PROJECT REPORT
1999-18

sustainable forest management network

réseau sur la gestion durable des forêts

Influence of Landscape Features on the Water Quality of Boreal Plain Lakes: The Land-Aquatic Interface

A Network of Centres of Excellence
Un réseau de centres d'excellence

Ellie E. Prepas and Paul Dinsmore

For copies of this or other SFM publications contact:

Sustainable Forest Management Network
G208 Biological Sciences Building
University of Alberta
Edmonton, Alberta, T6G 2E9
Ph: (780) 492 6659
Fax: (780) 492 8160
http://www.biology.ualberta.ca/sfm/

ISBN 1-55261-032-2

Influence of Landscape Features on the Water Quality of Boreal Plain Lakes: The Land-Aquatic Interface

SFM Network Project: Impacts of Natural Disturbance and Forest Harvesting on Water Quality, Primary Producers and Invertebrate Communities in Boreal Plain Lakes

by

Ellie E. Prepas and Paul Dinsmore

Department of Biology
University of Alberta
Edmonton, AB T6G 2E9

July 1999

EXECUTIVE SUMMARY

Recently, forest harvesting activities have expanded within the Boreal Plain ecozone of western Canada. Very little is known about the effects of anthropogenic activities such as timber harvesting, or natural disturbances such as fire, on Boreal Plain aquatic systems. Previous work on lakes on the Boreal Plain had focused almost exclusively on lakes in settled regions, with relatively large agricultural and residential perturbations in their drainage basins. Further, the relationship between landscape features and water quality has not been documented for these nutrient-sensitive systems. This study focuses on determining what landscape features are responsible for the water quality variation seen in undisturbed Boreal Plain lakes. These patterns will then be used in combination with drainage basin-scale perturbations to compare harvesting and fire impacts on Boreal plain surface waters. The objectives of this project are to: 1) model the effects of drainage basin features, forest harvesting and fire disturbances on water quality and aquatic biota; 2) compare drainage basin disturbance-water quality interactions for the Boreal Plain study lakes in Alberta with those for similar studies in the Boreal Shield ecozone of Québec; and 3) contribute to a focus on land management in the Boreal forest, which includes the dynamic features of the landscape-surface water interface.

During July, August and September 1996 to 1998, we collected euphotic-zone water quality, primary producer (phytoplankton), zooplankton and benthic invertebrate data for 42 headwater lakes in northern Alberta. Additional data were included from 11 lakes in the Terrestrial Riparian Organisms Lakes and Streams (TROLS) study of harvesting impacts in Alberta to complement our field investigations. For select lakes, other primary producers (periphyton, epiphyton and macrophyte) and phosphorus-leaching potentials from representative soils were investigated. Lake surface area, volume, water residence times and mean and maximum depths, plus drainage basin areas, mean slope and major vegetation types were also estimated for each study system (lake + drainage basin). The Caribou Mountains Research Partnership (CMRP) also provided a basis for comparing heavily burned Boreal Subarctic systems in northern Alberta with burn-impacted Boreal Plain lakes.

It has taken three years and a combination of human- and naturally-derived factors to assemble the working basis for this project. Selection and study of lakes was initially hampered by the relatively water-short nature of the region and the lack of experienced pilots who could work with us on these inaccessible systems. The latter was overcome during 1998 with the initiation of a working partnership with a small Alberta-based company that invested in appropriate aircraft and personnel. In 1995, our opportunities to explore recent natural disturbances were limited to fires that were concentrated in areas with extensive wetlands. Further, the 1995 fires were very patchy in central Alberta; extensive burn data for 1995 are available only for wetland-dominated drainage basins underlain with permafrost in the Caribou Mountains (CMRP). In terms of harvesting, we originally had four upland-dominated systems selectively logged during the winter of 1995-1996, plus comparable data from seven TROLS lakes harvested during 1996-1997. Unfortunately, harvesting in most of these drainage basins was far less than originally proposed (on average less than 20%). Following three partner-based

workshops in the winter of 1997-1998, we enhanced the disturbance-impacts data set during 1998 by adding lakes perturbed by extensive upland-dominated fires, lakes with intensive harvesting near the shoreline, and lakes with potential substantive harvesting planned within the next two years.

Water quality data from lakes in unperturbed drainage basins were examined first to provide a baseline to evaluate disturbance impacts. This portion of the study focused on 26 unperturbed headwater lakes covering an area of 109 600 km^2, and included data from four similar lakes collected during the 1980s. The 26 lakes are small and shallow (mean surface area and depth = 1.33 km^2 and 2.6 m, respectively), with low drainage basin slopes (range: 0.1 to 10.6%). The unperturbed system database was divided into upland- (<50% wetlands by drainage basin area) and wetland- (>50% wetlands) dominated systems. Vegetation cover within the upland-dominated systems averaged 17% wetlands and 64% deciduous and 17% coniferous forest, while the wetland-dominated systems averaged 76% wetlands and 3% deciduous and 21% coniferous forest.

Water quality comparisons between lakes in these unperturbed upland- versus wetland-dominated systems revealed detectable differences ($P<0.01$) in dominant ions and colour, but no differences ($P>0.15$) in trophic parameters (e.g., total phosphorus, chlorophyll *a*, inorganic nitrogen). Lakes in wetland-dominated drainage basins on average had higher colour, lower pH and lower anion and base cation concentrations. The ratio of catchment (lake + drainage basin) area/lake volume was the best predictor of colour, dissolved carbon and total phosphorus in the upland-dominated systems (r^2 = 0.72, 0.23 and 0.55, respectively), whereas percent wetland was best for the same parameters within wetland-dominated systems (r^2 = 0.68, 0.70 and 0.71, respectively). Inorganic nitrogen was negatively related to percent wetland and percent conifer within upland- and wetland-dominated systems, respectively, but the relationships were weaker (r^2 = 0.36 and 0.38, respectively). The negative relationship suggests these landscape features may act to retain nitrogen within drainage basins. Biomasses of the phytoplankton taxon Chlorophyceae were greater in wetland- than upland-dominated systems, suggesting higher nitrogen availability.

Our study demonstrates it will be necessary to discriminate between wetland- and upland-dominated systems to understand and manage water quality in Boreal Plain drainage basins. We are exploring the concept of wetland impacts on water quality within the context of drainage basin-lake connectivity, and how these impacts may change when disturbance events enter this relationship. Currently, we are examining the role of disturbance in our weakly fire- and harvest-perturbed systems through residual analysis, and quantifying the locations of disturbed patches relative to drainage basin features to elucidate their influence on water quality and aquatic biodiversity. The Virginia Hills fire of 1998 provided a unique opportunity to collect burn impacts data for upland-dominated systems, allowing comparisons with harvesting impacts in similar systems. For the harvest impacts portion of the study, we added new lakes in 1998 with intensive near-shore harvesting, and lakes with potential substantive harvesting planned within the next two years. We are also working with our industrial partners to establish intensively harvested stream drainage basin studies in the Virginia Hills region. Finally, studies on short-term and historic perturbation response by primary producers, toxin-producing cyanobacteria and soil phosphorus release, including our partnership with the Little Red River Cree/Tallcree First Nations, remain ongoing as graduate student projects.

ACKNOWLEDGEMENTS

The concept of comparing lakes with perturbed drainage basins to lakes with relatively little recent perturbation in both the Boreal Plain and Boreal Shield ecozones was initially conceived during conversations with B. Pinel-Alloul, as part of the process of developing the SFMN proposal in December 1994. This concept was launched as parallel programs in eastern (Boreal Shield) and western Canada (Boreal Plain) following a meeting in August 1995 that included Pinel-Alloul, R. Carignan, R.H. Peters and Y. Prairie.

This report contains, and makes reference to, water quality and associated data collected in co-operation with other SFMN investigators, specifically D.H. Vitt and L.A. Halsey (wetland classification), J.J. Gibson and T.D. Prowse (lake water residence times), and D. Planas and S. Paquette (phytoplankton). This program was initially funded in part during 1995 and 1996 with an SFMN grant held by W.M. Tonn and E.E. Prepas. Tonn, Prepas, and C.A. Pazkowski, in collaboration with associates C. Goater, G.J. Scrimgeour and K.A. Westcott, selected the original study lakes. Further, Tonn collected most of the data used to generate the bathymetric information contained herein for lakes surveyed during 1996 and 1997. The Boreal Plain water quality sampling program was directed by Scrimgeour in 1996, jointly by Scrimgeour and W.P. Dinsmore in 1997 and by Dinsmore in 1998.

The reference lake data set has been worked into a manuscript for submission to a primary journal; a condensed version of this manuscript is contained herein. The manuscript has been reviewed by Gibson, Halsey, Pazkowski, Planas, Prowse, Scrimgeour, Tonn and Vitt; some of their input has been incorporated within this report.

Several graduate students (listed below) have made contributions to the water quality survey portion in Alberta. Their work will be presented to SFMN as separate reports/theses when they reach an appropriate stage.

i) N. Armstrong (M. Sc., U of A); Prepas and Planas (UQAM) co-supervisors. Supervisory committee includes industrial representative from Alberta Pacific Forest Industries Inc. Thesis title: “The influence of lake phosphorus content, morphometry and weather on the ability of phytoplankton to represent biotic responses to drainage basin perturbation: the case for the periphyton community”.

ii) T. Charette (M.Sc., U of A); Prepas and Planas co-supervisors. Supervisory committee includes an industrial representative from Daishowa-Marubeni International Ltd.

Tentative thesis title: "Effects of fire on phytoplankton biodiversity: a historic perspective".

iii) S. Nicopoulos (M.Sc., UQAM); Planas and Prepas co-supervisors. Tentative thesis title: "The influence of lake phosphorus content, morphometry and weather on the ability of phytoplankton to represent biotic responses to drainage basin perturbation: the case for the epiphyton and macrophyte communities".

iv) P. McEachern (Ph. D., U of A); Prepas and McCormick (U of A, Anthropology) co-supervisors. Supervisory committee includes industrial representative from Daishowa-Marubeni Industries and Chief Johnsen Sewepagaham of the Little Red River Cree Nation. Thesis title: "An end-member mixing model to predict the impact of drainage basin disturbance on streams and lakes of the Caribou Mountains, northern Alberta".

v) I. Whitson (Ph. D., U of A); Prepas and Chanasyk (U of A, Renewable Resources) co-supervisors. Supervisory committee includes industrial representative from Alberta Pacific Forest Industries Inc. Thesis title: "The potential for phosphorus export from luvisolic soils of northern Alberta, within the context of drainage basin disturbance".

vi) R. Zurawell (Ph. D., U of A); Prepas supervisor. Thesis title: "Cyanobacterial toxin occurrence in Alberta lakes and its relationship to drainage basin disturbance".

P. McEachern in particular has provided an extensive interface with regards to comparisons between Boreal Subarctic and Boreal Plain aquatic systems within the context of drainage basin disturbance. An associated manuscript, entitled "The impacts of forest fire on aquatic ecosystems in the Boreal Subarctic", will be submitted to a primary journal.

Funding additional to SFMN sources was provided from an NSERC Research grant to E.E. Prepas. E. Allen, R. Bennett, D. Millions, B. Gingras, K. Westcott and J. White assisted with database management and morphometric analyses. K. Wolfstein and K. Gibson contributed to reference lakes data analyses and to manuscript organisation and preparation. Reference lakes data for this project were contributed in part by the Terrestrial and Riparian Organisms, Lakes and Streams (TROLS) project, centred at the University of Alberta; we thank S. Reedyk, N. Scott, M. Serediak and P. Siwik for their support. We gratefully acknowledge the support given by our industrial (Alberta-Pacific Forest Industries Inc., Blue Ridge Lumber Ltd., Daishowa-Marubeni International Ltd., Millar Western Forest Industries Ltd., Weyerhaeuser Canada), First Nations (Little Red River Cree and Tallcree First Nations), and government (Alberta Environmental Protection) partners. Air transportation was supplied by B. Allison Flying Services, Little Red River Air Services, Slave Air and Voyage Air. Research facilities were supplied by the Meanook Biological Research Station, University of Alberta.

INTRODUCTION

As elsewhere, surface water quality and aquatic ecosystems within the Boreal Plain ecozone of western Canada are influenced by inputs (suspended and dissolved) of terrestrial origin entering via surface and subsurface runoff. Drainage basin vegetation is an important contributor to runoff chemistry (Engstrom 1987). Wetland cover in particular may have a large impact on Boreal Plain water quality, as a source of dissolved organic carbon (DOC) and, under certain circumstances, of much higher concentrations of nitrogen and other ions relative to upland ecosystems (Richardson 1989; Halsey et al. 1997). Disruption of drainage basin vegetation cover and soils by natural and human-derived processes can potentially influence groundwater and surface runoff water quality and ultimately the limnology of receiving water bodies (Dillon and Kirchner 1975; Likens 1984; Byron and Goldman 1989; Bayley et al. 1992).

During the past 50-100 years, accelerated eutrophication (excessive phytoplankton and macrophyte growth) coincided in many Boreal Plain lakes with agricultural and urban development in their drainage basins (Cooke and Prepas 1998; Manning et al., in press), with negative consequences for water quality (Prepas et al. 1997) and aquatic biodiversity (Schindler 1987). Timber harvesting, which has also significantly increased external nutrient loading patterns to lakes in other regions (Likens et al. 1970; Keenan and Kimmins 1993; Rask et al. 1993), has undergone substantial expansion in northern Alberta during the past decade (CCFM 1997). In light of this recent development, there is an understandable demand for information on the impact of timber harvesting and other land uses on surface water quality in the Boreal Plain. However, at the onset of this study, no information existed on drainage basin-surface water interactions for this region, with the exception of recent studies focusing on streams (Munn and Prepas 1986; Cooke and Prepas 1998) and wetlands (Halsey et al. 1997).

