# Evaluation of the effects of different forest harvesting practices on lake ecosystems in British Columbia

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## Abstract

This study was designed to determine what effects different forest harvesting practices have on lake ecosystems in the Pacific (Vancouver Island) and Omineca-Peace (central interior) regions. The biogeoclimatic regimes in these two areas vary significantly with coastal western and mountain hemlock predominating on Vancouver Island and subboreal spruce and Engleman spruce comprising the areas of interest in the Omenica-Peace region. Landscape-scale responses to ecosystem disturbance was expected to vary between these two regions as the geomorphic and climatic regimes are quite different. Sediment cores from 21 lakes were obtained and dated using $^{210}$Pb techniques. Paleolimnological techniques including the analysis of diatoms allowed the comparison of species composition from before and after harvesting. In each of the regions a set of reference (control) lakes were sampled. Changes in organic matter content of the core were also used to evaluate the lake response to forest harvesting activities. $^{210}$Pb results allowed the calculation of sedimentation rates which were used in conjunction with lake and watershed morphometrics to estimate annual sediment yields to the lake. Geographic information system technology was used to incorporate spatial analysis of historical harvesting activities and basin morphometrics. Results from diatom analysis in the Vancouver Island lakes have all four impact lakes showing significant changes in species composition following logging. The largest changes were observed in the two lakes with the largest watershed area:lake area ratio, indicating that residence time of the water may be an important factor. In the northern lakes organic matter content increased followed harvesting in one of the impact lakes and three of the control lakes. This may reflect changes in climate, as the mean annual temperatures in the Prince George area have exceeded the 50 year mean since the mid 1970s, which is coincident with the period of harvesting. Sediment yields are significantly higher in the coastal region. Results from multivariate statistics indicate increased sediment yields associated with forest cut blocks on steeply sloped areas that are close to transport channels. Streamside harvest, stream crossings and road construction are other factors that are identified as potential activities that contributed to increases in sediment yield. Catchment morphology, for example slope also plays a statiscally significant role.

## Introduction

### Background and Rationale

The mandate for forestry management has vastly changed in the last two decades from one of primarily timber supply to a more integrated resource approach in which silvicultural practices need to take into account harvesting at a sustainable level while maintaining ecosystem integrity (Pedersen 1995; Kimmins 1995). Because of the intimate link between terresterial, riparian and lake ecosytems, the effects of forest harvesting can often be tracked by changes in water characteristics. For instance, clear-cutting has been shown to affect streamflow, turbidity, concentrations of dissolved ions in streamwater and stream temperature (Keenan and Kimmins 1993). Whereas in comparison to streams the impact of forest havesting on lakes has been greatly understudied.

Lake ecosytems are ideal sites for monitoring the effects of past and present forest harvesting methods because many of the aquatic organisms that are sensitive to chemical changes in the aquatic environments, as a result of harvesting, are preserved in the lake sediments. These lake sediments are deposited in chronological order and can be dated using $^{210}Pb$ measurements and thus can then be used as an archive of biological and chemical changes over long-time frames. Terrestrial erosion as a result of catchment disturbance can be tracked through grain size analysis, organic matter content and geochemical profiles in the lake sediments. An increase in terrestrial inorganic inputs, such as minerogenic silts and fine sands, results in decreased organic matter and an increase in rock-forming minerals such as sodium (Na), potassium (K), titanium (Ti), and magnesium (Mg). The dating of cores combined with measures of accumulated sediment allows estimates of rates of sediment deposition. Estimates of the annual watershed sediment yield can be calculated from the combination of sedimentation rate and information on watershed and lake size. Algae, particularly diatoms, are powerful indicators of environmental change (McCormick and Cairns 1994; Dixit et al. 1992b). Diatoms are an ecologically important group in most aquatic ecosystems, they respond rapidly to environmental changes, and because they are at the base of aquatic foodwebs can provide vital information on the health of the lake ecosystem. Diatoms, because of their taxonomically diagnostic siliceous cell walls that are preserved in lake sediments and their sensitivity to many limnological variables such as nutrients, ionic concentration and composition, and pH, provide a powerful means of establishing historical water-quality conditions.

Paleolimnological methods thus provide a means to reconstruct and interpret past environmental conditions using the physical, chemical and biological information preserved in the lake sediments. Paleolimnology has seen tremendous advances over the last decade. Much of this progress has been related to applied aspects of environmental management such as those dealing with lake eutrophication, lake acidification and recovery, metal pollution and other contaminants and fisheries assessments (e.g. see reviews by Charles et al. 1994; Dixit et al. 1992a,b; Smol 1994). Advances developed during these applied studies in core collection and sectioning, data analysis, and quality assurance/quality control can be transferred directly to specific water quality monitoring and watershed-management endeavours applicable to an integrated forest resource management.

Information from percent organic matter, geochemical and diatom profiles have been successfully used to reconstruct the effects of natural forest disturbance from fires and windthrow (e.g. Rhodes and Davis 1995) and can thus be applied to human-induced changes from forestry practices. The focus of the study will be on forestry practices in the Pacific (Vancouver Island) and Omineca-Peace (central interior) regions. The biogeoclimatic regimes in the two areas vary significantly with coastal western and mountain hemlock predominating on Vancouver Island and subboreal spruce and Engleman spruce comprising the areas of interest in the Omenica-Peace region. Landscape-scale responses to ecosystem disturbance will differ between these two regions. This is a function of the degree of coupling between geomorphic (soils and slopes) and hydrologic (precipitation and water delivery) conditions in the two regions. Both the magnitude and frequency of these ecological responses to watershed disturbances will be clarified through the use of paleolimnological techniques.

Analysis of diatoms, organic matter content, and sediment yields were used to investigate whether such changes occurred coincident with or following forest harvesting. The natural variablility of lake processes prior to harvesting was compared to responses following logging. This type of research can provide valuable information for an integrated terrestrial/watershed management approach, and can potentially be used as a cost-effective management tool for monitoring the environmental sustainability of different forestry practices within all the various forest types.

**Objectives**

The research priorities, as identified in the FRBC guidelines, which are addressed by this project include:1) the development of methodologies for monitoring the environmental sustainability of forest management practices; 2) a better understanding natural disturbance patterns and processes; 3) evaluating the geomorphic processes and the effect of management on them; 4) researching the landscape flows and linkages, particularly the linkages between watersheds and their receiving lakes; and 5) researching the effects of forestry practices on aquatic species and their habitats.

The overall objective of this project was to identify the watershed and lake characteristics that can influence the magnitude of impact from forest harvesting. By reconstructing and interpreting the sediment cores past physical (sediment yields and grain size), chemical (water quality and geochemistry) and biological (stability of diatoms species) information preserved in the lake sediments, we were able to evaluate the response of the aquatic system to both natural and anthropogenic disturbances in these watersheds. Paleolimnological tools were used to assess the impact of forest-harvesting practices on aquatic systems in the two geographically distinct regions. Landscape-scale responses (total sediment yields) to ecosystem disturbance were also assessed and compared in the two regions.

**Project History**

In 1996 twelve lakes were cored in the Vancouver Island (Fig. 1) region. The following summer another twelve lakes were sampled around Prince George in the central interior (Fig. 2). The cores were dated and analysed through the three years of this project. A geographical information system (GIS) data base was developed in years one and two. In the third and final year compilation and analysis of all of the data was undertaken for the preparation of final reports and published papers.

**Deliverables**

1) Scientific papers in the primary literature will be written evaluating the role of different forest harvest practices on biological assemblages, water quality and watershed sediment yields.
2) Recommendations will be provided to ministries (Foresty, Environment) and forest companies in the region as to the types of harvesting and/or management practices that exhibit the least aquatic impact.
3) An assessment of current riparian management approaches (as stated in the Forest Practices Code) in minimizing aquatic impacts will be assessed if an appropriate set of lakes exhibiting these conditions are found in these regions.

## Methods

**Study area, sites and study design**

The lakes examined in this study are located on the west coast of Vancouver Island (Fig. 1) and the central interior plateau of British Columbia (Fig. 2). The Vancouver Island lakes lie within the coastal western hemlock biogeoclimatic zone which is dominated by western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*). This area receives very high precipitation (250-500 cm/yr), primarily falling as rain from October to March, with increasing annual precipitation as one moves inland (Valentine et al. 1978). The dominant soils are acidic ferro-humic podzols, which are low in base cations (Valentine et al. 1978) and nutrients (Clayoquot Sound Scientific Panel 1995) and slopes range from gentle to extremely steep. The central interior lakes lie within the sub-boreal spruce biogeoclimatic zone which is dominated by white spruce (*Picea glauca*), and lodgepole pine (*Pinus contorta* var. *latifolia*), as well as by stands of trembling aspen (*Populus tremuloides*). Sub-alpine fir (*Abies lasiocarpa*) is common in the understory (Valentine et al. 1978). Average rainfall in Prince George is 620 mm occurring primarily between May and October, while snowfall average is approximately 230 cm occurring from November to March (Valentine et al. 1978). Dominant soils are gray luvisols, composed of a thin, poorly decomposed layer of organic matter, and an upper mineral layer of grayish brown silt and fine sand (Valentine et al. 1978). Slopes on average range from gentle to moderately steep.

The lakes were selected from government databases (e.g. Ministry of Forests files, Ministry of Environment fisheries inventory files, maps and air photos), based on the following criteria: 1) the presence of both reference and logged lakes within an area of similar precipitation, geology and vegetation; 2) the absence of known large-scale natural disturbances in the last 100 years, such as fire; and 3) an attempt to select impact and reference lakes with similar range of physical (e.g. lake area, watershed area, depth, simple bathymetry) (Table 1) and chemical (e.g. pH, conductivity, nutrients) characteristics (Tables 2 and 3). Watersheds used in this study are small in size (less than 67 $km^2$) with a mean drainage area of 17 $km^2$.

In the Vancouver Island area a total of twelve lakes were cored. However, based on the results of the $^{210}Pb$ profiles, detailed logging histories of the basins, and concentration and preservation of diatom assemblages in the cores, only eight lakes were analysed for diatoms while ten lakes were included in the sediment yield analysis. In the central interior region ten lakes were analyzed for diatoms using three categories: four reference lakes (no logging within the basin), three low-cut lakes (total cut in the watershed approximately 30%), and three high-cut lakes (total cut in the watershed approximately 45-70%). For the sediment yield analysis in this northern region the above ten lakes were analysed along with Wendle Lake which exhibited a 16.5 % cut in the basin.

The original surveys of the reference watersheds in the central interior did not indicate past fires in the basins. However, after site selection, detailed analysis of forest cover and stand ages indicated stand ages less than 100 years in the reference watersheds (Spicer 1999), suggesting potential fire, or other disturbance such as insect infestation or windthrow prior to 1960. In Justine Lake approximately 80% of the watershed has age stands less than 100 years old, approximately 40% in Unnamed and Secord lakes, and approximately 6% in Boomerang Lake.

**Field sampling**

The lakes were sampled either from a Beaver float plane, for those with no road access, or by canoe for those that were accessible by vehicle. Two cores were retrieved from the deep basin of each lake using a modified K-B gravity corer (Glew 1989) equipped with a 60-cm long core tube (internal diameter ~ 7.6 cm). The cores ranged in length from 30 to 50 cm and were secured upright in padded buckets in the plane during transport or sectioned vertically directly on shore. The cores were sectioned into whirlpack bags within 24-36 hours of core retrieval. Each core was sectioned every 0.25 cm for the top 40 cm for the central interior lakes and 0.25 cm for the top 20 cm for Vancouver Island lakes and every 0.5 cm thereafter. Core samples from each core were placed into large plastic bags, stored in a cooler on ice and shipped to Queen's University where they were stored at 4°C.

Water samples were collected approximately 0.5 m below the water surface of each lake, stored on ice and shipped to the Pacific Environmental Science Center (Canadian Federal Lab) in North Vancouver, B.C. within 24 hours of collection. Chemical analyses followed standard procedures outlined by the American Public Health Association (1980). Water samples were analyzed for total phosphorus, total nitrogen, nitrate, nitrite, all major anions and cations, dissolved metals, dissolved inorganic carbon, dissolved organic carbon, alkalinity and silica. Samples for metal analysis were filtered in the field with a 0.45µm cellulose acetate filter into acid-washed bottles. Total phosphorus and nitrogen were estimated from unfiltered samples. Estimates of chlorophyll *a* were obtained using standard methods based on a 1000 ml sample that was filtered on a 0.45µm cellulose acetate filter.

