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Comparison of the Effects of Fires and Logging on Algal Productivity, Quality and Biodiversity in Boreal Shield Lakes

SFM Network Project: Impacts of Watershed Disturbances on Phytoplankton and Periphyton Communities

by

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ABSTRACT

This project, within the framework of legacy one, contributes to the understanding of the consequences of natural disturbances on the primary producers of boreal forest lakes and the influence exerted by human activities in altering natural disturbance algal productivity and biodiversity patterns. In lakes the first expected responses to enhanced nutrient fluxes in perturbed watersheds are an increase in productivity as well as a shift in species composition and biodiversity of algal communities (phytoplankton - free-floating in the water column and periphyton - attached to littoral substrates). A model was developed to indicate the appropriate boundaries for forest harvesting when considering the conservation of algal production, algal quality and species richness. From june 1996 to September 1998 we sample 38 headwater lakes located in Haut Mauricie (Gouin Reservoir), the Boreal forest domain of the eastern Canadian shield. The selection process was a collaborative effort involving the Québec Land-Aquatic group and the Cartons St-Laurent, Donohue and Kruger industries. The lakes can be divided as follows: undisturbed (19), naturally disturbed by fire (10), and impacted by logging (9). The short term study confirms our expectations such that algal productivity was found to be higher in lakes of perturbed ecosystems having a high drainage basin to lake area (DA/LA) ratio. When only the lakes of >40% perturbation are considered, algal productivity is significantly higher in naturally perturbed lakes than in harvested lakes. However, algal biodiversity decreased when watershed perturbation was higher in harvested lakes. This preliminary result also indicates that in both naturally disturbed and harvested lakes having a large DA/LA ratio algal quality was not affected. The deliverables of this study are quantitative models relating algal productivity, quality and biodiversity at the base of the food web (algae) to natural vs anthropogenic disturbances and which account for watershed and lake morphometry. Models relating algal productivity to changes in terrestrial nutrient cycles, water quality (light, nutrients) and predators (invertebrates and fish) are also provided. This project provides useful tools that are contributing to management recommendations. Specifically we have identified simple variables, such as watershed and lake area, that could be included in geographic information systems used by the industry and enable the identification of lakes particularly susceptible to harvesting. Furthermore, the study also provides evaluation tools to be use in environmental monitoring. Both tools could be incorporated to the Sustainable Forest Management global assesement model to be delivered to the decision-makers in order to contribute to the continuing development of CSA and ISO certification guidelines for sustainable forestry.

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INTRODUCTION

Aquatic ecosystems occupy almost a third of the boreal ecoregion. Their water and fish are an important nutritional source for First Nations and they are also an important economical and recreational resource for communities of the boreal Shield. Thus the protection of lakes and running waters must be an integral part of strategies for sustainable forest development.

Timber harvesting in the Canadian boreal forest has raised concerns over potential impact on aquatic ecosystems. The expected disturbances associated with logging are an increase in the watershed export of suspended solids, dissolved organic carbon and other nutrients (Likens et al. 1977; Ramberg. 1996; Rask et al. 1998). As a consequence of these perturbations, nutrients could increase and light penetration decrease, thereby modifying the water quality and productivity in the aquatic milieu of impacted watersheds (Wright 1976; Kauffman et al 1994). Anthropogenic disturbance could also decrease the biological diversity of natural ecosystems (Connell 1978; Wilson 1988; Ehrlich and Daily, 1993). Since the 50's it has been stated that decreases of biological diversity would lead to decreased ecological stability and function (Elton 1958). In most situations an increase in plant productivity following addition of nutrients results in a decrease in the number of species coexistent in a given area or volume (Proulx et al. 1996). There are no studies on water quality alterations in lakes and phytoplankton biodiversity.

To achieve the goal of sustainable exploitation of an ecosystem it is not only necessary to consider the system under exploitation and adjacent ecosystems but also to determine patterns and indicators of ecosystem stress. To find patterns and indicators it is necessary to: i) do suitable field experiments of different spatial and temporal intensity; ii) do long term studies to cope with inter-annual variability and iii) compare ecosystems exposed to different types and magnitudes of stress (Lubchenco et al., 1991). Boreal forest ecosystems are well adapted to periodic fires (Wright and Heiselman, 1993), making them the more suitable natural disturbance base model to use in comparison with sustainable forestry in the boreal ecosystems. Forest fires would also increase nutrient export from the watershed to lakes and rivers (Bayley et al., 1992, Beaty, 1994) .

Lakes respond quickly to changes in the watersheds (Elber and Schanz 1989), particularly the microscopic organisms such as bacteria and algae. These microorganisms, at the base of the food web, have a short life span and consistently respond to increases of nutrients (e.g., Schindler, 1974). Increases of nutrients in lakes not only increases the algae biomass but also changes species composition. Thus, algae are a very good indicator of changes in water quality (Triphonova, 1988) and could be used as an early warning to predict changes in communities further up in the food chain. The algal community changes associated with water quality alterations have a cascading effect on the entire food web (Steiman 1998).

The littoral communities of lakes, although they are found within the photic zone as well as within the epilimnion of stratified lakes different from those of the pelagic zone with regard to fluxes of solutes and suspended matter. The attributes of the littoral zone resemble those of a closed system, lacking the strong vertical transport and intense recycling of the pelagic zone (Fisher and Grimm 1991). In lakes the littoral zone appears to be the main feeding area of many freshwater fish species (France, 1995; Hecky and Hesslein, 1995) and for the boreal Shield lakes results of Magnan and coworkers show that the more frequent and abundant fish species use the littoral as a habitat (Magnan and St Onge 1999).

Aquatic ecosystems are always driven, over long time periods and large scales, by climate and terrestrial processes in their catchment (Hormung and Reynolds, 1995). These driving forces are partially physical in character, but are strongly influenced by biological processes. Thus watershed perturbations that modify biological structures and processes in the landscape, could alter water life quality . In general the larger the catchment and the shallower the lake, the greater the influence of catchment on water quality (Schindler, 1971; Curtis and Schindler, 1997). Many average properties of boreal lakes can be reliably predicted from the ratio of drainage area to lake area (DA/LA), or watershed area to lake volume (Schindler 1998; Carignan et al 1999; Planas et al., 1998, 1999). If we could apply similar predictive tools, such as watershed characteristics and lake morphometry, variables easily measured with geographic information systems (GIS), to the biota of lakes we will have made a considerable contribution to sustainable forest management.

The objective of the project was twofold: 1) to compare the productivity, quality, biodiversity and size spectra of the pelagic free-floating algae (phytoplankton) and littoral attached (periphyton) algae in Boreal eastern Canadian Shield lakes, using as a natural disturbance model, lakes in burnt watersheds and as anthropogenically impacted, logged watersheds, and 2) to develop empirical models which will enable us to evaluate the intensity and frequency attributes to be used in forest management in order to preserve the productivity and quality of aquatic life.

Our hypotheses are:

I - The response of lakes to watershed disturbance will be of higher amplitude, faster, and of longer recovery time, in lakes with high DA/LA ratio.

II - The high input of nutrients to lakes with greater DA/LA ratios and elevated watershed perturbation will, i) increase algal productivity, particularly in the littoral zone; ii) decrease algal quality and biodiversity.

