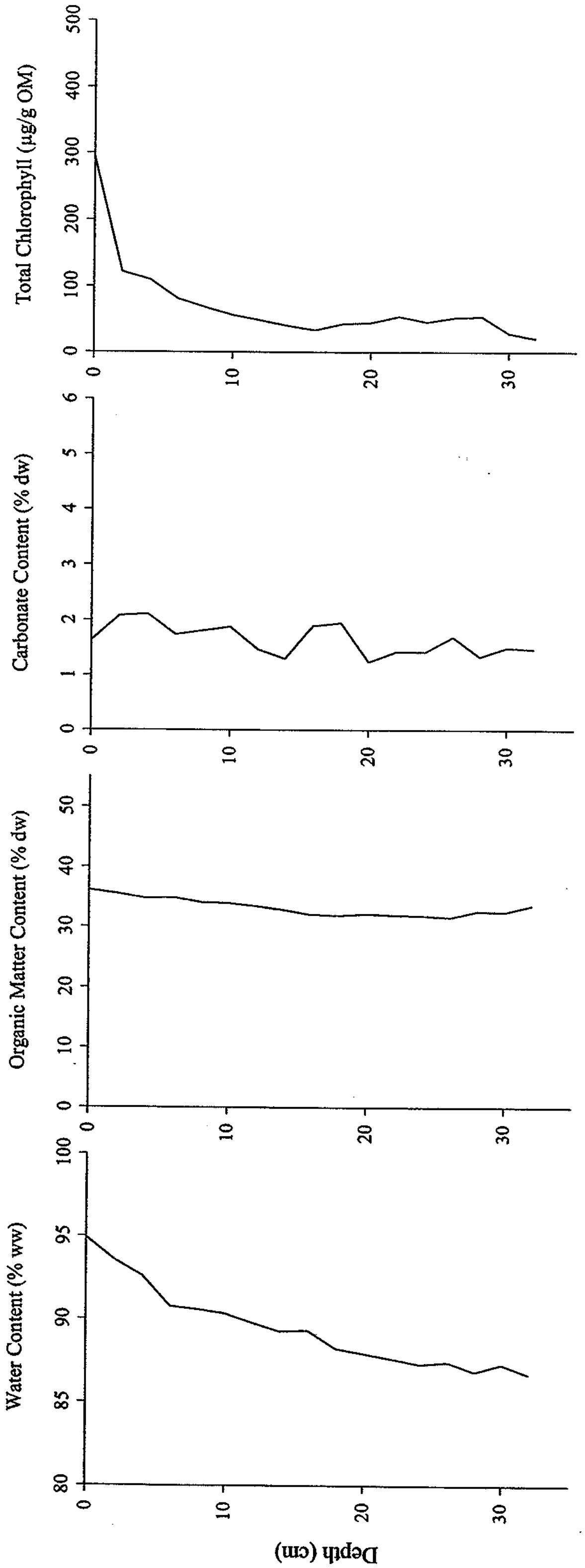

Figure 35: Loss on ignition of bulk sediment composition for White Lake.

Table 25: Sediment chronologies for Betula Lake calculated based on Constant Flux Model. Samples which were not dated are designated by n/a.

Sediment Depth (cm)	Median Year of Deposition	Mean Constant Flux Sedimentation Rate ($g/m^2/yr$)	Years per Sample
0-2	2000	200	4.9
2-4	1994	176	6.9
4-6	1986	199	7.7
6-8	1978	205	8.3
8-10	1969	171	10.3
10-12	1957	134	14.3
12-14	1942	128	15.3
14-16	1926	128	16.4
16-18	1909	116	17.6
18-20	1892	134	16.2
20-22	1875	117	19.4
22-24	1861	282	8.1
24-26	1855	781	3.0
26-28	n/a	n/a	n/a
28-30	n/a	n/a	n/a
30-32	n/a	n/a	n/a

Table 26: Sediment chronologies for White Lake calculated based on Constant Flux Model.

Sediment Depth (cm)	Median Year of Deposition	Mean Constant Flux Sedimentation Rate ($g/m^2/yr$)	Years per Sample
0-2	2001	329	2.2
2-4	1998	278	3.9
4-6	1994	258	4.8
6-8	1989	251	5.3
8-10	1983	240	6.3
10-12	1976	236	6.6
12-14	1969	229	7.2
14-16	1962	233	7.6
16-18	1954	199	9.0
18-20	1945	199	9.3
20-22	1934	185	11.0
22-24	1922	153	13.1
24-26	1908	141	15.6
26-28	1893	140	15.0
28-30	1879	178	11.9
30-32	1868	209	10.9
32-34	1855	154	14.9

Table 27: Sediment chronologies for Madge Lake calculated based on Constant Flux Model. Samples which were not dated are designated by n/a.

Sediment Depth (cm)	Median Year of Deposition	Mean Constant Flux Sedimentation Rate ($g/m^2/yr$)	Years per Sample
0-2	2000	157	6.2
2-4	1993	122	8.4
4-6	1983	104	10.6
6-8	1971	89	14.5
8-10	1957	93	13.6
10-12	1942	92	15.1
12-14	1927	89	15.4
14-16	1913	110	13.2
16-18	1900	124	11.6
18-20	1888	126	12.0
20-22	1878	173	8.9
22-24	1868	150	10.5
24-26	1861	329	4.7
26-28	1855	222	7.3
28-30	n/a	n/a	n/a
30-32	n/a	n/a	n/a
32-34	n/a	n/a	n/a
34-36	n/a	n/a	n/a

Table 28: Sediment chronology summary for Betula,White and Madge Lakes.

Lake	Constant Flux Sedimentation Range (g/m^2/yr)	Mean Sedimentation Rate (g/m^2/yr)	Pb-210 Flux (Bq/m^2/yr)	Focus Factor
Betula	116 - 781	213	113	0.7
White	140 - 329	213	176	1
Madge	89 - 329	141	175	1

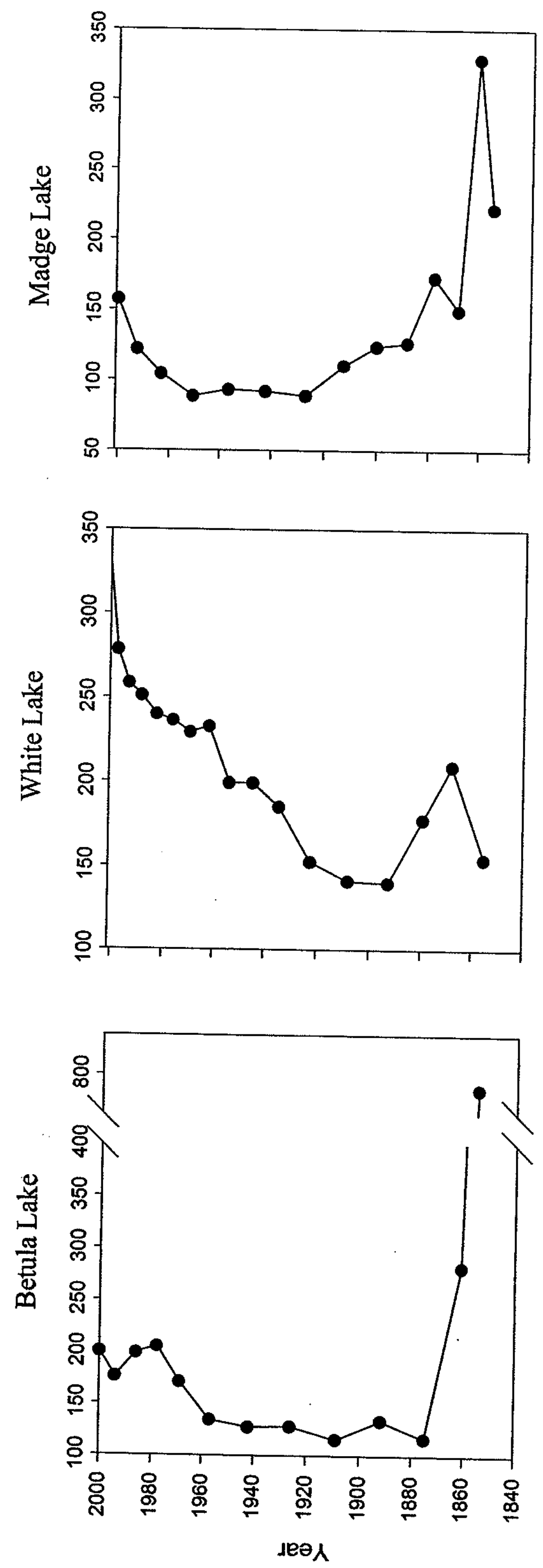

Figure 36: Sediment accumulation rates (g/m^2/yr) for three Whiteshell sediment cores over 150 years of deposition.

maintain relatively low concentrations of calcium with distinct large concentration peaks within the core. The Marion Lake profile demonstrated three distinct peaks towards the base of the core at 10, 15 and 25 cm in depth. Shirley Lake only experienced one large peak concentration in the middle of the core at 10 cm. Betula and White Lakes had relatively low mean calcium concentrations (Table 29). Betula Lake's mean calcium concentration was not significantly different from other Whiteshell lakes sampled (Table 30).

4.55-8 Boron

Betula Lake had the highest boron concentration of 46 μg/g at the top of the core. White and Jessica Lakes followed closely with maximum concentrations of 44 and 42 μg/g respectively (Figure 43, Table 29). In contrast, the lowest boron concentrations were < 1 μg/g in Marion and Shirley Lakes. Boron concentrations remained relatively constant with small concentration increases at the top of the cores. White Lake was the only lake which did not have a significantly lower mean boron concentration than Betula Lake.

4.56 Non-essential heavy metals

4.56-1 Arsenic

Hunt Lake had the highest arsenic concentration of 18.8 μg/g (Table 29). Barren, Brereton, Hunt and Star Lakes all had minimum concentration values greater than 5.9 μg/g. Hunt and Star Lakes had the highest mean arsenic concentrations of 15.95 and 12.29 μg/g respectively. Madge Lake had the lowest mean arsenic concentration at 2.7 μg/g. Jessica and Madge profiles showed an increase in arsenic concentrations up the core. Florence Lake also presented an increase in arsenic up the core with a mid depth peak and subsequent decrease (Figure 44). In contrast, the Marion Lake profile showed a decrease in arsenic concentration up the core. The remaining lakes appeared to experience small fluctuations. They remained relatively constant throughout the core. Barren, Hunt, and Star Lakes had significantly higher mean arsenic concentrations than Betula Lake (Table 30).

Table 29A: Macronutient mean (minimum and maximum) concentrations (μg/g) for 13 Whiteshell sediment cores.

Lake	Calcium Ca	Magnesium Mg	Phosphorus PO_4
Barren	6513.33 (5040.00 - 7140.00)	2074.44 (1490.00 - 2350.00)	2575.56 (2120.00 - 3090.00)
Brereton	3610.00 (3360.00 - 3790.00)	1853.33 (1730.00 - 1950.00)	2516.67 (2130.00 - 2950.00)
Betula	4800.00 (4090.00 - 5100.00)	2360.00 (2240.00 - 2470.00)	1815.00 (1270.00 - 3190.00)
Caddy	7126.00 (6750.00 - 7850.00)	4648.00 (4170.00 - 5290.00)	1424.00 (1180.00 - 1820.00)
Florence	5004.44 (4680.00 - 5290.00)	1892.22 (1750.00 - 2050.00)	3475.56 (2560.00 - 4880.00)
Hunt	11625.00 (10800.00 -12400.00)	2580.00 (1960.00 - 3090.00)	2025.00 (1630.00 - 3670.00)
Jessica	3623.33 (3040.00 - 4250.00)	2303.33 (1980.00 - 2580.00)	1357.17 (802.00 - 2190.00)
Madge	3834.29 (3100.00 - 4580.00)	1672.86 (1310.00 - 2080.00)	4471.43 (2870.00 - 9300.00)
Marion	11945.00 (1920.00 - 25500.00)	10688.33 (1410.00 - 23700.00)	3461.67 (2380.00 - 7910.00)
Red Rock	4420.00 (4200.00 - 4760.00)	1348.33 (1250.00 - 1440.00)	2688.33 (2350.00 - 3650.00)
Shirley	7496.67 (3570.00 - 26100.00)	5833.33 (2180.00 - 23000.00)	7981.67 (2610.00 - 10400.00)
Star	5948.75 (5190.00 - 6250.00)	1796.25 (1470.00 - 2050.00)	2657.50 (2030.00 - 3180.00)
White	4270.00 (4140.00 - 4530.00)	2400.00 (2310.00 - 2460.00)	1773.33 (1310.00 - 2440.00)

Table 29B: Macronutient mean (minimum and maximum) concentrations (μg/g) for 13 Whiteshell sediment cores.

Lake	Available Phosphorus P	Potassium K	Total Kjeldahl Nitrogen N
Barren	13.67 (11.00 - 18.20)	1019.89 (761.00 - 1210.00)	1.40 (1.23 - 1.61)
Brereton	13.00 (10.00 - 17.00)	858.33 (790.00 - 931.00)	1.56 (1.43 - 1.67)
Betula	18.17 (7.00 - 42.00)	1050.83 (971.00 - 1280.00)	1.80 (1.63 - 2.02)
Caddy	7.16 (4.60 - 11.90)	2182.00 (1860.00 - 2460.00)	0.65 (0.51 - 0.80)
Florence	40.10 (15.5 - 74.00)	1233.89 (866.00 - 1710.00)	1.93 (1.49 - 2.52)
Hunt	11.03 (5.40 - 30.10)	1370.00 (1020.00 - 1600.00)	1.48 (1.25 - 1.80)
Jessica	13.50 (7.00 - 24.00)	899.33 (745.00 - 1070.00)	1.37 (1.22 - 1.76)
Madge	20.74 (13.70 - 31.40)	897.14 (650.00 - 1130.00)	1.64 (1.33 - 1.91)
Marion	7.25 (5.30 - 10.30)	2142.83 (743.00 - 4160.00)	0.09 (<0.02 - 0.16)
Red Rock	35.50 (22.00 - 52.00)	703.83 (537.00 - 878.00)	2.56 (2.48 - 2.81)
Shirley	12.82 (10.60 - 15.50)	1665.00 (1040.00 - 3650.00)	1.30 (1.19 - 1.44)
Star	14.14 (9.90 - 20.20)	943.38 (740.00 - 1170.00)	1.66 (1.49 - 1.84)

Table 29C: Micronutient mean (minimum and maximum) concentrations (μg/g) for 13 Whiteshell sediment cores.