Knowledge of drainage basin-water quality interactions in the absence of disturbance is a prerequisite for aquatic resource management in the Boreal Plain ecozone. Starting in 1995, SFMN researchers undertook a widely-based field program to determine how drainage basin disturbance (fire and timber harvesting) might influence water quality and biotic responses in headwater lakes and streams in the boreal mixed-wood forests of western Canada. The objectives of this project were to:

i) assess the land-aquatic interactions for lakes in undisturbed drainage basins on the Boreal Plain, specifically the relationship between wetlands (defined as bogs, fens, swamps and marshes), relative catchment (drainage basin + lake) area, drainage basin slope, deciduous and conifer cover, and water quality variables such as nutrients (e.g., total phosphorus (TP), DOC and NH_4^+ concentrations) and dominant ions;

ii) use the above relationships to develop models describing the influences of forest harvesting and natural disturbance on water quality and aquatic biodiversity and community structure; and to

iii) compare and contrast effects documented for eutrophic Boreal Plain lakes in Alberta with a similar project in Québec focusing on less productive Boreal Shield lakes.

This report focuses on lake physical-chemical relationships; hydrological, wetlands and phytoplankton data are also provided where appropriate.

The selection of lakes in western Canada turned out to raise major challenges. There were no background data for our study on drainage basin-lake interactions for the Boreal Plain ecozone, although ample data have been assembled over the past two decades for the Boreal Shield. Timber harvesting is a very recent phenomenon for the Boreal Plain, relative to other regions of North America; thus, no data on long-term disturbance impacts are available. It may take many years of chronic disturbance before water quality impacts are detectable in Boreal Plain lakes; eutrophication in Alberta lakes with agricultural and residential perturbation was often not evident until several decades after settlement (Mitchell and Prepas 1990). Although large areas of Boreal Shield and Boreal Plain forests were burned in 1995, the Boreal Shield fires included merchantable timber, while the Boreal Plain fires were generally in wetland areas with less commercial importance. We were challenged with identifying patterns in lakes where drainage basins ranged from >50% wetland to white spruce/trembling aspen- (upland) dominated, and where the two forms of disturbance of interest were almost completely segregated between wetlands (fire) and uplands (harvesting). We chose to study small (mean surface area ~100-200 ha) headwater lakes within recent or projected fire- and harvest-impact sites in order to:

i) maximise the potential for large proportions of fire or harvest disturbance within small relative to large drainage basins;
ii) minimise variation in water quality associated with the relatively more complex morphometry of large lakes and the moderating influence of upstream lakes on drainage basin runoff; and
iii) allow comparisons between water quality trends documented for Boreal Plain systems with similar disturbance studies on the Boreal Shield that are also surveying small headwater lakes.

We were limited in the number of these lakes, particularly with burned and harvested drainage basins, which could be landed safely by floatplane. Originally, we could only land on lakes with a minimum longitudinal axis of 1 km in length. During 1998, we began a working partnership with a small Alberta-based charter company with appropriate aircraft and personnel that enabled us to select lakes with longitudinal axes as short as 500 m. Still, the size of the area of the Boreal Plain that we could economically access by air (109 600 km^2) excluded many potential study lakes.

To help address these challenges, the Boreal Plain water quality project within SFMN was linked to the TROLS (Terrestrial, Riparian, Organisms, Lakes & Streams) and CMRP (Caribou Mountains Research Partnership) programs, also centred in northern Alberta. These programs focus in part on the effects of forest harvesting (TROLS), and fire (CMRP) on water quality and biota in boreal lakes. We have compiled data for 81 remote lakes in northern Alberta

(42 this study, 11 TROLS and 28 CMRP), making it the most extensive study of its kind in western Canada. Where appropriate, we include water quality data generated by TROLS and CMRP within this study because:

i) the Boreal Plain ecozone includes drainage basins with large variations in topography, soil types and proportions of coniferous, deciduous and wetlands vegetative cover. To concentrate on disturbance effects, a substantial database is necessary to identify and partition out the background factors related to drainage basin characteristics that influence water quality;
ii) these data facilitate comparisons of disturbance impacts on lakes from aspen- (TROLS), coniferous- and permafrost- (CMRP), and mixedwood-dominated drainage basins (this study);
iii) these data enable us to examine how the proportion of drainage basin disturbance influences the magnitude of response within lake ecosystems. Currently, we have water quality data for systems burned during 1995, ranging from ~20% (core lakes, this study) to >80% (CMRP) of mean drainage basin area; and
iv) these data provide the opportunity to examine the generalities from intensive and process-orientated studies (e.g., hydrology, cyanobacteria, nutrient enrichment) initiated by the TROLS project.

We are also working with TROLS researchers in their experimental studies to identify the role of riparian buffer strips in minimising harvesting impacts on water quality and aquatic biota. While all provincial forest practice codes in Canada use riparian buffer strips to manage the land-water interface, current riparian buffer strip regulations in Alberta were developed outside the Boreal Plain ecozone, and thus are without ecological basis for this region. TROLS, with co-operation from our study, will provide a scientific basis for the design and management of riparian buffer strips for Boreal Plain forest practice codes. Our database is maintained separately from that of TROLS, yet data from each can be combined where appropriate to address specific questions. Our project also co-operates with TROLS personnel on field work logistics.

This report provides an overview of results to date from the Boreal Plain water quality project, covering the study period 1996 to 1998. The pre-treatment study (Section I) is nearing completion, while the disturbance impacts studies (Sections II and III) are works in progress, awaiting the incorporation of new data from 1998 and co-operation with the TROLS lake project:

I. Factors influencing water quality in lakes on the Boreal Plain: a comparison between wetland- and upland-dominated drainage basins;
II. Effects of fire and timber harvesting on Boreal Plain lakes in northern Alberta: preliminary results; and
III. Work in progress, plus new directions in the wake of the Virginia Hills Fire of 1998.

I. FACTORS INFLUENCING WATER QUALITY IN LAKES ON THE BOREAL PLAIN: A COMPARISON BETWEEN WETLAND- AND UPLAND-DOMINATED DRAINAGE BASINS

Introduction

Previous studies of drainage basin-surface water interactions in North America focused on using geographic characteristics such as lake morphometry, catchment hydrogeology, topography, drainage density, slope and land use to explain differences in water quality among lakes (Dillon and Kirchner 1975; Duarte and Kalff 1989; Rasmussen et al. 1989; Wolock et al. 1989; Soranno et al. 1996; D'Arcy and Carignan 1997). However, the majority of these relationships, established for lakes in the eastern and central regions of the continent, insufficiently explain water quality patterns observed in Boreal Plain lakes of western Canada.

Boreal Plain water quality differs in many ways from that of the more extensively studied Boreal Shield ecozone, due to the distinctiveness of their geological and climatic settings. Boreal Plain lakes, situated on thick, low-relief glacial tills, tend to be phosphorus (P)- and plankton-rich, yet relatively more nitrogen (N)-limited, than Boreal Shield lakes underlain by granitic bedrock (Neary et al. 1990; Mitchell and Prepas 1990). Internal P recycling from the sediments forms the major annual P input to the euphotic zone in Boreal Plain lakes (Shaw and Prepas 1990), whereas atmospheric P inputs dominates in Boreal Shield lakes where drainage basin area/ lake surface area ratios are small (D'Arcy and Carignan 1997). The Boreal Shield ecozone receives more precipitation on average than the Boreal Plain, where evapouration rates tend to be higher than precipitation (Mitchell and Prepas 1990). Wetlands (bogs, fens, swamps and marshes) are a prominent feature of the Boreal Plain landscape; Alberta, which is >50% Boreal Plain, has 17% wetlands coverage by province compared to 9% coverage for the Boreal Shield-dominated province of Québec (NWWG 1988; Vitt et al. 1998). Although wetlands have a significant impact on the chemistry of surface and subsurface runoff entering lakes (Halsey et al. 1997), they represented a minor portion of drainage basin area in most previous Boreal Shield-based studies (mean %wetlands per drainage basin: 7% (Dillon et al. 1991); 25% (Bayley et al. 1992) and 1.3% (D'Arcy and Carignan 1997). No data are available concerning drainage basin–lake interactions for poorly-drained, predominately wetland regions such as the Boreal Plain.

Knowledge of drainage basin-lake interactions in the absence of disturbance is a prerequisite for aquatic resource management strategies for this region. The purpose of this portion of the study was to assess variability in water quality for lakes in undisturbed drainage basins in the Boreal Plain ecozone. We focused on the relationship between water quality variables such as nutrients (phosphorus, carbon, and nitrogen) and dominant ions, with wetlands (classified into bogs, rich and poor fens, and swamps/marshes), catchment area (drainage basin + lake surface areas), drainage basin slope, and deciduous and coniferous tree cover.

Study Area

The 26 lakes examined in this portion of the project are located in an area covering 109 600 km^2 of northern Alberta (Fig.1). The surface waters of this region lie over a thick layer (up to 100 m) of unconsolidated glacial tills underlain by sedimentary bedrock (Pawlowicz and Fenton 1995). These tills are calcareous and rich in orthophosphate compounds, with equal amounts of sand, silt and clay-sized particles (Scott 1976). Soil types within the study region are typically organic in poorly drained areas and luvisolic/brunisolic in upland areas (Holowaychuk and Fessenden 1987). The drainage basins of all reference study lakes had minimal disturbance (<5% of natural vegetation removed) by natural processes or human activities within 50 years prior to our study. The study lakes are small (mean surface area = 0.82 km^2), shallow (average mean depth = 2.0 m) headwater lakes, reflecting a wide range of nutrient conditions from mesotrophic to hypereutrophic (Vollenweider 1968). We sampled 11 of the 26 study lakes, while the TROLS research project contributed data from another 11 lakes. Four other headwater lakes with low drainage basin disturbance studied previously (Mitchell and Prepas 1990) were chosen to complement the lakes by our study and to extend the range of depths and drainage basin slopes in our data set.

The study lakes are located in the Boreal Mixedwood ecoregion of the Boreal Plain ecozone (Strong and Leggat 1992). Deciduous and coniferous tree cover in the drainage basins range from 0 to 85 and 0 to 43%, respectively. Trembling aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), and white spruce (*Picea glauca*) are the dominant trees in the uplands whereas black spruce (*Picea mariana*) dominates the poorly drained areas. Wetlands cover between 0 to 99.7% of individual drainage basins. A drainage basin was defined as upland-dominated if it contained < 50% wetland by area, or wetland-dominated if it contained > 50% wetlands. In our data set, seven lakes had 50% or more wetland area in the drainage basin (mean wetland area of 76%). The remaining 19 lakes had a mean wetland area in the drainage basin of 17%. The majority of study lakes (22) are part of the Peace/Athabasca river drainage basins; the remaining four are in the adjacent North Saskatchewan/Beaver river drainage basins.

Climate for this region is dry continental. Thirty-year average annual precipitation ranges from 388 to 432 mm (33% as snow). Mean annual temperature ranges from 0.7 to 14 °C. During our sampling periods (June to September, 1996, 1997), the region received between 4% less and 52% more rain than the 30-yr normal, depending on location (Environment Canada, unpubl. data).

Methods

Twenty-two of the 26 lakes in this study were sampled a minimum of three times between mid-June to mid-September 1996. In 1997, 12 of these lakes were sampled again, while the drainage basins of the remaining 10 lakes were logged. The remote location and poor accessibility of these lakes (11 lakes were accessible only by air, while another 11 required access by all-terrain vehicle) limited the number of sampling trips possible. Comparable historic data for the remaining four lakes (Narrow, Long, Sauer, Moore) were obtained from Mitchell and Prepas (1990).

Samples for water quality analysis were collected from roughly the centre of each lake. Water quality parameters measured on-site included: 1) light extinction, measured with a LiCor Quantum Sensor meter at 0.5- to 1-m intervals from the lake surface to bottom; 2) dissolved oxygen and water temperature, measured with a YSI portable dissolved oxygen/ temperature meter along a similar gradient; and 3) water transparency, which was estimated with a Secchi disk. Vertically integrated water samples were collected from two sites in the euphotic zone (the section of the water column where photosynthesis can take place, or depths receiving ≥1% of surface light) with weighted Tygon tubing fitted with a one-way foot valve. Water quality parameters of interest were later analysed in the laboratory (see Prepas et al. (in prep.) for a detailed description of analysis methodology). In addition, stable isotope, phytoplankton, cyanobacterial toxin, and zooplankton samples were collected each trip; littoral macroinvertebrate samples were collected once per year in July.

Euphotic water quality parameters measured during 1996-1998 study

Dominant anions and cations	**Nutrients**	**Biogeochemical**
Chloride	Ammonium	pH
Sulfate	Nitrate + Nitrite	Colour
Sodium	Total Dissolved Nitrogen	Turbidity
Potassium	Particulate Nitrogen	Total Dissolved Solids
Calcium		
Magnesium	Dissolved Organic Carbon	Stable Isotopes
	Dissolved Inorganic Carbon	
Alkalinity	Particulate Carbon	Chlorophyll *a*
Conductivity		
	Total Phosphorus	Cyanobacterial Toxins
	Total Dissolved Phosphorus	
	Soluble Reactive Phosphorus	Phytoplankton
		Zooplankton
	Silica	Macroinvertebrates

Phytoplankton samples were identified, measured and counted with an inverted microscope following Sournia (1978). Cells from a constant area of the chamber bottom were counted under the microscope. Biodiversity was calculated as mean species richness, in each lake, for each year sampled (1996 and 1997).

Lake morphometric variables (surface area, volume, mean and maximum depths) were estimated using bathymetric maps created for each lake after depth data were collected at regular intervals along several transects per lake with a depth finder. Drainage basin areas and major vegetation types (bogs, fens, swamps, marshes, deciduous and coniferous tree cover) within each drainage basin were determined from 1:20 000 aerial photographs (Halsey and Vitt, unpubl. data). Mean drainage basin slope was estimated from 1:50 000 topographic maps following the method outlined in Rasmussen et al. (1989). Water residence times (in years) were calculated based on observed levels of evaporative isotopic enrichment in lake water with a steady-state isotope mass balance model (Gibson et al. 1993). Relationships between water quality and morphometric/drainage basin parameters for wetland- and upland-dominated systems were examined by linear and stepwise multiple regression.