III - Lakes with high algal biodiversity will buffer the response of primary producers to watershed perturbations.

These hypotheses were tested by measuring algal standing stock (chlorophyll-a and/or biomass), species abundance and quality, size distribution of biomass, total species richness and diversity, in phytoplankton and periphyton communities.

METHODS

Study site

The study was conducted in 38 (out of 64 000 lakes occurring in the region) headwaters lakes, located in the boreal forest eastern Québec, on a 50 000 km^2 area of the Canadian shield (47°52'-48°59'N and 73°19'-76°43'W) (Fig. 1). They were selected on the basis of comparable size, depth and watershed morphometry (Table 1). They are medium size lakes well stratified during the ice-free season, ultra-oligotrophic to oligo-mesotrophic, slightly acidic and coloured by humic acid substances (Table 1).

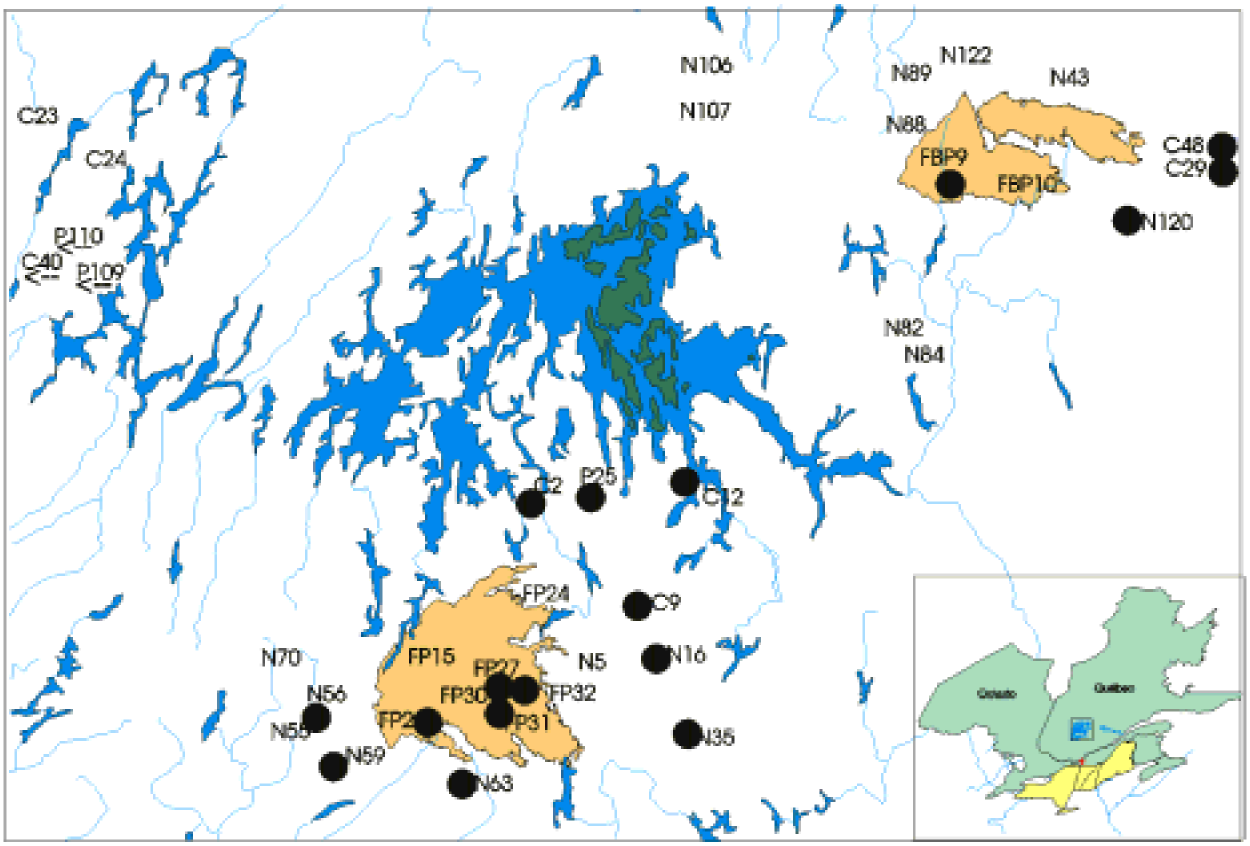

Figure 1. Location of the 38 study lakes in the Haut Mauricie. N = reference lakes; F = burnt lakes and C = cut lakes. The dots mark the lakes where periphyton was sampled.

Watershed Characteristics and Perturbations

The landscape is dominated by mixed forest (Balsam Fir, Black Spruce, Jack Pine, White Birch and Aspen) with less than 20 % wetland (bog, fen, swamp). Nineteen (1996-1997) and 15 (1997-98) of the lakes are located in undisturbed watersheds that have been untouched for at least the last 70 years (reference lakes); 9 lakes are in naturally disturbed watersheds, with between 50-100% of watershed area having been perturbed by forest fires in 1995 (burnt lakes), and 9 to 14 in anthropogenically impacted watersheds where 8-96 % of the area was logged, (8 logged in 1995, 1 in 1995 and 1997, and 5 in 1997-98; harvested lakes).

Tables 1. Morphological watershed and lake characteristics (Data provided by R. Carignan)

Variables	Reference[1]	Burnt[2]	harvest[3]
Lake Surface area (km^2)	0.44	0.56	0.40
Watershed area (km^2)	2.58	3.96	5.55
Watershed slopes (%)	10.8	9.1	11.9
Maximum Depth (m)	12.3	14.0	17.0
Extinction coefficient (m)	0.95	1.45	1.32
pH	6.37	6.29	6.46
Total phosphorus ($\mu g \cdot L^{-1}$)	6.87	9.12	11.8
Total nitrogen ($\mu g \cdot L^{-1}$)	203	233	286
Nitrates ($\mu g \cdot L^{-1}$)	8.18	8.19	49.18
Dissolved organic carbon ($mg \cdot L^{-1}$)	5.06	7.20	6.04
Percentage of perturbation (%)[a]	0.0	40.7	91.3

[1] 20 lakes in 1996-97; 15 in 1997-98; [2] 9 lakes in 1996-97 and 14 in 1997-98. [a] Percentage of watershed cut or burnt. DOC = dissolved organic carbon; TP = total phosphorus; TN = total nitrogen.

Sampling

Starting in 1996, phytoplankton lakes were visited three times, in spring, summer and fall; duplicate integrated photic zone samples were taken at the deepest part of the lake, concomitantly with the water quality data (Carignan et al. 1999). Periphyton was studied in 16 lakes (6 reference, 5 burnt and 5 harvest) using artificial substrates (Teflon mesh; Fig 2). Analyses of community attributes were carried out on duplicate substrates placed at a depth of 1 m at 2 to 4 stations per lake and left to colonize for 3 to 12 months.