Lake	Boron B	Cobalt Co	Copper Cu	Iron Fe
Barren	5.00 (4.00 - 6.00)	14.33 (11 - 18)	52.11 (40 - 59)	14366.67 (11100.00 - 19500.00)
Brereton	34.67 (32.00 - 38.00)	8.33 (7.00 - 10.00)	11.67 (11.00 - 12.00)	25166.67 (22100.00 - 29500.00)
Betula	43.00 (37.00 - 46.00)	4.33 (3.00 - 5.00)	13.67 (12.00 - 15.00)	14133.33 (11700.00 - 16400.00)
Caddy	6.80 (6.00 - 7.00)	13.80 (13.00 - 15.00)	27.40 (26.00 - 30.00)	22880.00 (18700.00 - 27700.00)
Florence	9.44 (7.00 - 11.00)	8.67 (7.00 - 10.00)	31.89 (29.00 - 34.00)	13988.89 (13100.00 - 15300.00)
Hunt	9.00 (8.00 - 10.00)	15.25 (12.00 - 20.00)	73.25 (50.00 - 87.00)	24925.00 (19200.00 - 29700.00)
Jessica	37.00 (31.00 - 42.00)	3.33 (3.00 - 4.00)	9.67 (8.00 - 11.00)	11423.33 (9060.00 - 15500.00)
Madge	5.57 (< 1.00 - 7.00)	8.86 (8.00 - 11.00)	19.00 (16.00 - 22.00)	12728.57 (11100.00 - 14300.00)
Marion	< 1	9.17 (5.00 - 13.00)	19.50 (6.00 - 32.00)	17970.00 (7920.00 - 27800.00)
Red Rock	32.67 (31.00 - 35.00)	2.50 (2.00 - 3.00)	11.83 (11.00 - 13.00)	19200.00 (16800.00 - 22900.00)
Shirley	< 1	11.17 (10.00 - 12.00)	25.17 (23.00 - 32.00)	24866.67 (21500.00 - 30400.00)
Star	7.13 (6.00 - 8.00)	18.38 (14.00 - 22.00)	48.50 (42.00 - 52.00)	22737.50 (18500.00 - 25000.00)
White	41.67 (39.00 - 44.00)	4.50 (4.00 - 5.00)	13.00 (13.00 - 13.00)	14733.33 (13000.00 - 17700.00)

Table 29D: Micronutient mean (minimum and maximum) concentrations (μg/g) for 13 Whiteshell sediment cores.

Lakes	Manganese Mn	Nickel Ni	Selenium Se	Vanadium V	Zinc Zn
Barren	397.44 (314.00 - 606.00)	36.22 (27 - 41)	2.67 (2.00 - 3.30)	31.22 (23.00 - 35.00)	92.00 (71.00 - 101.00)
Brereton	402.67 (348.00 - 498.00)	25.33 (23.00 - 27.00)	1.10 (1.00 - 1.20)	27.67 (26.00 - 29.00)	158.33 (149.00 - 167.00)
Betula	273.83 (233.00 - 314.00)	22.50 (19.00 - 25.00)	0.82 (0.7 - 0.9)	23.5 (20.00 - 25.00)	59.00 (53.00 - 65.00)
Caddy	417.80 (299.00 - 580.00)	33.60 (32.00 - 36.00)	1.42 (1.30 - 1.60)	43.00 (39.00 - 48.00)	105.20 (98.00 - 119.00)
Florence	40.22 (306.00 - 404.00)	24.44 (20.00 - 29.00)	3.11 (2.70 - 3.40)	22.67 (19.00 - 25.00)	66.67 (50.00 - 87.00)
Hunt	1748.75 (1350.00 - 2660	51.38 (37.00 - 62.00)	3.39 (2.60 - 3.80)	35.75 (23.00 - 45.00)	98.38 (82.00 - 126.00)
Jessica	242.67 (160.00 - 419.00)	17.33 (15.00 - 20.00)	0.72 (0.60 - 0.90)	19.17 (17.00 - 22.00)	52.00 (43.00 - 59.00)
Madge	428.29 (333.00 - 506.00)	17.71 (15.00 - 20.00)	2.53 (2.10 - 2.80)	23.57 (20.00 - 27.00)	63.00 (49.00 - 77.00)
Marion	380.00 (176.00 - 566.00)	22.17 (9.00 - 33.00)	0.93 (0.40 - 2.50)	30.67 (11.00 - 51.00)	61.83 (24.00 - 126.00)
Red Rock	271.67 (231.00 - 403.00)	15.33 (14.00 - 17.00)	1.23 (1.00 -1.40)	19.17 (17.00 - 21.00)	65.50 (61.00 - 74.00)
Shirley	467.50 (364.00 - 585.00)	23.00 (18.00 - 36.00)	2.17 (0.70 - 2.60)	38.50 (35.00 - 49.00)	116.17 (73.00 - 129.00)
Star	528.63 (364.00 - 796.00)	47.75 (42.00 - 52.00)	2.64 (2.20 - 2.80)	27.25 (23.00 - 29.00)	96.00 (75.00 - 108.00)
White	259.17 (227.00 - 308.00)	22.50 (21.00 -25.00)	0.88 (0.8 - 0.9)	22.17 (21.00 - 23.00)	64.00 (62.00 - 67.00)

Table 29E: Non-essential heavy metal mean (minimum and maximum) concentrations (μg/g) for 13 Whiteshell sediment cores.

Lake	Aluminum Al	Arsenic As	Cadmium Cd	Lead Pb	Mercury Hg
Barren	11970.00 (9030.00 - 13500)	9.54 (8.20 -11.50)	0.44 (0.3 - 0.6)	16.42 (6.9 - 31.8)	0.10 (0.08 - 0.15)
Brereton	11900.00 (10200.00 - 12900.00)	8.83 (7.8 - 9.6)	0.70 (0.60 - 0.80)	15.67 (7.00 - 24.00)	0.19 (0.13 - 0.31)
Betula	7560.00 (7220.00 - 8050.00)	5.15 (3.50 - 6.40)	0.32 (<0.4 - 0.5)	16.00 (8.00 - 23.00)	0.09 (0.04 - 0.12)
Caddy	16400.00 (15700.00 - 17900.00)	3.68 (3.00 4.10)	0.48 (0.40 - 0.50)	27.18 (14.80 - 39.30)	0.10 (0.07 - 0.12)
Florence	8227.78 (6590.00 - 9750.00)	4.48 (1.50 - 6.60)	0.58 (0.20 - 0.90)	32.96 (6.80 - 58.4)	0.10 (0.06 - 0.14)
Hunt	7153.75 (4680.00 - 8330.00)	15.95 (12.70 - 18.80)	0.53 (0.30 -1.00)	27.44 (7.4 - 69.5)	0.11 (0.05 - 0.19)
Jessica	7183.33 (6070.00 - 8340.00)	3.88 (2.60 - 5.00)	0.17 (<0.40 - 0.50)	9.33 (<5.00 - 16.00)	0.08 (0.03 - 0.13)
Madge	11622.86 (9370.00 - 14400.00)	2.70 (1.30 - 4.20)	0.44 (0.20 - 0.80)	20.37 (4.40 - 47.9)	0.10 (0.04 - 0.20)
Marion	12421.67 (4120.00 - 19700.00)	4.02 (1.30 - 7.40)	0.40 (0.20 -0.90)	13.22 (5.90 - 33.90)	0.05 (0.02 - 0.17)
Red Rock	6121.67 (5810.00 - 6300.00)	6.65 (2.20 - 8.10)	0.57 (< 0.40 - 0.80)	24.67 (6.00 - 36.00)	0.09 (0.04 - 0.14)
Shirley	18266.67 (17200.00 - 19100.00)	5.12 (2.20 - 6.90)	0.65 (0.40 - 0.90)	21.32 (8.60 - 36.90)	0.13 (0.03 - 0.21)
Star	8882.50 (7130.00 - 10400.00)	12.29 (10.2 - 14.6)	0.50 (0.30 - 0.80)	23.11 (4.90 - 56.60)	0.14 (0.07 - 0.31)
White	8540.00 (7940.00 - 8890.00)	5.50 (4.50 - 6.20)	0.47 (< 0.4 -0.6)	14.67 (8.00 - 20.00)	0.12 (0.07 - 0.15)

Table 29F: Element mean (minimum and maximum) concentrations (μg/g) for 13 Whiteshell sediment cores.

Lake	Barium Ba	Chromium Cr	Sodium Na	Strontium Sr
Barren	128.56 (97 - 146)	30.11 (23 - 34)	104.44 (80 - 123)	18.78 (15.00 - 21.00)
Brereton	116.67 (90.00 - 137.00)	32.00 (30.00 - 35.00)	56.67 (52.00 - 61.00)	16.33 (16.00 - 17.00)
Betula	70.50 (61.00 - 83.00)	21.17 (19.00 - 23.00)	72.67 (59.00 - 96.00)	15.33 (15.00 - 16.00)
Caddy	183.60 (169.00 - 210.00)	37.00 (35.00 - 41.00)	127.20 (115.00 - 143.00)	27.40 (26.00 - 30.00)
Florence	93.56 (86.00 - 109.00)	22.11 (18.00 - 25.00)	93.56 (86.00 - 103.00)	18.11 (16.00 - 20.00)
Hunt	139.00 (112.00 - 170.00)	20.88 (14.00 - 27.00)	520.50 (304.00 - 1000.00)	19.13 (17.00 - 21.00)
Jessica	58.50 (45.00 - 78.00)	18.33 (16.00 - 21.00)	63.33 (46.00 - 89.00)	15.00 (12.00 - 18.00)
Madge	134.29 (115.00 -159.00)	21.57 (18.00 - 24.00)	61.14 (42.00 -95.00)	17.71 (15.00 - 22.00)
Marion	87.50 (29.00 - 137.00)	25.83 (10.00 - 42.00)	156.83 (82.00 - 264.00)	17.67 (7.00 - 29.00)
Red Rock	61.33 (51.00 - 82.00)	17.33 (16.00 - 19.00)	103.83(84.00 - 143.00)	15.50 (14.00 - 18.00))
Shirley	133.50 (125.00 - 147.00)	31.50 (28.00 - 40.00)	117.17 (77.00 - 247.00)	20.17 (18.00 - 29.00)
Star	94.00 (77.00 - 126.00)	28.50 (24.00 - 30.00)	81.75 (70.00 - 90.00)	17.88 (16.00 - 19.00)
White	72.83 (63.00 - 85.00)	21.83 (21.00 - 23.00)	67.00 (60.00 - 81.00)	15.17 (14.00 - 16.00)

Table 30: Summary of the total number of mean macronutrient, micronutrient, heavy metal and element concentrations for 12 Whiteshell lakes which are significantly different from Betula Lake sediment.

Lake	Macro-nutrients	Micro-nutrients	Heavy Metals	Other	Total
Barren	0	6	2	2	10
Brereton	0	3	0	1	4
Caddy	1	6	1	3	11
Florence	1	3	0	0	4
Hunt	0	9	1	3	13
Jessica	0	1	0	0	1
Madge	1	2	1	1	5
Marion	3	2	1	1	7
Red Rock	0	1	0	0	1
Shirley	1	5	1	2	9
Star	0	7	1	0	8
White	0	0	0	0	0

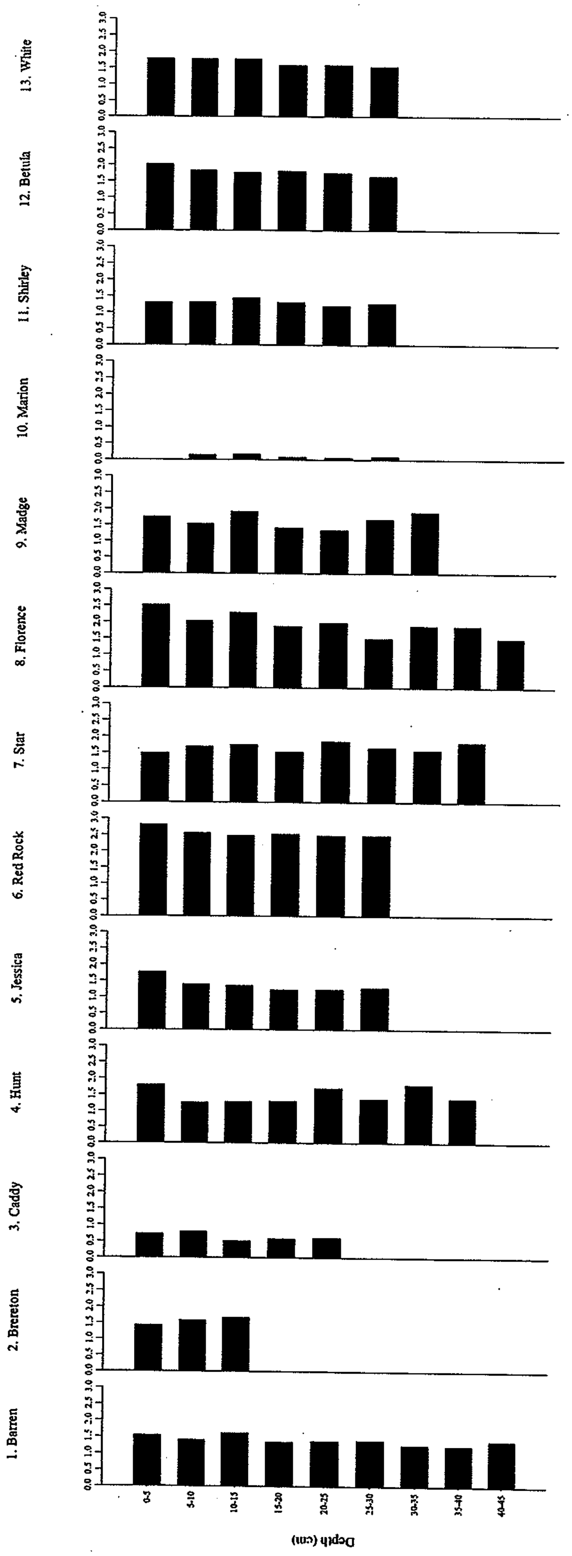

Figure 37: Sediment total Kjeldahl nitrogen concentration (% sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