Results and Discussion

The Boreal Plain lakes chosen for this study (Table 1) were more productive (mean TP of 54 vs. 8.66 $\mu g\ L^{-1}$; mean chl *a* of 19.0 vs. 2.72 $\mu g\ L^{-1}$, respectively) compared to a similar study conducted on the Boreal Shield (D'Arcy and Carignan 1997). Although drainage ratios (DBA/LA) were similar for both studies (7.86 vs. 7.55), our study had larger catchment areas (11.37 vs. 2.64 km^2, respectively), and less slope (mean slope1, slope2 = 2.84, 1.63% vs. mean CS1, CS2, CS3 = 12.9, 14.1, 11.9%, respectively; Table 2). Wetlands and deciduous cover (Tables 2 and 3) impacted more of our upland-dominated drainage basins (mean %wetland = 17.9 vs. 1.3%; mean %deciduous = 61.7 vs. 45.9 %), and conifer forest covered a lower percentage of either of our drainage basin types (mean %conifer = 17.8 and 21.1% in upland- and wetland-dominated, respectively, vs. 43.8%), relative to the Boreal Shield systems.

When the data from the 26 reference lakes were analyzed together, some patterns between drainage basin and water quality parameters emerged, but these patterns were generally weak. Chl *a* was strongly related to TP concentrations (r^2 = 0.70; $P \leq 0.001$), but the strongest relationship of TP concentration with a physical variable was with the ratio of catchment area to lake volume (CA/LV), accounting for 39% of the variation of TP concentration in our data set. Relationships were either weak or undetectable between log (TP) concentration and other physical variables such as drainage basin slope (r^2= 0.04, P>0.2), mean depth (r^2 = 0.26, $P \leq 0.001$) and vegetation features (%conifer, %wetland; r^2 = 0.20 and 0.04, P<0.01 and >0.2 respectively), in contrast to findings reported in other studies. Inorganic nitrogen (IN) was at best inversely related to the %conifer cover within the drainage basin (r^2 = 0.22; P<0.01). Similarly, drainage basin parameters were weakly related to DOC concentrations and colour for the 26-lake data set.

An investigation of water quality parameters between lakes in our upland- and wetland-dominated drainage basins revealed no detectable differences (P>0.15) in trophic parameters (e.g., TP, chl *a*, IN), however, detectable differences (P<0.01) were noted in variables that are based on dominant ions and colour. The lakes in wetland-dominated drainage basins were more coloured (mean colour = 186 vs. 38 mgL^{-1} Pt), had lower pH (pH = 5.7 vs. 7.6), and lower anion and base cation concentrations (e.g., mean HCO_3^- = 34 vs. 125 mgL^{-1}; mean Ca^{2+} = 10 vs. 25 mgL^{-1}) (Table 1). Upland-dominated drainage basins had steeper slopes with more deciduous cover, but coniferous cover was similar relative to wetland-dominated systems. Fens were the dominant wetland type in upland-dominated drainage basins, whereas bogs predominated in the wetland-dominated drainage basins (Table 2). Further analysis of our data set focused on separate analyses of upland- and wetland-dominated systems to clarify these relationships, unless otherwise stated. This is consistent with the literature; previous studies either excluded drainage basins with wetlands or were based on data collected from drainage basins with little wetland cover (e.g., D'Arcy and Carignan 1997).

In upland-dominated systems, CA/LV was the best predictor for nutrients other than IN (Table 4), suggesting that both internal and external sources are important for this lake type. In contrast, the best predictors of nutrients in wetland-dominated systems were %wetland and %conifer (Table 5). Soranno et al (1996) discussed the importance of determining which parts of a drainage basin are directly contribute nutrient inputs into water bodies. This effective contributing area may vary depending on rainfall and runoff. Since wetlands by definition form the majority of the drainage basin in these wetland-dominated systems, they must form the majority of the effective contributing area and, rather than CA/LV, define the operational limits of these drainage basins.

Colour and dissolved organic carbon

Lake water colour is an indicator of dissolved humic matter content, and can limit light availability for phytoplankton and macrophytes (Rasmussen et al. 1989). Colour was strongly influenced by wetland cover for lakes in wetland-dominated drainage basins (Equation 1), suggesting humic substance inputs from bogs and fens. In upland-dominated systems, colour was strongly related to CA/LV (Eq. 2). In both lake types, colour was inversely related to water residence time (Tables 4 and 5), consistent with *in-situ* removal of colour over time through photochemical and biological degradation (Engstrom 1987).

$$\text{Colour} = -190.295 \pm 76.804 + 4.973 \pm 0.990\ \%\text{wetland};\ r^2 = 0.68,\ P < 0.001 \quad [1]$$

$$\text{Log (Colour)} = 1.173 \pm 0.058 + 0.632 \pm 0.093\ \log(\text{CA/LV});\ r^2 = 0.68,\ P < 0.001 \quad [2]$$

Colour and DOC were related in both upland- and wetland-dominated systems (r^2=0.46 and 0.69, respectively). These relationships are weaker than those developed for the Precambrian Shield (Rasmussen et al. 1989), reflecting the larger contribution of autochthonous DOC by primary producers in the more productive Boreal Plain systems (Curtis and Prepas 1993). The stronger correlation of colour with DOC in the wetland-dominated systems is consistent with a relatively higher allochthonous DOC contribution from wetlands.

DOC concentrations were positively correlated with %wetland cover and negatively with %conifer cover in the wetland-dominated systems (Eq. 3, 4). The relationships between DOC and wetland coverage in the lakes in wetland-dominated drainage basins are consistent with those reported by Halsey et al. (1997) between DOC and bog coverage in lakes in the Birch Mountains of northern Alberta. As with colour, CA/LV was the best predictor of DOC in upland-dominated systems, although the model explained a lower proportion of overall variation (Eq. 5), again consistent with the hypothesis that autochthonous sources contribute a large proportion of DOC in these lakes.

$$\text{DOC} = -7.625 \pm 5.334 + 0.367 \pm 0.069\ \%\text{wetland};\ r^2 = 0.70,\ P \leq 0.001 \quad [3]$$

$$\text{DOC} = 31.389 \pm 2.185 - 26.621 \pm 4.448\ \text{arcsin sqrt}\ (\%\text{conifer});\ r^2 = 0.75,\ P \leq 0.001 \quad [4]$$

$$\text{DOC} = 11.175 \pm 4.599 + 12.151 \pm 5.728\ \log\ (\text{CA/LV});\ r^2 = 0.27,\ p < 0.055 \quad [5]$$

Engstrom (1987) suggested that drainage ratio (DBA/LA) was an important predictor of DOC for Precambrian Shield lakes where DBA/LA was <4. In our study, DBA/LA averaged 8.5 (Table 1), yet the related CA/LV was the best physical characteristic to predict DOC concentration in lakes with upland-dominated drainage basins (e.g., Eq. 5).

Phosphorus, nitrogen

Phosphorus is the key nutrient limiting phytoplankton (particularly cyanobacteria) biomass and productivity in Boreal Plain lakes (Trimbee and Prepas 1987). No detectable differences in TP and TDP concentrations existed between upland- and wetland- dominated systems ($P > 0.50$; Table 2). Both P fractions were positively correlated with DOC and colour, regardless of drainage basin type (Tables 4 and 5). Percent wetland was the strongest predictor of TP concentration in wetland-dominated systems (Eq. 6), while CA/LV was the strongest predictor of TP in upland-dominated systems (Eq. 7).

$$\log\ (\text{TP}) = 0.893 \pm 0.129 + 0.0107 \pm 0.002\ \%\text{wetland};\ r^2 = 0.78,\ P < 0.001 \quad [6]$$

$$\log\ (\text{TP}) = 1.399 \pm 0.063 + 0.495 \pm 0.103\ \log\ (\text{CA/LV});\ r^2 = 0.51,\ P < 0.001 \quad [7]$$

Dillon et al. (1991) and D'Arcy and Carignan (1997) also reported a positive relationship between wetland coverage and TP concentration, even though their Boreal Shield systems had relatively little wetland coverage. However, Eqn. 6 suggests a stronger relationship for Boreal Plain systems relative to the two op. cit. (r^2 = 0.38, 0.15, respectively). Richardson (1989) reported that wetlands with organic soil do not retain P as effectively as forested systems, and may therefore be more of a source than sink.

The pattern between in-lake TP concentration and relative drainage basin size in the upland-dominated drainage basins is the antithesis of that reported by D'Arcy and Carignan (1997). Schindler (1971) found a positive relationship between primary producers (chl *a* and midsummer phytoplankton production and biomass) and CA/LV for Boreal Shield lakes in northwestern Ontario and hypothesised that P and CA/LV would be similarly related.

Along with P, IN concentrations likely play an important role in defining phytoplankton community structure and occurrence of cyanobacterial toxins in Boreal Plain lakes (Kotak 1995). While mean IN concentrations covered two orders of magnitude across both lake types, there was no discernable difference in IN ($P > 0.15$) between drainage basin types (Table 1). Mean IN for the upland-dominated Boreal Plain systems was remarkably similar to values reported by D'Arcy and Carignan (1997) for Boreal Shield lakes (40 and 31 µg/L, respectively; Table 1).

NH_4^+ was the dominant form of IN the organically richer Boreal Plain lakes, compared to NO_3^- for Boreal Shield lakes. Nitrogen fixation forms the majority of IN inputs to Boreal Plain lakes, with minimal loading from terrestrial sources (Prepas and Trimbee 1988).

No strong predictors of IN emerged in our data set for either upland- or wetland-dominated systems. IN was related inversely to %conifer cover in the wetland-dominated systems (Eq. 8), while IN was inversely related to %wetland cover in the upland-dominated systems (Eq. 9).

$$IN = 498.825 \pm 149.126 - 826.969 \pm 303.588 \text{ arcsin sqrt (\% conif)};\ r^2=0.38,\ P = 0.02 \quad [8]$$

$$\log (IN) = 1.701 \pm 0.145 - 0.0152 \pm 0.007 \text{ \%wetland};\ r^2=0.18,\ P = 0.04 \quad [9]$$

Although portions of absolute conifer coverage were similar between the two drainage basin types (mean coverage = 18%), the proportion of conifer-dominated upland area was significantly higher for wetland- (74.5%) relative to upland-dominated systems (22.8%), which were dominated by trembling aspen. Conifer cover in upland areas may alter soil pH; thus, these areas may act as IN sinks within the drainage basin. D'Arcy and Carignan (1997) proposed that the relationship between wetlands and NH_4^+ may reflect an unrecognized topographic feature favouring IN retention. Further study in this area is needed to understand the mechanisms controlling these relationships in Boreal Plain systems.

Chlorophyll a and phytoplankton

Mean summer chl *a* concentrations were similar for both lake types, although individual means ranged from 2.5 orders of magnitude (Table 1). TP concentration was the best predictor of chl *a* for upland- and wetland-dominated systems (Eqns. 10 and 11, respectively).

$$\text{Log (chl } a) = -1.046 \pm 0.272 + 1.305 \pm 0.163 \log (TP);\ r^2=0.74,\ P < 0.001 \quad [10]$$

$$\text{Log (chl } a) = -1.39 \pm 0.553 + 1.50 \pm 0.323 \log (TP);\ r^2=0.64,\ P = 0.001 \quad [11]$$

Similarly to nutrients, chl *a* concentration was positively related with CA/LV (r^2=0.44 and 0.59 for upland- and wetland-dominated systems, respectively). As per Duarte and Kalff (1989), chl *a* was positively related to mean depth, and was stronger in the wetland- versus the upland-dominated systems (r^2 = 0.52, 0.39 respectively).

Although most groups of phytoplankton were similar, absolute and relative biomasses of Chlorophyceae were higher in the wetland-dominated systems, relative to both the upland-dominated systems in this study and previously studied Boreal Plain lakes (Mitchell and Prepas 1990). The predominance of Chlorophyceae in the wetland-dominated systems may coincide with greater availability of nitrogen relative to upland-dominated drainage basins. As well, absolute biomasses of Peridinae and relative biomasses of Cryptophycae were highest for wetland- and upland-dominated systems, respectively; biomasses of all three taxa were consistently elevated during both years of the study. Although there were no detectable differences in cyanobacteria abundances between the two lake types, cyanobacteria dominated the phytoplankton communities of many upland-dominated systems in this study, particularly Oscillatoriaceae, a taxon common in turbid, wind-mixed lakes (Reynolds et al. 1987).

Major ions

The relationships of major ions in the study lakes diverge from the patterns used to explain nutrients and drainage basin characteristics (Tables 6 and 7). The major anion in the study lakes is HCO_3^-; concentrations of SO_4^{2-} and Cl^- are much lower (Table 1). In both the upland- and wetland-dominated drainage basins, HCO^{3-} was strongly related to Mg^{2+} (r^2 = 0.82, 0.96 respectively; $P \leq 0.001$), depth (r^2 = 0.52 (Z_{mean}), 0.65 (Z_{max}) respectively; $P \leq 0.001$), and weakly inversely related to %bog (r^2 = 0.35, 0.31; $P<0.01$, 0.05 respectively). In the wetland-dominated drainage basins only, HCO_3^- was positively related to %fen (r^2 = 0.38, $P<0.05$). In the upland-dominated drainage basins, HCO_3^- was weakly related to τ and negatively related to colour (r^2 = 0.19, 0.25 respectively; $P<0.05$). In wetland-dominated drainage basins, where HCO_3^- concentrations are lower, a similar pattern can be seen with SO_4^{2-} (r^2 = 0.49, 0.30; $P<0.01$, <0.05;τ, colour respectively). CA/LV and slope were not correlated with anions in this data set.

The best predictors of most dominant cations in this study were other ions or depth variables. However, in upland-dominated systems Na^+ and K^+ were best related to drainage basin parameters. The best predictor of Na^+ concentrations was water residence time, followed by a weak negative relationship with CA/LV (r^2 = 0.44, 0.16; $P \leq 0.001$, <0.05, respectively). The best predictor of K^+ concentrations is %wetland as an inverse relationship (r^2 = 0.50; $P \leq 0.001$). In both upland- and wetland-dominated drainage basins, Mg^{2+} was related with %bog and %fen. While the relationship with %bog is inverse for both drainage basin types (r^2 = 0.37, 0.42; $P<0.01$, <0.05, upland, wetland respectively), the relationship with %poor fen is negative (r^2 = 0.23, $P<0.05$) for upland-dominated systems and positive with %fen (r^2 = 0.51, $P<0.01$) in wetland-dominated drainage basins. In the upland-dominated systems all cations except Ca^{2+} were positively related with water residence time (Table 6).

