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Experimental Freshwater Cage Aquaculture: Short Term Effects of Carbon, Nitrogen and Phosphorus
Budgets and the Metabolism of a Boreal Shield Lake

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**Experimental Freshwater Cage Aquaculture: Short Term
Effects on Carbon, Nitrogen and Phosphorus Budgets
and the Metabolism of a Boreal Shield Lake**

Prepared by:

Corben Emerson Bristow

Thesis submitted to the Faculty of Graduate and
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General Abstract

We conducted an experiment to determine the effects of cage aquaculture on the functional properties of a lake. We installed a commercial aquaculture operation into a lake located within a pristine headwater region of the boreal shield. We used a before-after control-impact design to evaluate the weight of evidence for causal effects. We quantified sinks, sources and exchanges of carbon, nitrogen and phosphorus to the lake and presented this information in a budget format. We then calculated retention rates for these chemicals and compared them to integral amounts of carbon, nitrogen and phosphorus accumulating in the water column. We also measured removal rates (sedimentation) of these elements from the water column and transformation rates (primary production) within the water column. We found that the amounts of nitrogen and phosphorus retained in the lake increased dramatically during farm operation. With the exception of an increase in particulate carbon, we did not observe an accumulation of these chemicals in the water column. We did however observe lake wide increases in carbon and nitrogen sedimentation. Primary production increased significantly in the aquaculture-impacted lake and the period of peak productivity shifted to later in the summer. We discuss our results in the context of consequences to aquatic life and source water and we provide some recommendations for management.

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I would also like to thank my advisory committee, Dr. Frances Pick (UO), Dr. Jeremy Kerr (UO) and Dr. Lenore Fahrig (Carleton University) for reviewing the final draft.

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General introduction

Commercial aquaculture: the blue revolution

Aquaculture is a technique used to farm aquatic organisms such as finfish, bivalves, crustaceans or seaweeds. In aquaculture, organisms are enclosed in either a natural or artificial environment, so their growth and survival can be enhanced and controlled.

Aquaculture is an ancient practice with its historical roots in Asia dating back some 2000 years. Contemporary aquaculture is an important source of food for many people. Given global trends in the importance of fish protein to humans (FAO, 1999), increases in fish consumption (FAO, 2000), and a growing scientific evidence that natural fisheries are on the decline (Pauly et al 2002; Myers and Worm 2003) and the fact that the surface area required to produce this much protein is far less and on land, some would think aquaculture is a good solution to global food security.

However, an increasing demand of fishmeal used in intensive aquaculture production has raised doubt concerning aquaculture's use in fisheries sustainability (Naylor et al 2000; Muir 2005). Regardless, global aquaculture production, for better or worse, has exploded in the past twenty years (Figure 1).

Traditionally, small-scale aquaculture operations supplied local communities with herbivorous species, such as carp, which were grown in ponds. This type of aquaculture requires minimal fishmeal inputs and still today, remains the largest producer in the global aquaculture sector. However, more recently, to

meet a growing global market demand, we have seen a sharp rise in the intensified production of carnivorous fish species. The onset of industrial aquaculture production, termed the “blue revolution”, is characterized by large farms, producing hundreds of tons of fish annually, supplying rich sources of affordable protein to especially, cold climate populations.

Cage aquaculture and the environment: a lack of scientific knowledge

Unfortunately, as with any industrialized process, waste bi-products and sustainability remain an environmental concern. Cage farming for example, is an intensive form of aquaculture, where fish are enclosed in high densities, in a natural environment, with their complete nutritional requirement supplied to them in the form of fishmeal. In these systems, feed is consumed, processed and wastes are discharged, untreated, into the receiving water body. The enrichment of natural waters with untreated aquaculture effluent is a concern for the public and farmers alike, because aquaculture pollution combined with high stocking densities can potentially degrade water and sediment quality, cause eutrophication, and lead to outbreaks of pathogens and parasites (SECRU, 2002; Walker et al., 2003).

With the expansion of the aquaculture industry in Canada, ENGOs and community groups have raised voiced their options concerning the environmental impacts of aquaculture (Walker et al., 2003). The resistance to expand aquaculture into inland waters is perhaps best represented by showing how it lags behind its marine counterpart (Figure 2). The stunted growth of the freshwater industry can partly be explained by uncertainties surrounding the

value of freshwater resources and the lack of a scientific understanding about the consequences of aquaculture to freshwater ecology (Moccia and Bevan 2003).

Environmental concerns for freshwater aquaculture in boreal shield lakes

In Canada, the rainbow trout (*Oncorhynchus mykiss*) is the most commonly cultured freshwater species. This carnivorous salmonid is predominantly cultured using aqua cages or net pens in the Great Lakes. Approximately half of the inland cage facilities (10) are located on the Great Lakes (Walker et al., 2003). Organic-rich wastes produced by these farms are discharged directly into the aquatic environment and sometimes can significantly enhance natural flows of nutrients such as phosphorus (Bird and Mesnage, 1996) (Table 1). Phosphorous is especially bio-reactive in nutrient poor shield lakes, and can stimulate algae growth (Schindler 1977). ().which upon decomposition, results in a depletion of oxygen or increase in carbon dioxide. The bio-availability of phosphorus and responses in oxygen (or carbon dioxide) concentrations in lakes, has been recognized as a key area of concern for the management of water quality in freshwaters, especially in smaller lakes with limited dilutive capacity (Yan 2005).

Eutrophication is a functional response to large inputs of nutrients, resulting in the proliferation of obnoxious algae. Eutrophication is not only a threat to aquatic life and source water for drinking but also this response can diminish farm productivity. This is why there is a need for more information about the impacts of cage aquaculture on functional components in lakes, especially information about nutrient cycling and productivity.

Experimental freshwater cage aquaculture: short term effects on the carbon, nitrogen and phosphorus budgets and the metabolism of a boreal shield lake