### $^{210}$Pb dating and percent organic matter

The wet weight of the sediment was determined for all the subsections of each core. Fifteen to twenty-two subsamples of wet sediment from one core of each lake were weighed in a crucible and oven-dried (24 hr at 105°C), and reweighed to determine percent water and dry weight of the sediment. Samples were ground to a fine dust in the crucible by use of a pestle and redried overnight at 105°C. The weight of the dried sediment was recorded after it was put in a tared plastic digestion tube used in determination of $^{210}$Pb activity and then shipped to MYCORE Ltd. The second core from five lakes in Vancouver Island and six lakes from the central interior was analyzed for $^{210}$Pb activity to determine reproducibility in the different systems. $^{210}$Pb activities were estimated by alpha spectroscopy using a 209-Po tracer of known activity. Unsupported $^{210}$Pb was calculated by subtracting supported $^{210}$Pb (the baseline activity determined from bottom samples of the core) from the total activity at each level. The sediment chronology and sedimentation rates were calculated using the constant rate of supply (CRS) model (Appleby and Oldfield, 1978) from the estimates of $^{210}$Pb activities and estimates of cumulative dry mass (Binford, 1990). Chronology for all cores is based on linear interpolation between dated intervals.

The percent organic matter for each of the $^{210}$Pb samples was determined using standard loss-on-ignition methods (LOI) (Dean, 1974). Briefly, a known quantity of dried sediment was heated to 550°C for 2 hours in a NEY® model 2-21350 muffle furnace with digital temperature control. The difference between the original weight of the sediment and the weight of dried sediment remaining after ignition was used to estimate the percent of organic matter in each sediment sample. Percent organic matter was also determined at a high resolution (approximately 1-3 year resolution) from approximately 1900 (Vancouver Island) and 1920 (central interior) to present.

### Diatom preparation and enumeration

Slides for diatom analysis were prepared using standard techniques (e.g. Cumming et al. 1995). Briefly, ~0.5 g of wet sediment was suspended in a 50:50 (molar) mixture of sulfuric and nitric acid in a 20-ml glass vial for 24 h prior to being submersed in a hot water bath at 70°C for 5-8 h. The remaining sediment material was settled for a period of 24 h, at which time the acid above the sediment sample was removed. Each sample was rinsed with distilled water and allowed to settle once again for 24 h. This procedure was repeated approximately 10 times until the sample was acid free (litmus test). The samples were settled onto coverslips in a series of four dilutions, which when dry, were mounted onto glass slides using a high-resolution mounting media called Naphrax®. For each sample, at least 400 diatom valves were enumerated on a Leica DMRB microscope under oil immersion at 1000X magnification using an objective with a numerical aperture of 1.3. Diatom species identifications were based primarily on the references of Krammer and Lange-Bertalot (1986, 1988, 1991a,b), Patrick and Reimer (1966, 1975), and Cumming et al. (1995).

**Statistical analyses for diatoms and organic matter**

Analysis of similarities (ANOSIM), a nonparametric multivariate statistical test (Clark and Warwick 1994), was used to test the null hypothesis that there was no difference in diatom species composition before and after the onset of forest harvesting, or before and after 1960 and 1975 in the central interior reference lakes. In this region 1960 is the approximate date of onset of logging for five of the six impacted lakes. The onset of logging in the other lake is 1975. In the Vancouver Island sites the reference lakes were tested before and after 1950.

ANOSIM uses a rank similarity or dissimilarity matrix to calculate within group and across-group differences (Clark and Warwick 1994). A Bray-Curtis similarity coefficient with no species transformations was used as the similarity coefficient in our analyses. Rare taxa (less than 2% in 2 samples) were grouped into diatom genera or other morphological categories (e.g. rare *Navicula*, rare centrics, rare araphes). ANOSIM tests were calculated using the statistical package PRIMER 4.0 (Plymouth Marine Laboratory 1996). The outcome of the ANOSIM comparison is termed an R statistic which may vary between -1 and 1. An R statistic near 0 indicates that the null hypothesis of no differences between the two groups of samples is likely true (i.e. the within and between group differences are similar), whereas an R of 1 indicates that samples within the each of the groups are always more similar to each other than comparisons across groups. The significance of the R statistic was evaluated using resampling procedures, where replicates are rearranged into all possible combinations, and during each rearrangement, an R statistic is calculated. The resulting distribution of the R statistic was then used to assess the probability that the R statistic based on the original groupings could be the result of chance. Significance was based a priori on a $p \leq 0.05$. Following the ANOSIM analysis, the program SIMPER in the statistical package PRIMER 4.0 (Plymouth Marine Laboratory 1996) was used to calculate the contribution of each species to the average dissimilarity between the two groups.

Profiles of organic matter changes were split into two groups, those intervals occurring before the onset of logging and those after logging, or before and after 1960 in the central interior reference lakes, or before/after 1950 in the Vancouver Island lakes. The two groups were tested for significant difference using a t-test in which the significance was evaluated using the program Resampling Stats® v. 3.16, in which samples equal in size to the original two groups were chosen at random from the entire data set without replacement 1000 times, thus generating a distribution of t-values. If the original t-value was in the extreme 5% ($p \leq 0.05$) of this distribution, then the null hypothesis that there was no difference between the mean organic matter in the two groups was rejected.

**Sediment Yields**

Sedimentation rates calculated by the Binford model (1990) for each core subsection were linearly interpolated for the remaining core segments producing an annual sediment yield profile for each lake. Sediment yield was calculated by using the annual sedimentation rate in g $cm^{-2}$ $yr^{-1}$ multiplied by the lake pelagic area, divided by the total catchment drainage area. The pelagic divide in each lake is determined by using the 4 m bathymetric contour interval and represented the depositional area of fine sediments within each lake. The use of the pelagic area avoids the inclusion of the littoral zone where bottom sediment mixing caused by wind and shoreline slumps could occur. Loss-on-ignition analysis was used to determine the ratio between organic and inorganic material potentially being delivered to each lake, allowing calculations of inorganic and organic yields.

To account for sediment yield responses when harvesting occurred concurrently with a known disturbance event we separated the known disturbance signal from the sediment yield profile thus removing potential overestimates of forest harvesting effects. A mining operation which extracted ore from 1962 to 1968 in Maggie Lake's catchment is coincident with logging and a considerable sediment yield response. A 1946 earthquake on Vancouver Island may have initiated an increase in sediment yield between the years of 1946 and 1965 in Frederick Lake's catchment. These event peaks are removed from the profiles of these two basins providing conservative estimates of impacts from harvesting.

**GIS data extraction and the impact statistic**

Forest cover maps were obtained in digital format from the British Columbia Ministry of Forests (MOF) 1995 inventory and terrain resource information maps (TRIM) from the British Columbia Ministry of Environment, Lands and Parks (MOELP). This information was entered into an Arc/Info geographic information system (GIS) for analysis. Basin characteristics and variables pertaining to forest harvest activities were extracted from these digital layers (Table 1, Figure 3). With the generation of a digital elevation model (DEM) from the contour layers, slopes upon which individual forestry activities took place were calculated. This allowed for the determination of such variables as cut block slope and the length of road construction on slopes greater than 30 degrees. Annual amounts of road construction were determined where possible from MOF documentation, and subsequently by observing dates of proximal cut block harvest if no information is available. Using the DEM, a surface irregularity index was calculated for each catchment to represent the frequency of slope change. As slopes increase within a catchment, a greater number of triangular irregular network (TIN) polygons were generated from the DEM to represent that change in slope. Therefore, a catchment with a greater average slope would have a larger number of TIN polygons than a lower sloped catchment. To generate a standardized value that would allow comparisons between the slopes of different sized catchments, the number of TIN polygons is divided by the drainage area. This resulted in the surface irregularity index with units of polygons per square kilometer. These TIN polygons that are generated from the DEM were also overlain with forest cover polygons that had been identified as harvested, resulting in a coverage that consists of polygons that have dates of harvest and slope. This allowed for the determination of cut block slope at the 20 meter resolution of the original DEM model.

An impact statistic was calculated for each TIN cut block using its slope and proximity to local stream channels and lake shore, as these factors should influence the amount of fine sediments delivered to the lake. This statistic would replace the measurement of percentage harvest per year in the statistical analysis with a value that would take into consideration the distance of that activity from transport channels and the slope upon which that harvest activity took place. The formula that was used to derive this statistic shown as equation 1.

(Equation 1) $$I_y = \Sigma_n^i (A\ S)\ D^{-1} C^{-1} 10000$$

Where (I) represents the impact statistic for the year (y) (no units);

(n) represents the number of TIN polygons that are harvested in (y);
(A) represents the area of the polygon ($m^2$);
(S) represents the slope factor of the polygon, calculated from the DEM;
(D) represents the down slope distance of that polygon to the nearest stream or lake shore (m);
(C) represents the catchment area ($m^2$), and
10000 is used to conserve decimal places in Arc/Info.

The formula was designed to increase the impact value of a harvested TIN polygon when its slope increases and as its down slope distance to streams and lake shore decreases. Conversely, if a harvested polygon had a very low slope and is located a considerable distance from a stream transport channel, the impact statistic calculated for this individual polygon would be much lower. The impact statistic of all cut blocks being harvested in a single year is summed to produce an annual impact statistic for each catchment. The division by the drainage area is made to allow annual impact values to be comparable between sample basins with respect to catchment area. Values for each of the variables required for calculating the impact statistic are available from the coverages presented in Figure 3, with the exception of the down slope distance. It was necessary to use Arc/Info's least-cost-path algorithm to determine the shortest down-slope distance from the lowest point of elevation in each TIN polygon to the linear features of streams or lake shore (Spicer 1999).

**Watershed databases and Cheong's similarity index**

A compilation of morphometric and annual harvest related variables were entered into an individual data base for each of the 21 study catchments. Annual organic and inorganic sediment yields calculated by $^{210}Pb$ dating and LOI were cross referenced by date to harvest variables. Annual precipitation and basin characteristics are also present, although catchment morphology had no annual variation. Most of the variables are standardized by basin area to allow for inter-basin comparison. From these 21 catchments, two regional databases referred to as the central interior and Vancouver Island full data sets are created. Although differences in basin size had been controlled for by using standardized units of measure, many other differences between basin morphologies still exist. Therefore before statistical analysis of the data, Cheong's (1993) similarity index was used to determine which basins in each regional set had comparable morphometric features. This dissimilarity analysis resulted in six and seven lakes with comparable morphometric characteristics for Vancouver Island and the central interior respectively. Using the comparable basins in each regional data subset resulted in a total of 206 collective years of post harvest data in the central interior and 192 years for the coast.

**Statistical approach for sediment yield analysis**

In order to compare organic and inorganic sediment yields to the morphometric and logging related impact variables that are generated using GIS, multivariate canonical correlation (CC) is performed on each data set using the Statistical Package for Social Science (SPSS). The use of the terms dependent and independent variable are used below for ease of discussion, as canonical correlation does not have dependent and independent variables, but simply two sides of one equation. However, in this context, the side that holds the variables of annual inorganic and organic sediment yield are referred to as dependent variables and all impact related variables on the opposite side are referred to as independent. Canonical correlation produces variable loadings that will be used to determine if any independent variables (logging activities) correlate to dependent variables (sediment yields). The technique is similar to multiple regression but allows more than one variable on the 'dependent' side of the equation. Groups of variables are combined on each side of the equation to produce a predicted value that correlates highest with the predicted value generated on the opposite side. Since there is more than one possible combination of variables that can be used, different solutions are generated and individual variable loadings for each solution are produced (Tabachnick and Fidell, 1996). The statistical significance, a correlation value and the amount of variance explained by each solution is derived. Variable loadings for each dependent and independent variable are generated for each solution. The value of a solution can also be assessed by its level of interpretability. The assumptions of CC that may be of concern include its dependence on finding linear relationships between variables within the data set. Non-linear relationships that exist between variables will not be found by this technique. A difficulty also arises in the interpretation of variable loadings in any given solution, since these relationships need to be substantiated by other statistical methods before rankings of variables can be drawn from the output. Principal component analysis (PCA) and factor analysis (FA) are two additional multivariate techniques that are conducted on each data set in order to verify statistical loadings produced from the canonical correlation. Statistical output between PCA, FA and CC is identical for the purposes of interpretation. Tests for multicollinearity between variables in each basin full and subset are conducted through correlation matrices while Mahalanobis distances are used to identify potential multivariate outliers in each data set (Tabachnick and Fidell, 1996). Correlations between sets and across sets did not exceed 0.90 and no multivariate outliers are identified that are not verified as being valid in the context of the data.

## Results

### Vancouver Island Lakes: Organic matter changes and resampling results

Increases in organic matter can be attributed to several factors including increased inlake production of organic matter, increased inwash of organic matter, or decreases in the load of inorganic matter to the lake. Resampling techniques were used to determine if the mean in organic matter was different before and after the onset of clearcutting, or before and after 1950 in the reference lakes. Only one logged lake (Pachena) showed a significant difference. With the onset of logging in Pachena Lake there was a coincident gradual decrease in percent organic matter from approximately 45% down to approximately 30% by 1990 (Fig. 4G). It is likely that this magnitude of change represents an increasing terrestrial input of inorganic material from the watershed associated with forest harvesting. Although Pachena Lake has the smallest length of streams, it does have the highest density of roads, as well as one of the steepest terrains (Table 1).