Phytoplankton and periphyton productivity measurements

Algal standing stock was measured using the concentrations of chlorophyll-*a* and biomass. Phytoplankton chlorophyll-*a*, was concentrated as soon as possible after sampling by filtering a known amount of water on Whatman GF/C filters and then immediately frozen. The chlorophyll was extracted with hot ethanol (Nush 1980), followed by spectrophotometer measurements, before and after acidification (Sartory and Grobelaar 1984). Periphyton chlorophyll-*a* determinations were conducted in a similar manner except that no filtration was necessary. Following collection the Teflon substrates were immediately frozen with the extraction in hot ethanol performed directly on the substrates (Desrosiers, Groulx and Planas, unpublished data).

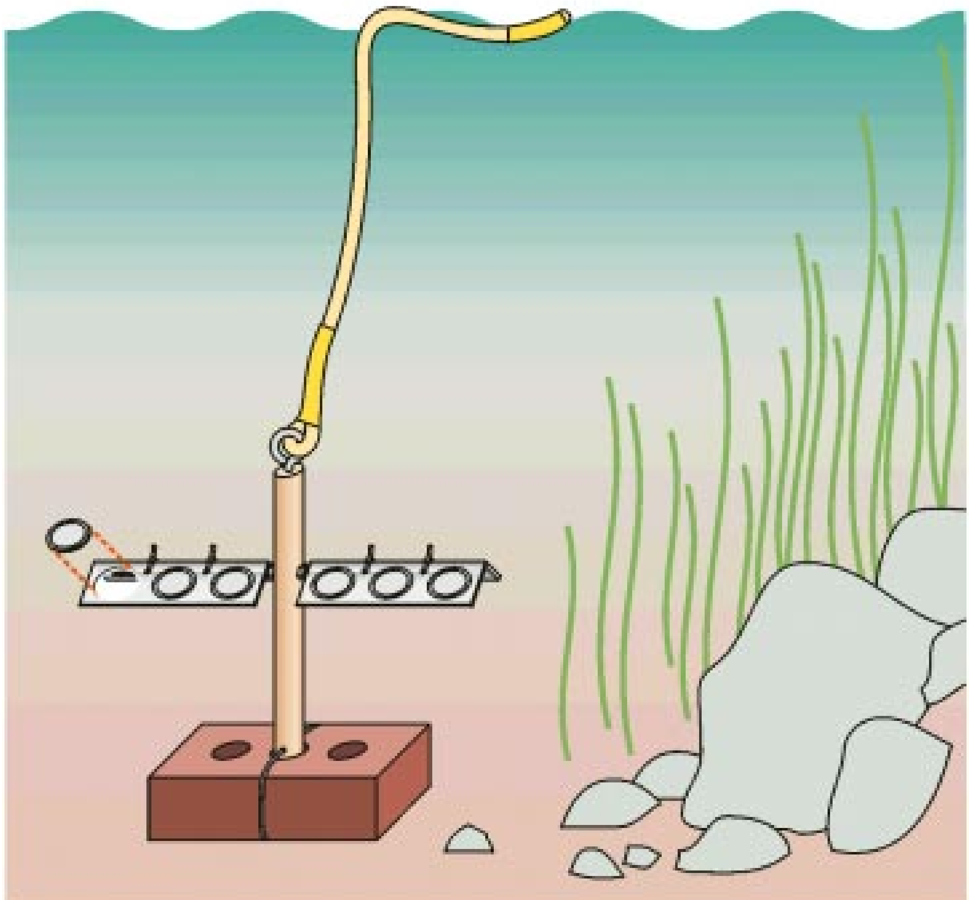

Figure 2. Periphyton artificial substrate module (Planas and coll. unpublished).

Phytoplankton and periphyton algal quality and biodiversity measurements

Phytoplankton and periphyton 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. The biomass of each species was calculated from the cell biovolume by applying appropriate geometric form and considering a cellular density of 1. Because the number of lakes in each set is different, biodiversity was calculated as the mean species richness per year in each lake (Planas et al. 1999).

SUMMARY OF DATA ANALYSIS

Response of primary producers

Phytoplankton chlorophyll a

During the 3 years of study the pelagic algal chlorophyll concentrations were higher ($p \leq 0.0001$) in lakes having naturally disturbed watersheds and in lakes of harvest watershed where more than 40% harvested than in reference. The highest response occurred in "burnt" lakes where the chlorophyll concentrations were almost double ($p \leq 0.05$) that those of reference lakes. In harvested lakes the phytoplankton response was intermediate (Fig. 3).

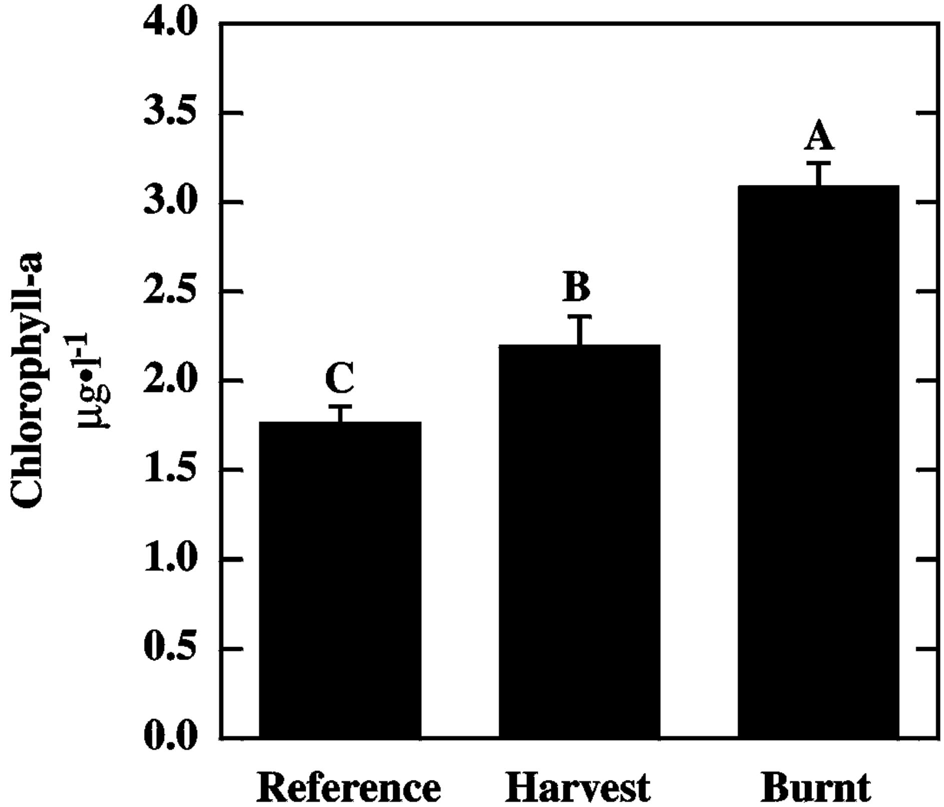

Figure 3 - Three year mean phytoplankton chlorophyll *a* concentrations in reference, harvested and burnt lakes. Different capital letters indicate significant difference ($p \leq 0.05$) between sets of lakes.

Periphyton chlorophyll a

Based on data from 2 years, attached algal chlorophyll concentrations were higher ($p < 0.0001$) in lakes in disturbed watersheds than in reference lakes (Fig. 4). Between disturbed watersheds production was higher ($p < 0.01$) in naturally as compare to anthropogenically perturbed lakes. In the burnt lakes chlorophyll concentrations were more than three time higher than reference lakes ($p < 0.0001$; Fig. 4).