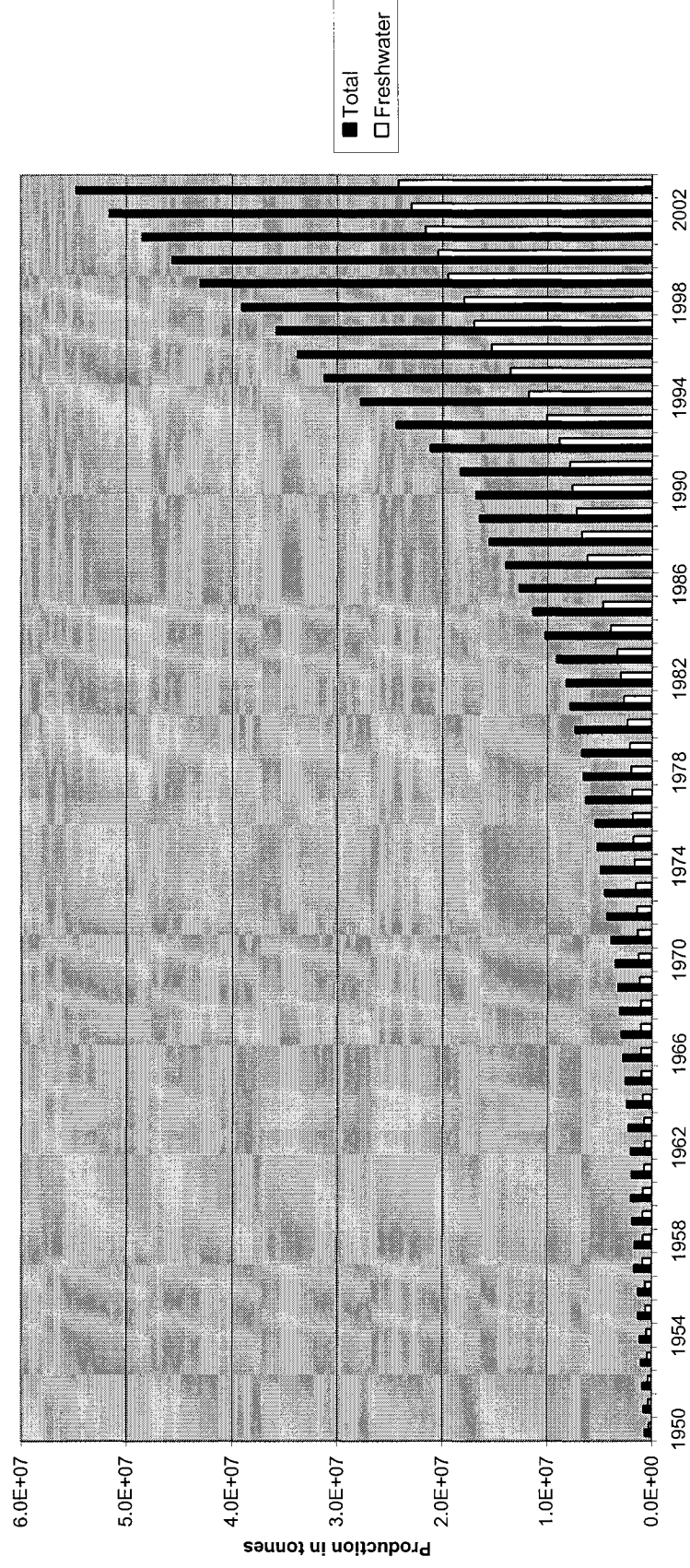
We conducted an experiment to explore the effects of aquaculture on lake function. We installed a commercial cage farm into a lake in a pristine headwater region of the boreal shield. The experiment was conducted in an area restricted to public access, the Experimental Lakes Area (ELA). A commercial operator supervised the aquaculture practices. We had historical chemical and productivity data on the aquaculture impacted and a reference lake, which provided valuable baseline information for the study. We tested hypotheses concerning the relationship between flows and stocks of chemicals and metabolites in lakes and how fish farming affected these relationships. Our conclusions were based on short-term responses (2 production cycles over two years) and our discussion was developed in the context of consequences to the health of the lake and we also provided recommendations that will hopefully lead to effective management of this industry.

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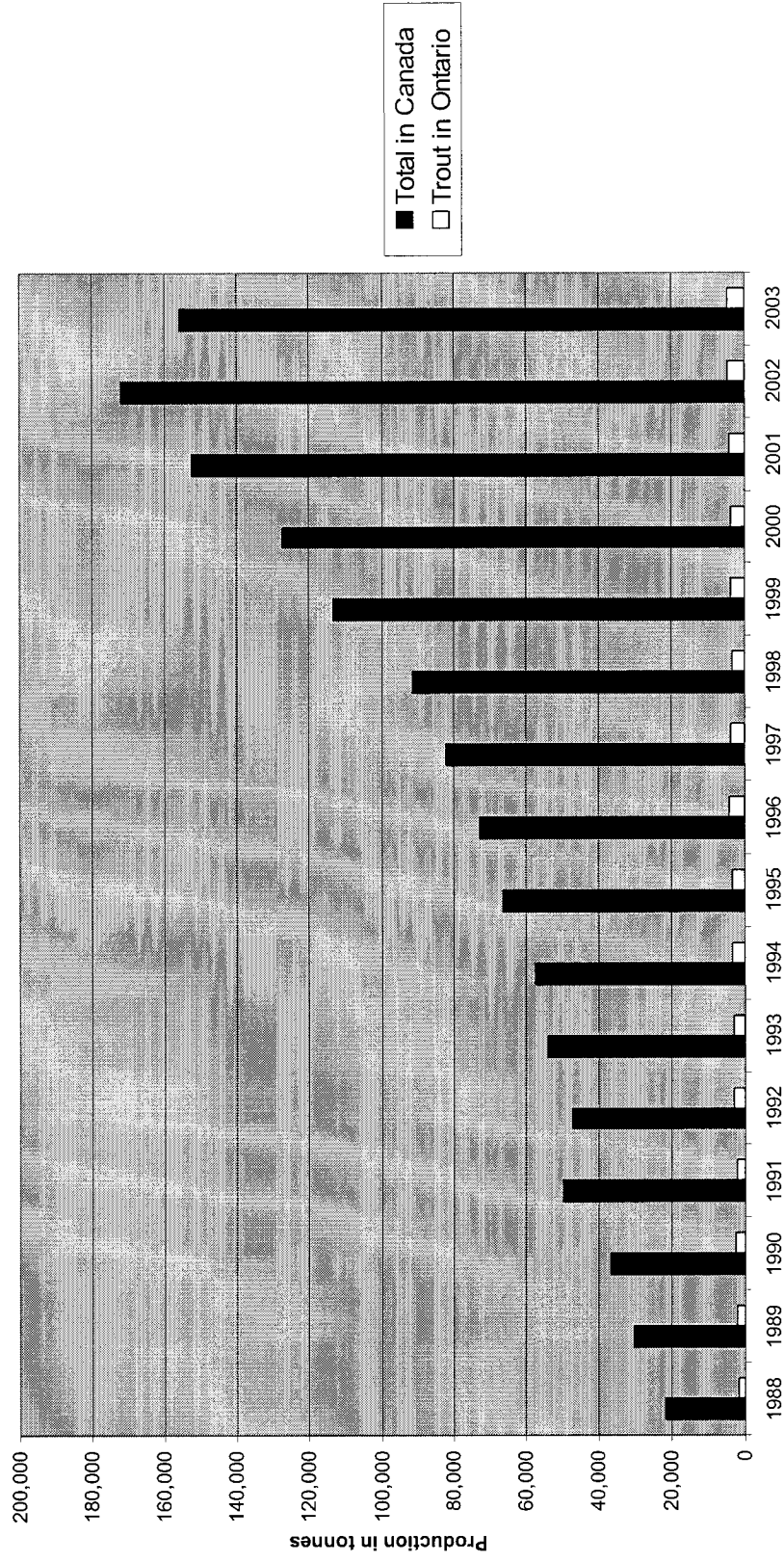
Global aquaculture production, 1950-2003



Source: Food and Agriculture Organization of the United Nations (FAO).