Although Maggie Lake did not show a significant difference in organic matter before and after the onset of logging, there is a distinct peak in organic matter corresponding approximately to the onset of logging (Fig. 4F). This distinct peak in organic matter is composed of a 5-6 cm layer of woody debris (chunks of wood, twigs, needles) that was deposited within a short time span (1-4 years). Near the same time as the onset of logging and road building, Hurricane Freda hit the region in 1962, bringing in torrents of rain that may have started debris slides on an already disturbed landscape. As well as the disturbance from logging and Hurricane Freda, there was an open pit iron mine upstream from Maggie Lake which operated from 1962 to 1968, which disturbed the surrounding landscape. It is difficult to untangle the contribution of the various disturbances to this apparent erosional event which deposited a thick layer of organic matter into the deep basin of the lake. A later peak in organic matter in the 1990s may be in part associated with a large January storm in 1992 which brought down nearly 75 cm of rain to the Barkley Sound area. The increased flow of water on a disturbed landscape may have resulted in debris slides, as described earlier. Disregarding these peaks in organic matter, there is a decrease in organic matter from approximately 20% prior to logging down to 11-15% from 1970 to 1985 that may be associated with a general increase in inorganic mineral inputs from the watershed corresponding to logging activity.

In Toquart Lake there is a large peak in organic matter centered around 1952, with another smaller peak in the 1960s (Fig. 4D). There is no known anthropogenic impact in the watershed during this time interval (John Deniseger, MOE, Nanaimo, B.C., pers. com.). Apparently the watershed does not have characteristically unstable soils, but has had some slides associated with unstable rocks (Bob Cerenzia, MOE, Port Alberni, B.C., pers. com., Arnaud 1997). However, with the long time span of the increased organic matter it seems unlikely that the peak is associated with an erosional debris slide and there is no evidence in the core such as chunks of wood, twigs, etc. as there was in Maggie Lake. Thus the increase in organic matter is uncertain, being either attributable to increased terrestrial input, potentially due to natural landscape disturbance, or there was increased productivity within the lake which resulted in the increased deposition of organic matter.

### Diatom species changes and ANOSIM results

An average of 19 samples per lake were analyzed for diatoms with an average temporal resolution of five to ten years. The diatom flora is very diverse in all of the lakes, with the exception of Angora Lake which only has 20 taxa. All others have greater than 100 taxa, with up to 170-190 taxa in Blue and Maggie lakes.

Sediment intervals in each lake were divided a priori into two groups: before and after forest harvesting, and before and after 1950 in the reference lakes. The difference in species assemblage between the two groups within each lake was tested using a multivariate nonparametric Analysis of Similarity (ANOSIM). The null hypothesis of no difference between diatom assemblages in the two groups could not be accepted in five of the eight lakes, at a significance level of 0.05 (Fig. 6A). All of the impact lakes, and one reference lake showed a significant difference in species assemblage between the two groups. However, in only three of the lakes, two impact lakes (Black and Pachena), and one reference lake (Little Toquart) are these differences associated with a high R statistic (Fig. 6A). Although the species abundances in the lakes that showed significant changes in the two groups are often quite subtle, they are more distinct in those lakes that had a high R value.

## Central Interior Lakes: Organic matter changes and resampling results

Mean organic matter was tested to determine if there was significant difference before and after the onset of clearcutting, or before and after 1960 in the reference lakes. Only one of the impact lakes (Woodcock) showed a significant increase in organic matter after the onset of logging, whereas three of the reference lakes indicated a significant increase after 1960. Although results were insignificant in Laurie Lake before/after 1960 there is a distinct increase of approximately 8% in organic matter starting at ca. 1980 (Fig. 5E). All of the above lakes are west of Prince George and the watersheds of Justine, Secord, and Unnamed lakes are thought to have had undergone extensive fire between approximately 1890 and 1960.

In Tang Lake there is a decrease, although non-significant, in organic matter after the onset of logging (Fig. 5I). In Pitoney Lake there is a decrease in organic matter between 1966 to 1976, which corresponds to some of the cutting history years (Fig. 5F). In Jakes Lake there is a decrease, although non-significant, in organic matter corresponding to the onset of logging in the watershed, whereas in Upper Summit Lake the percentage of organics has changed very little over the last 80 years, although there is a slight increase starting ca. 1980 (Fig. 5H, J).

**Diatom species changes and ANOSIM results**

An average of 14 samples per lake were analyzed for diatoms, giving approximately an equal number of samples before and after the onset of logging, or before and after 1960 in the reference lakes and an average resolution between samples of five to ten years. The average number of taxa across lakes is 77, with a range from 41 in Unnamed Lake to 118 in Tang Lake.

Sediment intervals in each lake were divided a priori into two groups: before and after the onset of forest harvesting, and before and after 1960 and 1975 in the reference lakes. The reference lakes were analyzed before and after 1960, because this is the approximate onset of logging in five of the six impact lakes. The reference lakes were also analyzed before and after 1975 to account for the one impact lake (Woodcock) in which the onset of logging did not occur until 1975. The difference in species assemblage between the two groups within each lake was tested using a multivariate nonparametric Analysis of Similarity (ANOSIM). The null hypothesis of no difference between diatom assemblages in the before/after 1960 groupings could not be accepted in four of the nine lakes, at a significance level of 0.05 (Fig. 6B). Three of the five impact lakes, and one reference lake showed a significant difference in species assemblage before and after ca. 1960. The null hypothesis of no difference between diatom assemblages in the before/after 1975 groupings could not be accepted in three of the five lakes, at a significance level of 0.05 (Fig. 6B). The one impact lake, and two reference lakes showed a significant difference in species assemblage before and after ca. 1975. For both time periods tested, in only two of the impact lakes (Woodcock and Laurie), are these differences associated with a high R statistic (Fig. 6B). Although the species abundances in the lakes that showed significant changes in the two groups are often quite subtle, they are more distinct in those lakes that had a high R value.

**Sediment Yields:Vancouver Island**

The canonical correlation for the Vancouver Island full and sub data sets are presented in Table 4a. In the case of the full data set, both solutions are presented for interpretation as they are both statistically significant. Loadings that are greater than + 0.35 are considered relevant. The closer the value is to + 1.0, the stronger the variable loading on the solution. Inorganic yield loads strongly on the first (0.98), while organic yield loads on the first (0.50) and second (0.87) solution. Independent variables which load positively with inorganic yield in the first solution include the cumulative impact statistic, stream crossings, road density on slopes greater than 30 degrees and streamside logging. Organic yield loads positively in the second solution with surface irregularity.

Focusing on the solution for the subset, increases of 22% over the explained variance accounted for in both solutions for the full data set are observed. Inorganic and organic yields both load positively on this solution along with the impact statistic, stream crossings, surface irregularity and road density on slopes greater than 30 degrees. The canonical correlation for the subset is 0.93, $p < 0.001$.

CC analysis indicates that basin morphometrics and several logging related activities influence sediment yields at the catchment scale. Morphometric variables include surface irregularity and in part the impact statistic. Logging effects include the impact statistic, the number of stream crossings, road density, road density on slopes greater than 30 degrees and the percentage of streamside logging. (Note that two of the variables incorporate both morphometric and anthropogenic effects). In most cases, the loadings of these variables and the amount of variance explained by the solutions increase as dissimilarities between catchments in the data sets decreases.

**Central interior**

Canonical correlation results for the central interior sample sets are presented in Table 4b. The second solution from the CC is presented for the full data set since it accounted for the greatest amount of variance (34.3%) and had loadings that could be readily interpreted. The canonical correlation for the full set solution is 0.66, $p < 0.001$, $\alpha = 0.05$. Inorganic and organic yields both positively loaded on the solution, along with the independent variables of the cumulative impact statistic, surface irregularity and road density. The interpretation of the CC indicates that as these independent variables increase, organic and inorganic yields also increase.

The second CC solution for the subset of central interior basins is also presented in Table 4b. Note that the amount of variation accounted for has increased to 53.6%. The canonical correlation for this solution is 0.76, $p < 0.001$. Again, inorganic and organic yields load positively on the solution. Independent variables that also load positively include the impact statistic, surface irregularity, road density and streamside logging. All of these variables have higher positive loadings in the subset as compared to the full set, while the percentage of streamside logging becomes large enough to be interpreted as an important variable. A loading for roads on slopes greater than 30 degrees cannot be calculated, as all values for this variable in the subset of catchments are zero.

A series of earthquakes that occurred in the proximity of Prince George in 1986 also had the potential to influence sediment yields in all central interior basins. Therefore a dichotomous variable was added to the years of 1986-1996 in the central interior sample set to represent these events (1: representing post earthquake yields; 0: representing pre earthquake yields) in order to determine potential influence. The results indicate that earthquakes were not a significant variable in the northern data set.

**Age of logging practices**

In order to determine if older, pre-1980 logging practices in British Columbia produced more fine sediments than recent harvest practices, dichotomous variables are added to each basin indicating the start of cut (1: pre 1980's, 0: control, -1: post 1980's). A second dichotomous variable is added to each based upon regional location (1: southern coast, -1: central interior).

Results indicate that coastal basins have a higher fine sediment yield than those in the central interior. This lends support to the notion that coastal catchments are more sensitive to disturbance, and differences between regional location and even between individual catchments can have varying degrees of sensitivity (Walling and Webb, 1996). The loadings also indicate that catchments which had harvest operations starting before the 1980's are more likely to have larger fine sediment yields than those basins which had more recent forestry operations. This supports the argument that harvest practices have had less impact since the 1980's in regard to lowering the amount of fine sediment production (Chatwin and Smith, 1993). However the number of watersheds that had post-1980 cuts was small in both regions so this relationship should be verified with a larger data base.

## Discussion

Although all four impact lakes in the Vancouver Island region showed a statistically significant change in diatom assemblage before and after the onset of logging, even in those with the strongest changes (i.e. high R statistic) the changes were relatively minor. The difference in assemblage before and after typically is the result of composition shifts in percentages as opposed to the appearance or disappearance of taxa. The two impact lakes that showed the greatest diatom changes (Black and Pachena) have the smallest WA/LA ratios (Table 1), with slope ranging from intermediate (Black Lake) to high (Pachena Lake). Engstrom (1987) suggested that his study lakes with a WA/LA ratio below four had a longer residence time of water, which may in part explain our findings in the impact lakes, due potentially to increased retention of phosphorus in lakes with increasing water residence time (D'Arcy and Carignan 1997). Phosphorus is well known to be the primary limiting nutrient in freshwater lakes (e.g. Schindler 1974) and increased loading of phosphorus from forest harvesting could result in eutrophication (Likens et al. 1978), with eutrophication resulting in changes to the diatom assemblage (e.g. see review by Hall and Smol 1999). However, podzols, the dominant soil type on the west coast of Vancouver Island, adsorb phosphorus, tightly binding it, due to the low soil pH, and thus release to streams is minimal (Clayoquot Sound Scientific Panel 1995).

Other chemical factors besides phosphorus can greatly affect diatoms and other algae in the lakes. Diatom assemblages are highly related to pH (e.g. see review by Batterbee et al. 1999), and diatom-inferred pH increases have been associated with fire (e.g. Rhodes and Davis 1995), land clearance associated with agriculture (Renberg et al. 1993), as well as logging in some studies (e.g. Davis et al. 1994). All of the lakes in the aforementioned studies are acidic lakes (pH<6.0) with low buffering capacity and thus are sensitive to changes in pH. The podzols of Vancouver Island are low in base cations (Valentine et al. 1978), and the lakes range around circumneutral (pH= 6.5-7.8), thus greater buffering capacity may in part account for there being only minor changes.

In summary, the surprisingly minor changes, albeit statistically significant, seen in the diatom assemblages of Vancouver Island after substantial logging in the watersheds may be due to several reasons including: 1) short water residence times of the lakes (with the greatest changes seen in those with the hypothesized longest residence times); 2) short-term changes in water chemistry that were not detected at the average study resolution of 5 to 10 years; 3) low phosphorus export due to highly adsorbtive soils; 4) high buffering capacity of the lakes and thus less susceptibility to pH changes associated with land disturbance; and 5) high rate of revegetation and low percentage of watershed cut in any particular year.