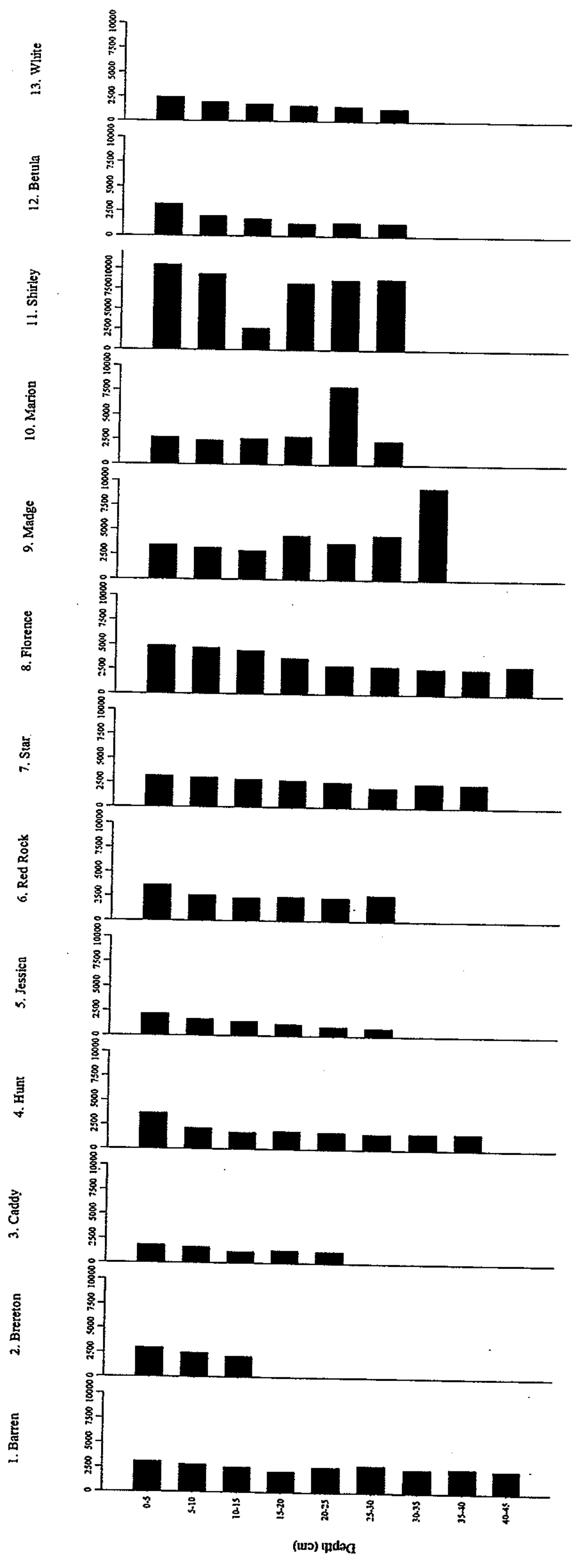

Figure 38: Sediment phosphorus concentration (% sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

4.56-2 Cadmium

Hunt Lake had the highest cadmium concentration of 1 µg/g (Table 29). Brereton, Florence, Hunt, Madge, Marion, Red Rock, Shirley, and Star Lakes all had maximum concentrations greater than 0.6 µg/g. Brereton Lake had the highest mean cadmium concentration at 0.7 µg/g. Jessica Lake had the lowest mean cadmium concentration at 0.17 µg/g. The majority of cores showed an increase in cadmium concentration up the core with a sub-surface peak (Figure 45). Marion Lake was the exception with a basal cadmium peak and decreasing concentrations up the core. Betula Lake's mean cadmium concentration was not significantly different from other Whiteshell lakes examined.

4.56-3 Lead

Hunt Lake had the highest lead concentration at 69.5 µg/g (Table 29). Barren, Caddy, Florence, Hunt, Madge, Red Rock, Shirley, and Star Lakes all had maximum concentrations greater than 35 µg/g. Florence Lake with 32.96 µg/g had the highest mean lead concentration. Jessica Lake had the lowest lead concentration and mean lead concentration of < 5 and 9.33 µg/g respectively. Lead profiles for all lakes were very similar in shape to cadmium profiles (Figure 46). The mean lead concentration for Betula Lake was not significantly different from other 12 lakes examined.

4.56-4 Mercury

Brereton and Star Lakes had the highest mercury concentration with 0.31 µg/g at the top of both cores. Brereton had the highest mean mercury concentration at 0.19 µg/g. Marion Lake had the lowest mercury concentration and mean mercury concentration of 0.02 and 0.05 µg/g respectively. Mercury concentration profiles showed a concentration increases up the core to a maximum concentration at the surface (Figure 47). Marion Lake was the exception with a basal peak and decreasing concentrations towards the top of the core. Fluctuations in mercury concentrations appeared to be correlated with fluctuations in the cadmium and lead profiles for the respective lakes (Figures 45 & 46).

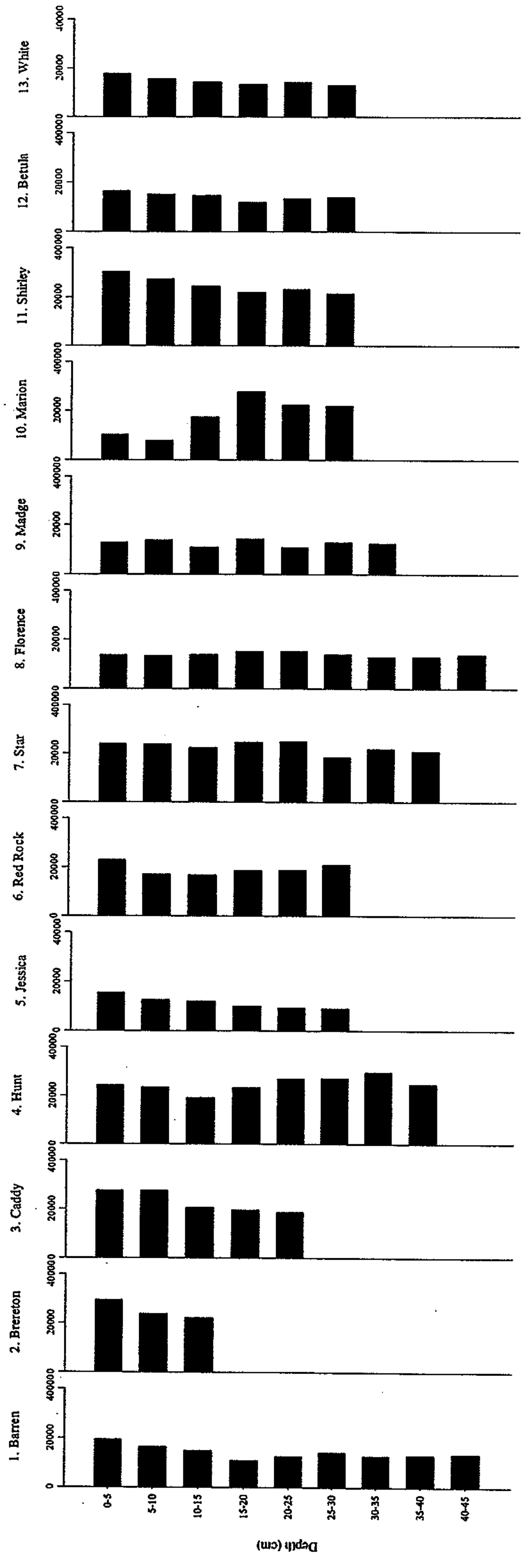

Figure 39: Sediment iron concentration (µg/g sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

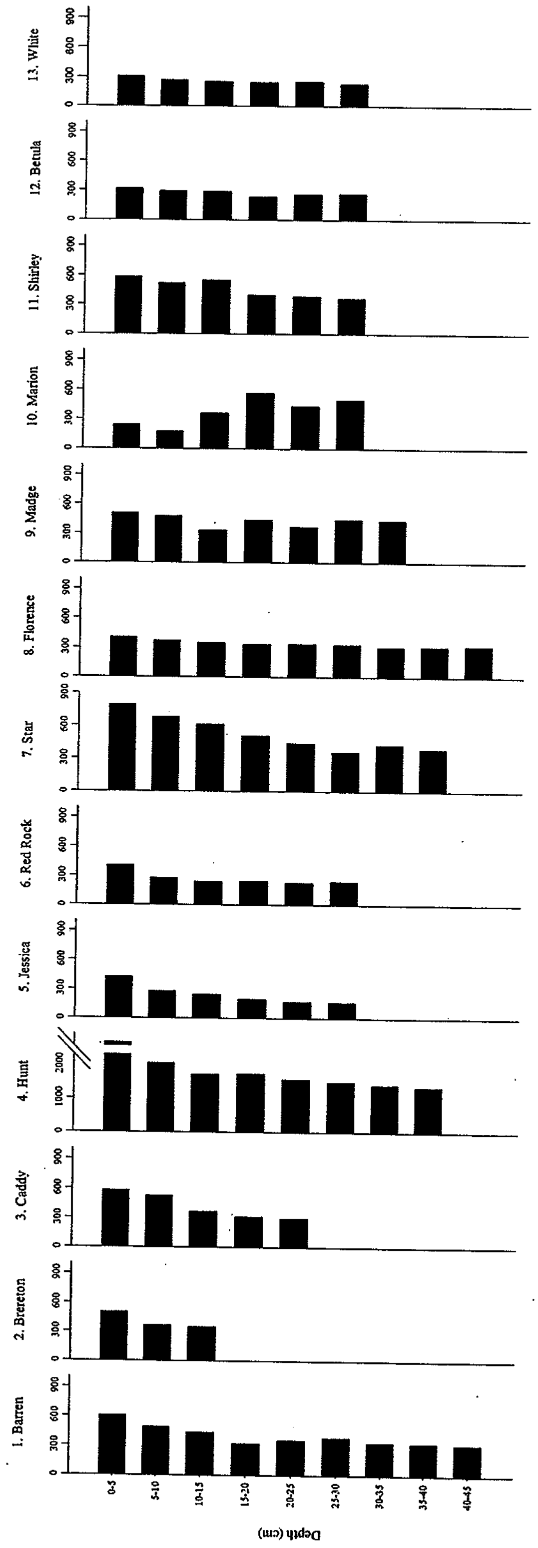

Figure 40: Sediment manganese concentration (μg/g sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

The concentration, range and significance of other elements analyzed have been summarized in Tables 30A-30F. The concentration of these elements remained relatively constant throughout the length of the core (Appendix).

4.6 Results Summary

- *L. wollei* infestations were found only in Betula and White Lakes.
- Infestations occurred in areas under intense land use where resorts, cottages, campgrounds, and boat launches were located.
- Infestation dry biomass ranged from 29 - 642 g/m^2.
- *L. wollei* maintained oxygen production after 5 days in stagnant water conditions under moderate and high temperature regimes.
- *L. wollei* produced 2 μg O_2/mg DW after 2 days of drying under moderate temperatures.
- Brereton, Caddy, and Big Whiteshell Lakes were most similar to the infested lakes based on intensity of land use parameters, whereas Brereton, Big Whiteshell and Jessica were most similar to the infested lakes based on lake morphology.
- Jessica and Red Rock Lakes were the most similar to the infested lakes based on water chemistry parameters, whereas Jessica, Red Rock, Madge and Florence Lakes were the most similar to the infested lakes based on sediment chemistry.
- All Whiteshell lakes examined maintain sedimentary organic matter concentrations at 30-50 % DW with the exception of Caddy, Marion and Star Lakes.
- Hunt, Star and Marion sediment profiles showed corresponding fluctuations in water and organic matter content.
- Hunt, Florence and Betula Lakes had the highest total chlorophyll concentrations under current sediment conditions. All lakes had the highest total chlorophyll concentration at the top of the core with the exception of Red Rock Lake.
- Betula, White and Madge Lake sediment cores 28-36 cm in length were dated using ^{210}Pb and ^{137}Cs and recorded over 150 years of depositional activity.
- Betula and White Lakes had substantially higher boron concentrations than the other Whiteshell lakes examined.

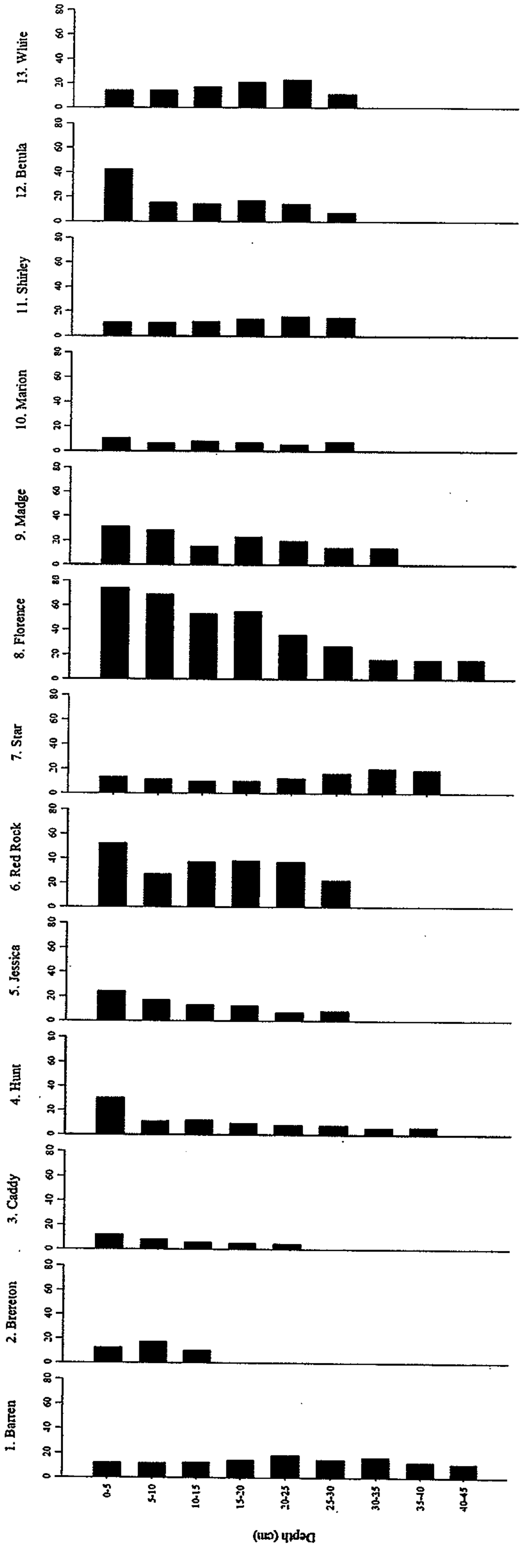

Figure 41: Sediment available phosphorus concentration (µg/g sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

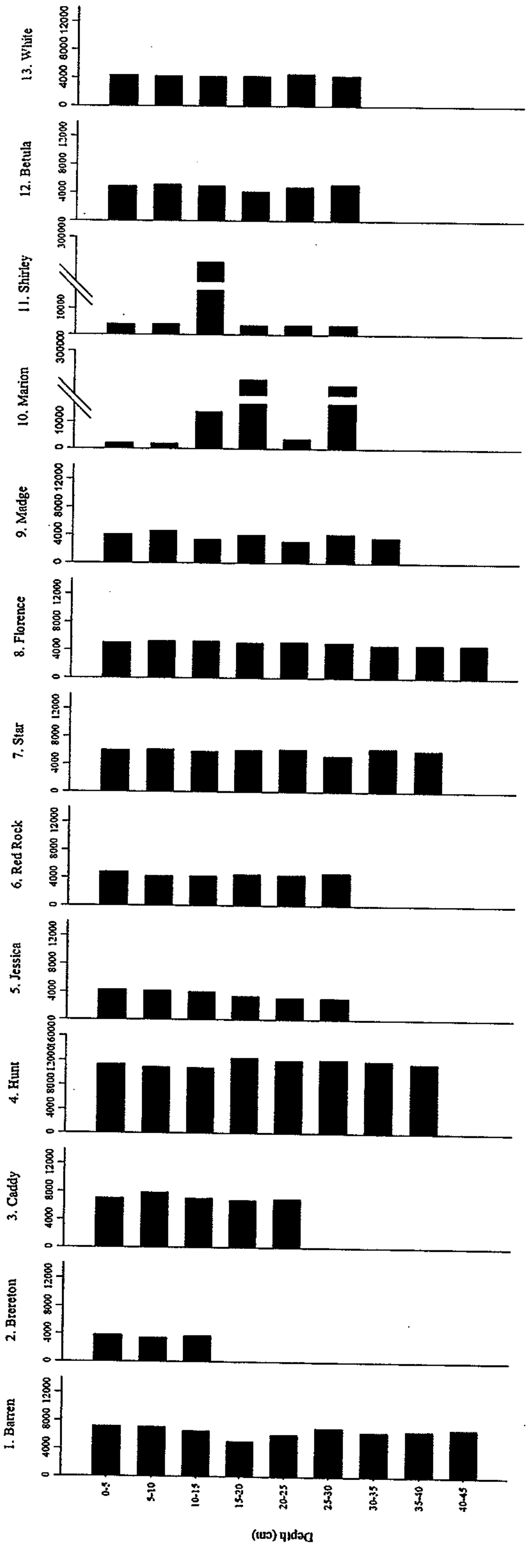

Figure 42: Sediment calcium concentration (µg/g sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

Chapter 5: Discussion

5.1 Objective 1

The primary objective of this study was to examine the distribution and inoculation source of *L. wollei* in Whiteshell Provincial Park.