Figure 1. Annual tonnes of total and freshwater global aquaculture production, from 1950 to 2003.

Aquaculture production in tonnes, in Canada, 1988 to 2003



Source: Statistics Canada. 2005. Canadian aquaculture statistics, 1988-2003.

Figure 2. Annual tonnes of total Canadian and Ontario trout aquaculture production, from 1988 to 2003.

Table 1. The phosphorus budget for aquaculture-impacted Lake Heney.

Components of balance	Total phosphorus (kg) Lake Heney ² (1995-1996)
Tributaries (excluding farm)	312
Aquaculture farm ¹	450
Atmosphere	186
Cottage septic systems	195
TOTAL external contributions	1143
Loss of P from lake	231
Quantity of P remaining in lake	912

¹Wastewater inputs including metabolic wastes and uneaten food pellets.

²Lake Heney has a maximum depth of 30-33 m and a surface area of 12.4 km².

Chapter 1: Short-Term Effects of Cage Aquaculture on Stocks and Flows of Carbon, Nitrogen and Phosphorus in a Boreal Shield Lake

Abstract

We conducted an experiment to determine the effect of cage aquaculture on the function of a boreal shield lake. We installed a commercial aquaculture operation into a boreal shield lake located within a pristine headwater region. We also used a before-after control-impact design to evaluate the weight of evidence for causal effects of aquaculture on the lake. The functional properties of the lake that interested us were the relationships between flows and stocks of chemicals in the lake. We accounted for sources, sinks and exchanges of chemicals to the lake and built a simple budget to estimate amounts of chemicals retained over time. Because of their importance to lake ecology and livestock production, we decided to focus on chemical species of the elements carbon, nitrogen and phosphorus. We found that the amounts of nitrogen and phosphorus retained in the lake increased dramatically, by on average a factor of two and almost four respectively. With the exception of an increase in particulate carbon, the accumulation of chemicals in the water column was not observed. This finding suggests there was an increase in the rate at which nitrogen and phosphorus were removed from the water column. This hypothesis was supported by lake wide increases in the rate of carbon and nitrogen sedimentation. Surprisingly, the amount of solid carbon collecting below the farm accounted for only 8, 3 and 25 percent of the carbon, nitrogen and phosphorus retained during year one of the operation. Although we have not observed an increase in total water column nitrogen and phosphorus, we have observed increases in suspended nitrogen

particulates in the epilimnion and total dissolved nitrogen in the hypolimnion. The results are discussed in the context of consequences to lake health and we provide recommendations for management.

Introduction

Background

Intensive forms of aquaculture like cage farming are now prevalent in lakes. In Canada, there are at least 20 cage facilities in operation (Walker et al, 2003). To better manage this growing industry, we need to increase our understanding of the effects farming has on lake ecology. Fish farming enriches lakes with solid and soluble material including feces, uneaten feed, fish tissue, dissolved phosphorus, ammonia, dissolved carbon and lipids (Kelly and Elberizon, 2001). The magnitude and composition of wastes generated by the farm is related to the feeding efficiency of the livestock, which depends feeding methods, feed quality and the environment (Cho and Bureau, 1998). In Canada for example, Chambers et al. (2001) estimates that aquaculture operations contribute 956 tonnes of nitrogen and 204 tonnes of phosphorus per year to inland waters, which for phosphorus is approximately equivalent to the secondary discharges of a wastewater treatment facility serving almost 1 million residents.

Chemical wastes discharged from cage farms into lakes have the potential to increase concentrations of these chemicals to a level that threatens aquatic life and source water (Walker et al., 2003). The installation of a farm into the tributary of Lake Heney (Quebec, Canada) for example was shown to drastically change the chemical balance or budget of a lake, nearly doubling natural inputs of phosphorus (Bird and Mesnage, 1996). For cage farming, some attention has been given to impacts on nutrient concentrations in the water column (Beveridge

1984; Persson 1991; Bird and Mesnage, 1996; Axler 1996; Hamblin and Gale 2002). What is less clear is the effect cage farms will have on chemical conditions in deep, cold, well-oxygenated oligotrophic boreal shield lakes, for which salmonid aquaculture seems well suited.

Part of the uncertainty arises from our poor understanding of the relationship between flows of chemicals through and within lakes, stocks of chemicals in the water column and the effect cage farming has on these relationships (Yan, 2005). The extent that a lake retains source chemicals for example, will largely determine the accumulation of these chemicals in a lake, which may sediment to the bottom of the lake or be dispersed throughout the water column. The effect of farms on these flows and stocks are important, especially with respect to potential threats to aquatic life and source water. Farms generate organic wastes and nutrients that are discharged in to the water column for example and it is important to determine the fate of these chemicals in the lake. Are the majority of wastes generated by the farm discharged at the outflow, or do they settle below the cage? Are farm wastes mixed evenly across the lake, increasing rates of sedimentation across the lake? Will concentrations of dissolved nutrients in the water column increase in the short-term? Assessing the causal relationship between aquaculture and these mechanisms, along with determining the ecological consequences of deviations from natural or background conditions will allow us to better evaluate the potential threat of aquaculture to aquatic life and source water.

The most direct method to establish whether cage farming will impact the flows and stocks of chemicals in a boreal shield lake is to conduct an experiment. A good design for such an experiment is a Before-After-Control-Impact design (BACI) where the processes and endpoints of interest are measured repeatedly and simultaneously before and during the impact, in a pristine 'reference' system and a manipulated system. With this approach we can address questions such as: what effect will farming have on the retention of chemicals in a lake: were do chemical species accumulate; are rates of chemical transfer increased in the lake? This experiment tests hypotheses about the effects of aquaculture on the functional components of a lake.

Purpose

An experiment has been undertaken to quantify the effects of farming on the budget and distribution of carbon, nitrogen and phosphorus in a lake using a BACI design. The budget was reconciled by accounting for sources, sinks and exchanges of these chemicals in the reference and the manipulated lakes and discussed in context of the lake's capacity to process and recycle these chemicals.

Objectives of the study also include discussing the consequences speculating on their implications to the "health" of the lake ecosystem. For example, if the current trends were to continue, how long do would take to see a dramatic change in the ecology of the lake? What are the consequences of increasing chemicals to aquatic life? Is the lack of change in nutrients due to the short-time frame of the study? What do the results say about guidelines and

regulations for fish farms in boreal lakes? What recommendations can be offered with respect to improving the sustainability of this industry?