Average annual temperature in Prince George, B.C. has typically been above the 50 year mean of the record since the mid 1970s, being most pronounced since ca. 1985. Annual precipitation has generally been below the 50 year average since ca. 1970, being most pronounced since the late 70s, with three intervening years in the early 80s, and 1990 with above average precipitation (Fig. 7). Potentially the increased organic matter which we see in the lakes are due to decreased inputs of inorganic terrestrial material from the watershed due to decreased flow associated with the below average precipitation. Alternatively, the organic profiles may be due to increased production associated with a warmer and longer growing season. In Woodcock Lake the significant increase in organics is coincident with the onset of logging (Fig. 4), however, these changes are also coincident with the changes in climate outlined above. Although statistically insignificant, there are decreases in percent organic matter in three of the impact lakes (Pitoney, Jakes, Tang) that are approximately coincident with the onset of logging (Fig. 3). On average these lakes have steeper slopes in their watersheds than the other study lakes (Spicer 1999) which may contribute to a greater supply of mineral material to the lake basin than those with gentler slopes (Hall and Smol 1993), particularly after soil disturbance. Note also in the Vancouver Island data set that Pachena Lake showed significant decreases in organic matter and exhibits one of the highest surface irregularity values (slope surrogate).

It is difficult to decipher whether the significant diatom changes that we see in four of the six impact lakes in the central interior region are due solely to the forest harvesting because of the significant increases of the organic matter seen in three of the four reference lakes, as well as increases in two of the impact lakes not coincident with the onset of logging. We hypothesize that the increases in organic matter may be either related to the younger age stands in the reference lakes or be related to climate. Significant changes in the diatom assemblages before and after 1975 are seen in two of the reference lakes (Fig. 6b), providing further suggestion that climate may be influencing some of the changes we are seeing.

The minimal changes seen with the forest clearing may in part be due to the rapid revegetation of the areas, and thus the natural cycling processes between the terrestrial and aquatic ecosystems were interrupted for only a short time. Other factors that can influence the response of a lake to land-use changes include climate, watershed characteristics (e.g. size, slopes, streams, vegetation type), lake basin characteristics (e.g. surface area, depth, water residence time), as well as mineralogy and nutrient status of the catchment soils.

**The sediment yield profiles and non harvest related disturbances**

Natural disturbance events, such as fire, earthquakes and high water years were identified as potential influences of the sediment yield profiles of basins within this study. The majority of these natural disturbance events occurred before the onset of harvesting (Spicer 1999) and so are not of concern here. As well all the mining history records for each watershed were investigated. Only Maggie Lake had a known extraction operation as previously mentioned. While extreme climatic events which occurred in this post harvest period can be detected from the monthly climate data available it is not possible to evaluate the response of the systems to high frequency, low magnitude events (periods of continous daily rainfall) which can potentially generate sediment movement in these watersheds. More detailed daily data for the climate stations in these two regions could allow a better evalation of the frequency of these type of events as shown by Wilby et al. (1997).

**Impact statistic**

The impact statistic is calculated to take into account the factors of slope and distance in relation to the amount of fine sediments that a lake would receive from a cut block. In order to test the effectiveness of the statistic, CC was run for each regional subset with an annual cumulative percent of catchment cut in the place of the impact statistic. The results indicate that the GIS derived impact statistic proved to be a much better indicator of disturbance than annual cut in the southern basins of

Vancouver Island. In the central interior data set the cumulative harvest resulted in a stronger correlation but several of the variables that had previously been significant dropped out of the solution (surface irregularity and streamside logging).

The impact statistic appears to be a better indicator of cut block influence on fine sediment mobilization and delivery, and factors such as slope, the distance of sediment sources from transport channels and the area of cut combine to play a key role. The cumulative annual percentage of catchment harvest does not appear to be a good single indicator of catchment sediment yield increases.

**Regional differences**

Central interior basins had lower dissimilarity scores than those observed for Vancouver Island, attesting to the greater variation in morphology of the coastal catchments. Harvest practices that statistically increase sediment yields within the coastal and central interior regions are similar, but two individual variables tested by canonical correlation are considered relevant only in a single region. The number of stream crossings influence yields on the coast, but fail to be of statistical importance in the central interior. This may be related to the difference in average slope between the two regions and the amount of annual rainfall received near the coast. Road density on the other hand is an indicator of sediment yield increases in the central interior while roads on slopes greater than 30 degrees is an influencing factor in the south (although there are no roads on slopes exceeding 30 degrees in the central interior data set). Differences in the type of soils and the grain size of the materials may play a role in this relationship.

**Deliverables Produced**

**Four papers submitted to primary journals:**

Laird, K., B.F. Cumming and R.N. Nordin. A regional paleolimnological assessment of the impact of clearcutting on lakes from the west coast of Vancouver Island, British Columbia, submitted to Canadian Journal of Fisheries and Aquatic Science.

Laird, K. and B.F. Cumming. A regional paleolimnological assessment of the impact of clearcutting on lakes from the central interior of British Columbia, submitted to Canadian Journal of Fisheries and Aquatic Sciences.

Spicer, C.P and E.L. Petticrew. Evaluating the impacts of logging,wildfire and earthquakes on sediment yields in small catchments throughout coastal and interior regions of British Columbia, Canada, submitted to Earth Surface Processes and Landforms.

Spicer, C.P and E.L. Petticrew. Determining the relationship between harvesting, roading and morphometric variables to historical sediment yield variability of coastal and interior catchments of British Columbia, Canada, submitted to Canadian Journal of Fisheries and Aquatic Sciences.

**Masters Thesis:**

C.P. Spicer. 1999. Evaluating the impacts of forest harvesting and natural disturbance events on sediment yields in small watersheds throughout British Columbia. Masters of Environmental Science, University of Northern British Columbia.

**Four poster presentations:**

Petticrew, E.L. and C.P. Spicer. 1998. Lake sediment responses to forest harvesting in coastal watersheds of British Columbia. Canadian Society of Limnology Annual Meeting. Kingston, Ontario.

Laird, K. B.F. Cumming and R. N. Nordin. 1998. Evaluation of limnological response to forest harvesting on Vancouver Island, British Columbia. Canadian Society of Limnology Annual Meeting. Kingston, Ontario.

Laird, K. B.F. Cumming, E.L. Petticrew, A. Smith, C. P. Spicer and R.N. Nordin. 1997. Evaluation of the effects of forest harvesting on lake ecosystems. Canadian Society of Limnology Annual Meeting. Ottawa, Ontario.

Laird, K. and B.F. Cumming. 1997. Changes in diatom assemblages in lake sediment cores in response to forest harvesting on Vancouver Island, British Columbia: preliminary results. North American Diatom Symposium. Douglas Lake, Michigan.

**Six Papers delivered at Conferences:**

Petticrew, E. L. 1999. Isolating land use effects on hydrology and sediment yields using lake cores. Canadian Water Resources Association Conference, (B.C. Chapter). Kelowna, B.C.

Petticrew, E.L. and C.P. Spicer, 1999. Watershed response to forest harvesting as detected by lake coring in coastal and interior British Columbia. Canadian Society of Limnology Annual Meeting, Edmonton, Alberta.

Spicer, C.P. 1999. Statistical relationships between harvesting, roading and morphometric variables and historical sediment yields in coastal and interior British Columbia. Canadian Society of Limnology Annual Meeting, Edmonton, Alberta.

Spicer, C.P. 1999. Evaluating the impacts of harvesting and natural disturbance events on sediment yields in lakes of British Columbia. Western Canadian Association of Geographers, Annual Meeting, Kelowna, British Columbia.

Petticrew, E.L. and C.P. Spicer, 1998. Evaluating the impact of forest harvesting on lake sedimentation rates in small coastal and interior B.C. watersheds. Forest Hydrology Seminar, Kelowna, British Columbia.

Spicer, C.P. 1998. Sediment yields as a response to forest harvesting activities in coastal British Columbia: preliminary results. Western Canadian Association of Geographers, Annual Meeting, Richmond, British Columbia

## Conclusions and Recommendations

### Recommendations

We have assembled the following list of lake and watershed characteristics which we consider important in the context of managing lake impacts from forest harvesting activities.

**Effects on algal composition:**

- lake water residence time
- soil nutrient composition and cation exchange capacity
- slope of watershed
- presence or absence of upstream wetlands or waterbodies

**Effects on sediment yields:**

- impact statistic which includes area harvested, local slope and distance to the nearest waterway (see methods)
- watershed topography
- road density
- streamside logging
- stream crossings (in Vancouver Island watersheds only)
- roading on slopes exceeding 30° (Vancouver Island watersheds only)

**Impact of project on BC forest sector**

The regulations pertaining to lake management in the current Foresty Practices Code deal predominantly with lake size and the width of the buffer strip required. We suggest that the lake volume to watershed area should be used in the categorization of lake sensitivity as this provides an estimate of water residence time which influences lake reponses more directly. The adsorbtive capacity of soils in the watershed can also influence the storage/delivery of nutrients as can the presence of upstream lakes or ponds which can act as traps or sinks of sediment and nutrients. The presence or absence of these features should be considered when evaluating the magnitude of response a lake system may exhibit to watershed disturbance.

Roading on high slopes and stream crossing are two factors which are already incorporated into the FPC and from our historical data base appear to play significant role in sediment delivery to Vancouver Island lakes. Streamside logging which was found to be significant in both regions is already incorporated in the FPC via the use of buffer strips along streams of a given size.

The development of an impact statistic to integrate the annual effects of slope, areal disturbance and distance from a waterbody was found to represent the disturbance on the watershed better than the variable of annual harvest.

**Role of Climate**

The response of both lake conditions and sediment delivery are influenced strongly by climatic variability. The influence of harvesting activities can be confounded by the prevailing climate if prolonged warm and dry periods occur, as was noted in the central interior region. Low frequency, high magnitude precipitation events can generate the more extreme responses in sediment delivery. Problems in obtaining long term historical and appropriately located climate records makes it difficult to diffentiate the role of climate versus the role of harvesting.

**Extension to end users**

The results of this study have been distributed to all of the cooperating agencies/end users we identified in our intial proposal. This includes individuals in government agencies in both regions (MOELP and MOF) and forest companies (Canfor, Northwood). Our results have been presented at conferences as six talks and four posters which reached a mixed audience of geomorphologists, limnologists, forest hydrologists, foresters, water resource engineers and resource managers. Four papers have been submitted to primary journals for publication.

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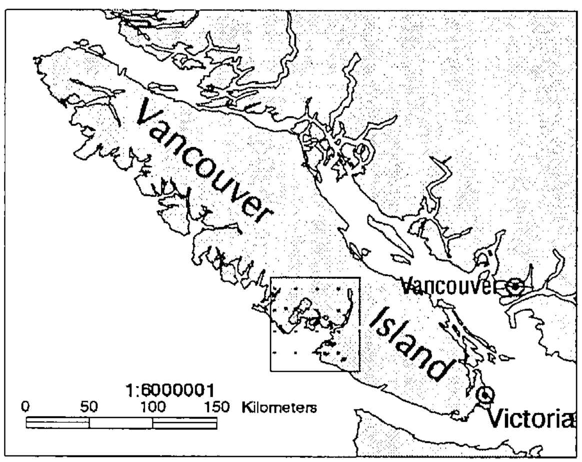
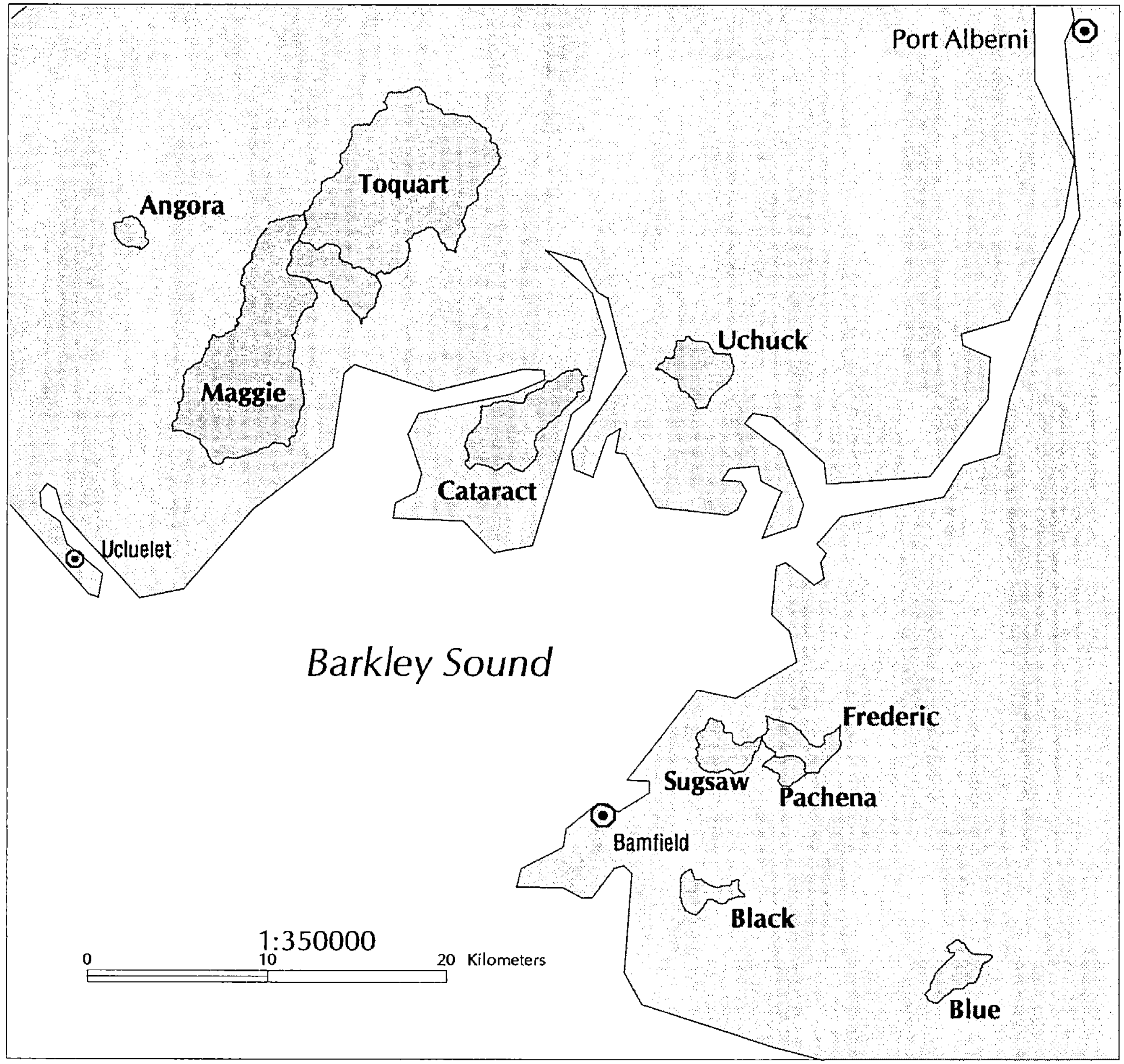
# Vancouver Island Watersheds