Watershed characteristics influencing algal productivity

The drainage basin to lake area ratios (DA/LA), the % of perturbation and the % of slope and mean depth explains around 55% of the variance in phytoplankton chlorophyll-*a* when all lakes are combined (Table 2). Almost 50 % of the variance of periphyton chlorophyll-a was predicted by the DA/LA ($p<0.000$) ratio (Table 3).

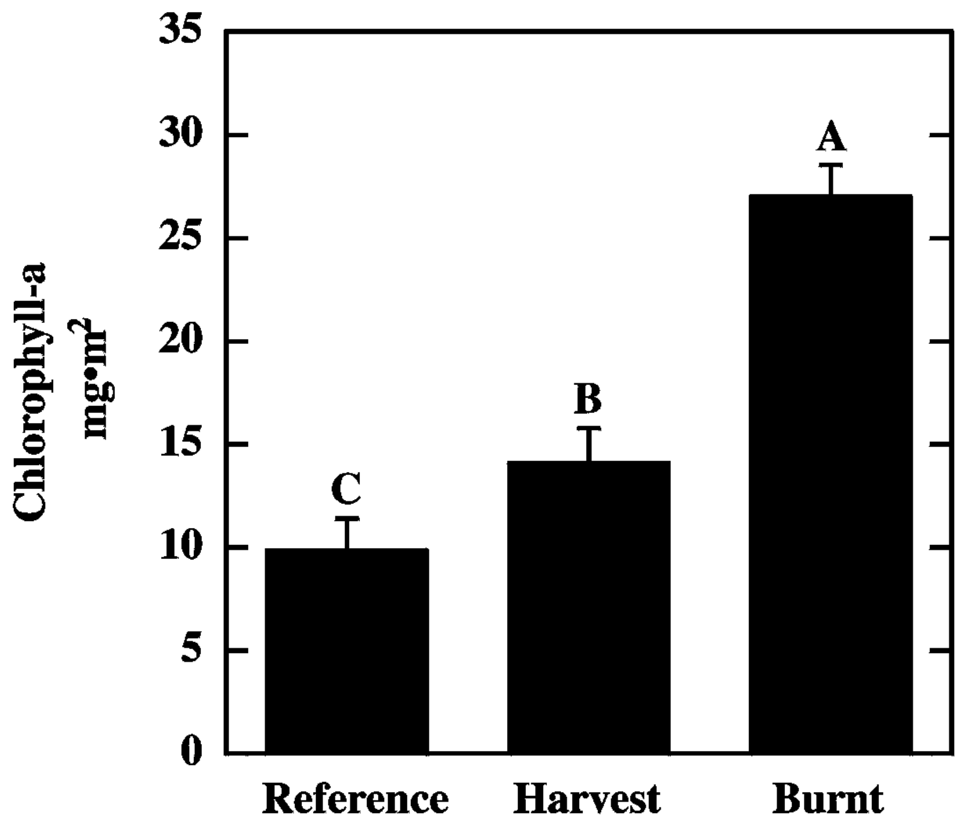

Figure 4. Two years mean periphyton chlorophyll-*a* concentrations in reference, harvested and burnt lakes. Different capital letters indicate significant difference ($p < 0.05$) between sets of lakes.

For each set of lakes, including reference lakes, algal chlorophyll was higher at high DA/LA ($p \leq 0.05$) than at low DA/LA (Fig. 5; Planas et al. 1999). These differences in algal production, in relation to DA/LA ratio, could be expected since we know the importance of watershed size to loading of nutrients in lakes (Carignan et al. 1999).

Physico-chemical variables influencing algal chlorophyll-a

The best physico-chemical predictors of pelagic chlorophyll-*a* for all lakes are total phosphorus (TP), explaining almost 50% of the partial variance followed by dissolved inorganic nitrogen (DIN) and light extinction coefficient. The whole model explains around 60% of the variance (Table 4). Total phosphorus was also a good predictor of periphyton chlorophyll-*a* (Partial $R^2 = 0.51$), followed by nitrate and DOC. This three variables account for almost 70% of the chlorophyll-*a* variance (table 5).

Table 2. Multiple regression model between phytoplankton chlorophyll-*a* (dependent variable) and watershed and morphometric lake characteristics[1] (independent variables).

Model	$p_1>\|t\|$	SE	r^2	adj r^2	Prob>F
log (chl-a)		0.006	0.558	0.542	<0.0001
0.378	<0.0001	0.047			
0.008DA/LA	0.0009	0.002	0.159		
0.002%pert	<0.0001	0.0002	0.276		
0.012%slope	<0.0001	0.002	0.094		
$-0.176\log_{10}(Z_{moy})$	0.0081	0.065	0.030		

[1] Watershed and morphometric data provided by Dr Richard Carignan's laboratory. $p_1>|t|$= probability associated with each independent variable; SE=Standard error of coefficients; r^2 = the partial coef. associated with each independent variable; adj r^2 = the adjusted r^2; *Prob>F* = model significance; * Mean Standard Error; log (Chl-a) = logarithm_{10} chlorophyll-*a*; DA/LA = Drainage area/Lake Area; % pert. = % perturbation; Zmax = maximal depth of the lake.

Table 3. Regression model between periphyton chlorophyll-*a* (dependent variable) and drainage basin to lake area[1] (independent variable).

Model	$p_1>\|t\|$	SE	r^2	adj r^2	Prob>F
log (chl-a)		0.034	0.503	0.486	<0.0001
0.700	<0.0001	0.088			
0.071DA/AL	<0.0001	0.013			

[1] Watershed and lake data provided by Dr Richard Carignan's laboratory. $p_1>|t|$= probability associated with each independent variable; SE=Standard error of coefficients; r^2 = the partial coef. associated with each independent variable; adj r^2 = the adjusted r^2; *Prob>F* = model significance; * Mean Standard Error; log (Chl-a) = logarithm_{10} chlorophyll-*a*; DA/LA = Drainage area/Lake Area