Methods

Experimental Design

We conducted an ecosystem experiment by manipulating conditions in a boreal shield lake. We installed a commercial sized cage aquaculture operation in Lake 375, which is a federally designated research lake on the property of the Experimental Lakes Area (ELA). A team of scientists measured ecological and aquaculture-related variables on Lake 375 before and after the addition of the farm. Similar measurements were also made on a nearby “reference” lake, Lake 373. Conclusions about effects of aquaculture on ecosystem components were drawn by comparing the results from these two lakes before and after the installation of the farm.

The study site

The Experimental Lakes Area (ELA) is located in a remote region of northwestern Ontario, Canada (49° 34' - 49° 47' north latitude, and 93° 36' - 93° 52' west longitude) (Figure 1). Approximately 58 lakes in this area have been reserved for experimental studies. ELA lakes are ideally suited for manipulation experiments because they are located in headwater region of the Canadian Shield, which limits the possibility of other “un-natural” inputs confounding the results of the manipulation experiment. ELA lakes are also well suited for lake budget and mass balance studies because their granite basins and thin soils reduce the need to account for ground and subsurface water seeping into or out of a lake.

Numerous limnology-related laboratories are located at the ELA field station including: hydrology, analytical chemistry, contaminants, isotopes, phytoplankton, zooplankton, aquatic invertebrates and fish laboratories. A meteorological station has been operated continuously from 1969 and data from this station has been used for lake budget, mass balance studies and modeling studies. Subcatchment and catchment outflows and lake levels are monitored for a number of lakes. Routine field sampling occurs throughout the ice-off period and periodic sampling occurs during winter visits.

As mentioned, the ELA is located on the Canadian Shield, specifically a pink granodiorite batholith outcrop (Davies and Pryslak, 1967) where upland soils are thin and prone to leaching, which explains the why groundwater inputs are minimal (Brunskill and Schindler, 1971). Lakes in this region can be generally characterized as soft-water lakes because atmospheric deposition on exposed bedrock results in relatively small inputs of chemicals weathered into the lake (Brunskill et al, 1971).

The historical climate of the ELA is summarized by Beaty and Lyng (1989). The terrestrial vegetation is dominated by Boreal sub climax forests that include pine, spruce, aspen and birch (Rowe 1959).

The experimental lake and the reference lake

The present study involves the single basin headwater (1st order) Lake 373 and the double-basin 375 into which lake 373 drains and which itself drains into Lake Winnange from the northeast (Figure 4, Figure 5, Figure 6). Both lakes are ice-free for 6 to 7 months each year, and both are typical of many of the deep

lakes in the ELA region insofar as they are (1) dimictic and stratify thermally in the summer and winter; and (2) dilute and oligotrophic resulting in a relatively high light transmission. Because Lake 375 is downstream of Lake 373, Lake 375 has a larger overall watershed area (Table 2). Compared to Lake 375, Lake 373 has a smaller drainage (catchment) area (ha), which means inputs from erosion are likely to be larger. Lake 373 also has a larger surface area and volume.

The farm

The cage farm that was installed in Lake 375 was designed to yield approximately 10 tonnes of rainbow trout (*Oncorhynchus mykiss*) per harvest. Suspended from a 100 m² square frame was a 760 m³ nylon mesh net with 5 cm² openings. The net was suspended to a depth of approximately 10 meters. The farm was moored in the center of the north basin, over 15 meters of water. The fish were fed conventional feed pellets (Profishent®) at a rate monitored by a commercial operator (Meeker's Aquaculture). The start and harvest dates in 2003 and 2004 were similar; the 2004 season started 1 week and finished 4 weeks earlier (Table 3). The range of water temperatures in this lake between the start and harvest dates ranged from 2 to 25°C. The population size of 2003 livestock was greater than in 2004. The total biomass gained by 2003 livestock was less than in 2004, which is partly explained by the greater amount of total feed applied to the farm in 2004. The feed conversion ratio is often used in the aquaculture industry as an indication of the economy of the farm. The Feed Conversion Ratio (*FCR*) is calculated by dividing the quantity of feed applied to

the farm (F) (kg) by quantity of wet weight gained by the livestock (ΔL) (kg) (Equation 1).

$$FCR = F / \Delta L \quad (1)$$

Water and chemical budgets for lakes

Presented throughout this study are lake budgets for water and chemical species of carbon, nitrogen and phosphorus. These budgets present a comprehensive set of estimates for quantities (stocks) of water (m^3) and chemicals (kg) within a lake and flows of water (m^3) and chemicals (kg) entering or exiting a lake over periods of days, weeks or years. Mass balance equations, which are formulated based on the principle of conservation of mass, are sometimes used to estimate stocks and flows indirectly.

Stocks of water and chemicals in lakes

Stocks of chemicals in Lake 373 and Lake 375 were calculated numerous times throughout the study. At any moment in time, the stock of a chemical in a lake was assumed to be the concentration of the chemical multiplied by the volume of water in the lake. Because chemicals, like heat, stratify in dimictic lakes, The stock of a chemical in a lake S (kg) is calculated by area A_z (m^2) at depth z (m) by the concentration of the chemical C_z (mg/m^3) at depth z integrated dz (m) from depths zero to the lake's maximum depth Z_{max} (Equation 2).

$$S = \int_0^{z_{max}} A_z C_z dz \quad (2)$$

To make this calculation we had to take samples at numerous depths, which we referred to as a chemical profile. The depth specific volumes required to calculate the stocks were acquired using bathymetric maps for lakes 373 (Figure 7) and 375 (Figure 8), which show the relationships between lake depth, area and volume. It was assumed that chemicals diffuse almost instantaneously across the horizontal plane of the lake and as such the equation used to determine chemical stocks needed to be only two dimensions.

Flows of water and chemicals in lakes

Flows of water and chemicals have been estimated for a number of lake processes. *Sources* are processes that direct chemical flows into the lake and in this study we consider atmospheric deposition (wet and dry or bulk), erosion (such as weathering and runoff), tributaries (stream influent) and in the case of Lake 375, aquaculture inputs such as feed and fish. Flows directing substances out of the lake, called *sinks*, include discharge at the outflow and the fish removed during harvest. We also estimated exchanges, which depending on conditions can either be a source to or a sink from a lake. Air-water gas exchange is an example of such a bi-directional flow, where depending on conditions in the lake and across the interface, chemicals can move into or out of the lake.