Many of our results for major ions are not consistent with previous findings for wetland-dominated Boreal Plain systems. Halsey et al. (1997) found inverse relationships between HCO_3^- and Mg^{2+} and %fen cover, whereas the same relationship was positive in this study. Drainage basin slope had no detectable influence on major ions in this study, contrary to D'Arcy and Carignan (1997), who reported inverse relationships between Ca^{2+}, Mg^{2+} and Na^+ with slope. The lack of relationships with slope in our data set could be a result of the relatively low relief in our drainage basins.

In summary CA/LV, as an estimate of potential drainage basin + atmospheric and/or internal loadings divided by the volume of the receiving water body, explained the most variation in DOC and TP concentrations in upland-dominated systems. In contrast, dominant drainage basin vegetation patterns, in particular wetland cover, was most closely related to DOC and TP in wetland-dominated drainage basins. Inorganic nitrogen was negatively correlated with percent wetlands and percent coniferous vegetation cover within upland- and wetland-dominated systems, respectively; the negative relationships suggest these vegetation types, or landscape features associated with them, may act to retain N within drainage basins. This study demonstrates the necessity of discriminating between wetland- and upland-dominated catchments to understand the impacts of land-based processes, both natural and human-related, on Boreal Plain surface waters. Also, this study suggests that potential disturbance impacts on surface water quality will be related to catchment size in upland-dominated systems, and to the proportion of wetlands impacted by disturbance in wetland-dominated systems.

II. EFFECTS OF FIRE AND TIMBER HARVESTING ON THE WATER QUALITY OF BOREAL PLAIN LAKES IN NORTHERN ALBERTA: PRELIMINARY RESULTS

Introduction

There has been growing interest in the forest products sector in natural disturbance patterns as templates for cut-block size and location, and the amount of residual timber left on the landscape. The implicit assumption is that mimicking natural disturbance will minimise disturbance impacts, encourage rapid recovery to pre-disturbance conditions and preserve biodiversity in terrestrial and aquatic ecosystems. Fire, as the dominant natural disturbance regime within the boreal forests of North America, can significantly alter external nutrient loading patterns to lakes, both directly in the short term (Bayley et al. 1992), and indirectly in the long term by influencing temporal and spatial patterns in vegetation community structure and soil composition (Larsen and MacDonald 1998). Large-scale fire disturbance should have similar impacts on Boreal Plain drainage basin-lake systems. However, little is known about disturbance-related changes in water quality within the boreal forests of western Canada, or of how the introduction of large-scale timber harvesting to the Boreal Plain will affect these as-yet undefined relationships.

Previous studies of timber harvesting (Likens et al. 1970; Keenan and Kimmins 1993; Rask et al. 1993) indicated that increased surface runoff and erosion after drainage basin disturbance led to increased nutrient inputs (primarily N and P) into surface waters. However, most previous studies were undertaken in the mountainous and coastal regions of western North America. Very little is known about the effects of timber harvesting on aquatic systems in the boreal forest in general, and the Boreal Plain ecozone in particular, where much of the future logging in Canada will occur. The Boreal Plain ecozone is unique relative to other regions of Canada because of the relatively low amount of surface water, its low topographic relief and the prevalence of fire as a natural disturbance regime. These aspects, combined with differences in soil characteristics and climate, make extrapolations from other studies to the Boreal Plain difficult.

The TROLS project is evaluating the role of riparian buffer strips and timber harvesting on lakes in Boreal Plain upland-dominated drainage basins. Up to 35% of the drainage basins of these lakes have been harvested (Prepas et al., in prep.). Over the course of two pre- and three post-harvest years, the TROLS study region has experienced both relatively wet and cool, and dry and warm annual conditions. This climatic variation necessitated the assessment of the importance of internal versus external P and N loading to the annual and seasonal variation in these aquatic systems. Large (up to 50%) increases in euphotic-zone TP concentrations were associated with both internal (within-lake) and external (drainage basin) loading, whereas similar increases in inorganic N (primarily NH_4^+) were associated with internal processes. The ratio of drainage basin area to lake volume was related to changes in post-harvest annual TP concentrations (r^2 = 0.69 and 0.46 during 1997 and 1998, respectively); the higher r^2 value for 1997 suggests that in-lake TP concentrations were more influenced by external inputs, relative to 1998. The remaining variability in lake TP appeared to be due to weather-related changes in internal P loading. These results from the TROLS study suggest that relative drainage basin size, and likely the proportion of disturbance within drainage basins, have an important effect on external loading of some important constituents into Boreal Plain lakes.

For the disturbance portion of the study, we are assessing how drainage basin-lake interactions developed for wetland-dominated systems with minimal perturbation (Section I, this report) are altered by fire. We are preparing drainage basin features of the lakes in upland-dominated drainage basins that were burned and first evaluated during 1998. We are also organising the drainage basin and lake data for a set of upland-dominated systems selectively harvested within the past three years (1996-1998), to compare with a set of similarly upland-dominated but relatively undisturbed systems on the Boreal Plain. For both disturbance regimes, we hypothesise that TP concentrations in receiving waters, and consequently chlorophyll *a* concentrations (as an indicator of eutrophication), will increase as a function of the relative size of the drainage basin and the proportion (as percentage area) of drainage basin disturbance. Increases in N in receiving waters will be a function of vegetative cover-disturbance interactions within drainage basins. Changes in water quality following disturbance will also be related to the location of burned or harvested areas within the drainage basin relative to the lake, and the extent to which intervening undisturbed vegetation features, such as wetlands and riparian areas, moderate nutrient export potential.

Methods

The eight lakes that were fire-impacted during May-June of 1995 have predominately wetland-dominated (> 50% by area) drainage basins. These lakes were sampled monthly from July-August during 1996 and 1997. Morphometric, drainage basin and euphotic-zone water quality data were collected, analysed and interpreted using methodologies identical to the reference systems study. These burned systems were compared to similarly wetland-dominated reference systems (Section I); significant (P < 0.05) differences were examined using *t*-tests modified for heterogeneous sample variance. Significant (P < 0.05) relationships between selected water quality and drainage basin parameters were examined by Pearson bivariate correlation. Percent wetland coverage per drainage basin was an effective predictor of colour, DOC and TP concentrations in the wetland-dominated reference systems, as presented earlier

(Eqns. 1, 3 and 6, respectively, Section I); these relationships were also examined for the burn-impacted systems. Percentage disturbance per drainage basin and elevation, as a surrogate parameter for regional effects such as differences in soils, precipitation, etc., were also tested.

Nine Boreal Plain lakes with upland-dominated drainage basins were selectively harvested, seven during the winter of 1995-1996 and two during the winter of 1997-1998. We collected summer (July-August) water quality data from four lakes from 1996-1998, one lake from 1996-1997 and four lakes (Kim, Boomerang, Cutblock and Beaverdam; Table 11) during 1998 only. Morphometric, drainage basin and euphotic-zone water quality data were collected, analysed and interpreted using methodologies identical to the reference and burn-impacted systems study. For these comparisons, we used the upland-dominated systems of the reference section, minus the four larger headwater lakes included in the unperturbed systems study. Significant ($P < 0.05$) relationships between selected water quality and drainage basin parameters were examined by Pearson bivariate correlation. Drainage basin parameters of particular interest were the ratio of catchment area to lake volume (CA/LV; Eqns. 2, 5 and 7, Section I), percent harvesting disturbance per drainage basin and elevation, as a surrogate parameter for regional effects such as differences in soils, precipitation, etc.

Results to Date

Burned systems

With the exception of the mean % fen per DBA, which was higher in the burned relative to the reference systems (44 and 30%, respectively; $P < 0.05$), drainage basin and lake morphometry parameter means and ranges were similar between the wetland-dominated burned and reference systems (Table 8). The average percent of drainage basin disturbance by fire for these study lakes was 19%, and ranged from 8 to 44% (Table 8).

Most water quality parameters measured during 1996 and 1997 in the 1995-burned lakes were similar to the wetland-dominated reference lakes during the same period (Table 9). Given the strong role played by wetlands in the unperturbed wetland-dominated drainage basins, we expect that only in-depth analyses of individual drainage basins will reveal perturbation effects in our impacted systems. Although silica concentrations were higher in the burn-impacted relative to the reference lakes (*t*-test; $P < 0.01$), silica was not correlated with a simple measure of %disturbance ($P > 0.6$). The amount of burn disturbance in the drainage basins we examined was relatively low (mean percent burned = 19%; Table 8); consequently, we expect that post-disturbance water quality impacts may be weak or take several years to develop. Also, given the low topography of these predominately wetland drainage basins (mean slope <2%), runoff may be slower to respond to perturbation than in drainage basins with steeper gradients, meaning that constituent loadings from the burned areas may be absorbed or otherwise altered during transit to the lake. Conductivity, HCO_3^-, alkalinity, Ca^{+2}, TDP, pH, and %disturbance were correlated with elevation ($P < 0.03$, 0.04, 0.02, 0.02, 0.03, 0.02, and 0.01, respectively), suggesting that regional differences in soils, hydrology, etc., between burn-impacted systems within this study may have an influence on observed trends in water quality. We are currently determining the positioning of burned patches within drainage basins to evaluate whether residuals between reference and burned wetland-dominated drainage basins are related to the amount of wetland or upland vegetation burned.

Harvested Systems

Drainage basin parameters were similar between the upland-dominated harvested and reference systems; however, lake-related physical parameters (surface area, mean depth, and volume) were on average smaller for the harvested systems (Table 10). There was a large range in CA/LV within the harvested systems relative to the reference group (3 to 48 versus 1.5 to 18, respectively; Table 10). Although mean values of parameters related to trophic indices (N, P and chl *a* concentrations) tended to be higher for harvest-impacted lakes relative to reference systems (Table 10), these trends need to be related to residual analysis to determine the relationship to drainage basin features.

III. WORK IN PROGRESS PLUS NEW DIRECTIONS IN THE WAKE OF THE VIRGINIA HILLS FIRE OF 1998

Work in Progress

For the burn impacts portion of this study, we are quantifying the proportions of major vegetation types (bog, fen and upland deciduous and coniferous stands) burned during 1995 for the wetland-dominated systems, and during 1998 for the upland-dominated systems currently under investigation. We hypothesise that the relative proportions of wetland/upland areas burned, in addition to their placement within the impacted drainage basin and the total size of the drainage basin, will have a role in determining whether changes in water quality are expected relative to unimpacted lakes. We expect that lake water quality will show greater responses to fire activity where the majority of disturbance occurs in upland as opposed to wetland areas, as surface and subsurface runoff from burned upland areas should transport more constituents directly into receiving water bodies. The location of burned patches within these impacted study systems will also be an important factor. We hypothesise that intervening wetland areas will absorb and "neutralise" chemical loadings from burned areas before they enter the lake. We will examine the distribution of standardised residuals generated for relationships between burned-impacted water quality and drainage basin parameters to determine effects of disturbance. Further, T. Charette (M.Sc. student) is quantifying long-term (<20-year) phytoplankton response to burn disturbance using sediment pigments analyses, in co-operation with one of our industrial partners.

We are also examining patterns in biotic communities as they relate to water quality in our study lakes, and how these patterns change with drainage basin disturbance. In a published study (Dinsmore et al. 1999), involving water quality data from this study, TROLS and CMRP, we found that profundal macroinvertebrate biomass was low in lakes with mean August dissolved oxygen below optimum concentrations of 4 mg/L. Thus, increased water column dissolved oxygen demand associated with eutrophication will likely negatively impact macroinvertebrate biomass, an important food item for many fish species. We are also working with Paquet and Planas (UQAM) on phytoplankton community relationships with burn disturbances in Boreal Plain lakes. In our wetland-dominated systems, densities of selected taxa were regressed against % wetlands (burned and reference systems) and % burn disturbance (burned). Preliminary results suggest that densities of most taxa were positively correlated with % wetlands, but negatively correlated with % burn disturbance.

A similar study of fire disturbance in wetland-dominated systems was undertaken in the Boreal Subarctic ecozone of northern Alberta (Caribou Mountains; McEachern et al., in prep.). This fire, which also occurred in 1995, was allowed to burn largely uncontrolled with resultant drainage basin disturbances ranging from 60 to 100%, compared to 8 to 44% for the Boreal Plain. The Caribou Mountains study area also has an extensive permafrost base; wetlands in the Caribou Mountains thus have a significantly thinner “active” layer to absorb nutrient and ion runoff inputs from disturbance, relative to wetlands in the Boreal Plain. Mean TP, dissolved phosphorus (DP) and soluble reactive phosphorus (SRP) concentrations, measured two years after the 1995 fire, were higher in the Caribou Mountains burned lakes (92, 50 and 27 µg/L, respectively), relative to the reference lakes (32, 14 and 5 µg/L, respectively). Similarly, mean TN and DN concentrations for the burned lakes were 825 and 632 µg/L, respectively, compared to 635 and 482 µg/L measured in the Caribou Mountains reference lakes. Following the inclusion of data from five additional Caribou Mountains lakes burned between 1961 and 1985, the combination of time since disturbance (years) and %disturbance explained 58% of variance in TP concentrations, suggesting that detectable fire impacts within lakes of this region may persist for decades. A comparison of our 1995- and 1998-burned Boreal Plain systems with McEachern et al.’s (In prep.) Caribou Mountains and D’Arcy and Carignan’s (1997) Boreal Shield systems should provide a basis for fire impacts on water quality within the diverse boreal forest of Canada.

For the timber harvesting impacts portion of this study, data analysis is in progress; particulate and total nitrogen, dissolved organic and particulate carbon, silica, pH, alkalinity and anion/cation analyses from 1998 have been completed and added to the existing database. Estimation of drainage basin boundaries and dominant vegetation of 11 lakes added to the lakes study in 1998 from aerial photographs has been completed by Halsey and Vitt. We are currently producing bathymetric maps for the new study lakes from depth data collected during the summer, from which we will calculate lake volume and mean depth. Stable isotope samples collected during 1998 are being analysed by Gibson; these data will be used to calculate water residence times for all lakes surveyed during 1998. These data, in co-operation with the TROLS data set, will form the basis for residual analysis of key parameters in the harvested lakes, relative to drainage basin features.