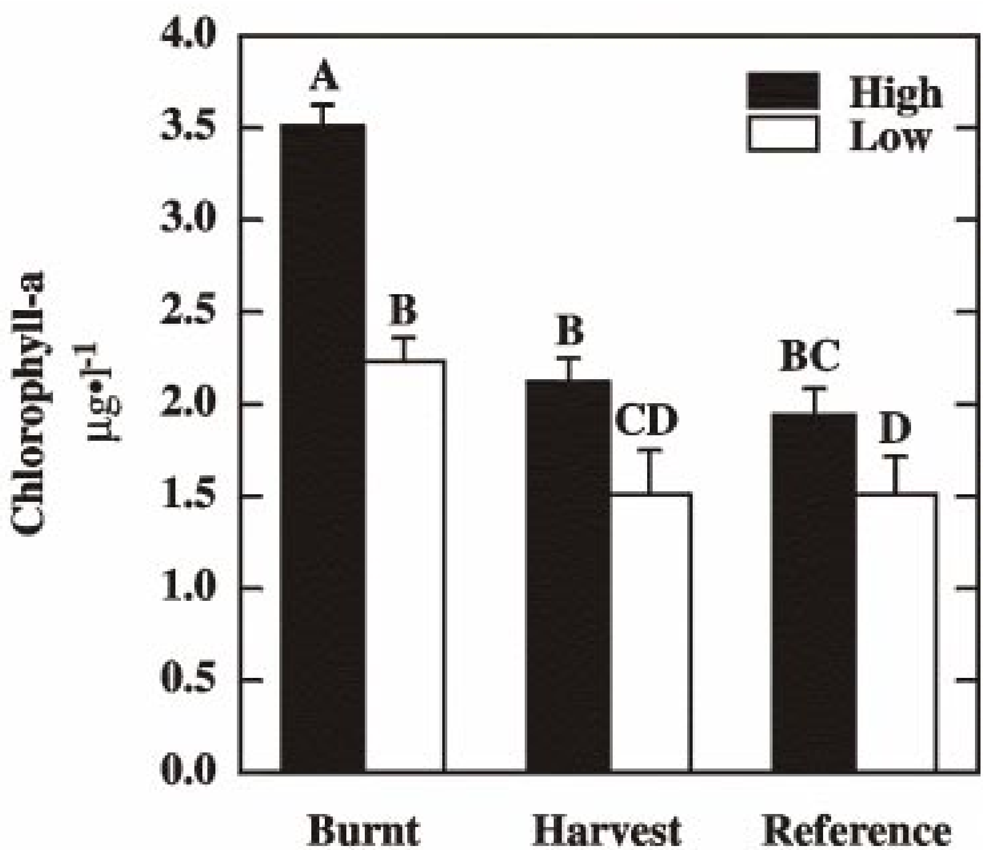

Figure 5. Mean chlorophyll *a* concentration in reference, harvest and burnt lakes with high DA/LA (> 4) and low DA/LA (< 4).

Table 4. Multiple regression model between chlorophyll-*a* (dependent variable) and the physical and chemical variables of the lakes (independent variables)[1].

Model	$p_1>\|t\|$	SE	r^2	adj r^2	Prob>F
$\log_{10}$(chl-a)		0.006	0.576	0.565	<0.0001
-0.207	<0.0006	0.059			
0.720$\log_{10}$(TP)	<0.0001	0.079	0.476		
0.065$\log_{10}$(DIN)	0.0036	0.022	0.047		
-0.070PAR	0.0003	0.019	0.053		

[1] Physical and chemical data provided by Dr Richard Carignan's laboratory. $p_1 >|t|$ = probability associated with each independent variable; SE=Standard error of coefficients; r^2 = the partial coef. Associated with each independent variable; adj r^2 = the adjusted r^2; *Prob>F* = model significance; * Mean Standard Error; log (Chl-*a)* = logarithm$_{10}$ chlorophyll-*a*; log (TP) = logarithme10 total phosphorus;.

Table 5. Simple regression models between periphyton chlorophyll-*a* (dependent variable) and total phosphorus.

Model	p_1>|*t*|	SE	r^2	adj r^2	Prob>F
$\log_{10}$(chl-a)		0.023	0.691	0.657	<0.0001
-0.228	0.2842	0.209			
0.720$\log_{10}$(TP)	0.0117	0.247	0.508		
0.065$\log_{10}$(NO_3)	0.0084	0.050	0.131		
0.070$\log_{10}$(DOC)	0.0410	0.309	0.053		

[1] Physical and chemical data provided by Dr Richard Carignan laboratory. p_1 >|*t*| = probability associated with each independent variable; SE=Standard error of coefficients; r^2 = correlation coefficient; *Prob>F* = model significance; * Mean Standard Error; log Chl-*a* = logarithm_{10}; log (TP) = logarithm_{10} total phosphorus.

In summary, wildfires and forest harvesting result in increased nutrients loading and dissolve organic carbon and, hence, impact water quality and increase lake productivity in perturbed boreal lakes compared to reference lakes. Variation in lake productivity should be more important in lakes with high DA/LA and/or more than 40% of the watershed is perturbed.

Phytoplankton community structure

Algal Quality

The phytoplankton communities in lakes with undisturbed watersheds had, in general, low biomass and were dominated by small (< 20 um) flagellated algae particularly Chrysophyta (Chryso; Fig 6) that are edible by grazing zooplankton. Low phytoplankton biomass and communities dominated by small flagellated algae are common features in oligotrophic lakes located on the boreal Precambrian shield (Kling and Holgrem, 1972; Lepisto and Saura, 1998). Blue-green algae (Cyano) and green algae (Chloro) had the lowest biomass of the six algal taxa in the study lakes. The Cyanobacterial species present are not toxic and characteristic of nutrient poor and slightly acidic brown waters (Blomqvist, 1996).

Although algal biomass was higher in lakes with perturbed watersheds, the increase was greater in burnt lakes ($p < 0.05$). This trend was particularly noticeable in diatoms ($p < 0.0001$) and to a lesser degree in Cryptophytes (Crypto; $p < 0.0001$) and Chrysophytes (Chryso; $p = 0.014$). The Blue-green algae decreased in all perturbed lakes ($p < 0.0001$) while green algae decreased in our harvested lakes ($p = 0.04$; Fig. 6; Planas et al. 1999).

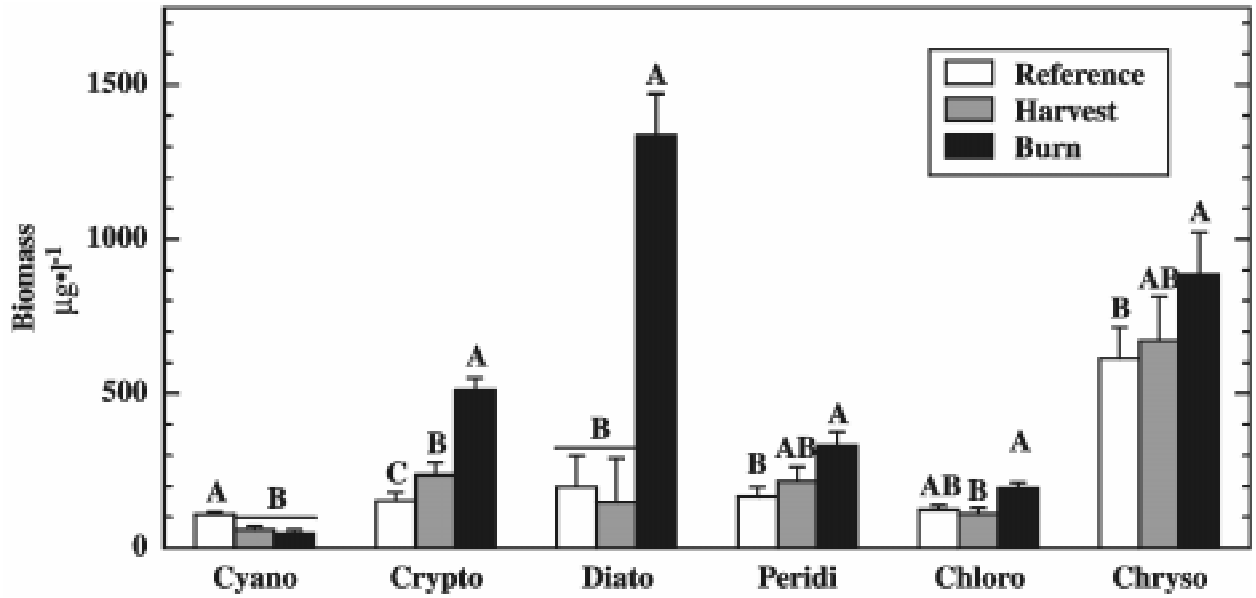

Figure 6. Three year mean biomass (wet weight) of the major pelagic algal groups in undisturbed (reference) and disturbed (fire and harvested) watersheds in eastern Canadian shield lakes. Cyano (Blue-green), Diato (diatoms), Chloro (green algae), Crypto (Cryptophytes), Peri (Dianoflagellates), Chryso (Chrysophytes). The Crypto, Peri and Chryso are flagellates. Different capital letters indicate a significant difference ($p < 0.05$).