In lakes, chemical flows are often linked to the movement of water into or out of a lake through processes such as wet atmospheric deposition (precipitation), erosion, tributary inflow and discharge. For example, the amount of chemical entering a lake by a tributary is the product of the rate at which water

is entering the lake and the chemical concentration of the influent. In this study, a new V-notch weir was installed at the outflow of Lake 373 (a tributary of Lake 375) in 2003 to measure the rate of discharge, the same year the fish farm was installed in Lake 375. Because we were interested in comparing the chemical budgets of Lake 373 and Lake 375 before and after the installation of the farm, we decided not to use the weir results, but instead standardize our method of estimation and calculate tributary inflows and outflows using a mass balance for water. We did however use the results of the weir to check the accuracy of the discharge estimates generated by the mass balance.

Mass balances for water in lakes

We estimated daily discharges at the outflows of lakes 373 and 375 (m^3) using a mass balance for water. At any moment in time, we assumed that the discharge O^D (m^3) of water at the outflow of a lake is calculated by subtracting the capacity of the lake V^C (m^3) from the volume of the lake V (m^3) plus the net inflow of water, which is calculated by subtracting outflows due to evaporation O^{Ev} (m^3) and water storage O^S (m^3) from combined inflows of direct precipitation I^P (m^3), runoff I^R (m^3) and tributaries I^T (m^3) (Equation 3).

$$O^D = V + I^P + I^R + I^T - O^{Ev} - O^S - V^C \quad (3)$$

The net amount of water entering the lake was calculated by subtracting the amount of water lost by evaporation and the amount stored by the lake (sometimes referred to as antecedent storage) by the cumulative amount of all inflows including precipitation, runoff and tributaries. The capacity of lakes 373 and 375 are presented in Table 2. Water lost by evaporation and storage can

theoretically exceed water gained by precipitation, runoff and tributaries. If these conditions persist, the volume of water in a lake can fall below the capacity of the lake, resulting in zero discharge, sometimes for extended periods of time.

The daily flow of water directly onto a lake from precipitation I^P (m^3) was calculated by multiplying the surface area of the lake A^S (ha) by the rate of precipitation p (mm/day) (Equation 4).

$$I^P = A^S * 10000 * p * 0.001 \quad (4)$$

The precipitation rate is measured and recorded daily at a meteorological station about 15 km south of the two lakes.

Erosion is a general term used for inputs to the lake from weathering and runoff. We estimated daily flows of runoff water to Lakes 373 and 375 by extrapolating the results of weir-recorded runoff rates from the eastern subcatchment of nearby Lake 239. A number of considerations were taken into account before extrapolating this data to the drainage areas of lakes 373 and 375. For one, the subcatchments of only two lakes in the area are monitored with weirs. Secondly, water from this subcatchment is sampled and analyzed regularly for chemical constituents, which was crucial for our chemical budgets. Another important consideration was we knew the areas for all three catchments and therefore could normalize the flow of Lake 239 runoff and scale these rates according to the catchment sizes of lakes 373 and 375. Finally, the eastern subcatchment of Lake 239 is large and typical of most subcatchments in the area, including the drainage areas of lakes 373 and 375 (K. Beaty pers. comm.). The daily amount of runoff from the subcatchment into the lake I^R (m^3) can be

calculated by dividing the weir- determined average daily discharge rate from the eastern subcatchment of Lake 239 r (m³/second) by the drainage area of that subcatchment $A^{D(239)}$ (ha) then multiplying it by either the drainage area A^D (ha) of Lake 373 or Lake 375 (Equation 5).

$$I^R = \frac{r * 60 * 60 * 24}{A^{D(239)} * 10000} * A^D * 10000 \quad (5)$$

Lake 373 is a headwater lake so there are only small tributaries from the catchment area, which we have designated to runoff. The only tributary to Lake 375 is the outflow discharged from Lake 373.

Daily evaporation (m³) was calculated by multiplying the surface area of the lake (ha) by an evaporation coefficient (mm/day). The evaporation coefficient was determined using a mass transfer equation, which is a function of surface water temperature (°C), air temperature (°C), relative humidity, wind speed (m/second), and an empirically determined mass transfer coefficient based on historical water balances for Lake 239 (K. Beaty pers. comm.). The daily amount water evaporating off the lake O^{Ev} (m³) is calculated by multiplying the surface area of the lake A^S (ha) by the monthly evaporation rate ev (mm/month), which is a function of average daily wind speed w (m/second), relative humidity RH , temperatures for water Tw and air Ta (°C) and an empirically determined mass transfer coefficient K^C (Equation 6)

$$\begin{aligned} O^{Ev} &= A^S * 10000 * ev * 0.001 / 30 \\ ev &= (1 + 0.06 * (\frac{w * 60 * 60}{1000})) * (es1 - ea) * K^C \\ es1 &= (EXP(52.57633 - (6790.4985/(Tw + 273.15)) - 5.02808 * LOGN(Tw + 273.15))) * 7.5006 \\ ea &= es2 * RH \\ es2 &= (EXP(52.57633 - (6790.4985/(Ta + 273.15)) - 5.02808 * LOGN(Ta + 273.15))) * 7.5006 \\ K^C &= 10 \end{aligned} \quad (6)$$

Air temperature, relative humidity and wind speed are measured and average daily at the meteorological station. Temperatures are recorded at the surface of each lake every two weeks during the ice-off period.

The daily amount of water stored in the lake basin (m^3), for example by plants, woody debris and soils, is a measure of a basin's capacity to sponge water from the lake. The daily amount of water removed from the lake and stored in the basin O^S (m^3) is calculated by multiplying the surface area of the lake A^S (ha) by the daily change in water level ΔL (m) (Equation 7).

$$O^S = A^S * 10000 * \Delta L \quad (7)$$

Storage can be negative, indicating that during heavy rainfall events the basin can become over saturated and an additional source of water to the lake.

Assessing the accuracy water discharge estimates

In 2003 and 2004, we compared our mass balance predictions of daily discharge from Lake 373 to those recorded at the weir. In 2004 (Figure 9, Figure 10), balance predictions and weir recordings are in good agreement. 2003 predictions are however less accurate (Figure 11, Figure 12). The summer of 2003 was unusually hot and dry. For extended periods, runoff estimates were zero because there were no measured flows draining from the Lake 239 subcatchment. As a result, our estimates of evaporation often exceeded the sum of all water inputs, causing a gradual reduction of water in both the lake. This depletion kept the lake well below its capacity resulting in no overflow and thus no discharge. The discrepancy between our prediction and the weir observations can be perhaps explained by alternative sources of water to the tributary, for

example, groundwater seepage from wooded areas adjacent to the stream or direct runoff to the stream during rain events. The implication of this potential underestimate is further discussed in the proceeding chapters, as it relates to sources of error in the chemical budget.

The annual discharge (m^3) of water from Lake 375 is greater than in Lake 373, which is not unusual given that Lake 375 is downstream of Lake 373 (Table 4). The hydraulic residence time RT (years) is calculated by dividing the volume of the lake V (m^3) by the annual amount of water discharged at the outflow O^D (m^3) (Equation 8).

$$RT = \frac{V}{O^D} \quad (8)$$

The residence time of Lake 375 is shorter than that of Lake 373 indicating water molecules on average spend less time in this lake before discharged at the outflow.