5.11 *Lyngbya wollei* Distribution

The results suggest, it is unlikely that the Whiteshell River system was the source of *L. wollei* transportation and inoculation. *L. wollei* distribution appears to be unrelated to the location of the Whiteshell River inflow and outflow sources. White Lake flows into Betula Lake via the Whiteshell River. In White Lake the *L. wollei* infestation is located in the north–eastern bay adjacent to the Whiteshell River inflow. *L. wollei* was not found to occur near the White Lake outflow. In Betula Lake, *L. wollei* was found across the lake from the Whiteshell River inflow and outflow in the south-western bay.

Infested basins in Betula and White Lakes had similar morphology and light regimes, yet the Betula Lake infestation was substantially more established than the White Lake infestation. In Betula Lake *L. wollei* maintained a constant biomass and appeared to form a continuous mat along the lake bottom from Block 1 to 4. The Betula Lake infestation had a substantial impact on recreational users, with large amounts of *L. wollei* biomass observed washed up on the beach and floating in the water. In contrast, the White Lake infestation had a patchy distribution. *L. wollei* growth was extremely dense in select areas around the campground but did not form a continuous mat over the entire bay. Along Blocks 1, 2 and 3 *L. wollei* collected had formed small clumps mixed with a large amount of sediment. It is unknown whether these samples were retrieved from the sediment surface or from within the sediment. The beach had minimal *L. wollei* growth and mats were not readily observed. As a result, the patchy White Lake infestation had minimal impact on recreational users.

L. wollei infestations may be the result of anthropogenic activities. *L. wollei* distribution was best correlated with intensity of land use. Betula and White Lake shoreline development

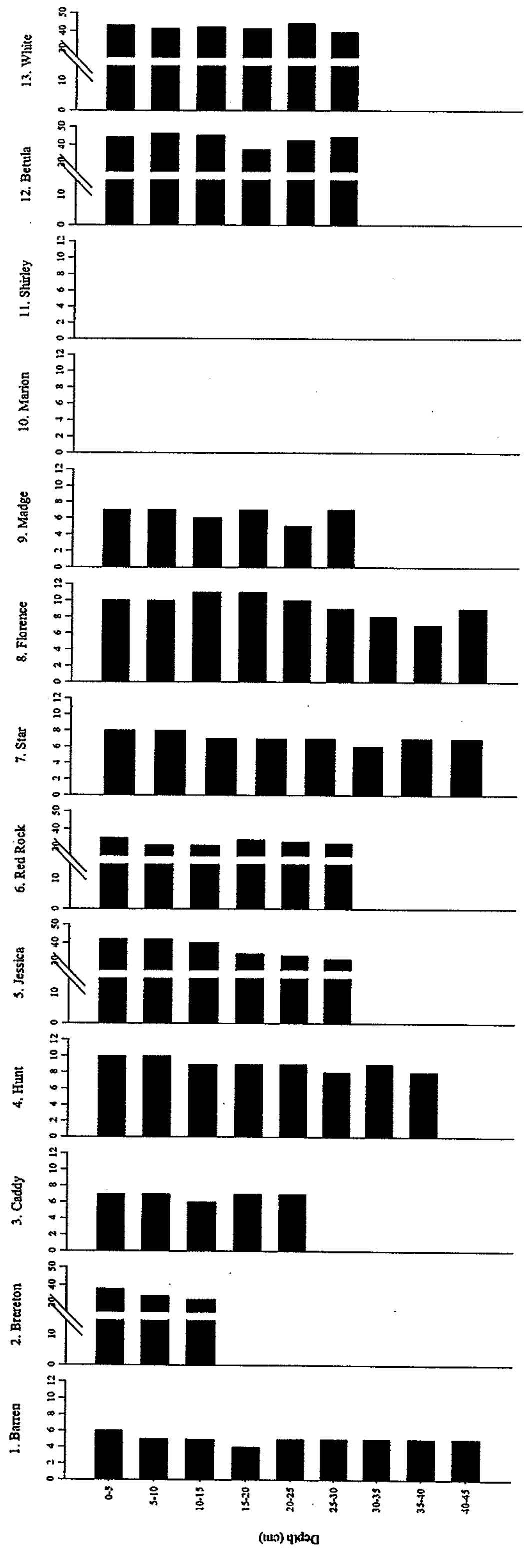

Figure 43: Sediment boron concentration (µg/g sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

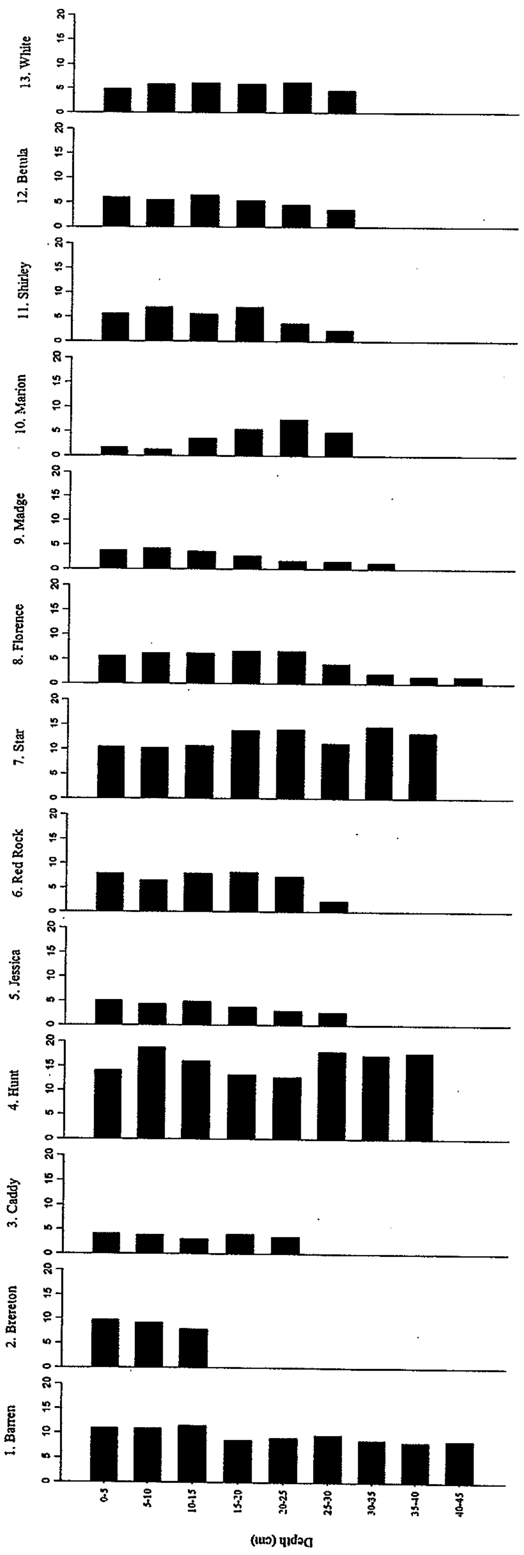

Figure 44: Sediment arsenic concentration (µg/g sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

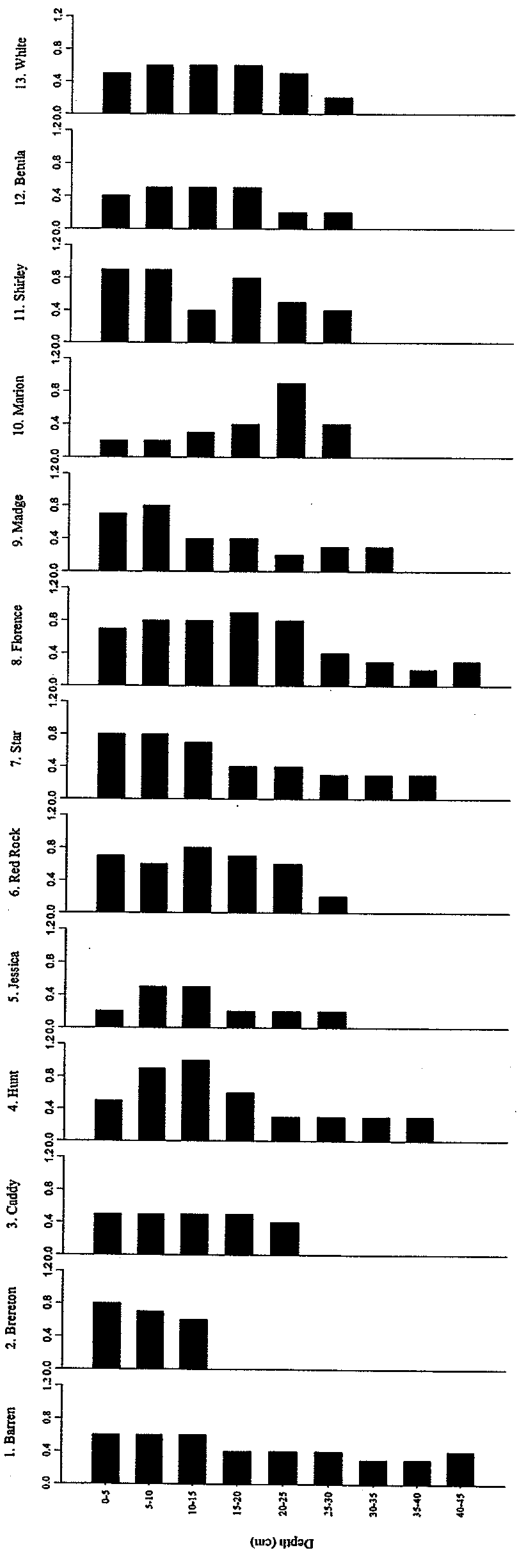

Figure 45: Sediment cadmium concentration (μg/g sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

is confined to approximately 50 and 25 % of each lake respectively. The most populated areas at both lakes occur around the campground, where infestations were most pronounced. Facilities in these areas include: campground, private cottages, resorts, gas station, public beach and convenience store or restaurant. The only two boat launches located on White Lake are located in the infested campground area. In the early 1970s, the Betula Lake boat launch was moved from the campground beach to the beach at Block 5. As a result, it may be concluded that historically all recreational facilities were concentrated in areas which are now infested by *L. wollei*.

5.12 *Lyngbya wollei* Inoculation Source

The proliferation of *L. wollei* infestations around historic boat launch sites suggests recreational watercraft movement may have been the source of *L. wollei* inoculation. Water skiing is one recreational activity which brings visitors from around the continent to Betula and White Lakes. Water skiing clubs promote water skiing and wakeboarding through shows, tournaments and clinics. Historically boats have been moved between lakes for such events.

Stagnant and dried *L. wollei* filaments transported by recreational watercraft may provide a viable inoculation source for the infestation of pristine lakes. Desiccation experiments were conducted as a preliminary investigation of the potential survivability of *L. wollei* for inter-lake transfer. Hypothesizing that *L. wollei* was transferred between lakes by recreational watercraft it was my intention to investigate the transportation site within or on the watercraft. Dried treatments represented filaments transported on the hull of the watercraft or within the bilge pump. The stagnant samples represented filaments transported within the watercraft in small pools of water or live wells. The results from the July experiment suggested *L. wollei* may remain viable under moderate drying temperatures and times. August desiccation results presented in this study indicated *L. wollei* was capable of survival and remained highly productive after five days in minimal stagnant water under extreme light and temperature conditions.

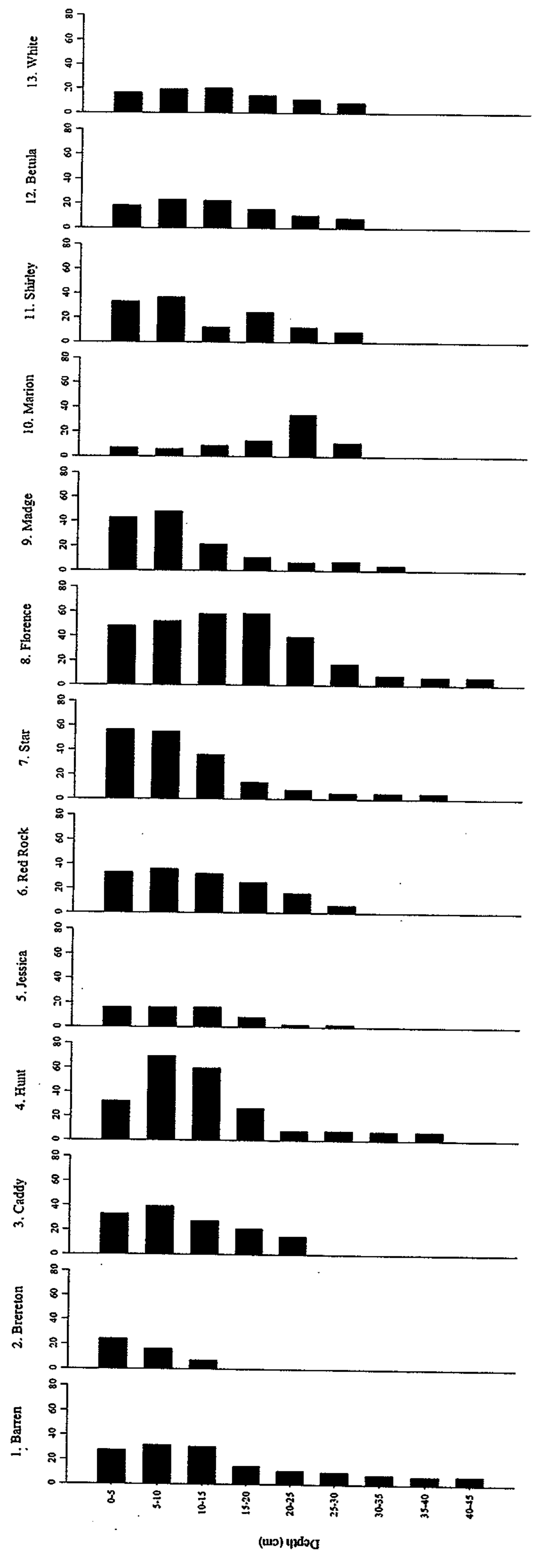

Figure 46: Sediment lead concentration (µg/g sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