Table 6 - Pearson correlations between algal taxa and some watershed and lake characteristics. Only significant correlations are shown.

Algal Taxa	Variables[1]			
	% pert	Ex. Coef.	$\log_{10}$(TP)	$\log_{10}$(DIN)
$\log_{10}$ (Cyan)	0.424	-0.344	0.428	0.458
$\log_{10}$ (Chlor)	0.442	-0.716	ns	0.699
$\log_{10}$ (Cryp)	0.521	-0.534	0.470	0.688
$\log_{10}$ (Chrys)	0.534	-0.622	ns	ns
$\log_{10}$ (Diat)	0.713	-0.677	0.519	0.693
$\log_{10}$ (Peri)	0.475	-0.663	ns	ns

[1] Watershed and physical - chemical variables data provided by Dr Richard Carignan's laboratory. % pert = percentage of watershed harvested or burnt; Ex.coef = Light extinction coefficient; log (PT) = logarith_{10} total phosphorus concentration; log (DIN) = logarith_{10} total dissolve inorganic nitrogen (nitrates + amonia); log (Cyan) = logarithm_{10} Cyanobacteria; log (Cryp) = logarithm_{10} Cryptophyta; log (Diat) = logarithm_{10} Diatoms; log (Peri) = logarithm_{10} Dinoflagellates; log (Chlor) = logarithm_{10} Chlorophytes; log (Chrys) = logarithm_{10} Chrysophytes.

Variables influencing changes in algal quality

Pearson correlations between the main algal groups in large perturbed watersheds and physico-chemical lake characteristics show that the % of perturbation and nutrients are positivively correlated with the majority of algal taxa, particularly diatoms and Cryptophytes. In contrast light extinction coefficient is negatively correlates with all algal groups (Table 6).

Algal Quality forecast

In lakes with large watersheds and disturbance (harvested or burnt), algal quality was not detectably different than in reference lakes. Three years after perturbation, no algae known to have toxins associated with them have appeared, however, export of DIN began to decrease in 1998 in disturbed watersheds while export TP has remained high after 3 years of perturbation. These changes in the DIN/TP ratio could favour N_2-fixing algae which could bloom and become a nuisance. The growth of N_2-fixing blue-greens**,** could not only deteriorate water quality but out compete the edible algae (Chrysophytes, diatoms and Cryptophytes) that dominate our Canadian Shield lakes. These changes in algal quality have been reported in enrichment experiments in lakes and ponds (Schindler, 1974; de Noyelles and O'Brien, 1978). For the 1996 and 1997 data, algal biomass differences between sets of lakes were reflected in zooplankton biomass (Patoine, 1999) indicating a bottom-up effect (Carpenter et al. 1991). If algal quality change occurs, the zooplankton growth could be impaired and consequently the fish.

Algal sizes distribution

Phytoplankton size is very important in relation to food availability to consumers. Usually three fractions are considered: picoplankton (< 2 µm) nanoplankton (2 - 20 µm) and microplankton (> 20 µm), the two first fractions being the most heavely grazed.

Nanoplankton is the dominant fraction in our study lakes, as anticipated in oligotrophic ecosystems This fraction was not significantly altered in harvested lakes. Perturbation impaired the growth of picoplankton ($p < 0.0001$) in lakes within burnt as well as harvested watersheds (Fig. 7).

Variables influencing algal size

Pearson correlations between main taxa and watershed and physico-chemical variables show the importance of disturbance and DA/LA, nutrients and light in altering the algal community structure, particularly in the more edible phytoplankton taxa in Canadian shield lakes (Table 7).

In summary, in the short term (three years after perturbation) phytoplankton quality was not detectably altered in disturbed lakes, but the biomass of some "edible" algal groups was higher in lakes with burnt watersheds as compared to harvested and undisturbed watersheds.

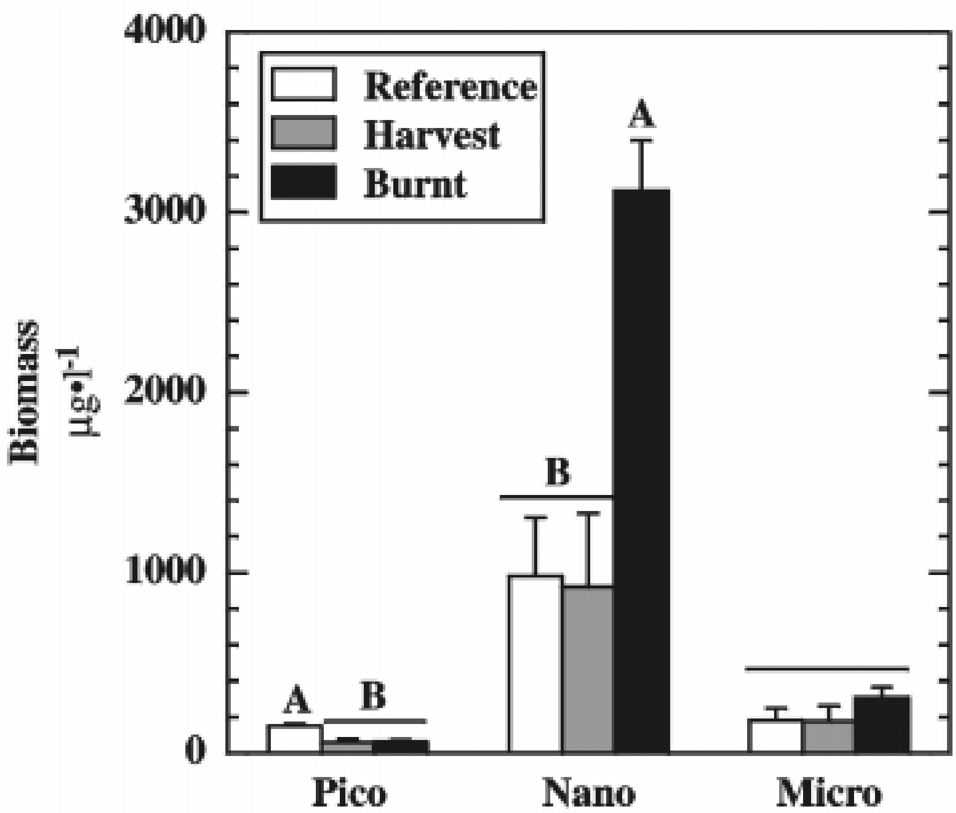

Figure 7. Three years means of the different phytoplankton fractions in reference, harvest and burnt lakes.