Software used for budget calculations

Stocks and flows of water and chemicals were calculated using the modeling software STELLA 7.0.3 Research©. We used Euler's integration method to make daily calculations ($dt=1$) during the off-ice period. Observations were not always available on a daily basis but estimates were still obtainable because the software interpolates values between observations.

Lake sampling

We sampled water and measured temperature, secchi depth and light transmission on lakes 375 and 373. During this time, we also collected integrated

water samples for primary production estimates and phytoplankton and zooplankton enumeration. The physical and chemical properties of these lakes are well known; both lakes have been monitored extensively dating back to 1983. Temperature and concentrations of major ions, nutrients and metals have been measured a number of times over the past years and done so at different depths. Historically, continuous measurements have been made at one sampling station on each lake. The locations of these stations have not changed from their original positions anchored over the deepest points in each lake.

We chose to use these stations and continue sampling previously selected depths. We sampled depths of 1, 5, 10, 15, 20 and 24m on Lake 375 and 1, 5, 10, 15 and 20 on Lake 373. We decided to add a third station in 2002, to the north basin of Lake 375, to see if what effect distance from the farm had on our ability to detect changes in water chemistry. Sampling depths at this station were 1, 5, 10 and 15m (maximum depth). The original station on Lake 375 lies about 400m to the south of the farm whereas the new station rests only 25m to the south of the farm.

Surface water samples and physical measurements were made bi-monthly during the ice off period. Using a peristaltic pump, water was pumped up a plastic tube into 250 mL Nalgene© labeled according to location, station and depth. The surface water was sampled more frequently.

Meteorological sampling

Meteorological conditions at the ELA have been monitored since 1969. Climate monitoring and air and precipitation chemistry monitoring is supported by

the Meteorological Service of Canada (MSC). MSC protocols are followed and precipitation (bulk rain and bulk snow), air temperature and wind speed are recorded at least once a day at a meteorological station located approximately 15 km south of lakes 373 and 375.

Hydrological sampling

Runoff to Lake 239, outflow from Lake 373 and water levels on lakes 373 and 375 are recorded at permanent stations, which are calibrated throughout the ice-free season. Discharge rates are recorded every minute from v-notch weirs and water levels are recorded every hour.

Chemical analyses

Samples were processed at the analytical water chemistry laboratory of the ELA within 24 hours. Using methods described in Stainton (1979), samples were analyzed for chemical species of carbon, nitrogen and phosphorus, specifically dissolved inorganic (DIC) and organic carbon (DOC) (mmol/m^3), total dissolved nitrogen (TDN) and phosphorus (TDP), and particulate carbon (PC), nitrogen (PN) and phosphorus (PP) (mg/m^3). Samples were also analyzed for ammonium (NH_4^+) (mg/m^3), nitrate (NO_3^-) (mg/m^3), chlorophyll A (mg/m^3) and pH using Stainton's (1979) methods.

Carbon dioxide measurements

Carbon dioxide was a parameter we were interested in measuring. This species of inorganic carbon can dissolved in solution and volatilize to the atmosphere, which is important when building budgets that include gas exchange

at the air-water interface of a lake. Following the method of Hesslein (1990), surface water was collected in a serum bottle, equilibrated then analyzed for carbon dioxide partial pressure ($p\text{CO}_2$) (ppm). Once the pressure was measured, the concentration of carbon dioxide (mg/m^3) was determined by multiplying the pressure by Henry's constant adjusted for lake temperature and salinity (Harned and Scholes, 1941; Harned and Davis, 1943).

Samples were collected in 160 ml Wheaton glass serum bottles. Prior to sampling, 8.9 g of KCl (a preservative to inhibit microbial activity) was added to each bottle, then evacuated, sealed (with Vacutainer® stoppers) and backfilled with 10 mL of N_2 to create the head space. To collect a sample, the bottle was submersed just below the surface (<30 cm) and filled by puncturing the cap with a needle. Bottles were filled to a capacity (leaving only the head space) then shaken vigorously until the salt dissolved completely.

In the laboratory, bottles were placed in a wrist action shaker for 10 minutes to equilibrate dissolved gases with N_2 . Head space $p\text{CO}_2$ was then measured using a LICOR LI-800 GasHound CO_2 Analyzer®.

Statistical method

A repeated measures ANOVA was used in this study to test lake by period interaction, with lake (lakes 373 and 375) and period (before and after installation of the farm) representing the fixed factors and time as the repeated factor (weeks or months) and $n=4$ years (2001 to 2004).

Chemical budgets for lakes

We built budgets to compare stocks of chemical species of carbon, nitrogen and phosphorus within and between lakes 373 and 375 and the flow of these chemicals through these lakes, before and after the installation of the farm into Lake 375. Schindler and Nighswander (1970), Schindler et al (1976), Dillon and Rigler (1974 and 1975) and Kirchner and Dillon (1975) used variations of these budgets to calculate the retention of chemicals in lakes and build models to predict the accumulation of chemicals in the water column. We quantified stocks and flows of dissolved organic and inorganic carbon, total dissolved nitrogen and phosphorus and particulate carbon, nitrogen and phosphorus. We added species of elements together to generate a comprehensive estimation for overall stocks and flows of carbon, nitrogen and phosphorus.

We quantified stocks of chemicals (kg) in lakes 373 and 375 by integrating the product of chemical concentration (mg/m^3) and lake area (ha) over depth (m) (Equation 2). We identified the major processes that move chemicals into and out of lakes and attempted to quantify these flows. Once a process was identified, it was categorized, depending of the direction of the flow, into one of three categories. Sources, sinks and exchanges were the categories used to indicate whether the process behind the flow moved chemicals respectively, into the lake, out of the lake or in either direction. To further develop our understanding of the fate of these chemicals, we also quantified some flows within lakes.

Sources: flows of chemicals into lakes

We identified and quantified five sources of chemicals to lakes 373 and 375. These sources were atmospheric deposition (bulk rain and bulk snow), erosion (weathering and runoff), tributaries and in lake 375, flows of livestock and feed into the lake.

The weekly amount of bulk chemical falling directly on the lake from atmospheric deposition (AD) (kg) was equal to the product of the weekly rate of precipitation (I^P) (m^3) and the weekly concentration (mg/m^3) of chemical collected in the bulk deposition collector (C^{AD}) at the ELA meteorological station (Equation 9).

$$AD = I^P * C^{AD} * 10^{-6} \quad (9)$$

Bulk samples were collected for chemical analyses and we considered this bulk amount a combination of wet and dry deposition.