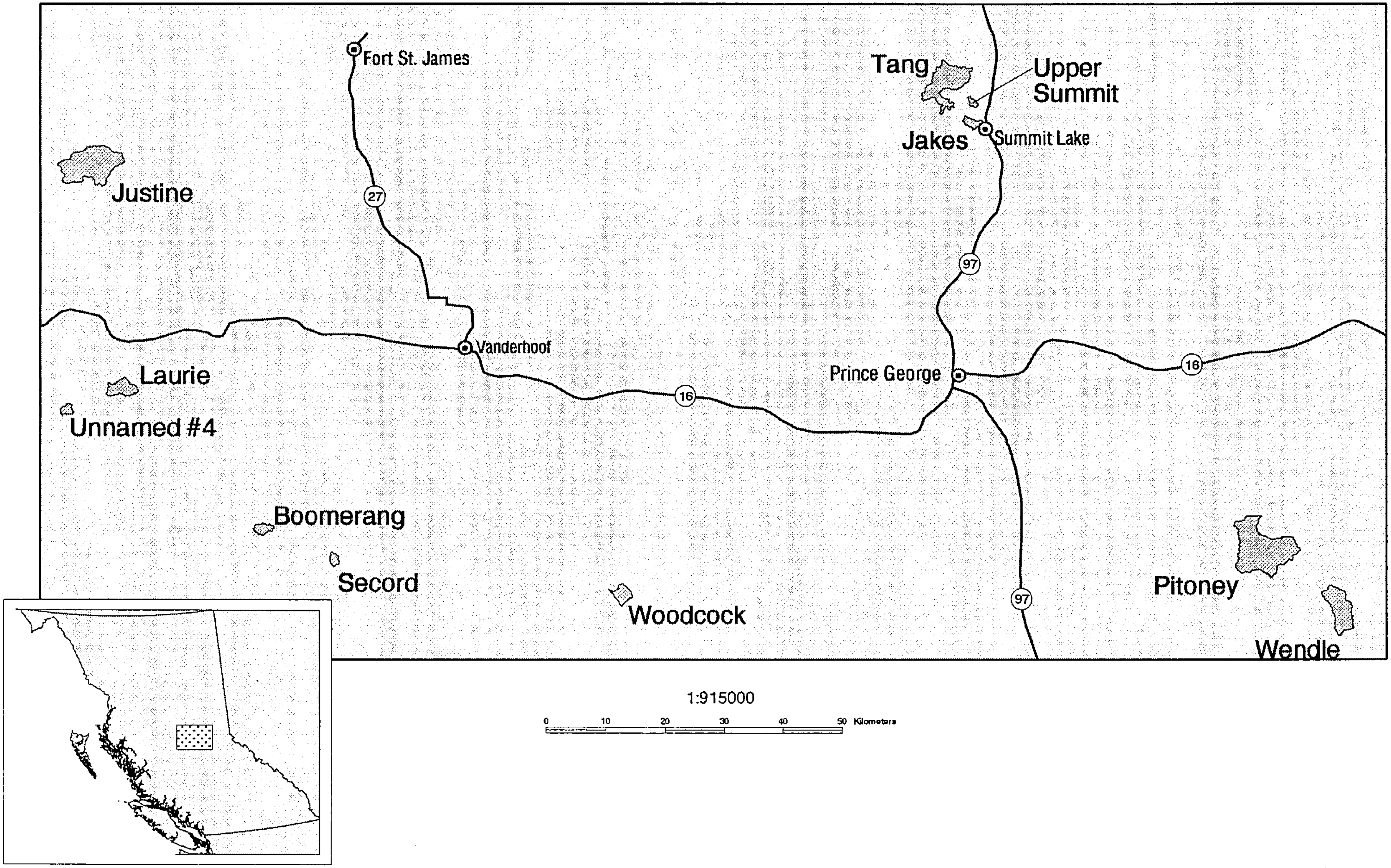



D.A. Spencer

Source:
Ministry of Environment, Lands, and Parks

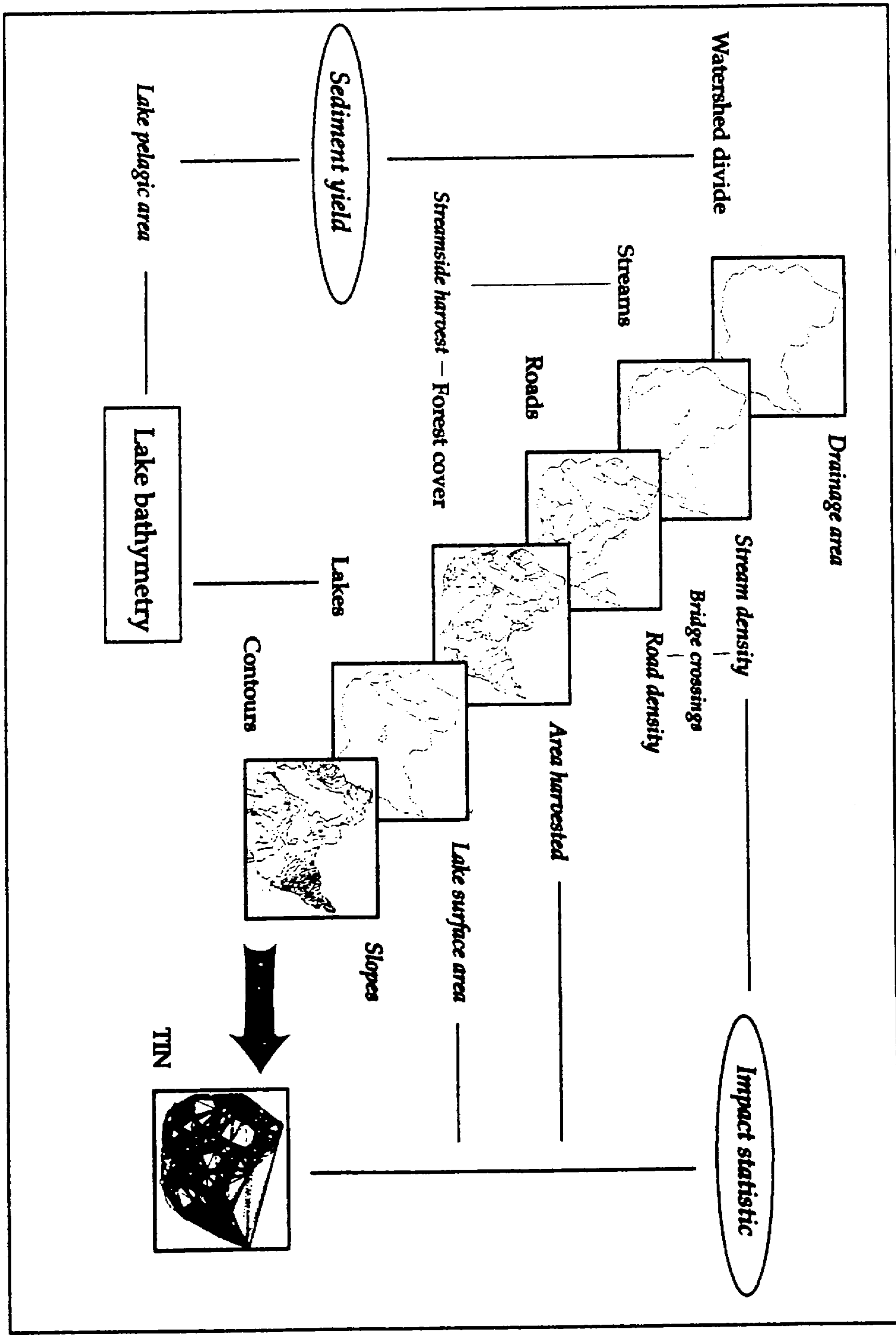
# Northern Watersheds




D.A. Spencer

Source: Ministry of Environment, Lands, and Parks

Figure 3



GIS coverages and related variables
Watershed divide
Drainage area
Streams
Stream density
Roads
Bridge crossings
Road density
Streamside harvest — Forest cover
Area harvested
Lakes
Lake surface area
Contours
Slopes
TIN
Sediment yield
Impact statistic
Lake pelagic area
Lake bathymetry