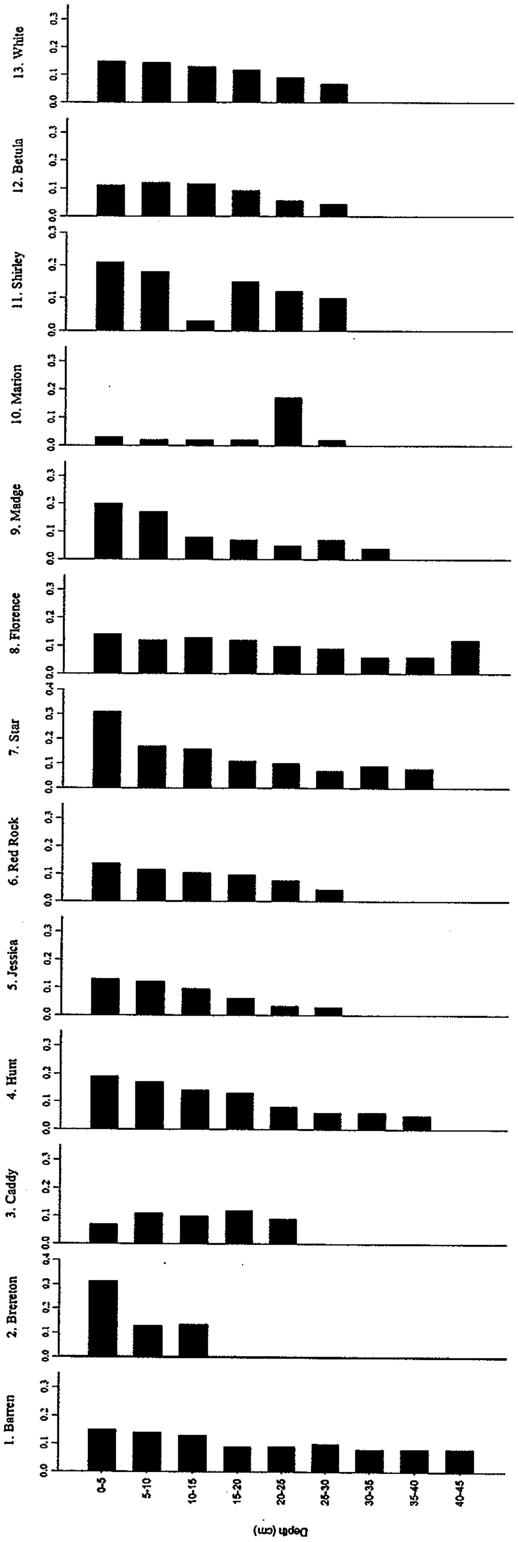

Figure 47: Sediment mercury concentration (µg/g sediment dry weight) profiles for 13 Whiteshell lakes. Lakes 1-7 are located in intensive use area, 8-11 are back country lakes and 12-13 are *L. wollei* infested lakes.

5.13 *Lyngbya wollei* Inter-Lake Transfer

Recreational watercraft are moved between infested lakes and other waterbodies in the Whiteshell and around the continent. This puts many lakes around the continent at risk of *L. wollei* inoculation, which may lead to the infestation of other lakes. The Whiteshell Resident Survey responses indicated cottagers moved boats between Whiteshell lakes primary for fishing purposes. Whiteshell residents also indicated their visitors brought watercraft from throughout Canada and the United States; examples included: Saskatchewan, Alberta, Minnesota, North Dakota, Indiana, and Nebraska. As a result, Group 12 lakes were connected directly or indirectly as a result of watercraft movement. Campground visitor journals documented transient visitors moved watercraft between numerous Manitoba water bodies and the infested Whiteshell lakes.

It is essential that users are aware of *L. wollei* infestations, and thoroughly wash recreational watercraft when removed from infested lakes, to prevent the spread of *L. wollei* to other pristine lakes. On Sunday July 27, 2003 an article appeared on the cover of the Winnipeg Free Press with the headline 'Black plague at lakes'. This incorrect and negative publicity warned people about *L. wollei* infestations occurring in Betula and White Lakes. I was concerned this article would discourage people from visiting the infested lakes. As a result, on Saturday August 2, 2003 a public boat launch survey was conducted at Betula, White, Jessica and Caddy Lakes. The tunnels which connect Caddy Lake to North and South Cross Lakes attract many transient boat visitors. As a result, it was expected that Caddy Lake would have a highest number of boat launches, which was confirmed by our survey. Contrary to my expectation Betula Lake experienced the second highest number of boat launches, followed by White and Jessica Lakes respectively. Recreational users did not appear to be concerned about *L. wollei* infestations. In fact, beach goers at White Lake were heard joking about the black algae. As a result, the article did not appear to negatively impact lake use, but rather heighten recreational user awareness, which was its intended purpose.

5.2 Objective 2

The second objective of this study was to investigate why *L. wollei* infestations are only known to occur in Betula and White Lakes. It may be hypothesized, that *L. wollei* has been introduced into other Whiteshell lakes through the movement of recreational watercraft, although currently, infestations have not been identified in other lakes. As a result, select Whiteshell lakes were examined based on land use, morphology and water and sediment chemistry parameters to determine if Betula and White Lakes exhibit unique characteristics which distinguish them from other Whiteshell lakes. If the infested lakes are not found to be unique, shared characteristics may be used to identify other lakes susceptible to *L. wollei* infestations.

5.21 Land Use Intensity

Falcon, Caddy, Brereton and Big Whiteshell Lakes experienced the highest density of transient visitors because of campground and resort facilities. Consequently, if *L. wollei* is transported by watercraft these lakes would be the most susceptible to *L. wollei* inoculation. Watershed land use intensity was investigated based on services and recreational facilities located at twelve Whiteshell lakes in intensive use areas (Group 12). Intensity of land use may be indicative of anthropogenic impact on the lake by the surrounding watershed. Correspondence Analysis distinguished lake groups primarily based on the occurrence of campgrounds, resorts and services. As a result, Betula, White, Caddy, Brereton and Big Whiteshell Lakes were grouped together. All of these lakes have campgrounds, resorts, gas stations and other services. Falcon Lake was an outlier as a result of its considerable development and numerous modern facilities. The remaining lakes did not have campground facilities and minimal services. Jessica and Red Rock Lakes both have resorts which distinguish them slightly from the other low intensity lakes. As a result, based on intensity of land use Falcon, Betula, White, Caddy, Brereton and Big Whiteshell Lakes would be expected to have the highest water and sediment concentrations of anthropogenic pollutants such as phosphorus and heavy metal contaminants. The objective of analyzing intensity of land use variables was to determine if water and sediment chemistry similarities could be determined from land use parameters which are less expensive and easily collected. Water and sediment chemistry were examined to address this hypothesis.

5.22 Lake Morphology

All Whiteshell lakes may possess potential habitat for *L. wollei* growth. Lakes examined had shallow areas and a mean photic depth greater than two and a half meters. Lake morphology was examined to distinguish Group 12 based on suitable *L. wollei* habitat. PCA analysis identified Jessica, Brereton and Big Whiteshell as most similar to the infested lakes morphologically. These lakes have large surface areas, perimeter length and fetch. As a result, Jessica, Brereton and Big Whiteshell Lakes possess a large amount of suitable *L. wollei* habitat. Star, Barren and Red Rock Lakes are smaller lakes and therefore have a reduced amount of suitable *L. wollei* habitat. Falcon and Hunt Lakes are deep and consequently, may have limited ideal *L. wollei* habitat in comparison to the other lakes. Water and sediment chemistry parameters were investigated to further distinguish infested and non-infested lakes.

5.23 Water Chemistry

Water samples collected in 2002 from pelagic areas adequately represent lake water chemistry. Surface water samples were collected monthly from designated pelagic sampling sites from May to August 2002. It was suggested that sampling at pelagic sites was inappropriate when examining lakes for their capability to support *L. wollei* growth in littoral areas. As a result, in 2003 four lakes: Betula, White, Jessica and Caddy were selected for an intensive water chemistry study. This study compared water chemistry parameters measured at three sites on each lake. No significant difference was found between the sites within each lake with the exception of total phosphorus at White Lake. Water chemistry parameters measured in boating lanes with high and low intensity of traffic on Betula Lake also showed no significant difference between water chemistry parameters. Consequently, Group 12 and

Group 13 were used to examine water chemistry similarities between the infested and non-infested lakes.

Mean water chemistry parameters may be inadequate for distinguishing Betula and White Lakes from other Whiteshell lakes. Seven lakes: Betula, White, Jessica, Caddy, Barren, Star and Red Rock Lakes all had similar mean water chemistry parameters. Consequently, based on the measured parameters Betula and White Lakes were not unique from other Whiteshell lakes examined. The remaining lakes: Brereton, Green, Big Whiteshell, Falcon and Hunt Lakes were identified as outliers with unique chemical characteristics. As a result, the number of lakes and water chemistry parameters measured were modified to determine if unique water characteristics or lakes with the most similar water chemistry to the infested lakes could be identified.

Betula, White and Jessica Lakes had the highest concentration of phosphorus suggesting these lakes experienced eutrophication by the surrounding watershed. Group 13 consisted of lakes located in intensive, extensive and wilderness areas. Based on July water chemistry these lakes were compared to examine water chemistry at the height of the recreational season. Florence, Madge, Marion and Shirley Lakes are located in extensive and wilderness areas, designated here as 'backcountry' lakes. It was hypothesized that backcountry lakes with minimal anthropogenic disturbance would have lower phosphorus concentrations distinguishing them from lakes in intensive use areas. PCA results confirmed this hypothesis segregating the backcountry lakes from Betula, White and Jessica Lakes at opposite ends of the ordination. High concentrations of TPP, TP, TSS may be the result of anthropogenic disturbance which may lead to increased lake productivity indicated by high chlorophyll a concentrations. Results indicated Betula, White and Jessica Lakes may experience the highest anthropogenic disturbance, indicated by high concentrations of TPP, TP, TSS and chlorophyll a. The backcountry lakes had low concentrations of these water chemistry parameters.

Four separate analyses maintained Betula and White Lakes have very similar water chemistry. The water chemistry of the infested lakes was not unique, but rather enabled other Whiteshell lakes with similar water chemistry to be identified. Water chemistry analyses suggest Jessica and Red Rock Lakes are consistently the most similar to the infested lakes. Jessica Lake constantly had the most similar water chemistry to the infested lakes in all analyses. Red Rock Lake was the next most similar chemically to the infested lakes. Sailing and South Cross Lakes are backcountry lakes which were found to have similar water chemistry to the infested lakes. All of these lakes had high concentrations of TPP, TP and TSS based on July water chemistry. Sailing and South Cross Lakes may be useful in future research functioning as a control used for comparison with the infested lakes, to determine if elevated TPP, TP and TSS concentrations were caused naturally or resulted from anthropogenic sources.

5.24 Sediment Chemistry

Sediment chemistry analyses provided unique results which furthered our understanding of lake susceptibility to *L. wollei* infestations. Sedimentary element concentrations provide insight into historic lake conditions and an overall indication of element availability for *L. wollei* growth. Sediment cores collected from thirteen Whiteshell lakes were used to compare lakes based on current, mean and heavy metal sediment concentrations. PCA of current and mean sediment concentrations produced similar lake groups. These analyses identified Betula, White, Jessica, Red Rock, Florence and Madge Lakes to have similar sediment chemistry. Jessica and Red Rock Lakes were also identified by water chemistry analyses to be the most similar chemically to the infested lakes. In contrast, the identification of backcountry lakes Florence and Madge contradict results of July water chemistry analyses which indicated these lakes had substantially lower concentrations of phosphorus, total suspended solids and chlorophyll a. Florence and Madge have the highest mean phosphorus sediment concentrations after Shirley Lake. As a result, element concentrations, additions and cycling are all important aspects to consider when examining lake susceptibility to *L. wollei* infestations. Consequently, sediment core element concentrations were investigated as a function of depth to determine if high element concentrations occurred naturally or resulted from anthropogenic disturbance. Based on current and mean sediment chemistry Jessica, Red Rock, Florence and Madge Lakes have the most similar sediment chemistry to the infested lakes. Consequently, concentration profile similarities and differences between these lakes have been emphasized.

The Canadian Sediment Quality Guidelines for the Protection of Aquatic Life summarizes the Interim Sediment Quality Guidelines (ISQG) and Probable Effect Levels (PEL) for arsenic, cadmium, lead and mercury. As a result, these heavy metals were examined to assess anthropogenic contamination of Group 13. The results of these analyses were unexpected. Based on land use parameters measured in this study Star Lake experienced much lower land use intensity than Brereton Lake, but had the same high mercury concentration. Florence Lake located in the backcountry with ostensibly minimal anthropogenic impact had the highest lead concentrations. Nutrient and heavy metal sedimentary concentrations as they relate to *L. wollei* infestations is discussed in further detail in section 5.28 Sediment Geochemistry.

5.25 Multivariate Statistical Analysis Summary

Land use parameters examined were unable to accurately distinguish lake groups with similar water and sediment chemistry. Land use intensity, lake morphology and water chemistry data was combined to examine Group 12 based on all measured parameters. The lake groups produced by CA were consistent with those produced by the land use intensity parameters alone. In contrast, when all data matrices for Group 13 were combined water and sediment chemistry parameters were highly correlated and distinguished lakes into groups consistent with trends observed in separate analyses. The Group 12 complete data matrix identified Brereton, Caddy and Big Whiteshell as most similar to infested lakes. In contrast, the complete data matrix for Group 13 identified Jessica and Red Rock as most similar to the infested lakes based on water and sediment chemistry.

Contrary to my expectations backcountry lakes examined had the highest mean sedimentary phosphorus concentrations of all lakes sampled. I hypothesized that backcountry lakes would have low sediment concentrations of phosphorus and heavy metals associated with anthropogenic disturbance. As a result, element concentration profiles were examined in order to determine the source of high concentrations, focused on nutrients and heavy metals indicative of anthropogenic disturbance discussed in section 2.34 Lake Productivity. Sediment profiles provided evidence to determine if high concentrations were a natural phenomenon or the result of anthropogenic activity in the watershed. This knowledge was then used to determine if intensity of land use or water and sediment chemistry are better indicators of anthropogenic influence on Whiteshell lakes.