The weekly amount of chemical erosion to the lake (E) (kg) was equal to the weekly runoff from the catchment (I^R) (m^3) (Equation 5) multiplied by the concentration of chemical (mg/m^3) in a weekly sample of runoff water (C^E) (Equation 10).

$$E = I^R * C^E * 10^{-6} \quad (10)$$

Runoff water was chemically analyzed from the nearby and compositionally similar eastern subcatchment of Lake 239.

The weekly amount of chemical entering a lake by a tributary (T) (kg) was calculated by multiplying the weekly volume of water inflowing from the upstream catchment (I^T) (m^3) by the concentration of chemical (mg/m^3) in a weekly sample

taken from the inflow (C^T). The concentration of chemical in the surface water of the upstream lake was used as a proxy for C^T (Equation 11).

$$T = I^T * C^T * 10^{-6} \quad (11)$$

The amount of chemical entering the lake upon initial stocking with livestock (L^I) (kg) was the product of the number of individuals (n), the average wet weight of an individual (f) (g) and the chemical composition of a fish (C^{Lx}) ($\text{g}_{\text{chemical}}/\text{g}_{\text{wet fish}}$). In this case, we are interested in the carbon (C^{LC}), nitrogen (C^{LN}) and phosphorus (C^{LP}) composition of a rainbow trout, which can be determined by using equations for weight dependent chemical composition (Equation 12).

$$\begin{aligned} L^I &= n * f * 10^{-3} * C^{Lx} \\ C^{LC} &= (9.57 * f^{0.099}) / 100 \\ C^{LN} &= ((0.1581 * f - 0.0911) / 6.25) / f \\ C^{LP} &= (0.0036 * f - 0.0173) / f \end{aligned} \quad (12)$$

The chemical composition of a trout changes as they mature and the coefficient reflects this, it is a function of weight. Hall (1990) published an equation for determining the carbon composition of trout (Equation 12) and Bureau (2003) did the same but for nitrogen (Equation 12) and phosphorus (Equation 12).

The weekly amount of chemical in entering the lake in livestock feed (F) (kg) was calculated by multiplying the weekly amount of feed applied to the farm (fd) (kg) by the chemical composition of the feed (C^F) ($\text{kg}_{\text{chemical}}/\text{kg}_{\text{feed}}$) (Equation 13).

$$F = fd * C^F \quad (13)$$

Feed was dried for approximately 12 hours at 60°C then ground into a powder with mortar and pestle and analyzed using a CHN analyzer.

Sinks: flows of chemicals out of lakes

We identified two sinks of chemicals from lakes 373 and 375. These sinks were discharge at the outflow and in lake 375, livestock removed during harvest.

The weekly amount of chemical discharged at the outflow (D) (kg) was calculated by multiplying the weekly volume of water discharged at the outflow (O^D) (m^3) (Equation 3) by the chemical concentration of the discharge (C^O) (mg/m^3) (Equation 14).

$$D = O^D * C^D \quad (14)$$

In this study case, we use the chemical concentration of the surface water of the lake instead of the concentration at the outflow.

The amount of chemical removed from the lake upon harvesting the livestock (L^H) (kg) was calculated by multiplying the number of individuals (n), the average wet weight of an individual at harvest (f) (g) and the chemical composition of a fish (C^{Lx}) ($g_{chemical}/g_{wet\ fish}$) (Equation 15).

$$L^H = n * f * 10^{-3} * C^{Lx} \quad (15)$$

The number of individuals at harvest was determined by subtracting the number of observed mortalities from the initial number of fish used to stock the farm.

Exchanges: bi-directional flows of chemicals into or out of lakes

We identified one bi-directional flow of chemicals to and from both lakes, which was gas exchange at the air-water interface of the lake.

The weekly exchange of a chemical either dissolving into the lake or volatilizing to the atmosphere (kg) was calculated using the Stagnant Film Model (Liss and Slater, 1974). This model describes diffusive gas exchange (or flux) across the stagnant film or boundary layer at the air-water interface. The flux is proportional to the difference in chemical concentration (mg/m^3) measured in the water and at the top of the boundary layer. The boundary layer is considered to be in equilibrium with the atmosphere. If chemical concentrations in the surface water exceed those in the boundary layer, the chemical will evade from the lake. If the opposite is true, the chemical will invade the lake from the atmosphere. The velocity of this movement is dependent on the thickness of the boundary layer, which is related to the wind shear across the top of the lake. An equation for mass transfer velocity at the interface of lakes (m/second) is published by (Cole and Caraco, 1998). In summary, the weekly amount of volatile chemical evading from the lake by gas exchange (GE) (kg) was calculated by taking the difference between weekly measures of the equilibrated atmospheric chemical concentration in the boundary layer and the aqueous concentration in the water ($C^{AQ}-C^{EQ-ATM}$) (mg/m^3) and multiplying this difference by the area of the lake (A^S) (ha) and a mass transfer velocity (k) (m/second). The mass transfer coefficient is a published equation dependent on wind speed (w) (m/second) (Equation 16).

$$GE = (C^{AQ} - C^{EQ-ATM}) * A^S * 10000 * k * 60 * 60 * 24 * 7$$
$$k = 2.07 + 0.215 * w^{1.7}$$
(16)

The boundary layer concentration of the chemical was considered in equilibrium with the atmosphere. In the case on carbon dioxide the boundary concentration was determined by applying Henry's constant to an atmospheric pressure held constant at 375 μatm (Keeling and Whorf, 2004).

The retention of chemicals in a lake

The weekly amount of chemical retained in a lake R (kg) was calculated by subtracting weekly chemical sinks and exchanges from weekly chemical sources. In this case, chemical sources include atmospheric deposition AD (kg), erosion E (kg), tributaries T (kg), initial stocking with livestock L^I (kg) and the feed applied to the farm F (kg). Sinks include discharge at the outflow D (kg) and the livestock removed during harvest L^H (kg). Exchanges considered sinks in this case are gases volatilizing or evading from the lake GE (kg) (Equation 17).

$$R = AD + E + T + L^I + F - D - L^H - GE \quad (17)$$

Flows of chemicals within lakes

We generated three estimates of flows of chemicals within the two lakes. These estimates were flows of particulate chemicals sedimenting to the bottom of the lake and in the case of lake 375, flows of solid chemicals settling below the cage (manure, uneaten pellets, scales) and flow of total chemical waste (solid and particulate) generated by the farm.

The weekly amount of particulate chemical sedimenting to the bottom of the lake S (kg) was calculated by multiplying the average weekly concentration of chemical collected in sediment traps C^S (mg/m^3) by the surface area of the lake

A^S (ha) and dividing this by the average area of trap openings A^T (m²) (Equation 18).

$$S = C^S * 10^{-6} * \frac{A^S * 10000}{A^T} \quad (18)$$

Sediment traps (870 mL capacity with 62 cm² opening) were set in the north basin, south basin and at center buoy (above the deepest point in the lake) of Lake 375 at a depth of 10 metres. One sediment trap was set at the center buoy in Lake 373. Traps were sampled weekly during the ice -free period and their contents were analyzed for particulate chemicals (1µm GVC filter) using methods described by Stainton (1979).