We feel that water quality responses for harvest-impacted systems require a broader range of perturbations. The TROLS project shows trends in post-harvest TP concentrations in lakes with relatively large drainage basin to lake volume ratios, although there were few lakes with large percentages of drainage basin disturbance; we would like to include upland-dominated systems with 50% or more harvesting in our study. The role of wetlands in moderating harvest impacts may be important in cases where wetland areas lie within surface and subsurface runoff pathways. As with the burned systems, we will generate standardised residuals from water quality/drainage basin parameter regressions, and examine the relationship of these residuals to %disturbance, catchment area/lake volume, and the locations of harvested areas within drainage basins. We will work with an industrial partner to co-ordinate removal of larger areas of timber in headwater systems.

New Directions

In 1995-96, we proposed an investigation of heterogeneity of water quality and biodiversity in Boreal Plain lakes, as it related to drainage basin characteristics and natural disturbance (fire). At the time, the program included lakes with drainage basins burned during the 1995 spate of fires, centred mainly in northeastern Alberta, and lakes with drainage basins harvested during 1995-1996. During analyses of the 1996 and 1997 water quality data, we ascertained clear differences between predicted water quality response to drainage basin disturbance in upland-versus wetland-dominated drainage basins. The Mariana Lakes Fire of 1995, from which most of our original fire database was derived, burned at a relatively low intensity (mean: 19% of drainage basin), in wetland-dominated areas without merchantable timber; most harvesting activity is restricted to upland regions where merchantable stands are likely to occur. Concentrating on modeling disturbance responses in upland-dominated systems would be more beneficial to the development of effective forest management policy.

In November 1997 and January and April 1998, the direction of the Boreal Plain water quality program was reviewed at a series of workshops held with our partners (including Alberta Pacific Forest Industries Inc., Alberta Environmental Protection, Daishowa-Marubeni International Ltd., Environment Canada, Little Red River Cree/ Tallcree First Nations, Millar Western Industries Ltd. and Weyerhaeuser Canada Ltd.) and SFMN theme representation (at the time EBS, P&P, SES and MIT). Specifically, we were encouraged to work with partners to:

i) locate burned systems in upland areas, comparable to sites preferred for harvesting, where the percent burn disturbance per drainage basin is 2-4 times greater than that in our existing data set, to enhance possibility of finding differences where they exist;

ii) establish pre- and post-disturbance data sets, to assist with obtaining clear results in a timely fashion;

iii) quantify the relative contributions of macrophytes, periphyton, epiphyton and phytoplankton to overall aquatic primary productivity, and how these contributions may change in the wake of drainage basin disturbance;

iv) document temporal changes, or succession in aquatic habitat and biota, by examining responses to historical fire events;

v) expand the current Boreal Plain water quality program to consider contaminants in addition to nutrients, to envelope human health concerns; and to

vi) prepare a report to partners outlining the locations of the 1996, 1997 study lakes, with key water quality parameter and biotic community information. This report, entitled "Workshop Proceedings Part I: Land-Water Interface Workshop November 1997", was distributed in December 1997.

As part of this redirection, we concentrated on collecting data from upland-dominated systems during 1998; most of its original wetland-dominated study lakes were dropped in favour of documenting water quality within drainage basins most likely to undergo harvesting. Eight lakes (lakes N13-N29; Table 11) were sampled a third consecutive year to contribute to a long-term database for Boreal Plain lakes which could be compared to year-to-year regional climatic variation. Still, many of the important recommendations arising from the fore-mentioned workshops were, prior to the summer of 1998, outside of the opportunities and resources available.

The Virginia Hills Fire of June 1998 afforded us the opportunity needed to study the effects of extensive burn disturbance on aquatic systems in an upland-dominated region with important reserves of merchantable timber. The warm and dry winter conditions in the Boreal Plain ecozone of western Canada following El Niño in 1997-1998, and the high occurrence of older, more fire-susceptible forest stands in central Alberta were important factors behind the above-average fire activity of summer 1998. The Virginia Hills Fire, the largest of more than 50 separate fires occurring that summer, burned at temperatures (> 300^{o}C) among the hottest recorded for North America. The amount of disturbance exceeded 90 % in some stream and lake drainage basins. Four burned and one reference system (Marigold – Shell S, Table 11) were selected along the burn periphery west of Swan Hills; percent burn disturbance is still to be quantified, but appears to cover >50% of all impacted drainage basins.

The Virginia Hills Fire also provided us with an opportunity to study the influence of fire disturbance on flowing waters in predominately upland Boreal Plain forest. As of 1998, there were six streams on the Boreal Plain of Alberta with intensive water quality data available: four in the Baptiste Lake drainage basin (Cooke and Prepas 1998) and two in the Virginia Hills (Munn and Prepas 1986). Of the previously studied Virginia Hills streams, the headwaters of one (Sakwatamau) was severely (>90%) burnt in 1998. Thus, pre-disturbance data were fortuitously available from Munn and Prepas (1986), and from an Environment Canada water quality monitoring project (1995-1997) on Sakwatamau and a second stream (Two Creek) just outside the fire. Data generated from this upland region will be compared to burn-impacts data for streams located within wetland-dominated drainage basins, burned during 1995, generated by

Dr. P. Chambers and associates of the National Water Research Institute in Saskatoon, in association with the TROLS project and Alberta-Pacific Forest Industries Inc.

In addition to continuing studies of fire impacts on nutrient transport into standing waters, we will collaborate with Alberta Health in using the Virginia Hills Fire to examine contaminant loadings in fish and wild game following fire events and their associated human health implications. A joint pilot sampling venture was conducted during fall 1998 on two burn-impacted (Sakwatamau and Freeman) and one reference (Little Smoky) streams; this survey will be expanded to also include contaminant loadings to lakes in the wake of burn disturbances.

Finally, the middle reach of the Sakwatamau River in the Virginia Hills is slated for intensive harvest by Millar Western Industries Ltd. in 2000-01, providing a further opportunity to study combined fire and harvesting impacts. As with the above comparisons of burned stream systems, we will have the opportunity to compare these proposed harvesting impacts on Virginia Hills streams with a similar project on the southeastern Caribou Mountains slopes. P. McEachern (Ph.D. student) has gathered pre-harvest water quality data for three streams in an area slated for harvesting during winter 1999-2000 by High Level Forest Products Ltd. Data from this comparison will contribute valuable data towards forest management in conifer-dominated regions of the Boreal Plain.

MANAGEMENT APPLICATIONS

The reference systems manuscript in preparation (Section I) lays the groundwork for associating patterns in nutrients and dominant ion chemistry to drainage basin features for Boreal Plain lakes. Our data suggest that disturbance impacts must be evaluated separately in upland- and wetland-dominated systems, or alternatively with a model which adequately features the role of wetlands. The reference systems data also suggest that the size of the drainage basin is an important influence on water quality, possibly by determining potential amounts of dissolved constituents entering the lake via surface and subsurface runoff.

Water quality in both perturbed and reference lakes exhibited a large degree of background variation, although in the reference data set drainage basin features could account for most of this variation. To effectively demonstrate short-term disturbance impacts on water quality, the ideal situation would be to survey extensive perturbations in similarly upland- or wetland-dominated study systems within a before- and after-disturbance experimental design, in addition to detailed analyses of our existing database to look for trends. This approach will yield a database upon which to build representative models of how aquatic systems react to perturbation on the Boreal Plain. Similar studies in the Boreal Shield of Québec and Ontario will contribute towards a national strategy for boreal forest management in Canada.

In addition to studying short-term responses to drainage basin disturbance within Boreal Plain aquatic systems (i.e., the effects of fire and harvesting events occurring between 1995 and

1998), we are examining long-term (20-year) patterns in disturbance response following historical fire events (T. Charette, M. Sc. student). The history of eutrophication of lakes over many years following settlement and agricultural expansion in the province of Alberta suggest that we may have to consider disturbance impacts at a larger temporal scale. Large-scale (>50% of drainage basin impacted) fire and harvesting disturbance appear to be the best way of demonstrating water quality impacts in Boreal Plain systems in a timely fashion (i.e., within a 1-3 years post-disturbance timeframe). As well, phytoplankton biomass is commonly held to represent whole-lake primary production, without consideration of the contributions made by macrophyte, epiphyton and periphyton communities. At present, no empirical models exist to describe their responses to drainage basin disturbance, or their contribution to total primary production in Boreal Plain lakes. Primary producer studies undertaken by two graduate students and one postdoctoral fellow (N. Armstrong, S. Nicopolos and K. Wolfstein, respectively) will help contribute to the empirical background necessary for effective legislation which couples landscape management with the land-aquatic interface.

Finally, initiatives developed with our partners to quantify organic contaminant dynamics in the wake of the 1998 Virginia Hills fire provide an important extension of current research on drainage basin disturbance regimes to include studies of the toxicological implications of forest fires for boreal ecosystem and human health.

CONCLUSIONS

Physical landscape features and patterns in dominant vegetative cover within drainage basins appear to have a strong influence on Boreal Plain lake water quality. In upland-dominated drainage basins, topographical features like CA/LV seem to control dissolved organic carbon and total phosphorus concentrations in lakes, whereas the percentage of wetland cover was most closely related to the same parameters in wetland-dominated drainage basins. Inorganic nitrogen was negatively related to percent wetland and percent conifer within upland- and wetland-dominated systems, respectively, but the relationships were weaker. As a result of our study of undisturbed lakes on the Boreal Plain, we suggest it will be necessary to discriminate between wetland- and upland-dominated systems to understand water quality patterns in disturbed drainage basin/ surface water systems.

All regions within a drainage basin do not contribute equally to constituent loadings entering a lake. The majority of loading usually comes from a contributing area much smaller than the drainage basin as defined by drainage basin boundaries (Soranno et al. 1996). Relative size of the contributing area is dependent on drainage basin topography, while a subregion of this area, known as the effective drainage basin area, changes in size within the contributing area according to seasonal variations in precipitation and evapotranspiration (McEachern et al., in prep.). We hypothesise that the low topographical relief of the Boreal Plain, coupled with the complex dynamics of water movement within bogs and fens (Halsey et al. 1997), will limit effective drainage basin areas to a small percentage of the total drainage basin. We, in co-operation with J. Gibson, are exploring calculations of effective drainage basin areas using the stable isotope methodology. J. Gibson is currently developing water quality/effective drainage basin models for its wetland and upland reference systems, in conjunction with similar analyses by P. McEachern for Boreal Subarctic systems. Once an adequate database is available, we will examine how reference system/ effective drainage basin dynamics change with the introduction of disturbance into the model.

It will prove fruitful to develop other forms of nutrient flux indices that better reflect the ability of a particular landscape feature to influence water quality. In the case of wetlands, T. Prowse has indicated that the degree of their "connectivity" to a lake, as a function of both distance and degree of spatial linkage to the lake, could determine the relative contribution of each wetland area to lake water quality. Although relationships between water quality and bog/fen coverage did not figure statistically in these analyses, the relative importance of bog and fen connectivity within drainage basins as a determinant of water quality may still prove important in further analyses. Also, the role of wetland disturbance on water quality needs to be explored; wetlands are often extensively disturbed during fire events, but minimally impacted during harvesting.

Water quality in the disturbance-impacted study lakes was highly variable, as was the case for the undisturbed reference lakes (Section I). The complex hydrological and aquatic dynamics in the Boreal Plain ecozone will necessitate the use of residual analysis as well as the separation of wetland- and upland-dominated drainage basins with extensive pre-/post-disturbance data. We anticipate that potential disturbance impacts on surface water quality will be related to catchment size in upland-dominated systems, and to the proportion of wetlands impacted by disturbance in wetland-dominated systems. We are exploring the role of wetlands in regulating runoff constituent loadings entering Boreal Plain lakes, and working with our industrial partners to collect pre- and post- intensive harvesting data for a selected group of lakes.

REFERENCES

Bayley, S.E., Schindler, D.W., Beaty, K.G., Parker, B.R., and Stainton, M.P. 1992. Effects of multiple fires on nutrient yields from streams draining boreal forest and fen drainage basins: Nitrogen and phosphorus. Can. J. Fish. Aquat. Sci. 49: 584-596.

Byron, E.R. and Goldman, C.R. 1989. Land-use and water quality in tributary streams of Lake Tahoe, California-Nevada. J. Environ. Qual. 18: 84-88.

Canadian Council of Forest Ministers (CCFM) 1997. Compendium of Canadian Forestry Statistics 1996. National Forestry Database Program. 234 pp.

Cooke, S.E. and E.E. Prepas. 1998. Stream phosphorus and nitrogen export from agricultural and forested drainage basins on the northern Boreal Plain. Can. J. Fish. Aquat. Sci. 55: 2292-2299.

Curtis, P.J. and Prepas, E.E. 1993. Trends of dissolved organic carbon (DOC) concentrations from freshwater to saltwater. Verh. Internat. Verein. Limnol. 25: 75-81.

D'Arcy, P and Carignan, P. 1997. Influence of catchment topography on water chemistry in southeastern Québec Shield lakes. Can. J. Fish. Aquat. Sci. 54: 2215-2227.

Dillon P.J., and Kirchner W.B. 1975. The effects of geology and land use on the export of phosphorus from drainage basins. Wat. Res. 9: 135-148.

Dillon, P.J., Molot, L.A. and Scheider, W.A. 1991. Phosphorus and nitrogen export from forested stream catchments in Central Ontario. J. Environ. Qual. 20: 857-864.

Dinsmore, W.P., Scrimgeour, G.J., and Prepas, E.E. 1999. Empirical relationships between profundal macroinvertebrate biomass and environmental variables in boreal lakes of Albert, Canada. Freshwater Biology, 41, 91-100.

Duarte, C.M., and Kalff, J. 1989. The influence of catchment geology and lake depth on phytoplankton biomass. Arch. Hydrobiol. 115: 27-40.

Engstrom, D. 1987. Influence of vegetation and hydrology on the humus budgets of Labrador lakes. Can. J. Fish. Aquat. Sci. 44: 1306-1314.

Gibson, J.J., Edwards, T.W.D., Bursey, G.G., Prowse, T.D. 1993. Estimating evaporation using stable isotopes: quantitative results and sensitivity analysis for two catchments in northern Canada. Nordic Hydrol., 24: 79-94.