Figure 4. Vancouver Island percent organic matter and cutting history

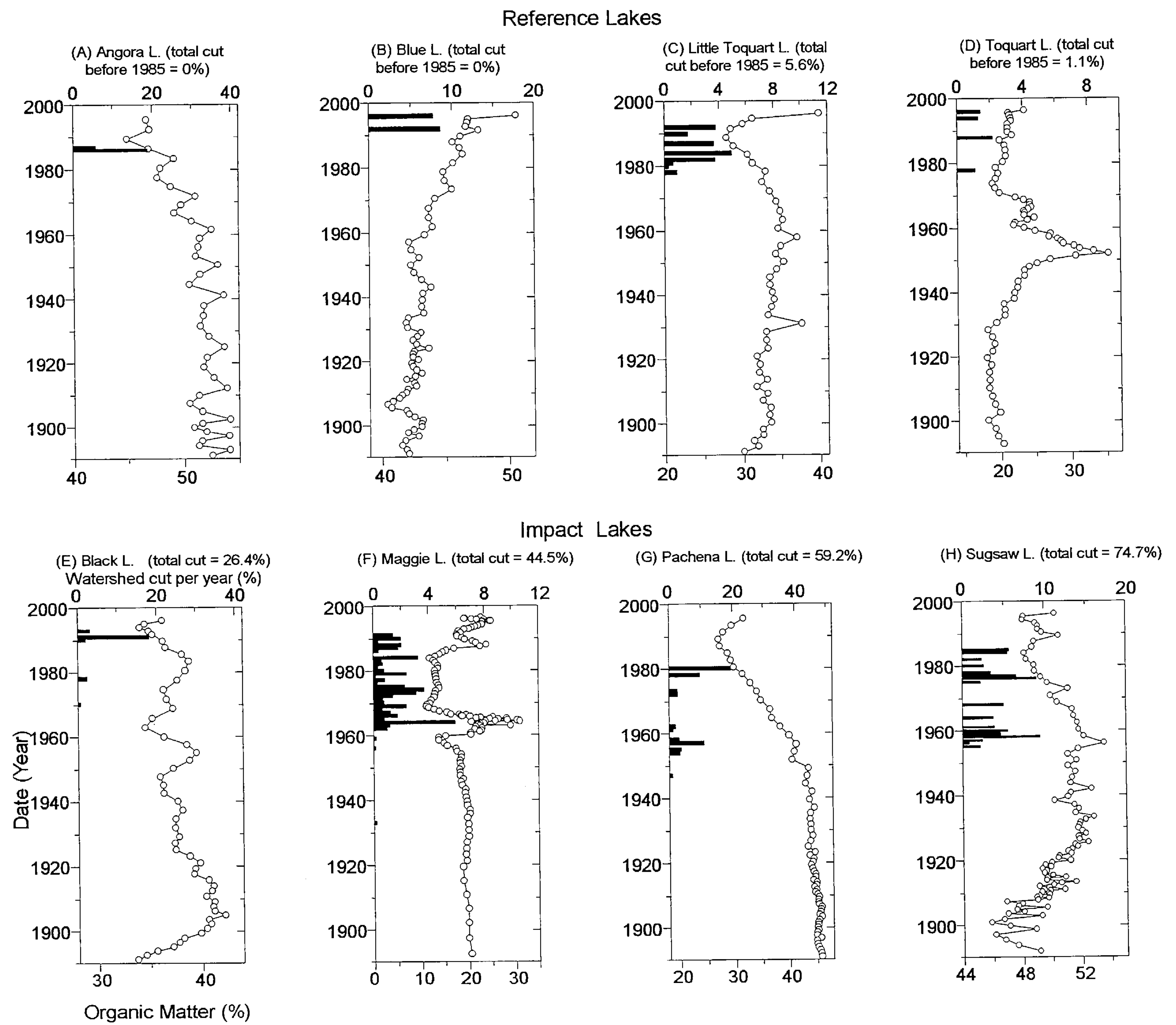


Figure 5. Central Interior percent organic matter and cutting history

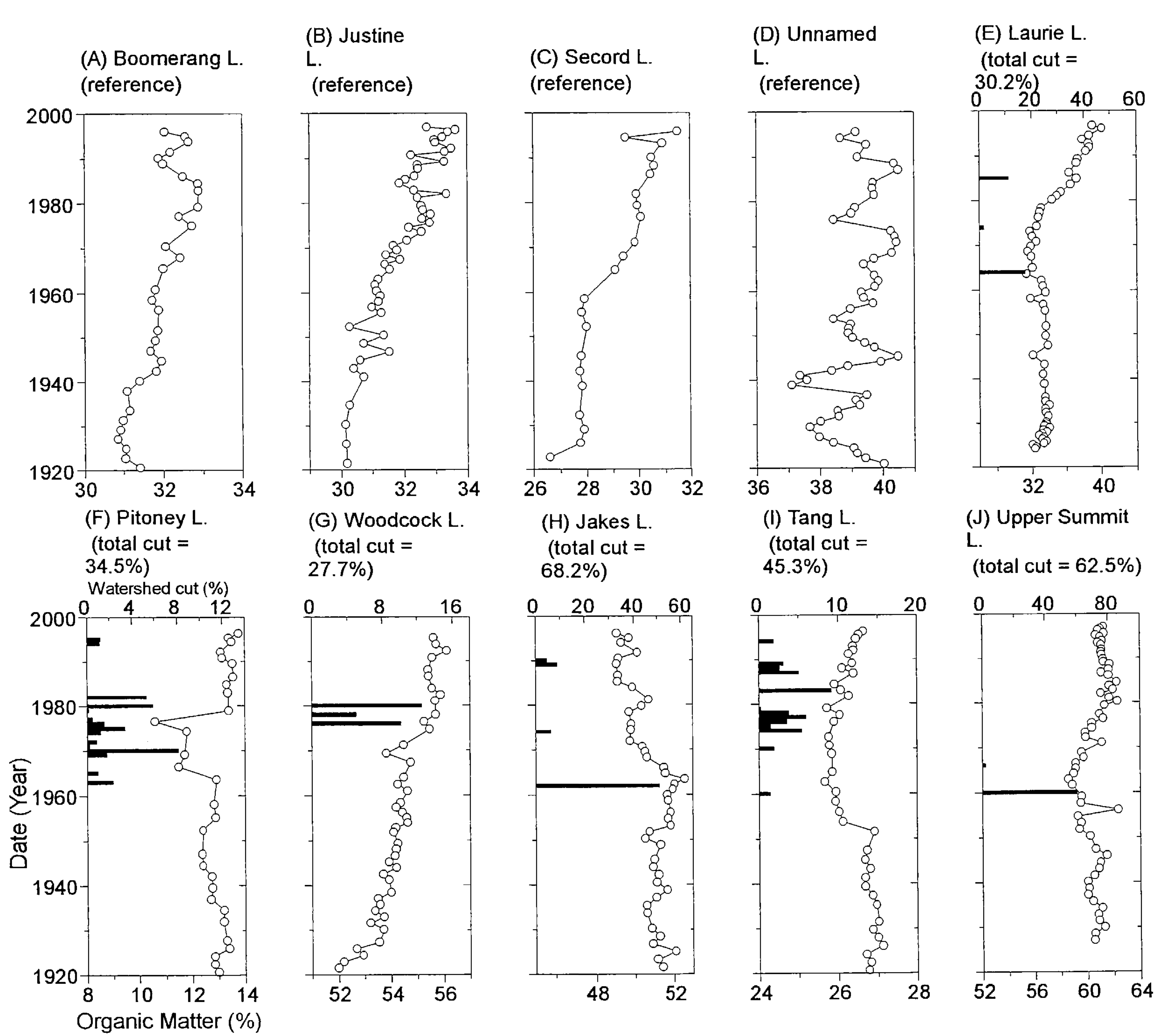


Fig. 6A. Vancouver Island ANOSIM Results (Before/After 1950)

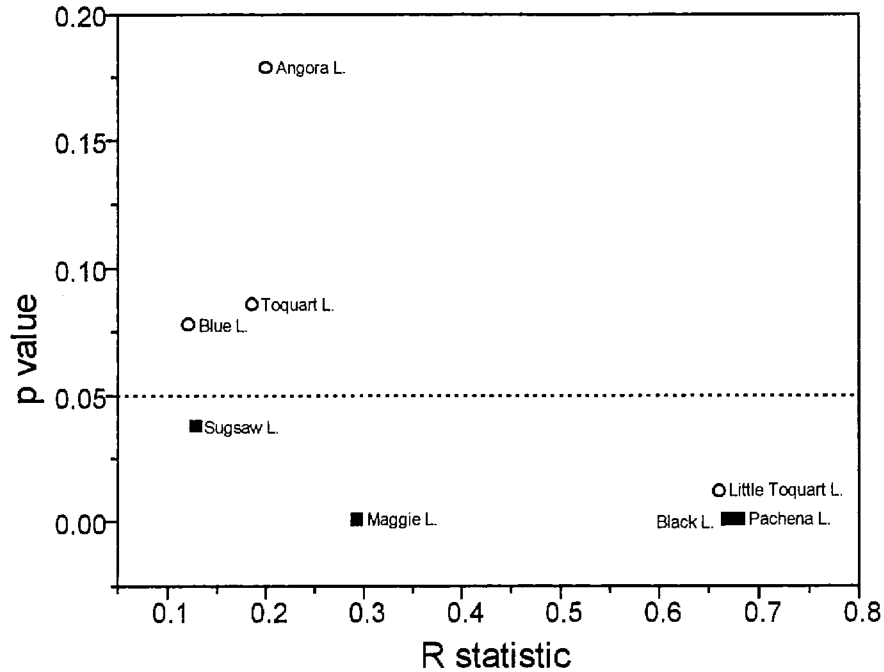
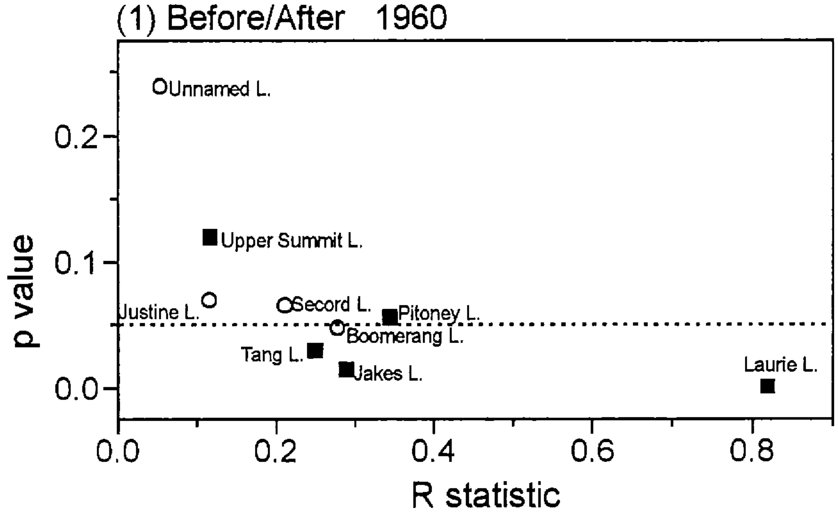