Table 7. Pearson correlations between algal size and some watershed and lake characteristics. Only significant correlations are shown.

	Pico	Nano	Micro
DA/LA	-0.510	ns	ns
% perturbation	ns	0.739	ns
Ex. Coef.	ns	-0.771	-0.557
$\log_{10}$ (TP)	ns	0.485	ns
$\log_{10}$ (DIN)	ns	0.732	ns

Watershed and physico - chemical variables data provided by Dr Richard Carignan's laboratory. DA/LA = Dranaige to lake area; % pert = percentage of watershed harvested or burnt; Ex.coef = Light extinction coefficient; log (PT) = logarith_{10} total phosphorus concentration; log (DIN) = logarith_{10} total dissolve inorganic nitrogen (nitrates + amonia) concentration.

Algal Biodiversity

In the undisturbed lakes, there were about 40 phytoplankton species. Algal biodiversity in lakes in burnt watersheds was not distinguishable from lakes in undisturbed watersheds. However in harvested lakes, algal biodiversity decreased (p= 0.0003) where the disturbance was relatively large and is slightly higher than in reference and burnt lakes when the disturbance is lower (Fig. 8; Planas et al., 1999).

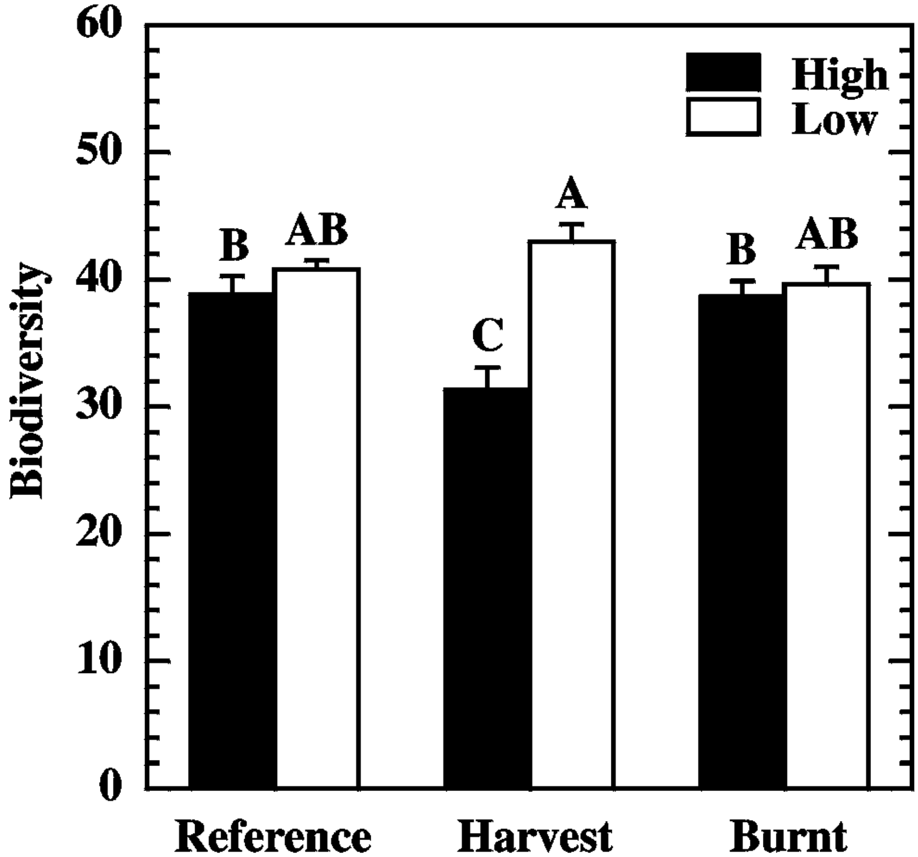

Figure 8. Algal biodiversity in reference lakes, in lakes in harvested watersheds (perturbation > 40%) and in lakes in burnt watersheds. Different columns in each set of lakes correspond to lakes with an DA/LA ratio less than 7 and more than 7.

Lack of detectable effects of watershed disturbance on algal biodiversity when the disturbance was small supports the “intermediate perturbation” hypothesis. This hypothesis states that the response of community structure to perturbation depends not only on the intensity and frequency of disturbance, but also on the stress level at which the community is living. In some situations, where nutrients or other factors limit plant productivity to low levels, a moderate increase in the limiting factor allows more species to survive, leading to an increase in plant species richness or diversity (Currie and Paquin, 1987; Proulx et al., 1996). In the Boreal Shield lakes under study, nutrients limit algal growth. In this setting moderate increases in nutrients (that do not change the trophic status) will favour biodiversity. However, if the dissolved organic carbon (DOC) concentration increases, water colour will be augmented and high water colour would decrease light penetration (Kirk, 1994). In our study, lakes in perturbed watersheds have higher nutrient and DOC concentrations and lower light penetration than lakes in unperturbed watersheds (Carignan et al. 1999). A negative relationship was found between algal biodiversity and light extinction coefficient (Fig 9; r^2 = -0.525, p < 0.0001). This inverse relationship was strongest in harvested lakes with a relatively large disturbance in the watershed. A negative relationship between algal biodiversity and light extinction coefficients, in our study lakes, suggests that light could be the variable that impairs growth in some algal species. In the perturbed, particularly harvested lakes, high light extinction coefficients could be linked to reduced biodiversity.

In summary, algal biodiversity was similar in undisturbed and naturally perturbed watershed lakes. In anthropogenically impacted lakes, where the disturbance was relatively small, biodiversity was slightly higher than undisturbed and naturally disturbed watersheds. However, algal biodiversity decreased when the watershed perturbation was large (i. e., more than 40% of the watershed was cut and when the DA/LA ratio was higher than 7).