Halsey, L.A., Vitt, D.H., and Trew, D.O. 1997. Influence of peatlands on the acidity of lakes in northeastern Alberta, Canada. Water, Air and Soil Pollut. 96: 17-38.

Holowaychuk N., and Fessenden, R.J. 1987. Soil sensitivity to acid deposition and the potential of soils and geology in Alberta to reduce the acidity of acidic inputs. Alberta Research Council, Earth Sciences Report 87-1.

Keenan, R.J. and J.P. Kimmins. 1993. The ecological effects of clear-cutting. Environ. Rev. 1: 121-144.

Kotak, B.G. 1995. Concentration and toxicity of microcystin-LR in compartments and organisms of aquatic food webs. Ph. D. thesis, University of Alberta, Edmonton AB.

Larsen, C.P.S. & MacDonald, G.M. 1998. An 840-year record of fire and vegetation in a boreal white spruce forest. Ecology 79: 106-118.

Likens, G.E., F.H. Bormann, N.M. Johnson, D.W. Fisher and R.S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook drainage basin-ecosystem. Ecol. Monogr. 40: 23-47.

Likens, G.E. 1984. Beyond the shoreline: A drainage basin-ecosystem approach. Verhandl. Intern. Verein. Theor. Angew. Limnol. 22: 1-22.

Mitchell P.A. and Prepas E.E. 1990. Atlas of Alberta Lakes. University of Alberta Press, Edmonton, Alberta.

Munn, N. and E.E. Prepas. 1986. Seasonal dynamics of phosphorus partitioning and export in two streams in Alberta, Canada. Can. J. Fish. Aquat. Sci. 43:2464-2471.

National Wetlands Working Group (NWWG). 1988. Wetlands of Canada. Sustainable Development Branch, Canadian Wildlife Service, Environment Canada, Ecological Land Classification Series No. 24, Polyscience Publications Inc., Montreal, Québec, Canada

Neary, B.P., Dillon, P.J., Munro, J.R, and Clark, B.J. 1990. The acidification of Ontario lakes: an assessment of their sensitivity and current status with respect to biological damage. Ont. Min. Env. Tech. Report.

Pawlowicz J.G., and Fenton, M.M. 1995. Drift thickness of Alberta. Alberta Geological Survey, Map No. 227.

Prepas, E.E., and Trimbee, A. 1988. Evaluation of indicators of N-limitation in deep prairie lakes with laboratory bioassays and limnocorrals. Hydrobiologia 159: 269-276.

Prepas, E.E., T.P. Murphy, W.P. Dinsmore, J.M. Burke, P.A. Chambers and S. Reedyk. 1997. Lake management based on lime application and hypolimnetic oxygenation: the experience in eutrophic hardwater lakes in Alberta. Water Qual. Res. J. Canada 32: 273-293.

Rask, M., L. Arvola and K. Salonen. 1993. Effects of catchment deforestation and burning on the limnology of a small forest lake in southern Finland. Verh. Internat. Verein. Limnol. 25: 525-528.

Rasmussen, J.B., Godbout, L., and Schallenberg, M. 1989. The humic content of lake water and its relationship to drainage basin and lake morphometry. Limnol. Oceanogr. 34: 1336-1343.

Reynolds, C.S., Oilver, R.L. and Walsby, A.E. 1987. Cyanobacterial dominance: the role of buoyancy regulation in dynamic lake environments. N.Z. J. Mar. Freshwat. Res. 21: 379-390.

Richardson, C.J. 1989. Freshwater wetlands: transformers, filters, or sinks? Freshwater wetlands and wildlife, DOE Symposium Ser. No. 61. Edited by R.R. Sharitz and J.W. Gibbons, USDOE office of scientific and technical information, Oak Ridge, Tennessee.

Schindler, D.W. 1971. A hypothesis to explain differences and similarities among lakes in the Experimental Lakes Area, northwestern Ontario. J. Fish. Res. Bd. Canada 28: 295-301.

Schindler, D.W. 1987. Detecting ecosystem responses to anthropogenic stress. Can. J. Fish. Aquat. Sci. 44: 6-25.

Scott, J.S. 1976. Geology of Canadian tills. In Glacial till: an interdisciplinary study. Edited by R.F. Legget. R. Soc. Can. Spec. Publ. No. 12: 50-66.

Shaw, J.F.H., and Prepas, E.E. 1990. Exchange of P from shallow sediments at nine Alberta lakes. J. Environ. Qual. 19: 249-256.

Soranno, P.A., Hubler, S.R., Carpenter, S.R. and Lathrop, R.C. 1996. Phosphorus loads to surface waters: A simple model to account for spatial patterns of land use. Ecol. Appl. 6: 865-878.

Souria, A. (ed.) 1978. Phytoplankton Manual. UNESCO, Paris. 337 p.

Strong, W.L., and Leggat K.R. 1992. Ecoregions of Alberta. Alberta Forestry, Lands and Wildlife, Land Information Services Division, Edmonton.

Trimbee, A.M. and Prepas, E.E. 1987. Evaluation of total phosphorus as a predictor of the relative biomass of blue-green algae with emphasis on Alberta lakes. Can. J. Fish. Aquat. Sci. 44: 1337-1342.

Vitt, D.H., Halsey, L.A., Thormann, M.N., and Martin, T. 1998. Peatland inventory of Alberta. Phase 1: overview of peatland resources in the natural regions and subregions of the province. Ecological Basis of Sustainability, Sustainable Forest Management Network, University of Alberta, Edmonton.

Vollenweider, R.A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Rep. DAS/CSI/68.27, Organisation for Economic Co-operation and Development, Paris.

Wolock, D.M., Hornberger, G.M., Beven, K.J., and Campbell, W.G. 1989. The relationship of catchment topography and soil hydraulic characteristics to lake alkalinity in the northeastern United States. Wat. Resour. Res. 25: 391-393.

Table 1. Water quality statistics for upland- and wetland- dominated reference lakes. Probabilities (*p*) calculated using a two-tailed t-test. S.E. = ±1 standard error. TP = total phosphorus; TDP = total dissolved phosphorus; Chl a = chlorophyll a; IN = inorganic nitrogen; DOC = dissolved organic carbon.

	Upland-dominated lakes (n=24)					**Wetland-dominated lakes (n=14)**					
Variable	**Mean**	*Median*	*SE*	**Min**	**Max**	**Mean**	*Median*	*SE*	**Min**	**Max**	***p***
TP (μg • L^{-1})	52	44	6.8	12	160	57	51	9.4	26	162	0.67
TDP (μg • L^{-1})	17	14	2.0	5.2	44	19	18	2.5	5.3	42	0.54
Chl *a* (μg • L^{-1})	18	13	3.4	2.0	76	21	14	4.6	2.0	57	0.67
NH_4^+ (μg • L^{-1})	35	18	8.3	2.5	149	136	27	89.9	6.4	1271	0.27
NO_3^- (μg • L^{-1})	5.5	4.8	0.6	1.1	13	11	4.4	6.7	1.1	99	0.38
IN (μg • L^{-1})	40	22	8.6	5.2	154	148	32	91.7	7.5	1281	0.26
SO_4^{2-} (mg • L^{-1})	7.1	2.5	3.1	0.1	74	4.2	0.8	2.2	0.2	25	0.44
Cl^- (mg • L^{-1})	1.4	0.4	0.8	0.1	20	0.3	0.3	0.03	0.1	0.6	0.18
Na^+ (mg • L^{-1})	8.7	4.9	3.6	1.0	88	2.4	1.3	0.7	0.3	8.8	0.09
DOC (mg • L^{-1})	15	13	1.0	10	29	20	18	2.1	10	33	0.05
Colour (mg • L^{-1} Pt)	38	31	5.2	8.0	125	186	191	29.1	29	358	0.0002
Alkalinity (mg • L^{-1})	110	99	14.4	40	389	28	13	8.4	2.9	95	0.00002
HCO_3^- (mg • L^{-1})	125	117	15.1	49	379	34	16	10.1	3.6	116	0.00002
pH	7.6	7.8		6.9	8.7	5.7	6.3		4.9	7.4	<0.00001
Si (μg • L^{-1})	1563	1304	235	56	4383	703	614	194	40	2750	0.008
Ca^{2+} (mg • L^{-1})	25	24	1.9	10	52	10	5.0	3.2	0.9	37	0.0002
Mg^{2+} (mg • L^{-1})	10	8.6	1.5	3.7	40	2.3	1.2	0.6	0.3	7.1	0.00003
K^+ (mg • L^{-1})	3.3	2.5	0.4	0.7	8	0.6	0.4	0.2	0.2	2.4	<0.00001
Conductivity (μS • cm^{-1})	265	234	33.5	100	910	80	55	23.3	11	271	0.00006

Table 2. Watershed and lake morphometry statistics for upland- and wetland-dominated reference study lakes. S.E. = ±1 standard error.

		Upland-dominated lakes (n=19)					Wetland-dominated lakes (n=7)				
Parameter	**Variable**	**Mean**	**Median**	**S. E.**	**Min**	**Max**	**Mean**	**Median**	**S. E.**	**Min**	**Max**
Catchment area (km^2)	CA	12.11	6.36	4.79	0.58	88.24	9.41	8.60	2.82	0.75	20.42
Drainage basin area (km^2)	DBA	10.71	5.75	4.37	0.49	82.40	8.27	6.99	2.64	0.56	18.80
Slope 1 (%)	SLOPE 1	4.06	3.50	0.51	1.10	10.60	1.13	0.80	0.47	0.30	3.90
Slope 2 (%)	SLOPE 2	2.28	1.90	0.36	0.20	6.50	0.79	0.60	0.29	0.10	2.30
Coniferous (% of DBA)	CON	17.5	15.4	2.8	1.2	42.4	21.1	20.1	6.7	0	43.2
Deciduous (% of DBA)	DEC	63.7	61.4	4.0	27.9	85.3	3.1	0	2.8	0	19.6
Wetlands (% of DBA)	WETL	16.5	16.2	2.3	0	43.7	75.6	71.3	7.1	56.8	99.7
Bogs (% of DBA)	BOG	2.4	1.0	1.1	0	19.6	43.9	46.3	11.3	11.0	85.5
Fens (% of DBA)	FEN	8.8	6.5	1.9	0	29.8	29.8	38.4	5.6	7.8	44.7
Swamps & marshes (% of DBA)	SWAMP	5.4	4.4	0.9	0	12.2	1.9	0.7	1.0	0	7.0
Lake elevation (m)	ELEV	633	625	11.3	549	740	613	576	36.4	505	730
Lake area (km^2)	LA	1.40	0.62	0.53	0.08	9.28	1.15	1.01	0.24	0.19	2.00
Mean depth (m)	Z_{mean}	3.8	3.3	0.7	0.9	14.4	1.3	1.1	0.27	0.67	2.9
Maximum depth (m)	Z_{max}	8.2	5.2	2.1	1.8	38.0	3.1	1.8	0.68	1.8	5.8
Lake volume ($m^3 \times 10^6$)	LV	8.00	1.74	4.19	0.27	77.40	1.80	1.47	0.70	0.19	5.72
Water residence time (years)*	τ	10.8	1.1	5.7	0.20	100	0.54	0.33	0.16	0.08	2.3
Drainage basin area/Lake volume	DBA/LV	3.6	2.8	0.86	0.48	16.7	6.5	3.4	2.5	1.3	19.7
Catchment area/Lake volume	CA/LV	4.0	3.0	0.91	0.56	17.8	7.4	4.1	2.6	2.0	21.2

*Upland-dominated lakes (n=24), wetland-dominated lakes (n=14) for this parameter only.

Table 3. Watershed and lake morphometry data for the 26 reference study lakes. ELEV = elevation above sea level; DBA = drainage basin; LA = lake area; LV = lake volume; CA/LV = catchment area/lake volume ratio; SLOPE 1 = drainage basin estimate 1; SLOPE 2 = drainage basin estimate 2; CON = % coniferous cover per drainage basin; DEC = % deciduous cover per drainage basin; WETL = % wetland cover per drainage basin; Z_{mean} = mean lake depth; Z_{max} = maximum lake depth.