Fig. 6B. Central Interior ANOSIM Results

(1) Before/After 1960




(2) Before/After 1975

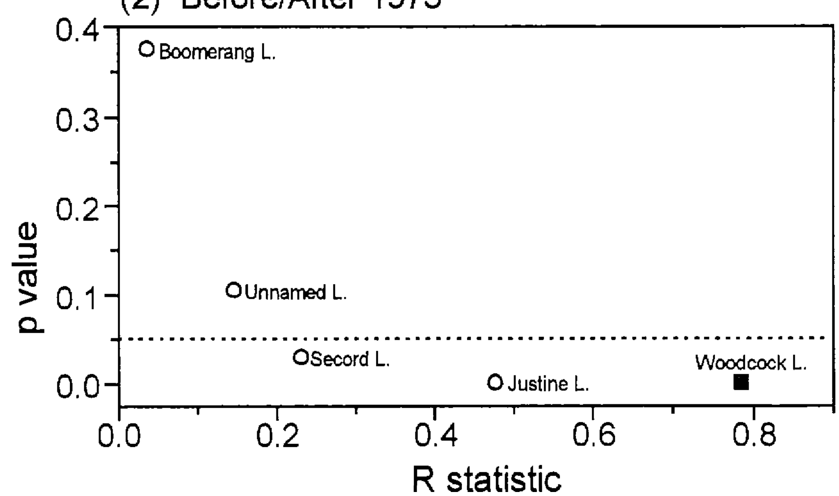


Figure 7. Prince George climate data

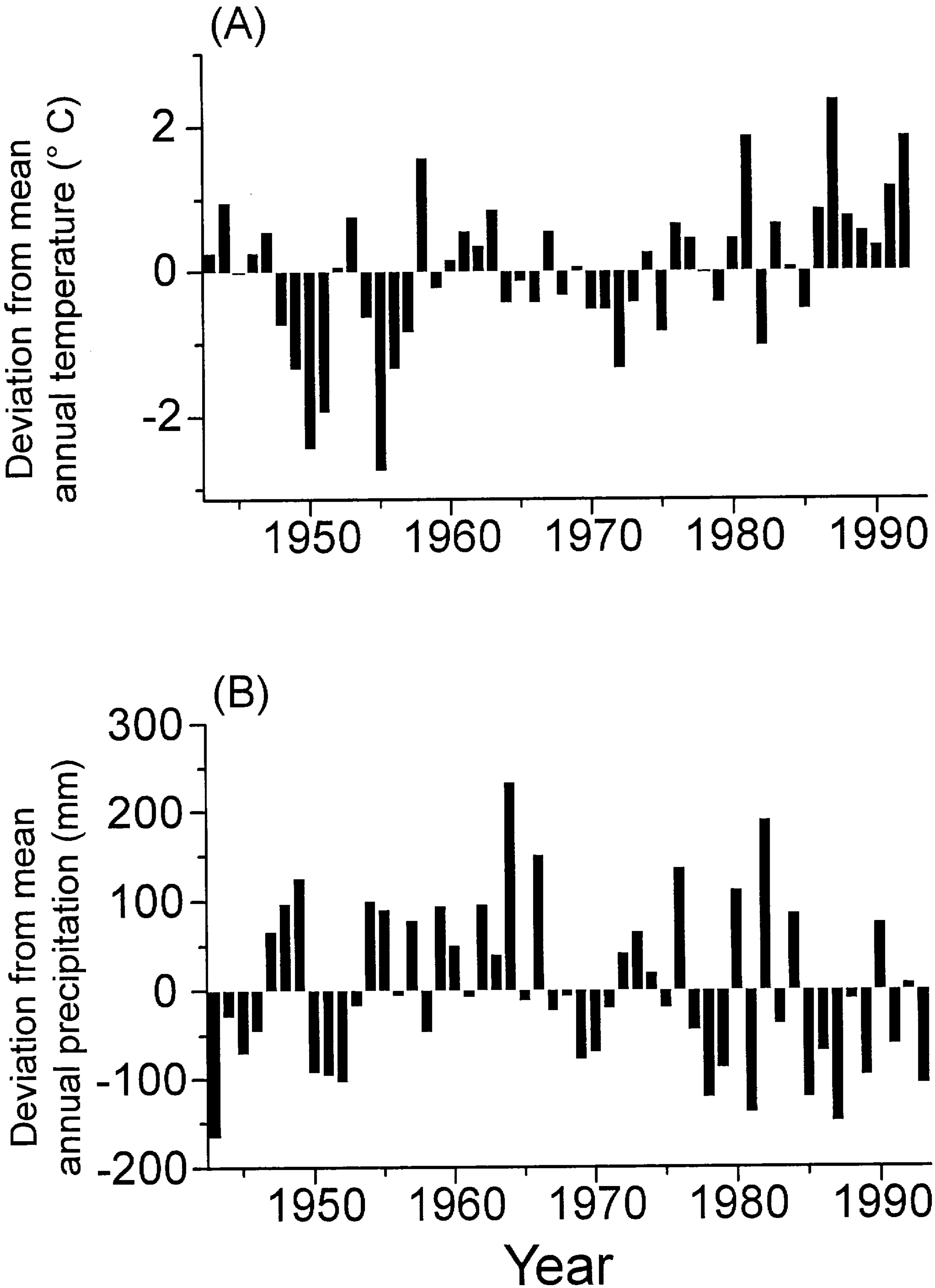


**Table 1: General Lake Characteristics**

| Vancouver Island lakes | Primary lake surface area (sq km) | Primary lake pelagic area (sq km) | Watershed: primary lake area ratio | Total lake surface area (sq km) | Number of water bodies |
|---|---|---|---|---|---|
| **Pachena** | 0.54 | 0.39 | 3.5 | 0.54 | 1 |
| **Sugsaw** | 0.61 | 0.38 | 9.8 | 0.61 | 4 |
| **Toquart** | 1.15 | 0.81 | 58.0 | 1.30 | 5 |
| **Little Toquart** | 0.55 | 0.44 | 18.0 | 0.60 | 3 |
| **Black** | 0.64 | 0.47 | 5.6 | 0.64 | 1 |
| **Blue** | 0.47 | 0.31 | 11.3 | 0.47 | 1 |
| **Frederick** | 0.37 | 0.31 | 16.2 | 0.40 | 2 |
| **Cataract** | 1.44 | † | 11.3 | 1.70 | 8 |
| **Angora** | 0.31 | 0.20 | 6.8 | 0.31 | 2 |
| **Maggie** | 2.49 | 1.99 | 21.8 | 3.00 | 14 |
| **Central Interior lakes** | | | | | |
| **Woodcock** | 1.33 | 0.96 | 4.2 | 1.33 | 2 |
| **Tang** | 0.44 | 0.30 | 70.2 | 1.10 | 13 |
| **Pitoney** | 1.76 | 1.28 | 34.3 | 2.20 | 15 |
| **Laurie** | 1.00 | 0.73 | 9.3 | 1.10 | 5 |
| **Upper Summit** | 0.97 | 0.48 | 3.4 | 0.97 | 1 |
| **Wendle** | 0.51 | 0.30 | 46.0 | 0.51 | 3 |
| **Jakes** | 0.58 | 0.41 | 2.1 | 0.58 | 1 |
| **Unnamed** | 0.79 | 0.63 | 2.7 | 0.79 | 1 |
| **Secord** | 0.40 | 0.10 | 5.5 | 0.40 | 1 |
| **Boomerang** | 0.52 | 0.11 | 7.5 | 0.52 | 2 |
| **Justine** | 2.48 | 1.82 | 17.6 | 2.50 | 2 |

† lake bathymetry not available

| Vancouver Island lakes | Watershed area† (sq km) | Total stream length (km) | Total road length (km) | Start of harvest activity | Surface irregularity index |
|---|---|---|---|---|---|
| **Pachena** | 1.9 | 0.7 | 7.3 | 1947 | 1748 |
| **Sugsaw** | 6.0 | 5.7 | 23.4 | 1955 | 1171 |
| **Toquart** | 66.8 | 130.4 | 15.4 | 1983 | 1082 |
| **Little Toquart** | 9.9 | 11.7 | 11.6 | 1980 | 1403 |
| **Black** | 3.6 | 6.9 | 11.6 | 1969 | 1573 |
| **Blue** | 5.3 | 5.6 | 11.3 | 1992 | 1063 |
| **Frederick** | 6.0 | 9.8 | 16.7 | 1936 | 2174 |
| **Cataract** | 16.2 | 20.6 | 15.2 | 1965 | 1910 |
| **Angora** | 2.1 | 2.1 | 3.2 | 1984 | 3663 |
| **Maggie** | 54.3 | 103.0 | 161.9 | 1933 | 1590 |
| **Central Interior lakes** | | | | | |
| **Woodcock** | 5.6 | 3.0 | 7.8 | 1976 | 251 |
| **Tang** | 30.9 | 53.2 | 53.0 | 1960 | 545 |
| **Pitoney** | 60.3 | 116.7 | 80.9 | 1963 | 833 |
| **Laurie** | 9.3 | 8.7 | 11.7 | 1964 | 544 |
| **Upper Summit** | 3.3 | 0.9 | 11.0 | 1960 | 472 |
| **Wendle** | 23.5 | 49.4 | 10.6 | 1982 | 1649 |
| **Jakes** | 1.2 | 0.4 | 2.1 | 1962 | 724 |
| **Unnamed** | 2.1 | 0.0 | 0.0 | - | 426 |
| **Secord** | 2.2 | 1.1 | 0.7 | - | 305 |
| **Boomerang** | 3.9 | 5.0 | 0.0 | - | 460 |
| **Justine** | 43.7 | 112.6 | 0.0 | - | 518 |

† Calculated without lake surface area

Table 2. Water Chemistry for the Vancouver Island Study Lakes

| Lake | pH | Specific Cond. (µS) | Alkalinity (mg/L) | Total P (mg/L) | Total N (mg/L) | Chl a (µg/L) | Silica (mg/L) | DOC (mg/L) |
|---|---|---|---|---|---|---|---|---|
| Angora | 7.75 | 42.8 | 13 | 0.004 | 0.090 | <0.5 | 1.48 | 3.6 |
| Toquart | 6.66 | 28.6 | 13.9 | 0.003 | 0.110 | <0.5 | 1.32 | 2.5 |
| L Toquart | 6.54 | 22.5 | 8.2 | 0.003 | 0.130 | <0.5 | 0.86 | 6.3 |
| Maggie | 6.65 | 39.5 | 14.6 | 0.019 | 0.100 | 1.1 | 1.19 | 3.7 |
| Cataract | 7.70 | 67.6 | 31.9 | <0.002 | 0.090 | <0.5 | 0.92 | 2.9 |
| Sugsaw | 7.15 | 29.4 | 9.1 | 0.003 | 0.190 | 0.8 | 1.18 | 3.7 |
| Frederick | 7.21 | 39.4 | 14.9 | 0.006 | 0.110 | 0.6 | 1.54 | 5.1 |
| Pachena | 7.23 | 27.3 | 7.7 | 0.012 | 0.120 | 0.5 | 0.98 | 2.4 |
| Black | 7.14 | 30.2 | 9.5 | <0.002 | 0.160 | 0.7 | 1.06 | 3.4 |
| Blue | 6.96 | 24.3 | 4.0 | 0.005 | 0.170 | 1.9 | 0.47 | 5.8 |

Table 3. Water Chemistry for the Central Interior Study Lakes

| Lake | pH | Specific Cond. ($\mu$S) | Alkalinity (mg/L) | Total P (mg/L) | Total N (mg/L) | Chl a ($\mu$g/L) | Silica (mg/L) | DOC (mg/L) |
|---|---|---|---|---|---|---|---|---|
| Boomerang | 7.1 | 50 | 25.3 | 15 | 410 | 7.4 | 5.0 | 15.3 |
| Justine | 7.1 | 59 | 26.8 | 27 | 470 | 12 | 7.2 | 17.0 |
| Secord | 7.0 | 55 | 21.5 | 15 | 350 | 7.0 | 5.1 | 12.3 |
| Unnamed | 7.5 | 68 | 34.0 | 18 | 320 | 5.7 | 3.2 | 6.9 |
| Laurie | 7.6 | 65 | 27.6 | 11 | 330 | 7.4 | 1.1 | 9.4 |
| Pitoney | 6.7 | 30 | 15.4 | 15 | 290 | 3.7 | 5.5 | 10.0 |
| Woodcock | 7.8 | 118 | 63.9 | 7 | 360 | 7.1 | 0.6 | 10.2 |
| Jakes | 7.6 | 57 | 29.4 | 2 | 20 | 6.7 | 0.6 | 6.7 |
| Tang | 7.4 | 47 | 23.8 | 11 | 20 | 8.0 | 3.6 | 12.4 |
| U.Summit | 7.6 | 78 | 40.3 | 6 | 400 | 3.6 | 0.4 | 12.1 |
| Wendle | 7.3 | 32.2 | 16.5 | 15.0 | 200 | 13.8 | 6.1 | 4.7 |

**Table 4a: Vancouver Island CC variable loadings**

| | **South - Full Set** *First Solution* | **South - Full Set** *Second Solution* | **South - Subset** *First Solution* |
|---|---|---|---|
| *Percent Variance* | 38.154 | 11.960 | 72.06 |
| *Eigen Value* | 1.734 | 0.429 | 6.510 |
| *Correlation* | 0.796 | 0.548 | 0.931 |
| *Significance* | < 0.001 | < 0.001 | < 0.001 |
| | | | |
| *Dependent Variables* | | | |
| Inorganic Yield | **0.978** | 0.209 | **0.994** |
| Organic Yield | **0.497** | **0.868** | **0.821** |
| | | | |
| *Independent Variables* | | | |
| Impact Statistic | **0.473** | 0.177 | **0.638** |
| Stream Crossings | **0.876** | -0.022 | **0.606** |
| Surface Irregularity | 0.026 | **0.452** | **0.769** |
| Road Density | 0.031 | 0.231 | -0.073 |
| Road Density > 30 deg | **0.511** | 0.102 | **0.546** |
| Streamside Logging | **0.446** | -0.214 | 0.309 |
| Annual Rainfall | 0.021 | 0.052 | -0.002 |

**Table 4b: Central Interior CC variable loadings**

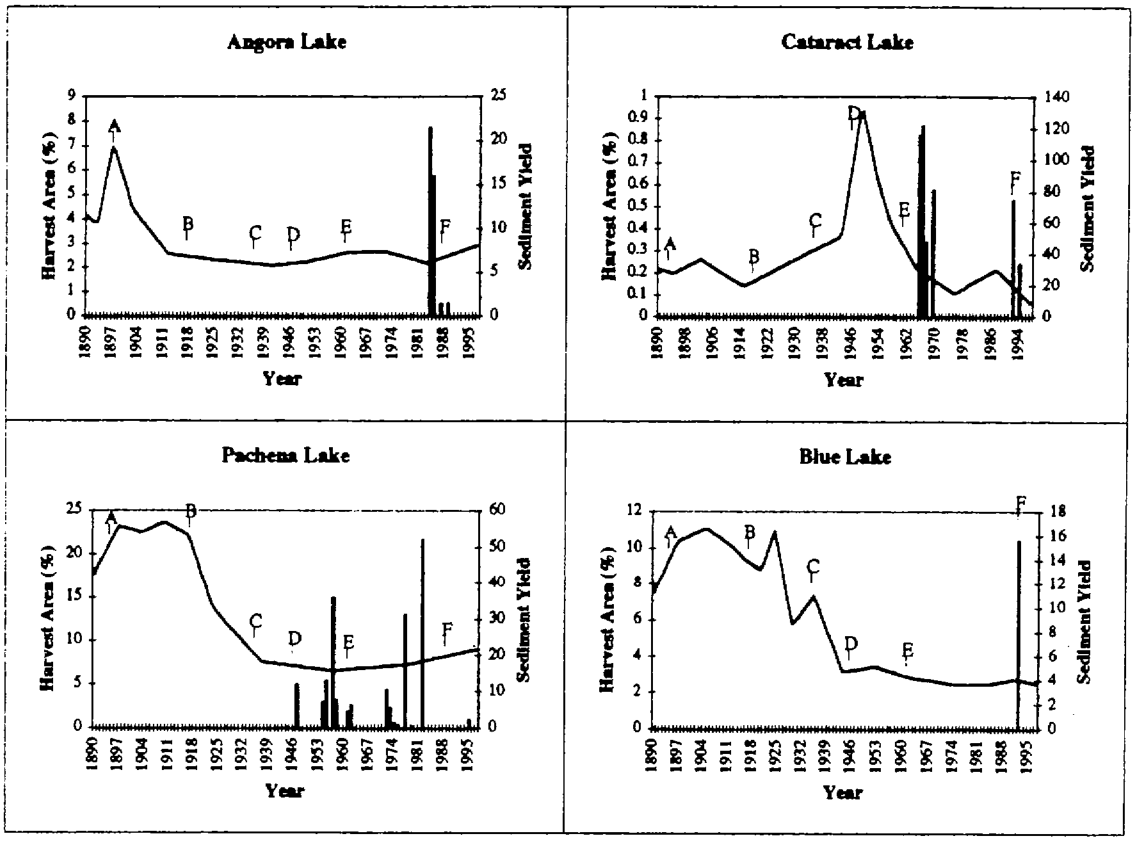
| | North - Full Set<br>*Second Solution* | North - Subset<br>*Second Solution* |
|---|---|---|
| *Percent Variance* | 34.250 | 53.570 |
| *Eigen Value* | 0.760 | 1.340 |
| *Correlation* | 0.657 | 0.757 |
| *Significance* | < 0.001 | < 0.001 |
| *Dependent Variables* | | |
| Inorganic Yield | **0.999** | **0.989** |
| Organic Yield | **0.768** | **0.945** |
| *Independent Variables* | | |
| Impact Statistic | **0.532** | **0.665** |
| Stream Crossings | 0.110 | 0.177 |
| Surface Irregularity | **0.390** | **0.830** |
| Road Density | **0.451** | **0.583** |
| Road Density > 30 deg | 0.279 | 0.000† |
| Streamside Logging | 0.237 | **0.424** |
| Annual Rain Fall | -0.064 | -0.045 |
| Earthquakes | 0.332 | 0.277 |