5.26 Bulk Sediment Composition: Loss on Ignition

Historically all lakes cored have experienced watershed disturbance such as fire and cottage and road development, but sediment accumulation and composition appeared to experienced only minor fluctuations in most cores examined. Substantial fluctuations in sediment water content and organic matter profiles indicated Hunt, Marion and Star Lakes experienced the greatest watershed disturbance effects of all thirteen lakes examined. Watershed disturbance results in extensive sediment deposition into the lake, causing sediment compaction. Irregular sediment deposition may have resulted from natural and anthropogenic watershed disturbances including: fire, logging, mining and subsequent erosional activity increasing allochthonous input. With compaction events organic matter content is decreased as a result of dilution due to increased sediment accumulation. Hunt, Marion and Star Lakes have highly correlated water content and organic matter content profiles. These sediment cores were not dated and without dates it is difficult to determine the cause of the sediment compaction. Consequently, watershed history was used to identify disturbances which may have resulted in sediment compaction.

Sediment deposition in Hunt, Marion and Star Lakes was substantially altered by watershed disturbances which resulted in sediment compaction. Hunt and Marion Lakes experienced a single disturbance event indicated by water and organic matter content profiles. Profiles showed a single large compaction event followed by resumed natural sediment accumulation. Hunt Lake is a small lake with eight cottages. Disturbance by the construction of these cottages may have resulted in increased sediment accumulation and subsequent sediment compaction. Marion Lake has no cottage development, but in 1929, the north and east sides of the lake were burned by a wildfire. Sediment cores were collected from the north-eastern corner of the lake. As a result, the compaction event observed may be the result of the debris and erosion which may have resulted from the fire. Star Lake in contrast, experienced a number of compaction events at the base of the core. Historically the Star Lake watershed experienced a number of disturbances including a fire in 1929, mining from 1928-1945 and cottage construction which began in the early 1930s (Zimmerman 1991). The distinct erosion events indicated by sediment compaction and reduced organic matter content may be the result of these watershed activities.

Current high levels of productivity in Whiteshell lakes may be correlated with increased nutrient concentrations resulting of cultural eutrophication. Hunt, Florence and Betula Lakes are currently the most productive lakes. Betula and White Lake had the most conspicuous increase in total chlorophyll and therefore productivity at the top of the sediment core. Organic matter content and total chlorophyll profiles were used to examine historic productivity. Correlations were observed between fluctuations in organic matter and total chlorophyll concentrations, which effectively describe autochthonous productivity. Fluctuations observed throughout the sediment cores may be the result of watershed disturbances which impacted lake productivity. Total chlorophyll concentrations were greatest at the top of the core for all lakes with the exception of Red Rock Lake. Increases in growth limiting nutrients such as phosphorus were observed in sediment concentration profiles and may account for increased productivity.

5.27 Sediment Dating

The results presented in this study indicate lakes in intensive use areas experience higher rates of sediment deposition than the backcountry lake examined. Anthropogenic disturbance may account for increased sediment deposition in Betula and White Lakes resulting from catchment erosion or increased productivity due to nutrient enrichment. Sediment cores collected from Betula, White and Madge Lakes document the change in sediment deposition since the 1800s. Sediment accumulation rates showed an increase over time. Currently the sediment deposition rate in White Lake is more than two fold higher than Madge Lake. Madge Lake is a backcountry lake with minimal anthropogenic impact. Hypothesizing that Madge Lake may be used as a control, the substantial increase in sediment deposition in White Lake may be the result of catchment erosion or increased autochthonous productivity by increased nutrient addition. Loss on Ignition profiles would provide evidence of erosion or increased productivity but analyses were conducted on separate cores taken from different depositional areas of the lakes. As a result, the anthropogenic disturbance which resulted in increased sediment deposition remains unknown. Organic matter and sediment accumulation profiles from Madge Lake remain relatively constant indicating natural sedimentation rates, making it an effective control lake. Both White and Madge sediment cores were collected from deposition areas indicated by a focus factor of one. The Betula Lake core was not collected from a depositional area yet sedimentation rates were only slightly below those found in White Lake. This may suggest that sedimentation rates are actually higher in Betula Lake.

5.28 Sediment Geochemistry

It was the objective of this study to use the temporal scale represented by each sediment core to differentiate natural eutrophic conditions from cultural eutrophication. Sediment cores collected from Betula, White and Madge Lakes date back to the 1800s, recording natural sediment conditions in these lakes prior to development. For the purposes of this study, select nutrient and heavy metals concentration profiles were used as cultural eutrophication indicators. Without sediment dates, cultural eutrophication may be indicated by increasing nutrient and heavy metal concentration profiles up the core resulting from anthropogenically induced enrichment.

5.29 Sediment Geochemistry: Nutrients & Heavy Metals

Increased TKN concentrations may be the result of anthropogenic disturbance. Betula, White, and Jessica Lakes experienced an increase in TKN up the core. Red Rock Lake had high TKN concentrations throughout the core but the sediment was soft and flocculent and the time line represented by this core is unknown. An associated time line would have enabled me to determine if the base of the core represents naturally occurring concentrations prior to anthropogenic development of the area. As a result, it cannot be determined if high TKN concentrations in Red Rock Lake are the result of natural or anthropogenic nitrogen enrichment. Betula and White Lakes had the third and fourth highest mean TKN concentrations. These profiles show a small but distinct increase in TKN up the core. Sediment dating provided a time line for these cores which presented conclusive evidence, that concentrations at the base of the core represent natural concentrations.

Betula and White Lakes had relatively high sedimentary nitrogen concentrations, but nitrogen limited environments may not restrict *L. wollei* growth. *L. wollei* was found to exhibit nitrogenase activity under suitable environmental conditions (Philips et al. 1992). Cowell and Botts (1994) concluded that nitrogen increases did not result in increased colony growth. Marion Lake was the only core with a mean TKN concentration significantly less than the Betula Lake core. As a result, Marion Lake TKN concentrations may not limit *L. wollei* growth.

Comparison between sediment core element concentration profiles was limited to main sedimentary trends. The sediment cores collected from Betula, White and Madge Lakes were dated and found to record historic sediment deposition back to the 1800s. As a result, samples from the base of the core represent natural sediment concentrations prior to development. The remaining Whiteshell cores were not dated, lacking an associated chronology. All Whiteshell lakes sampled with the exception of the wilderness lakes, showed a distinct increase in phosphorus concentrations up the core. Increased phosphorus concentrations may result from cultural eutrophication or natural sedimentary processes.

Backcountry lakes sampled provided a control group for comparison with intensive use lakes to examine evidence of cultural eutrophication. Correlation between phosphorus, iron, and manganese concentration profiles were investigated to assess probability of natural sedimentary concentration of phosphorus up the core.

Backcountry lakes had the highest sediment phosphorus concentrations. It was expected these lakes would have relatively low phosphorus concentrations, resulting from minimal anthropogenic impact. As a result, high phosphorus concentrations in these lakes are hypothesized to result from natural sources or a specific watershed disturbance. It may be hypothesized the unknown geology and history of these lakes may account for the high phosphorus concentrations. The Shirley Lake sediment core showed high phosphorus concentrations throughout the length of the core. Consequently, Shirley Lake may have unique geology which enriches sediment with phosphorus. In contrast, Madge and Marion Lakes experienced one large basal phosphorus concentration peak with moderate concentrations throughout the remainder of the core. These lakes may have experienced a watershed disturbance such as fire which resulted in the basal concentration peak. The wilderness lakes had large phosphorus concentrations but did not show an increasing trend up the core as seen in the other lakes examined. As a result, cultural eutrophication may account for increasing phosphorus concentration profiles observed in sediment cores collected from intensive use lakes.

Increasing phosphorus concentration profiles may be the result of natural sedimentary processes. The Whiteshell sediment cores examined showed phosphorus profiles were correlated with either iron, manganese or both profiles, with the exception of Madge and Marion Lakes. Phosphorus and associated iron and manganese concentration profiles increase up the core. If iron and manganese concentrations remained constant for the length of the core then increasing phosphorus concentration profiles would indicate increased phosphorus inputs (Wetzel 2001). Instead profile correlations suggest phosphorus profiles were affected by sediment redox conditions. As the sediment redox potential decreased the iron, manganese and phosphorus complexes moved up the core until immobilized by redox conditions (Wetzel 2001). This process may have concentrated phosphorus at the top of the core.

Lakes with available phosphorus concentration peaks located at the sediment surface may support a more substantial *L. wollei* infestation if inoculated. The Betula *L. wollei* infestation is considerably more developed than the White Lake infestations. The White Lake *L. wollei* infestation may be limited by sedimentary available phosphorus concentrations. Available phosphorus concentration profiles separated Group 13 into two groups based on surface or basal available phosphorus concentration peaks. Betula, Jessica and Red Rock Lakes had maximum available phosphorus concentrations at the top of the sediment cores. In contrast, White Lake experienced a decreasing trend with the highest available phosphorus concentration located towards the base of the sediment core. Currently, Betula and White Lakes differ in their available phosphorus concentrations while both supporting *L. wollei* infestations. *L. wollei* maintains a higher density and distribution in Betula Lake. As a result, increased available phosphorus concentrations in surface sediment resulting from natural or anthropogenic sources may enhance *L. wollei* proliferation. Currently, Florence, Red Rock, Madge and Betula Lakes have the highest mean available phosphorus concentrations respectively.

Utilization of high boron concentrations may have facilitated *L. wolle*i adaptation to low calcium environments. The results of this study indicate lakes with *L. wollei* infestations and lakes identified as most susceptible: Betula, White, Jessica, Red Rock, Florence and Madge all had relatively low calcium concentrations. Based on the infestation density in Betula and White Lakes it may be concluded that *L. wollei* has adapted to environments with low calcium concentrations. Boron is required to maintain growth under calcium limiting conditions (Bonilla et al. 1995). Naturally high boron concentrations in these lakes may compensate for low calcium concentrations enabling the proliferation of *L. wollei*. Boron concentrations in Betula and White Lakes were the highest of all Whiteshell lakes examined. Jessica and Red Rock Lakes had the third and fifth highest boron concentrations respectively.

Barren, Hunt and Star Lakes may be located in areas with naturally high arsenic concentrations. The Canadian Sediment Quality Guidelines for the Protection of Aquatic Life summarizes the ISQG and PEL for heavy metals. The ISQG for arsenic is 5.9 μg/g, with an associated 5 % incidence of adverse biological affects. All lakes with the exception of Caddy, Jessica and Madge had concentrations greater than 5.9 μg/g. The PEL is 17 μg/g with an associated 25 % incidence of adverse biological affects. As a result, the majority of Whiteshell lakes sampled may have a 25 % incidence of adverse biological affects as a result of arsenic concentrations greater than 17 μg/g. In most lakes arsenic concentrations experienced only minor profile fluctuations. Betula Lake had significantly lower arsenic concentrations than Barren, Hunt and Star Lakes, which maintained high arsenic concentrations throughout the length of the core. As a result, natural arsenic concentrations may be higher in these areas. Small increases and fluctuations observed in the other profiles may be the result of anthropogenic activities.

Jessica Lake had the lowest mean cadmium concentration, while Florence, Madge and Red Rock Lakes had relatively high cadmium concentrations. The ISQG for cadmium is 0.6 μg/g and the PEL is 3.5 μg/g. The greatest cadmium concentration found in all cores was 1 μg/g in Hunt Lake. As a result, all lakes had cadmium concentrations less than the PEL. In most Whiteshell sediment cores cadmium showed a typical increasing trend up the core to a subsurface peak. Lead and mercury concentration profiles had a similar shape.

Leaded gasoline may be the primary source of lead contamination in Whiteshell lakes. The removal of lead additives from gasoline has protected lake water and sediment quality. Lead concentrations were low at the base of all cores indicating natural concentrations. Typically lead concentrations increased up the core experienced a subsurface peak and subsequently decreased to the top of the core. Lead concentration peaks were correlated with the late 1970s in dated sediment cores. As a result, it may be concluded the removal of lead additives from gasoline resulted in current decreasing lead concentrations. The ISQG for lead is 35 μg/g and the PEL is 91 μg/g. Eight Whiteshell lakes had lead concentrations greater than the ISQG. The greatest lead concentration was 69.5 μg/g in Hunt Lake. Rown and Kalff (1993) found a positive relationship between site depth and sediment metal concentrations. Hunt Lake is small and deep. Consequently, sediment focusing may account for the high lead concentrations found in this lake. Florence Lake had the highest mean lead concentration. Based on the Madge Lake sediment dates this peak may be correlated to with the Artic Ice fuel division logging camp activity in the 1920s. The lead concentration peak at the base of Marion Lake may be the result of a fire disturbance which resulted in erosional deposition of lead into the lake from the surrounding watershed. As a result, anthropogenic activity in the watershed may further contribute to lead contamination.

Mercury contamination may have resulted from anthropogenic activity in the surrounding watershed. Mercury atmospheric deposition is hypothesized to be relatively consistent throughout the Whiteshell. Mercury concentration profiles showed an increasing trend up the length of each core with relatively low presumably natural concentrations at the base. Star and Brereton Lakes under current sediment conditions had 0.31 μg/g mercury. At this concentration Star and Brereton Lakes have substantially higher current mercury concentrations than other Whiteshell lakes investigated. Discarded electrical components at municipal dumps and sanitary landfill sites are a primary source groundwater contaminant by mercury (CCME 1987). At Star Lake a brush dump was located 600 meters south of the Star Lake cabin area. This dump operated for over 15 years as a waste disposal site for brush, bulky metallic and other dry waste (Karp 1987). The dump was located on sand and silt deposit 3 – 6 meters in depth and groundwater flowed northerly towards the lake. Karp (1987) concluded the waste disposal grounds contaminated groundwater. Test drilling was recommended to determine the extent of contamination. Until sometime in the 1980s raw garbage was also disposed at this site. A waste disposal site at Brereton Lake was closed prior to 1977 (Karp 1987). The type of waste disposed at this site is unknown. As a result, waste disposal sites at these lakes may have contributed to mercury contamination observed in sediment profiles. Small scale gold miners used mercury to extract gold from sand (Kishe and Machiwa 2003). Star Lake had a small gold mine which operated from 1928 -1945. It was located close to the brush dump site and may have further contributed to groundwater and consequently sediment contamination.

It may be suggested that water and sediment chemistry best identify lakes with similar environmental conditions. Betula Lake mean sediment concentrations were compared to other Whiteshell lakes examined. Betula Lake was chosen as a result of favorable growing conditions based on *L. wollei* abundance and distribution in the lake. ANOVA and Tukey-Kramer significance tests identified lakes with element concentrations significantly different from Betula Lake (Table 31). When results were combined White, Jessica, Red Rock, Florence, and Madge Lakes had the most similar mean sediment chemistry to Betula Lake respectively. These results are consistent with PCA of water and sediment data, which identified the same lakes as most similar to the infested lakes. The parameters used to examine current intensity of land use did not accurately identify lakes with similar water and sediment chemistry based on intensity of land use.