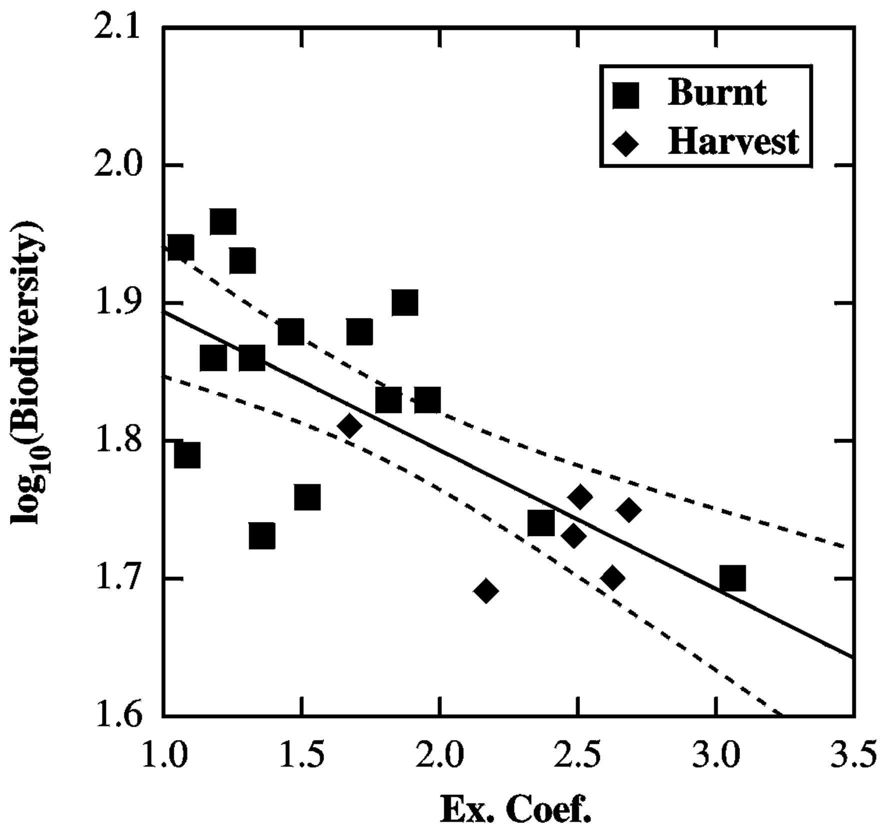

Figure 9. Regression between algal biodiversity and light extinction coefficient in lakes with large perturbed watersheds.

MANAGEMENT APPLICATIONS

The responses of primary producers in lakes located in post-fire and post-harvest watersheds are shown to be comparable. The similarity in the responses was either at the level of processe (biological productivity) or community structure (algal biodiversity and quality) and indicates that cutting regimes could be adapted to fire frequencies.

The responses of primary producers can be predicted with very simple empirical models (such as the one developed for water quality by Carignan et al. 1999) using a small number of independent variables easily measured from maps, such as watershed and lake areas combined together with perturbation scenarios (Fig. 10). These models allow for the evaluation and comparison of forest management practices and ensure the sustainability of aquatic ecosystems.

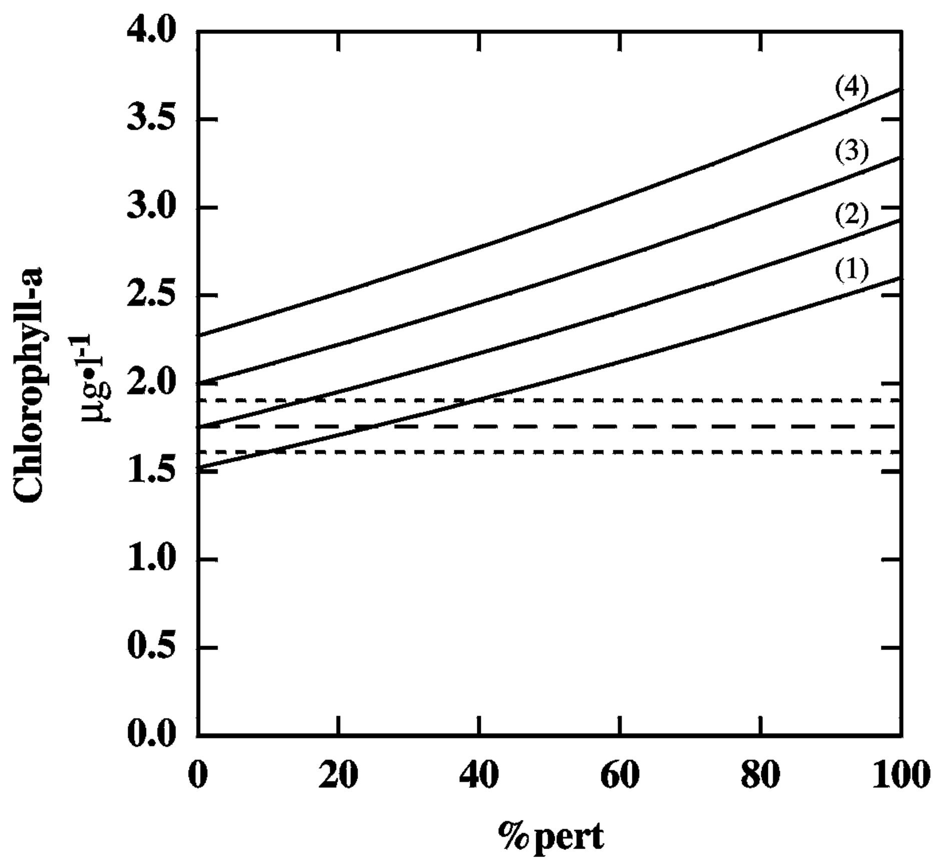

Figure 10. Empirical model to predict changes in algal productivity, as a function of the drainage basin area to lake area, in different harvesting scenarios. Numbers indicate different DA/LA scenarios, (1) DA/LA = 3.5, (2) DA/LA = 7, (3) DA/LA = 10.5 and (4) DA/LA = 14.

These models are imperative for the maintenance of the desirable trophic status of lakes and allow for the preservation of quality and biodiversity of aquatic life. The maintenance of trophic status would avoid lake deterioration, e. g., i) decrease of oxygen concentrations that impede the survival of fish species, such as trout, that in summer take refuge in deeper regions of lakes (where oxygen deficiency occurs) and ii) increase of internal loading of nutrients and contaminants that will have a synergic effect in lake deterioration. To preservation of algal quality will prevent the proliferation of undesirable species that could threaten the health of their consumers, from zooplankton to fish, Maintenance of algal biodiversity reinforces the stability of the aquatic systems, avoiding disturbance responses that significantly deviate from natural variability.

The algal responses to perturbations could also be used as indicators of sustainable Forest Management (SFM) since their time response to perturbation is very fast (the life span of algae is from hours to days) and because algal community changes have a cascading effect on the entire food weeb. Algae could also be used as an early warning to predict changes further up the food chain (e.g., fish).

The deliverables of this study could aid the decision makers with the identification of indicators that are easily measured, cost-effective and relevant to forest activities at the two levels required to be operational: predictive tools to aid in planning and evaluative tools to use in environmental monitoring (Kneeshaw et al., 1999). These tools will be incorporated into the biophysical model, currently under development between SFM-Network researchers of legacy 1, to maintain ecological standards of the whole watershed including water resources and aquatic life. The biophysical model represents one level in the global assessment model to be delivered to the decision-makers in order to reach certification and ISO standards.

CONCLUSIONS

In the short term, watershed disturbances (natural and anthropogenic) increase the productivity of algae, by increasing the biomass of some algal groups, mainly in lakes with the largest drainage area in relation to lake area and % perturbation. Watershed perturbations, still in the largest watersheds of the lakes monitored, do not detectably modify algal quality. Phytoplankton biodiversity was not detectably altered in naturally disturbed lakes, nor in human perturbed lakes when the disturbance was relatively small. However, algal productivity and phytoplankton species biodiversity could be jeopardized in lakes with large watersheds, when a relatively large portion of the watershed is harvested. Thus, watershed attributes could be useful tools that allow planners to maintain, at least in the short term, healthy aquatic ecosystems, while providing economic, social and cultural opportunities for the benefit of present and future generations.

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