† all values zero in variable

# Appendix

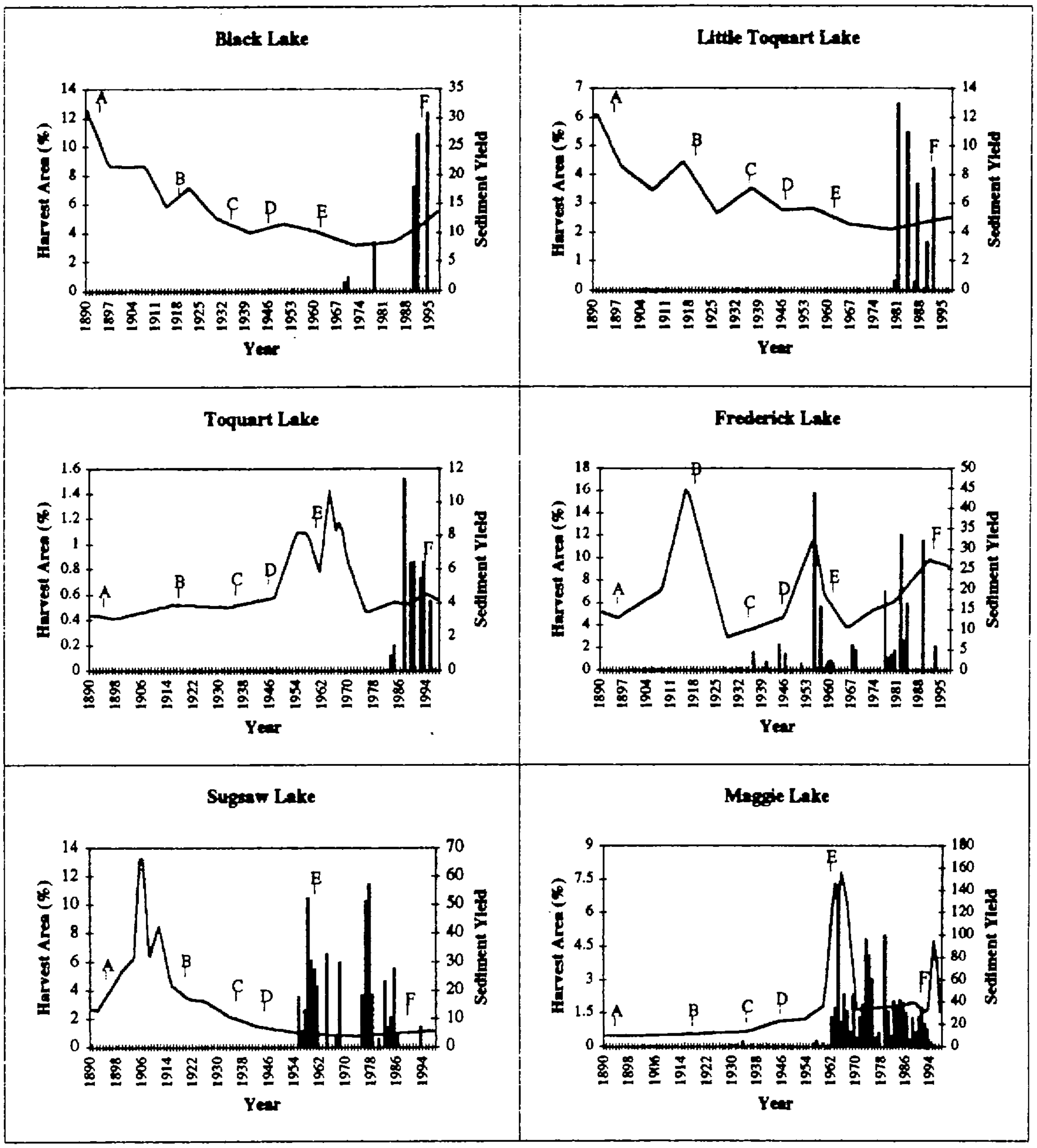
## 'Sediment yield profiles'

**Vancouver Island Catchments** Sediment Yield in t $km^{-2}$ $yr^{-1}$



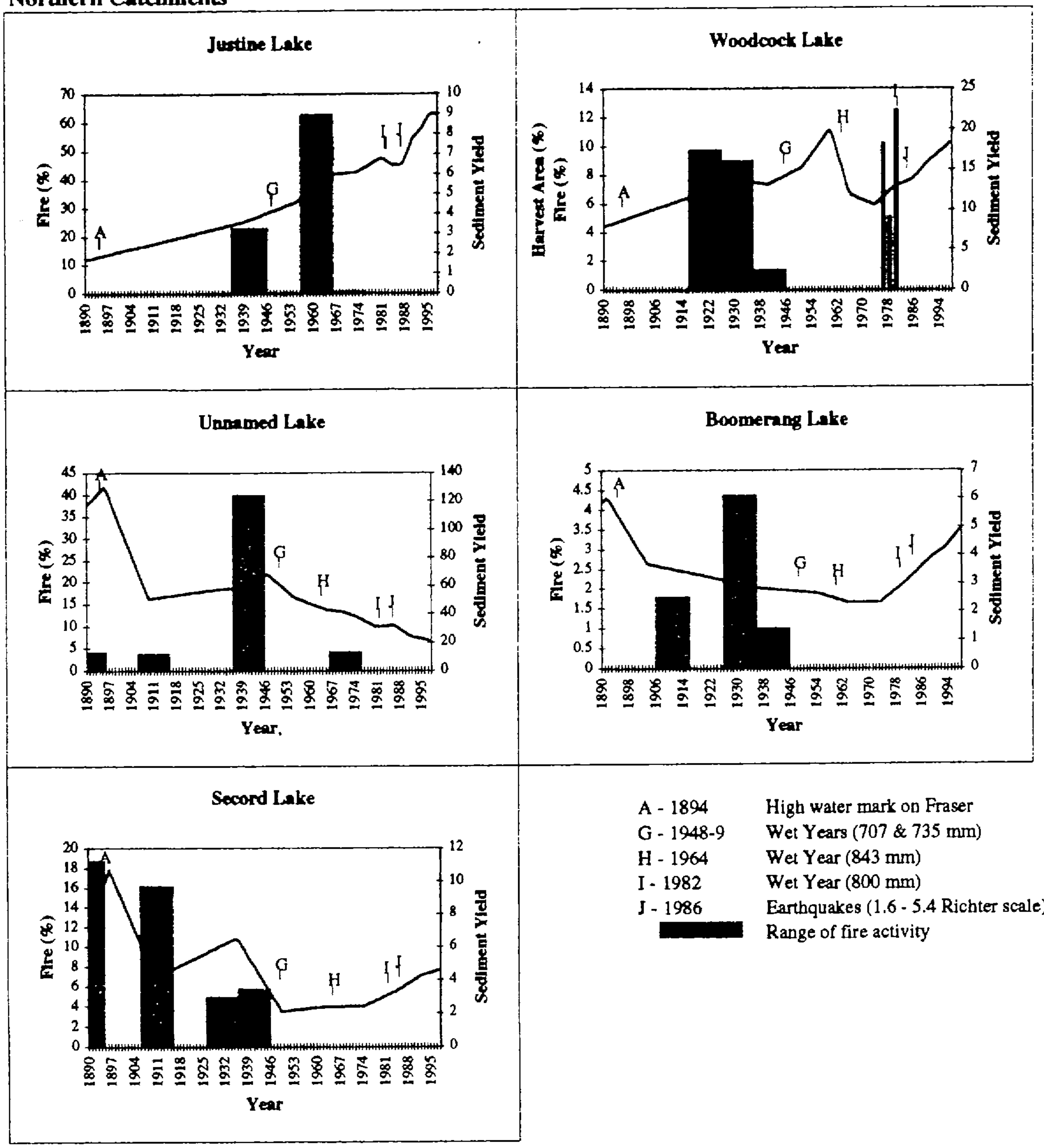

| | | | |
|---|---|---|---|
| A - 1894 | High water mark on Fraser | D - 1946 | Central Island earthquake |
| B - 1918 | West coast earthquake | E - 1962 | Hurricane Freda |
| C - 1935 | Storm | F - 1992 | January storm (742 mm) |

**Vancouver Island Catchments**



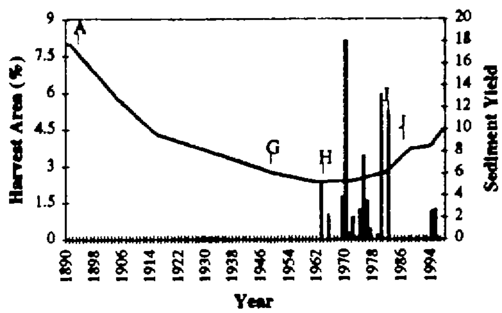
**Northern Catchments**

Sediment Yield in t $km^{-2}$ $yr^{-1}$

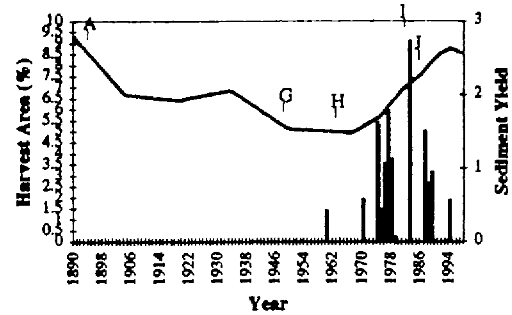


## Northern Catchments

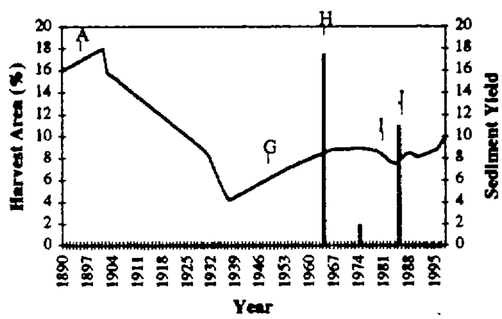
**Pitoney Lake**



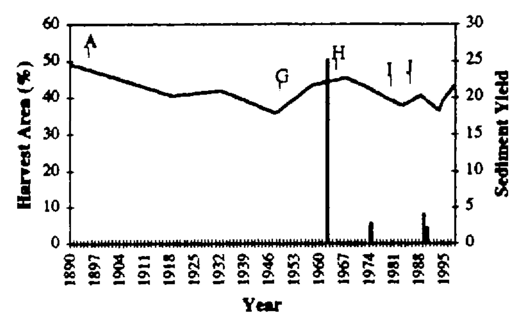

**Tang Lake**



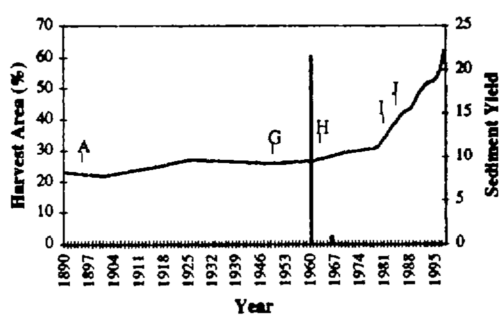

**Laurie Lake**




**Jakes Lake**




**Upper Summit Lake**




**Wendle Lake**