5.3 Comparison between Whiteshell and America L. wollei *Infestations*

L. wollei may be considered a competitive invasive exotic species in Whiteshell Provincial Park. *L. wollei* infested nearshore areas to a depth of 2.5 meters in Betula and White Lakes. In the summer, portions of the mats were buoyed to the surface, which resulted in the vertically stratified *L. wollei* mats. This was consistent with *L. wollei* habitat descriptions from the southeastern United States. Whiteshell lakes had similar *L. wollei* total standing crop biomass to lake examined in the United States. Standing crop biomass determined for Betula and White Lakes were consistent with quantities reported from lakes and reservoirs throughout South Carolina, Georgia and Alabama were this invasive species primarily occurs (Speziale *et al.* 1991).

Four water chemistry variables: alkalinity, conductivity, ammonia and total phosphorus, account for 57.8 % of the variability in *L. wollei* biomass (Cowell and Botts 1994). It was hypothesized these water chemistry parameters would distinguish Betula and White Lakes from other Whiteshell lakes. When all twelve lakes sampled in 2002 were compared Betula Lake was differentiated from White Lake by lower ammonia concentrations. Lower ammonia concentrations may provide better *L. wollei* growing conditions and account for the greater *L. wollei* distribution in Betula Lake. Four other lakes: Jessica, Caddy, Barren and Big Whiteshell were identified as similar to Betula and White based on these water chemistry parameters. In contrast, PCA identified Jessica, Red Rock, Florence and Madge Lakes as most similar to the infested lakes. *L. wollei* acquires nutrients from both the water column and sediment. As a result, it is hypothesized PCA results based on both water and sediment chemistry may provide a more accurate indication of lakes with similar chemistry to Betula and White Lakes and therefore suitable *L. wollei* habitat.

It is likely that the Whiteshell strain of *L. wollei* has effectively adapted to this Manitoba environment through physiological modification. One example presented in this study was high sedimentary boron concentrations in infested lakes thought to compensate for low calcium concentrations. As a result, the strain of *L. wollei* which occurs in the Whiteshell may have unique physiological adaptation from strains which typically occur in marl lakes in the south-eastern USA.

Whiteshell managers should proceed based on current management knowledge and work to identify emergent macrophytes native to the Whiteshell which may be used to limit *L. wollei* growth in infested areas. Numerous management techniques have been examined in the United States (see section 2.25 Management Techniques). The distribution and morphology of *L. wollei* resulted in the failure of most management techniques. The benthic and vertical distribution of *L. wollei* mats limited the effectiveness of herbicide applications. The long filaments and dense mats prohibit most heterotrophs from consuming *L. wollei* in significant quantities. Whiteshell infestations pose the same problems for the application of management strategies. In the United States emergent macrophytes have proven to be the most effective management technique for reducing *L. wollei* biomass.

Chapter 6: Conclusions

The distribution and transportation of *L. wollei* was best correlated with anthropogenic activity. Historically, all recreational facilities at Betula and White Lakes were concentrated in areas which are now infested. Betula and White Lakes are the only Whiteshell lakes with waterskiing clubs. These clubs have been attracting visitors from around the continent for more than half a century. Preliminary desiccation experiments suggest stagnant and dried *L. wollei* filaments transported by recreational watercraft may provide a viable inoculation source for the infestation of pristine lakes. Whiteshell residential and campground surveys indicated that recreational watercraft are moved between infested lakes and other lakes in the Whiteshell and around the continent. As a result, it is essential that Whiteshell users are aware of *L. wollei* infestations and thoroughly wash recreational watercraft when removed from infested lakes to prevent the spread of *L. wollei* to other pristine lakes.

The transportation of recreational watercraft within the Whiteshell suggests other lakes may have been inoculated with *L. wollei* without currently possessing infestations. As a result, land use intensity, lake morphology, water and sediment chemistry parameters were investigated to determine if Betula and White Lakes had a unique characteristic which enabled the proliferation of *L. wollei*. Betula and White Lake were consistently very similar based on the parameters investigated but were not found to be wholly unique from other Whiteshell lakes. As a result, these analyses were used to identify Whiteshell lakes most susceptible to *L. wollei* inoculation and infestation. Land use intensity parameters identified Falcon, Caddy, Brereton and Big Whiteshell Lakes as most susceptible to *L. wollei* inoculation. These lakes have many recreational facilities and services which attract users from within the Whiteshell and around the continent. In contrast, water and sediment chemistry parameters identified Jessica, Red Rock, Florence and Madge Lakes to be the most similar to the infested lakes chemically. Consequently, it may be suggested these lakes would experience the greatest biomass and adverse affects of *L. wollei* infestations. Florence and Madge Lakes are backcountry lakes and as such have a reduced risk of *L. wollei* inoculations and subsequent infestations. Future efforts should be focused on protecting Jessica, Red Rock and other lakes in the intensive use zones from *L. wollei* inoculation.

The Whiteshell strain of *L. wollei* may have unique physiological adaptations. American research indicated high calcium concentrations were crucial for the proliferation of *L. wollei*. In contrast, the infested Whiteshell lakes maintained low calcium concentrations. As a result, it is suspected *L. wollei* uses high boron concentrations to compensate for growth in calcium limited environments. Although the Whiteshell *L. wollei* strain may have unique physiology, *L. wollei* distribution and morphology ultimately determines the effectiveness of the management techniques. As a result, I suggest that Whiteshell managers proceed based on current American management knowledge and work to identify macrophytes native to the Whiteshell which may be used to limit *L. wollei* growth in infested areas.

Chapter 7: Recommendations

7.1 Recommendations for Researchers

7.11 Expand desiccation experiments

Desiccation experiments conducted for this study were preliminary and exploratory investigations. It is my recommendations that desiccation experiments be repeated under strictly monitored conditions. The length of drying, rewetting and experimental time may be varied to investigate the effect on *L. wollei* viability. An oven may be employed to effectively control and monitor drying temperatures. The oxygen concentration of the stagnant water may be monitored to provide important information on the ability of *L. wollei* to withstand saturating oxygen concentrations which typically induce photorespiration. Filtered water would ensure oxygen production or consumption measured may not result from autogenic productivity or heterotrophic respiration from organism in lake water. These controls may provide conclusive evidence on the specific conditions which enable *L. wollei* to remain viable. Autecological factors affecting *L. wollei* growth such as light, temperature and nutrient limitation should also be investigated experimentally. This information would provide an effective means to determine the appropriate methods for cleaning recreational watercrafts.

7.12 Investigate *L. wollei* sediment association.

Literature and field investigations indicate that the association between *L. wollei* and lake sediment warrants further investigation. In White Lake *L. wollei* was found to form small clumps mixed with large amounts of sediment. *L. wollei* filaments were observed on the surface of the BT2 sediment core collected from the infested area of Betula Lake. Long white filaments which appeared morphologically similar to *L. wollei* filaments were observed up to a depth of 15 cm within the sediment core. This poses two research questions: Do viable *L. wollei* filaments occur below the sediment surface? Are filaments within the sediment column heterotrophic? Infested areas of Betula and White Lakes have a photic depth greater than the maximum depth. Is light penetration great enough below the sediment interface to sustain *L. wollei* growth?

7.13 Investigate source of *L. wollei* nutrient acquisition.

Research in the United States has focused on the effect of aqueous nutrient additions on *L. wollei* growth. American research also reported *L. wollei* acquired nutrients from the sediment. As a result, future research should focus on the source nutrient acquisition by *L. wollei*. This information may provide insight into habitat preference and infestation development.

7.14 Investigate *L. wollei* impact on ecosystem.

The ecological implications of *L. wollei* infestations are unknown and require investigation. Betula Lake appeared to have an exceptional number of minnows inhabiting nearshore areas infested by *L. wollei*. Minnows were not observed in this quantity at any other Whiteshell lake sampled. When portions of *L. wollei* mats were retrieved from the lake they were consistently infested with invertebrates. As a result, I propose *L. wollei* infestations may provide model minnow habitat with a plentiful food source and ideal cover. American research concluded fish were unable to effectively consume *L. wollei* due to its long and dense filaments. An experiment investigating the density and diversity of native heterotrophs may be used to determine how *L. wollei* infestations affect the aquatic ecosystem. Do *L. wollei* infestations enhance ecosystem productivity? What effect do *L. wollei* infestations have on native species diversity and density? Is *L. wollei* simply an aesthetic problem for humans?

7.15 Determine if *L. wollei* in the Whiteshell produces toxins.

America research concluded *L. wollei* produced saxitoxins. As a result, *L. wollei* samples from the Whiteshell should be tested for saxitoxin production. A single sample collected from Betula Lake in the summer of 2002 tested negatively for the production of saxitoxin. The is only one sample from one area at one time. The literature suggests saxitoxin production may be a produced in response to interspecific competition (Yin et al. 1997). As a result, it is important to test samples for saxitoxin production from various locations in the infestation at different times of the year. For example, in the spring *L. wollei* may produce saxitoxins to limit the competitive capabilities of macrophytes trying to establish themselves in nearshore areas. If *L. wollei* is found to produce these neurotoxins experiments must be undertaken immediately to determine the health implications for recreational users.

7.16 Investigate the competitive capabilities of macrophytes.

Detailed vegetation maps may enable future managers to return infested areas to natural conditions. It is my recommendation that priority is given to creating detailed maps documenting emergent and submerged macrophytes abundance and taxonomy be conducted on infested lakes and those at greatest risk of infestation, such as Jessica and Red Rock Lakes. Mesocosms may then be constructed in infested areas at Betula and White Lakes and various species of native emergent and submerged macrophytes may be planted to examine their competitive capabilities.

7.2 Recommendations for Managers

7.21 Combine zebra mussel and *L. wollei* campaign.

I propose the zebra mussel campaign be expanded to an exotic species campaign including *L. wollei.* Zebra mussels are a well known exotic which have wrecked havoc on the Great Lakes. Today the Manitoba Government actively campaigns to educate the public in order to prevent the spread of zebra mussels to our waterways. In contrast, *L. wollei* has already invaded our lakes and little is being done to prevent the further spread of this noxious alga. Students employed by the government to examine boat trailers for zebra mussels should expand their search to include *L. wollei.* Prevention methods employed for zebra mussel management are the same as those proposed for *L. wollei*: watercraft must be thoroughly washed after being removed from infested waterbodies. As a result, a combined *L. wollei* and zebra mussel campaign would go hand in hand.

7.22 Centralize *L. wollei* management.

Currently many people are working to minimize the impact of *L. wollei* on Whiteshell recreational users, although these efforts are not coordinated by a single entity and often one party is employing methods unbeknownst to other groups. For example, the Seven Sisters District dredges the Betula Lake swimming area at the campground beach to limit *L. wollei* impact on recreational users, while cottagers idle out from the shore in watercraft to limit *L. wollei* disturbance. The Water Quality Management Division of Manitoba Conservation were unaware of these practices until 2003. I propose *L. wollei* management should be centralized and all management strategies employed should be overseen by a single management group. The management group should work to develop and establish guidelines to achieve *L. wollei* management.

I further propose that Whiteshell Park Staff be educated on the *L. wollei* infestations. Many Park personnel are unaware of the problem and its implications. I think increased education would increase co-operation and implementation of management strategies. Management strategies which could be set in place by Park personnel would be documenting watercraft movement and providing suitable watercraft cleaning stations. For example, campground personnel could be required to document the origin and destination all visitors with recreational watercrafts and provide them with a brochure on *L. wollei* infestations in the Park. Whiteshell interpreters could provide a presentation on *L. wollei* infestations. Education is the key to limiting the spread of *L. wollei.*

7.23 Develop a multi-stakeholder management committee.

I propose the management group establish a multi-stakeholder management committee. Open communication would increase the effectiveness of research endeavors and ultimately strengthen process towards the common goal for *L. wollei* management. This committee would include individuals from all parties with a vested interest in Whiteshell lakes. Members may include cottage owners, Whiteshell Park staff, Scientists conducting research and government personnel.

7.3 Recommendations for Cottagers

7.31 Familiarize yourself with *L. wollei* infestations.

Cottagers need to be informed so they can be an effective first line of defense against *L. wollei* infestation. Cottagers spend a great deal of time at the waters edge observing their surroundings. I recommend Betula and White Lake cottagers visit the main campground beaches at these lakes and examine *L. wollei*. Once familiar with the appearance and smell of *L. wollei* cottagers may report future infestation development and anomalies to managers and researchers. As a result, cottagers may provide important insight into future *L. wollei* development and be an integral part of the multidisciplinary management committee.

7. 32 Protect non-infested lakes and rivers by washing recreational watercraft when removed from infested lakes.

I recommend washing all recreational watercraft when removing them from infested Whiteshell lakes in order to remove all *L. wollei* filaments. Shoes and clothing with Velcro should also be investigated for the occurrence of attached *L. wollei* filaments. Such precautions may limit the spread of *L. wollei* to other water bodies.

7.33 Cottagers and water skiing clubs educate friends and visitors on the importance and methods for preventing the spread of *L. wollei*.

Waterskiing clubs should educate Betula and White Lake users on the occurrence and proper management techniques used to limit the spread of *L. wollei* to non-infested lakes. This may be accomplished by showing visitors *L. wollei* infestations and encouraging them to wash transference items such as clothing, footwear and recreational watercraft when leaving the infested lakes.

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Appendix A: Whiteshell Provincial Park Supplementary Material

Geography & Geology

Whiteshell Provincial Park, located approximately 140 km east of Winnipeg, encompasses 2 719 km^2 of southeastern Manitoba (Figure 1) (Schneider 2002). The park boundary corresponds with the Whiteshell River to the North and the Ontario border to the East. The park is located in the Precambrian Boreal Forest region of Manitoba (Jones *et al.* 1980). In this area the Precambrian Shield and Boreal Forest overlap (Whitesel 2001).

During the Precambrian Era when the earth's crust was molten, a mass of granite rose to the surface overlying heavier volcanic rock. As the granite mass cooled and hardened it increased in weight pushing down on the underlying lava. Consequently, rare elements were concentrated in fissures within and around the granite mass. This granite shield was exposed to and smoothed by episodes of glacial advance and retreat during the Pleistocene epoch (Hilderman 1969). A final glacial retreat ten thousand years ago left the Precambrian Drift Plain topography that can be seen today. This topography is characterized by rolling to hilly relief, rock outcrops, variable amounts of glacial drift, bogs and eskers (Barto and Vogel 1978).

The composition of the Precambrian rock is mainly granite and granitic gneisses with granodiorite, quartz diorite and orthogneiss (Barto and Vogel 1978 & Hegenson and O'Connor 1978). Glacial drifts are unconsolidated glacial till which may reach over one meter in thickness. When Lake Agassiz inundated the Whiteshell area it deposited lacustrine varved silts and clays in low relief areas. Pronounced relief, prevailing winds and lake level fluctuation resulted in well-graded sandy till deposits on the upper slopes of hills. These deposits were washed down onto mid to low slopes and covered lacustrine deposits. In other areas lacustrine silts and clays overlaid glacial till. As a result, soil conditions are variable throughout the shield (Forrester 1978). Poorly drained depressions accumulated organic deposits while exposed bedrock prevailed in high relief positions. Four surface deposits persist in Whiteshell Provincial park: lacustrine sediments, moraine deposits, glaciofluvial outwash and organic deposits (Forrester 1978). Isostatic rebound helped to produce the drainage basins of Whiteshell Provincial Park. Lakes occupy the majority of glacially excavated depressions in the area and fault basins (Moenig et al 1978). There are 131 lakes in the Whiteshell ranging in depth from 1 to 115 meters (Schneider 2002). Today, bogs and lakes cover 40-60 % of the surface of this region (Forrester 1978).