Lake	Catchment Type	Year	Lat. (°N)	Long. (°W)	ELEV (m)	DBA (km^2)	LA (km^2)	LV (m^3x10^6)	CA/LV (m^{-1})	SLOPE 1 (%)	SLOPE 2 (%)	CON (%)	DEC (%)	WETL (%)	Z_{mean} (m)	Z_{max} (m)
N4	Wetland	1996, 97	55°43'	110°02'	576	0.56	0.19	0.19	3.90	3.9	2.3	43.0	0.0	57.0	1.01	5.49
N6	Wetland	1996, 97	56°13'	111°19'	720	4.28	0.90	0.96	5.42	0.8	1.2	28.0	0.0	71.3	1.06	1.83
N7	Wetland	1996, 97	56°10'	111°32'	721	1.87	1.01	1.47	1.96	0.8	0.8	43.2	0.0	56.8	1.45	3.35
N8	Wetland	1996, 97	56°27'	112°31'	505	9.14	0.69	0.46	21.15	0.5	0.1	8.0	0.3	91.7	0.67	1.83
N9	Wetland	1996, 97	56°15'	112°20'	522	18.80	1.62	1.73	11.80	0.3	0.3	5.2	1.8	93.1	1.07	1.83
N16	Wetland	1996, 97	55°45'	112°50'	552	6.99	1.62	2.08	4.14	0.6	0.2	0.0	0.0	99.7	1.29	1.83
N26	Wetland	1996, 97	56°49'	116°27'	686	16.22	2.00	5.72	3.18	1.0	0.6	20.1	19.6	59.8	2.87	5.79
N5	Upland	1996, 97	55°49'	110°28'	555	5.15	1.20	1.38	4.60	1.4	1.2	28.5	27.9	43.7	1.15	4.57
N11	Upland	1996	55°08'	111°45'	552	5.75	0.62	2.51	2.53	8.0	3.5	6.8	83.1	9.9	4.09	4.00
N20	Upland	1996, 97	54°59'	113°38'	648	4.52	0.30	0.27	17.84	3.3	2.0	26.4	61.4	10.8	0.89	1.83
N24	Upland	1996, 97	56°47'	114°13'	625	1.51	0.25	0.49	3.60	6.6	3.4	14.2	65.3	20.5	1.93	3.96
N29	Upland	1996, 97	56°55'	116°40'	716	2.58	1.70	2.32	1.84	2.6	0.7	23.7	33.4	23.8	1.37	2.44
N31	Upland	1996	55°08'	111°39'	640	1.06	0.14	0.42	2.86	4.7	4.7	9.4	85.3	5.3	3.02	5.20
N32	Upland	1996	55°10'	111°54'	617	1.88	0.33	0.63	3.50	3.3	1.4	4.2	72.6	22.1	1.91	3.20
N33	Upland	1996	55°12'	111°38'	587	4.73	1.04	3.88	1.48	3.6	1.7	3.0	83.5	13.6	3.75	6.80
N34	Upland	1996	55°11'	113°39'	625	6.31	0.52	2.52	2.71	3.5	1.7	5.6	81.2	11.1	4.80	11.20
N35	Upland	1996	55°05'	113°46'	625	2.63	0.18	0.62	4.58	3.0	3.7	3.0	70.1	25.4	3.35	6.50
N37	Upland	1996, 97	55°07'	113°43'	640	6.50	0.74	1.85	3.92	1.1	0.2	1.2	82.2	16.2	2.48	2.20
N38	Upland	1996	55°25'	113°42'	682	10.02	1.57	7.66	1.51	4.5	0.3	42.4	44.5	13.0	4.89	8.10
N39	Upland	1996	55°21'	113°43'	625	7.02	0.56	0.77	9.83	3.9	2.5	18.9	59.5	21.5	1.38	2.20
N40	Upland	1996	55°23'	113°38'	640	9.53	0.45	1.74	5.73	3.7	1.9	28.8	58.6	12.6	3.84	8.50
N41	Upland	1996	55°22'	113°38'	617	6.19	0.65	1.57	4.36	3.9	3.3	15.4	59.4	20.7	2.42	3.60
Narrow	Upland	1983	54°35'	113°38'	685	8.06	1.14	16.40	0.56	3.4	1.4	25.5	52.0	21.2	14.40	38.00
Sauer	Upland	1982	53°37'	114°05'	735	0.49	0.09	0.35	1.63	10.6	6.5	40.0	60.0	0.0	4.20	8.50
Long	Upland	1983	54°26'	112°45'	621	82.40	5.84	29.30	3.01	3.4	2.0	15.0	83.0	0.0	4.30	9.00
Moore	Upland	1980	54°31'	110°31'	549	37.10	9.28	77.40	0.60	2.6	1.3	20.7	48.0	22.9	8.30	26.00

Table 4. Pearson correlation coefficients of the most important morphometric variables and water quality data of 19 upland lakes (n=24 when 1996 and 1997 data included). DOC, log_{10} dissolved organic carbon; COL, log_{10} colour; CHLA, log_{10} chlorophyll a; TP, log_{10} total phosphorous; TDP, log_{10} total dissolved phosphorous; NH4, log_{10} ammonium; NO3, nitrate; IN, log_{10} inorganic nitrogen; SI, silica; CA/LV, Log_{10} catchment area/lake volume; SLOPE 1, Arcsine square root transformed catchment slope 1; SLOPE 2 Arcsine square root transformed catchment slope 2; WETL, % of dba composed of wetlands; CON, % of dba with conifer cover; τ, water residence time, Z_{max}, log_{10} maximum lake depth; Z_{mean}, log_{10} mean lake depth.

	COL	CHLA	TP	TDP	NH4	NO3	IN	SI	CA/LV	SLOPE 1	SLOPE 2	WETL	CON	τ	Z_{max}	Z_{mean}
DOC	0.68**	0.56**	0.54**	ns	ns	ns	ns	ns	0.47*	ns	ns	ns	ns	ns	-0.51*	-0.65*
COL		0.63**	0.72**	0.52**	ns	ns	ns	ns	0.82**	ns	ns	ns	ns	-0.65**	-0.85**	-0.83**
CHLA			0.86**	0.65**	0.50*	ns	0.48*	ns	0.66**	ns	ns	ns	ns	ns	-0.52**	-0.62**
TP				0.86**	0.54**	ns	0.52**	ns	0.72**	ns	ns	ns	ns	ns	-0.72**	-0.66**
TDP					0.61**	ns	0.59**	ns	0.49*	ns	ns	-0.53**	ns	ns	-0.55**	ns
NH4						0.42*	0.99**	ns	ns	ns	ns	ns	ns	ns	ns	ns
NO3							0.52*	ns	ns	ns	ns	ns	ns	ns	ns	ns
IN								ns	ns	ns	ns	-0.42*	ns	ns	ns	ns
SI									0.44*	ns	ns	ns	ns	ns	ns	ns
CA/LV										ns	ns	ns	ns	-0.52**	-0.73**	-0.77**
SLOPE 1											0.76**	-0.54**	ns	ns	ns	ns
SLOPE 2												ns	ns	ns	ns	ns
WETL													ns	ns	ns	ns
CON														ns	ns	ns
τ															0.54**	0.47*
Z_{max}																0.88**

** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 5. Pearson correlation coefficients of the most important morphometric variables and water quality data of 7 wetland lakes (n=14 when 1996 and 1997 data included). DOC, dissolved organic carbon; COL, colour; CHLA, $\log_{10}$ chlorophyll a; TP, $\log_{10}$ total phosphorous; TDP, total dissolved phosphorous; NH4, ammonium; NO3, nitrate; IN, inorganic nitrogen; SI, $\log_{10}$ silica; CA/LV, $\log_{10}$ catchment area/lake volume; SLOPE 1, catchment slope 1; SLOPE 2, Arcsine square root transformed catchment slope 2; WETL, % of dba composed of wetlands; CON, Arcsine square root % of dba with conifer cover; τ, $\log_{10}$ water residence time; Z_{max}, maximum lake depth; Z_{mean}, $\log_{10}$ mean lake depth.

	COL	**CHLA**	**TP**	**TDP**	**NH4**	**NO3**	**IN**	**SI**	**CA/LV**	**SLOPE 1**	**SLOPE 2**	**WETL**	**CON**	**τ**	**Z_{max}**	**Z_{mean}**
DOC	0.83**	ns	0.74**	0.68**	0.55*	ns	0.57*	ns	ns	ns	-0.62*	0.84**	-0.87**	ns	ns	ns
COL		ns	0.67**	0.56*	ns	ns	ns	ns	0.61*	ns	ns	0.82**	-0.69**	-0.63*	-0.62*	-0.57*
CHLA			0.80**	ns	ns	ns	ns	ns	ns	-0.82**	-0.77**	0.77**	-0.74**	ns	-0.75**	ns
TP				0.85**	ns	0.70**	ns	ns	ns	ns	-0.69**	0.88**	-0.93**	ns	-0.60*	ns
TDP					0.57**	0.72**	0.61*	ns	ns	ns	ns	0.65*	-0.75**	ns	ns	ns
NH4						ns	0.99**	ns	ns	ns	ns	ns	-0.59**	ns	ns	ns
NO3							ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
IN								ns	ns	ns	ns	ns	-0.62*	ns	ns	ns
SI									ns	ns	ns	ns	ns	ns	ns	ns
CA/LV										ns	-0.53*	0.69**	ns	-0.57*	-0.55*	-0.73**
SLOPE 1											0.83**	-0.57*	0.57*	ns	0.68**	ns
SLOPE 2												-0.78**	0.81**	ns	0.60*	ns
WETL													-0.93**	ns	-0.79**	ns
CON														ns	0.58*	ns
τ															ns	0.84**
Z_{max}																0.59*

** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 6. Pearson correlation coefficients between water quality variables and selected lake and watershed morphometric variables in upland-dominated lakes (n=24). HCO3, $\log_{10}$ bicarbonate; SO4, $\log_{10}$ sulfate; Cl, chloride; Ca, calcium; Mg, $\log_{10}$ magnesium; Na, Sodium; K, $\log_{10}$ potassium; COL, $\log_{10}$ colour; CA/LV, $\log_{10}$ catchment area / lake volume; SLOPE 1, Arcsine square root transformed catchment slope 1; SLOPE 2 Arcsine square root transformed catchment slope 2; WETL, % of dba composed of wetlands; CON, % of dba with conifer cover; τ, water residence time; Z_{max}, $\log_{10}$ maximum lake depth; Z_{mean}, $\log_{10}$ mean lake depth.

	SO4	**Cl**	**Ca**	**Mg**	**Na**	**K**	**COL**	**CA/LV**	**SLOPE 1**	**SLOPE 2**	**WETL**	**CON**	**τ**	**Z_{max}**	**Z_{mean}**
HCO3	0.48*	0.52**	0.51*	0.91**	0.63**	0.41*	-0.50*	ns	ns	ns	ns	ns	0.44*	0.68**	0.72**
SO4		ns	0.43*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cl			ns	0.64**	0.98**	ns	ns	ns	ns	ns	ns	ns	0.69**	0.44*	ns
Ca				0.51*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Mg					0.71**	0.41*	ns	ns	ns	ns	ns	ns	0.48*	0.62**	0.60**
Na						ns	ns	ns	ns	ns	ns	ns	0.66**	0.50*	0.41*
K							-0.50*	-0.41*	ns	ns	-0.71**	ns	0.52**	ns	0.58*
COL								0.82**	ns	ns	ns	ns	-0.65**	-0.85**	-0.83**
CA/LV									ns	ns	ns	ns	-0.52**	-0.73**	-0.77**
SLOPE 1										0.78**	-0.54**	ns	ns	ns	ns
SLOPE 2											ns	ns	ns	ns	ns
WETL												ns	ns	ns	ns
CON													ns	ns	ns
τ														0.54**	0.47*
Z_{max}															0.88**

** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 7. Pearson correlation coefficients between water quality variables and selected lake and watershed morphometric variables in wetland-dominated lakes (n=14). HCO3, Log_{10} bicarbonate; SO4, sulfate; Cl, chloride; Ca, Log_{10} calcium; Mg, Log_{10} magnesium; Na, Log_{10} sodium; K, potassium; COL, colour; CA/LV, Log_{10} catchment area / lake volume; SLOPE 1, catchment slope 1; SLOPE 2 Arcsine square root transformed catchment slope 2; WETL, & of dba composed of wetlands; CON, Arcsine square root % of dba with conifer cover; τ, Log_{10} water residence time; Z_{max}, maximum lake depth; Z_{mean}, Log_{10} mean lake depth.

	SO4	**Cl**	**Ca**	**Mg**	**Na**	**K**	**COL**	**CA/LV**	**SLOPE 1**	**SLOPE 2**	**WETL**	**CON**	**τ**	**Z_{max}**	**Z_{mean}**
HCO3	0.66*	ns	0.97**	0.98**	ns	0.66*	ns	ns	ns	ns	ns	ns	ns	0.81**	ns
SO4		ns	0.65*	0.65*	ns	0.98**	-0.55*	ns	ns	ns	ns	ns	0.70**	0.62*	0.82**
Cl			ns	ns	ns	ns	0.56*	ns	ns	ns	ns	ns	ns	ns	ns
Ca				0.98**	ns	0.66*	ns	ns	ns	ns	ns	ns	ns	0.75**	ns
Mg					ns	0.66*	ns	ns	ns	ns	ns	ns	ns	0.85**	ns
Na						ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
K							-0.60*	ns	ns	ns	ns	ns	0.74**	0.63*	0.84**
COL								0.61*	ns	ns	0.82**	-0.69**	-0.63*	-0.62*	-0.56*
CA/LV									ns	-0.53*	0.69**	ns	-0.57*	-0.55*	-0.73**
SLOPE 1										0.83**	-0.57*	0.57*	ns	0.68**	ns
SLOPE 2											-0.78**	0.81**	ns	0.60*	ns
WETL												-0.93**	ns	-0.79**	ns
CON													ns	0.58*	ns
τ														ns	0.84**
Z_{max}															0.59*

** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 8. Drainage basin and lake morphometry statistics for wetland-dominated reference and burned study systems. S.E. = ±1 standard error.

		Wetland-dominated reference (n=7)					Wetland-dominated burned (n=8)				
Parameter	**Variable**	**Mean**	**Median**	**S. E.**	**Min**	**Max**	**Mean**	**Median**	**S. E.**	**Min**	**Max**
Catchment area (km^2)	CA	9.41	8.60	2.82	0.75	20.42	8.95	7.57	2.62	1.83	20.51
Drainage basin area (km^2)	DBA	8.27	6.99	2.64	0.56	18.80	8.02	6.54	2.49	1.39	19.46
Coniferous (% of DBA)	CON	21.1	20.1	6.7	0	43.2	17.7	16.8	4.5	0	35.9
Deciduous (% of DBA)	DEC	3.1	0	2.8	0	19.6	12.2	2.8	5.6	0	38.6
Wetlands (% of DBA)	WETL	75.6	71.3	7.1	56.8	99.7	69.8	36.1	5.9	50.4	100
Bogs (% of DBA)	BOG	43.9	46.3	11.3	11.0	85.5	21.2	14.3	7.6	0	54.5
Fens (% of DBA)	FEN	29.8	38.4	5.6	7.8	44.7	43.7	44.3	2.1	31.6	51.3
Swamps & marshes (% of DBA)	SWAMP	1.9	0.7	1.0	0	7.0	5.0	2.3	2.7	0	22.2
Lake area (km^2)	LA	1.15	1.01	0.24	0.19	2.00	0.92	0.63	0.21	0.40	2.05
Mean depth (m)	Z_{mean}	1.3	1.1	0.27	0.67	2.9	1.3	1.1	0.2	0.7	2.5
Maximum depth (m)	Z_{max}	3.1	1.8	0.68	1.8	5.8	3.3	2.0	1.2	1.5	11.6
Lake volume ($m^3 \times 10^6$)	LV	1.80	1.47	0.70	0.19	5.72	1.18	0.98	0.29	0.32	2.55
Water residence time (years)*	τ	0.54	0.33	0.16	0.08	2.3	0.40	0.22	0.12	0.08	1.56
Drainage basin area/Lake volume	DBA/LV	6.5	3.4	2.5	1.3	19.7	7.6	5.6	2.2	1.6	17.5
Catchment area/Lake volume	CA/LV	7.4	4.1	2.6	2.0	21.2	8.5	6.4	2.3	2.0	18.4
Disturbance (% of DBA)	DISTURB	-----	-----	-----	-----	-----	18.9	14.7	4.1	8.1	44.2

*Wetland-dominated reference (n=14) and burned (n=16) for this parameter only.

Table 9. Summer (July-September) means for water quality parameters measured in wetland-dominated reference and burned systems, 1996-1997. S.E. = ±1 standard error. TP = total phosphorus; TDP = total dissolved phosphorus; Chl a = chlorophyll a; IN = inorganic nitrogen; TN = total nitrogen; DOC = dissolved organic carbon.

	Wetland-dominated reference (n=14)					Wetland-dominated burned (n=16)				
Variable	**Mean**	*Median*	*SE*	**Min**	**Max**	**Mean**	*Median*	*SE*	**Min**	**Max**
TP (µg • L^{-1})	57	51	9.4	26	162	57	55	7.9	26	127
TDP (µg • L^{-1})	19	18	2.5	5.3	42	22	17	4.5	7.5	64
Chl *a* (µg • L^{-1})	21	14	4.6	2.0	57	21	16	3.3	5.3	52
NH_4^+ (µg • L^{-1})	136	27	89.9	6.4	1271	82	28	35	5.5	535
NO_3^- (µg • L^{-1})	11	4.4	6.7	1.1	99	13	6.7	3.5	4.2	49
IN (µg • L^{-1})	148	32	91.7	7.5	1281	95	43	35	9.7	544
TN (µg • L^{-1})	1253	1042	208	532	3297	1235	1242	119	643	2244
DOC (mg • L^{-1})	20	18	2.1	10	33	22	21	1.9	10	32
Colour (mg • L^{-1} Pt)	186	191	29.1	29	358	191	185	33	25	388
Light Extinction Coeff.	3.8	3.6	0.6	1.3	8.7	3.6	3.6	0.4	1.1	5.7
Alkalinity (mg • L^{-1})	28	13	8.4	2.9	95	38	33	6.2	12	84
HCO_3^- (mg • L^{-1})	34	16	10.1	3.6	116	45	40	7.2	15	102
SO_4^{2-} (mg • L^{-1})	4.2	0.8	2.2	0.2	25	8.1	1.2	2.9	0.1	31
Cl^- (mg • L^{-1})	0.3	0.3	0.03	0.1	0.6	0.4	0.3	0.09	0.1	1.5
Na^+ (mg • L^{-1})	2.4	1.3	0.7	0.3	8.8	2.0	1.5	0.4	0.5	6.8
Ca^{2+} (mg • L^{-1})	10	5.0	3.2	0.9	37	11.3	7.1	2.5	2.4	36
Mg^{2+} (mg • L^{-1})	2.3	1.2	0.6	0.3	7.1	2.6	2.0	0.5	0.6	6.8
K^+ (mg • L^{-1})	0.6	0.4	0.2	0.2	2.4	0.9	0.5	0.2	0.2	3.1
Conductivity (µS • cm^{-1})	80	55	23.3	11	271	111	80	19	44	270
pH	5.7	6.3		4.9	7.4	6.7	6.6		6.1	7.6
SiO_2 (µg • L^{-1})	703	614	194	40	2750	1601	1335	234	635	4060

Table 10. Drainage basin and lake morphometry statistics for upland-dominated reference and harvested systems. Means for reference and harvested systems were compared with two-tailed t-tests modified for heterogeneous variances; probabilities (*p*) are listed. Chl a = chlorophyll a; TP = total phosphorus; TDP = total dissolved phosphorus; IN = inorganic nitrogen; DOC = dissolved organic carbon.

	Upland-dominated reference (n=15)					Upland-dominated harvested (n=9)				
Parameter	**Mean**	**Median**	**S. E.**	**Min**	**Max**	**Mean**	**Median**	**S. E.**	**Min**	**Max**
Catchment area (km^2)	5.71	6.35	0.76	1.20	11.59	4.19	2.94	1.06	0.80	10.03
Drainage basin area (km^2)	5.03	5.15	0.71	1.06	10.02	3.84	2.61	0.97	0.77	8.88
Uplands (% of DBA)	81	83	2.6	56	95	76	81	5.1	56	95
Wetlands (% of DBA)	18	16	2.4	5.3	44	23	18	4.7	5.2	42
Lake area (km^2)	0.68	0.55	0.13	0.14	1.70	0.35	0.30	0.11	0.03	1.15
Mean depth (m)	2.7	2.5	0.3	0.9	4.9	1.3	1.3	0.2	0.5	2.6
Maximum depth (m)	5.0	4.0	0.7	1.8	11.2	3.2	2.4	0.8	0.8	7.6
Lake volume ($m^3 \times 10^6$)	1.91	1.57	0.49	0.27	7.66	0.66	0.30	0.34	0.02	3.30
Elevation (m above sea level)	629	625	10	555	716	616	610	15	560	671
Disturbance (% of DBA)	-----	-----	-----	-----	-----	18	17	2.1	10	27
Catchment area/Lake volume	4.73	3.60	1.08	1.48	17.84	15.61	8.73	4.77	3.04	48.48
Chl *a* ($\mu g \bullet L^{-1}$)	19	14	3.8	3.8	76	28	14	6.5	2.4	78
TP ($\mu g \bullet L^{-1}$)	56	45	7.6	22	160	71	50	16	15	238
TDP ($\mu g \bullet L^{-1}$)	18	15	2.3	5.1	44	24	18	5.2	6.7	84
NH_4^+ ($\mu g \bullet L^{-1}$)	33	19	8.2	2.5	149	38	23	9.5	8.7	131
NO_3^- ($\mu g \bullet L^{-1}$)	5.2	4.8	0.5	1.1	11	10	5.4	2.9	2.7	45
IN ($\mu g \bullet L^{-1}$)	39	24	8.3	5.2	154	48	34	10	11	136
DOC ($mg \bullet L^{-1}$)	16	13	1.1	10	29	20	20	1.7	8.6	31
Colour ($mg \bullet L^{-1}$ Pt)	43	35	5.5	14	125	75	69	8.1	33	132

*Upland-dominated reference (n=20) and harvested (n=16) for water quality parameters.

Table 11. Drainage basin and morphometric data for 23 lakes sampled by WAG in 1998. All lakes except Narrow, Sauer, Long and Moore were sampled monthly from July-September 1998; the fore-mentioned were sampled once during August of the same year. DBA = drainage basin; LA = lake area; CA = catchment area; Zmax = maximum lake depth; Zmean = mean lake depth; CA/LV = catchment area/lake volume ratio.

Lake	Class	Treatment	Lat. (°N)	Long. (°W)	DBA (km^2)	LA (km^2)	CA (km2)	Zmax (m)	Zmean (m)	Volume ($m^3 \cdot 10^6$)	CA/LV	Upland (%)	Wetland (%)	*Disturbance* (%)
N13	Upland	Burn	55°57'	111°50'	10.01	0.81	10.82	2.6	1.0	9.1	1.2	69	28	35
N17	Upland	Harvest	55°39'	111°54'	5.93	0.43	6.36	7.6	1.8	8.2	0.8	88	11	17
N20	Upland	Harvest	54°59'	113°38'	4.52	0.30	4.82	1.8	0.9	2.7	1.8	88	11	10
N21	Upland	Harvest	55°43'	114°23'	2.47	0.47	2.94	2.6	1.3	6.5	0.5	81	19	27
N22	Upland	Harvest	56°03'	114°54'	8.88	1.15	10.03	6.1	2.6	33.0	0.3	73	25	17
N25	Wetland	Burn	56°46'	116°19'	1.40	0.60	2.00	2.7	1.3	8.1	0.3	49	50	16
N26	Wetland	Reference	56°49'	116°27'	16.22	2.00	18.22	5.8	2.5	5.7	0.3	40	60	< 5
N29	Upland	Reference	56°55'	116°40'	2.58	1.70	4.28	2.4	1.4	2.3	0.2	71	24	< 5
Marigold	Upland	Reference	54°40'	115°37'	1.10	0.55	1.65	6.4	2.6	1.5	1.1	87	13	< 5
Shelley	Upland	Burn	54°40'	115°41'	1.06	0.23	1.29	4.0	1.8	0.4	3.1	91	9	N/A
Mons	Upland	Burn	54°36'	115°46'	0.37	0.19	0.56	2.1	1.1	0.2	2.6	93	7	N/A
Shell N	Upland	Burn	54°40'	115°53'	24.99	0.31	25.3	17.3	N/A	N/A	N/A	88	12	N/A
Shell S	Upland	Burn	54°37'	115°53'	28.22	0.14	28.36	13.1	N/A	N/A	N/A	95	5	N/A
Natasha	Upland	Reference	56°18'	115°21'	13.59	0.85	14.44	2.1	1.1	1.0	14.8	59	41	< 5
Carol	Wetland	Reference	56°17'	115°17'	12.77	0.35	13.12	1.5	0.9	0.3	41.7	49	51	< 5
Kim	Upland	Harvest	56°17'	115°03'	7.03	0.33	7.36	1.5	0.9	0.3	24.8	88	12	26
Boomerang	Upland	Harvest	57°05'	114°43'	0.77	0.03	0.80	0.8	0.5	0.02	48.5	56	41	21
Cutblock	Upland	Harvest	57°01'	114°49'	1.25	0.07	1.32	1.8	1.0	0.07	18.3	58	42	11
Beaverdam	Upland	Harvest	57°01'	114°49'	1.11	0.11	1.22	2.4	1.3	0.1	8.7	59	36	13
Narrow	Upland	Reference	54°35'	113°38'	8.06	1.14	9.20	38	14.4	16.4	0.06	78	21	< 5
Sauer	Upland	Reference	53°37'	114°05'	0.49	0.09	0.58	8.5	4.2	0.3	0.2	100	0	< 5
Long	Upland	Reference	54°26'	112°45'	82.40	5.84	88.24	9.0	4.3	29.3	0.3	100	0	< 5
Moore	Upland	Reference	54°31'	110°31'	37.10	9.28	46.38	26	8.3	77.4	0.06	69	23	< 5

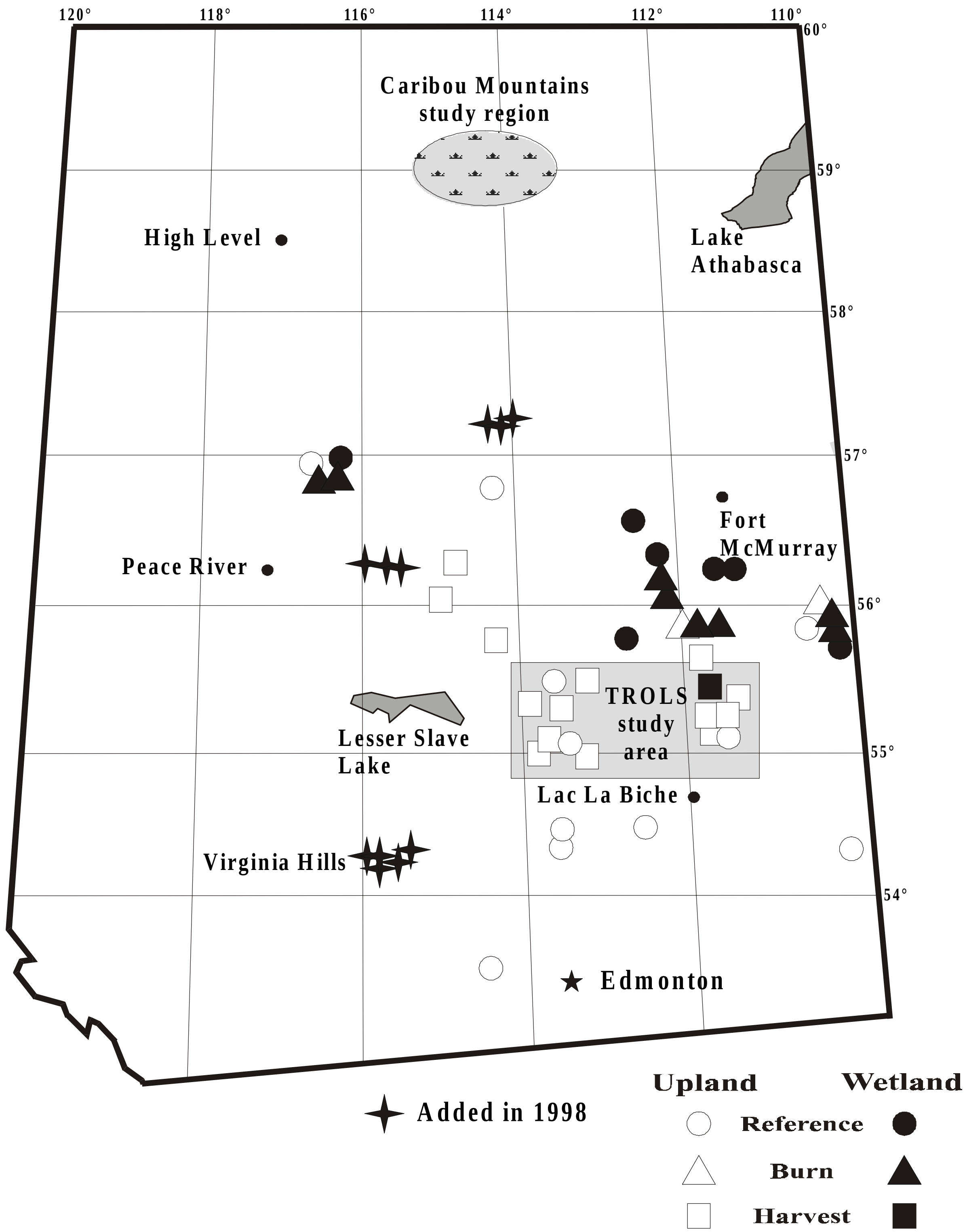

Fig. 1. Locations of Boreal Plain lakes studied by this study (SFMN) and the Terrestrial Riparian Organisms Lakes and Streams (TROLS) project, 1996-1998. The Caribou Mountains study region is also indicated.