There are three distinct geological anomalies found in Whiteshell Provincial Park, which distinguish two Whiteshell Lakes. West Hawk Lake is the product of meteorite impact determined by the occurrence of 'recrystalization, matrix binding forming glossy fragments and shock effects such as the accumulation of breccia in open faults' (Suggett 1984). As a result, West Hawk Lake, at 115 meters in depth, is significantly deeper than all other Whiteshell lakes. Glacially excavated Whiteshell lakes have a maximum depth less than 26 meters (Ralley 1995). The other Whiteshell geological anomalies occur in Star Lake were the occurrence of pillow lava and a volcanic plug are evidence of Precambrian volcanic activity in the Whiteshell area (Suggett 1984). These are unique geological features and distinct from the typical rolling to hilly relief, rock outcrops, glacial drift, bogs and lakes found in Whiteshell Provincial Park due to glacial activity (Barto and Vogel 1978).

Whiteshell History

Archaeological evidence suggests that Whiteshell cultures initially used the area seasonally as early as 7 000 B.C. for its natural resources. Archaeological evidence of prehistoric cultures includes: processed animal bones, pottery, stone artifacts and boulder mosaics. Caddy, Falcon, Jessica and Numao Lakes are a few of the many Whiteshell lakes which have archaeological evidence of prehistoric cultures (Pettipas 1978). Various cultural groups used specific sites within the park indicated by different styles of arrow heads, scrapers, hammerstones and ceramics found at excavated sites (Schneider 2002). Today these prehistoric artifacts may be viewed at the Whiteshell Natural History Museum located at

Nutimik Lake. Another important tourist attraction in the Park is the boulder mosaics including turtle and snake figures at the Bannock Point site near Nutimik Lake. Boulder mosaics are found at many Whiteshell lakes and are an important cultural feature of the area.

It is generally accepted that the 'Whiteshell' name is related to the small shell used to generate life (Whitesel 2001).The 'Whiteshell' name is associated with the 'megis' shell. The original Whiteshell inhabitants, the Anishinabe people ancestors of the Ojibwa, place symbolic importance on this shell. Oral tradition reveals that the small, white, sacred shell was used by their Creator to breathe life into the first human being. As a result, this symbolic shell may be worn by Ojibwa today as a reminder of their origin and history (Schneider 2002). The Anishinabe people considered the Whiteshell a sacred area.

Prior to 1870, canoes were used to access inland resources and lead expeditions. This canoe era brought Pierre Gaultier de Varennes de la Verendrye of New France, to the Whiteshell area, in a search of an inland waterway to the western sea (Whitesel 2001). La Verendrye traveled down the Whiteshell River, then known as the 'La riviere Pichikoka'. All previous expeditions had traveled north along the rivers flowing into Hudson's Bay (Schneider 2002). At the time the area was inhabited by Anishinabe and Cree. In the early nineteenth century the Cree people moved west and north and the Saulteaux, a branch of the Ojibway, moved to the Whiteshell area from Lake Superior (Schneider 2002). The Whiteshell River became an important fur trade route for the North West Company and what later became the Hudson's Bay Company. The development of the railway brought the canoe era to an end (Schneider 2002).

In 1887, the Canadian Pacific Railway (CPR) began construction in the Whiteshell area. Twenty five years after the completion of the CPR line the Canadian National Railway (CNR) started construction on a second railway through the area (Suggett 1984). The latter was completed in 1908. The town of Rennie was developed as a coal and water stop for steam locomotives, which were used until the late 1950s. Today, Rennie features the Alfred

Hole Goose Sanctuary and the Rennie District Park Office (Schneider 2002). In 1888, the Cross Lake Flag station was established along the main Canadian Pacific Railway line (Suggett 1984). Cross Lake proved difficult during the construction of both railroads and required extensive amounts of fill to be used to build up the grade. Tunnels were also blasted through the rock below the railroad to permit water to flow averting high water levels, which would adversely affect its structure (Schneider 2002). Today, these tunnels are part of the Caddy Lake canoe route, an important Whiteshell tourist attraction. The railway was fundamental in the initial development and access to the Whiteshell area.

At the beginning of the twentieth century, gold was discovered across the border near the town of Keewatin, Ontario. As a result, prospectors flocked to the Whiteshell area in search of gold. Some of the earliest mining claims made in Manitoba were in the Falcon-West Hawk-Star Lake district in 1901 (Whitesel 2001). 'Patent Mining Claims' purchased before 1914 enabled owners to construct homes on their plot. This initiated colonization of the area by Europeans. A few patent mining claims, which could not be bought by the government, constitute the only privately owned land in the park today. In 1907, James Westropp Brereton established the first homestead on Crown land at Cross Lake. Homesteads were also established in the area surrounding Brereton Lake after 1907, with the completion of the CNR through the area. Following World War I, 400 ha of Crown land within the George Lake district was distributed as 'soldier grants' to returning soldiers interested in farming (Suggett 1984). This area was not a profitable agricultural area due to thin, undesirable soils. As a result, most of the land was returned to the Crown (Suggett 1984). The fuel division of the Arctic Ice Company had a logging camp located at Florence Lake in the 1920s. The camp was complete with stables to accommodate seven teams of horses, a blacksmith shop, oil shed and a twenty-five ton capacity ice house (Zimmerman 1991). In 1929, the Arctic Ice Company ceased production at Florence Lake and cottage development commenced.

By the 1920s the recreational potential of the Whiteshell area had been recognized and the Crown set aside land around a few lakes for recreational purposes. As a result, summer resort lots were surveyed in areas around Brereton, Nora, Florence, West Hawk and Falcon Lakes, which were accessible by railroad. This would mark the beginning of recreational users in the Whiteshell area.

Whiteshell Provincial Park Inception

Establishment of outdoor recreational areas was initiated in the late nineteenth century by the creation of federal park reserves along the railway line. These reserves served as the future sites of National and Provincial Parks. In 1914, a 230 square mile area in south eastern Manitoba, the future site of the Whiteshell, was proposed as a forest reserve (Anonymous 1978). By 1927, two sites, Whiteshell and Riding Mountain were being considered as the future site of Manitoba's only National Park. Although Riding Mountain National Park was created by the Order-in Council, on December 28, 1929, the Whiteshell was still recognized as an important recreational area. In 1930, natural resources where transferred from Dominion to Provincial control. In that same year, the Manitoba Provincial Lands Act and the Forest Act were passed. The Manitoba Provincial Lands Act enabled the Province to reserve or dispose of its own land, mineral, water and timber resources. Under the Forest Act, Provincial Forest Reserve areas were 'withdrawn from disposition, sale, settlement or occupancy'(Anonymous 1978). As a result, the Whiteshell Forest Reserve was established in 1931. Although the Forest Act stipulated that this area would be withheld from sale or settlement, it was intended for public outdoor recreation. As a result, surveyed lots within the reserve were not sold but rather leased on a permit system following the precedent set by the "Rocky Mountain Park Act" of 1887. Surveyed lots were leased with annual permits which were perpetuity renewable, as long as lease terms were abided by(Anonymous 1978). Building plans were overseen and approved by the Forest Service and development of the Whiteshell area for recreational activities commenced.

Whiteshell Development

All land clearing and road construction initiated in the 1930s was completed by the Single Unemployed Men's Relief Commission, as overseen by the Forest Service. In 1931, the gravel Highway #44 was constructed to the Ontario border (Anonymous 1978). This provided recreational users further access to Falcon, West Hawk, Caddy, Star and Brereton Lakes. Between 1931 and 1933, access roads and forested land around surveyed lots in cottage subdivisions were cleared around these lakes. In 1932, the first public camping ground was cleared near West Hawk Lake for visitors using tents. In total, 218 camping permits were issued that year. By 1933, 400 surveyed lots with 137 under permit were dispersed along nine Whiteshell lakes (Anonymous 1978). In 1935, work began on a highway north of Highway #44, now known as #307. As construction progressed new lakes were opened up to recreational use and new cottage subdivisions were surveyed. In the 1940s, the Jessica Lake cottage subdivision and seven camp grounds throughout the Whiteshell were developed as were kitchenettes, docks and beach facilities. The #307 highway was completed in the 1950s and new cottage subdivisions were located on Big Whiteshell, Barren, Betula and other lakes (Anonymous 1978). While new subdivisions were constructed, extra lots were added to old subdivisions. Construction of the highways was fundamental to the development of the Whiteshell as a recreational area. The largest increase in recreational activity in the park occurred in the 1950s, when the number of permitted lots increased dramatically from 598 to 2 621 in 1950 and 1960 respectively (Anonymous 1978).

Commercial concessions and tourist camps were built on commercial lots within the park. In 1931, the first two stores were built at West Hawk Lake. By 1939, commercial bungalow camps were established at West Hawk, Falcon and Brereton Lakes. As a result, in 1946, the park boasted 90 tourist bungalows, five stores and three service stations. The Falcon Beach townsite was developed in the mid-1950s, with two motels opened in 1958. Falcon and West Hawk Lakes continued in the forefront of development with the establishment of seasonal trailer villages with sewer, water and electricity. In 1960 more seasonal trailer camps were developed in these areas and a third motel was constructed at Falcon Lake (Anonymous 1978).

By 1960, the Falcon Beach Townsite was developed with all amenities to be the 'commercial, service and recreational center' of the Whiteshell. The beach was improved, hard-surfaced roads with side-walks and gutters were built. The shopping center included a beauty salon, hardware store and pharmacy which enabled people access to all amenities within the park. Regular garbage collection was organized in more populated areas. Law enforcement became formalized with the establishment of an Royal Canadian Mounted Police. Marinas were established at this time on Falcon, West Hawk and White Lakes (Anonymous 1978).

Falcon Beach townsite was established as the 'game center' of the Whiteshell, and remains the most populated center in the Whiteshell today. In 1958, an 18-hole golf course was opened there. The following year, six tennis courts were asphalted and a riding stable was established. Further gaming development included a lawn bowling green and miniature golf course opened in 1963 (Anonymous 1978). Winter outdoor recreational activities were developed in the early 1960s at Falcon Lake. In 1960, the Falcon Lake ski slopes were opened including two cleared and graded slopes as well as rope tow and a temporary shelter. Winter recreation at Falcon Lake continued to grow and the ski slopes were upgraded with four new slopes cleared and a permanent chalet featuring a restaurant and equipment rentals was constructed (Anonymous 1978). Toboggan slides and skating rinks were also constructed for winter recreation. By the 1970s snowshoeing and cross-country ski trails were developed in the area for enthusiasts. As a result, the Whiteshell remained an important area which facilitated both summer and winter outdoor recreational activities.

Since the 1970s interpretative programs have been used to communicate with Whiteshell visitors to enhance their enjoyment of the Park. Interpreters improve visitor knowledge and appreciation of the park and its resources through education. Hiking trails, amphitheater programs and guided walks are used to educate visitors on important park features which may enhance their recreational experiences (Jones *et al.* 1980). There are numerous self-guiding trails throughout the park which provide thoughtful information on the trail and park. There are four outdoor amphitheaters throughout the park, which facilitate summer evening interpretive programs. Amphitheaters are located at Nutimik, Big Whiteshell, West Hawk and Falcon Lakes. Evening programs provide family entertainment and information on the park. Visitors may also explore Whiteshell history at the Whiteshell Natural History Museum, West Hawk Geology and Mining Museum and the Whiteshell Trapper's Museum (Schneider 2002). The Alfred Hole Goose Sanctuary in Rennie is another important tourist attraction for visitors interested in learning more about the park and its wildlife. Interpretive programs and facilities throughout the park enhance visitor understanding and appreciation of Whiteshell Provincial Park.

In 1939, portages were cleared and docks built to make the Whiteshell River more desirable to canoe enthusiasts. Since that time fire-pits have been installed in back-country campsites, portages have been cut and maintained between lakes and canoe routes have been mapped throughout the park (Anonymous 1978). Today there is an extensive network of canoe routes through intensive, extensive, backcountry and wilderness areas of the Whiteshell which attract visitors from around the globe.

Table A1: Whiteshell Provincial Park fishing culture stocking conducted in 2002 and 2003 by the Whiteshell fish hatchery.

Lake	Total Fish Stocked 2002 -2003	Date Stocked	Species	Life Stage
Betula	300 000	26/5/2002	Walleye	Fry
		16/5/2003	Walleye	Fry
White	1 100 000	25/5/2002	Walleye	Fry
		19/5/2003	Walleye	Fry
Jessica	500 000	6/5/2003	Walleye	Fry
Caddy	700 000	27/5/2002	Walleye	Fry
		16/5/2003	Walleye	Fry
Big Whiteshell	300 000	17/5/2003	Walleye	Fry
Green	0	n/a		
Red Rock	250 000	25/5/2002	Walleye	Fry
		14/5/2003	Walleye	Fry
Brereton	500 000	25/5/2002	Walleye	Fry
		14/5/2003	Walleye	Fry
		19/5/2003	Walleye	Fry
Hunt	6 000	15/5/2002	Brook Trout	18+ cm
		11/6/2002	Brook Trout	18+ cm
		10/6/2002	Rainbow Trout	18+ cm
Star	1 200 000	28/5/2002	Walleye	Fry
		24/5/2002	Walleye	Fry
		15/5/2003	Walleye	Fry
Falcon	5 350 000	26/5/2002	Walleye	Fry
		28/5/2002	Walleye	Fry
		15/5/2003	Walleye	Fry
		21/5/2003	Walleye	Fry
Barren	1 000 000	24/5/2002	Walleye	Fry
		14/5/2003	Walleye	Fry
Florence	300 000	28/5/2002	Walleye	Fry
		16/5/2003	Walleye	Fry
Lyons	4 540	31/5/2002	Splake	12-15 cm
		10/6/2002	Rainbow Trout	18+ cm
		22/5/2003	Rainbow Trout	Adult
Marion	300 000	29/5/2002	Walleye	Fry
		16/5/2003	Walleye	Fry
Sailing	800 000	25/5/2002	Walleye	Fry
		18/5/2003	Walleye	Fry
West Hawk	13 875	31/5/2002	Splake	12-15 cm
		31/5/2002	Lake Trout	12-15 cm
		20/5/2003	Walleye	Fry
Granite	200 000	18/5/2003	Walleye	Fry
South Cross	500 000	16/5/2003	Walleye	Fry

Appendices on CD

- Appendix A: Whiteshell Publications.
- Appendix B: Betula Lake Boat Lane Study.
- Appendix C: 2002 Whiteshell Resident Survey.
- Appendix D: Sediment Chemistry.
- Appendix E: Water Sampling Sites & Chemistry.
- Appendix F: Maps of *L. wollei* Distribution.
- Appendix G: Photographs