The amount of solid chemical settling below the cage M (kg) can be calculated by multiplying the average concentration of chemical collecting in receptacles below the farm C^M (mg/m³) by the surface area of the farm A^F (m²) and the average area of the receptacle openings A^R (m²) (Equation 19).

$$M = C^M * 10^{-6} * \frac{A^F}{A^R} \quad (19)$$

The receptacles were attached to an apparatus that was suspended diagonally (SE to NW direction) from opposite corners of the farm platform to a depth below the net (approximately 10m) (Figure 13). Six receptacles (1.4m long PVC with one opening 0.1m in diameter) were attached to the apparatus in series at intervals of approximately 2m. This resulted in samples being taken at distances of 1, 3 and 5m from the center of the cage. In 2004, two sediment traps were suspended just beyond the cage, 10m from the center and at a depth of 10m, to determine if the majority of solids discharged from the farm were settling

directly below the cage. Sampling was not conducted routinely, rather when personnel were available to assist in the sampling. To collect the contents of the receptacles the apparatus was untied from one corner then guided along one side of the farm until the apparatus was suspended from adjacent corners. The apparatus could then be lifted to the surface, without disturbing the net, and tied off. Individual receptacles were then inverted, their contents collected in individual buckets. These large samples were individually homogenized, sub sampled (in 250ml Nalgene™ bottles), centrifuged (30min at 10000rpm), the liquid decanted, the solid then dried (12 hours at 60°C) and weighed to the nearest 0.001 mg. Samples were then analyzed for carbon, nitrogen and phosphorus content using a CHN analyzer.

The weekly amount of chemical waste produced by the farm W (kg) is estimated by mass balance. It is equal to the weekly difference in chemical gained in livestock biomass G (kg) and chemical in feed applied to the farm F (kg). Biomass gained by the livestock population can be estimated by multiplying the number of individuals n by the average change in individual wet weight Δf (g) by the chemical composition of an individual fish C^{Lx} (g_{chemical}/g_{wet weight}). The number of individuals n can be calculated by subtracting mortalities m from the initial population size n^I (Equation 20).

$$\begin{aligned}
 W &= F - G \\
 G &= n * \Delta f * 10^{-3} * C^{Lx} \\
 n &= n^I - m
 \end{aligned}
 \tag{20}$$

To calculate the amount of chemical bound in the biomass gained in the livestock, we multiplied the estimated average chemical weight of a fish

(Equation 12) by the population size and from it subtracted the initial mass of chemical bound in the livestock. Periodic estimates of the average individual wet weight were made throughout the farming cycle. The average wet weight of an individual (in grams) was estimated about once a month, from a sample of approximately 100 individuals, which were caught during feeding events, using a grab net. Weekly estimates of the number of individuals in a population were calculated by subtracting the weekly sum of daily mortalities from the initial population size (Equation 20).

Results

The chemical composition of livestock feed and lake budgets for carbon, nitrogen and phosphorus

The chemical composition of the livestock feed is presented in Table 5. Carbon composes (53%) roughly half the dry weight of the feed. Nitrogen (8%) and phosphorous (1%) content are in line with industry standards. Annual flows and stocks of carbon (Table 6), nitrogen (Table 7) and phosphorus (Table 8) are presented in budget format for lakes 373 and 375, before (2001-2) and following (2003-4) the installation of the farm in Lake 375. The net movement of carbon into or out of a lake can be considerable and annually can be equivalent to 40% of the carbon found in the water column. The mass of carbon in the water column is relatively inelastic when compared to the variation of carbon entering or leaving the lake. Gas evasion to the atmosphere, in all cases, is the dominant sink of carbon to these lakes and annual estimates of carbon leaving the lake by the process was at times equivalent to 49% of the stocks of carbon in the lake. Estimates of carbon evasion were sometimes negative implying a net movement of carbon into the lake, during the first year of farming for example. The accuracies of gas exchange estimates are important because of their overall consequence to the carbon budget. The amount of carbon in feed applied to the farm was at times greater than the sum of flow from atmospheric deposition, runoff, tributaries and discharge (2003). At first glance, in comparing values of carbon retention before and following the addition of the farm, it would seem that

aquaculture increased the rate of carbon retention in lakes, which is supported by an increase, albeit small increase in carbon stocks in the water column. Annual retention estimates are more often than not negative, suggesting that during these four years, these lakes were sometimes net sources of carbon. The nitrogen and phosphorus budgets of lakes are simpler than for carbon mainly because we decided to exclude estimates of exchanges for both. Although there are volatile nitrogenous compounds (e.g. NH_3 , N_2O , N_2) we assumed that at this time evasion or invasion of these compounds to the lake was negligible. For ammonia, aqueous ammonium was not yet elevated enough, nor was the pH high enough (basic) to warrant a calculation of this estimate. The addition of N_2 invasion by nitrogen fixing cyanobacteria maybe a worthwhile addition in algae blooming becomes apparent. As for phosphorus, a volatile compound containing this element does not occur in any considerable amount, if at all. From the standpoint of a chemical budget, the effect of the farm on the lake was more profound for nitrogen and phosphorus than for carbon. For both lakes, during all four years, lakes were net sinks for nitrogen and phosphorus. The annual addition of nitrogen in livestock feed approached (75-80%) average stocks of nitrogen in the lake. The harvest of nitrogen bound in livestock was the greatest sink of nitrogen from the lake, occurring in one day and surpassing the annual discharge of nitrogen at the lake outflow. The effect of the farm on the phosphorus budget was similar to nitrogen except amplified. The contribution of aquaculture related phosphorus to the lake comprised between 87-92% of all sources of phosphorus to the lake. The harvest of phosphorus bound in the

livestock was equivalent to nearly double the total average stock of phosphorus in the water column. Average stocks of nitrogen and phosphorus in the water column remained relatively stable and inelastic to changes in nutrient retention to these lakes with the exception of possibly a mild increase during the aquaculture years. The lack of a clear indication of rising nutrient levels in the water column following the addition of the farm suggests these nutrients are collecting at the bottom of the lake or have been scavenged by the lake's biota.

Modelling outflow volume and the effect on chemical discharge estimates

Two methods for estimating the amounts of chemicals discharged at the outflow of Lake 373 were compared in 2003 and 2004: estimates based on weir recordings versus estimates based on mass balance (Table 9). Although the discrepancy between methods may become more important in larger or pristine systems, in our case the overall contribution of this sink to the total budget, especially in comparison to lake with the farm, this discrepancy is fairly inconsequential. For example, the difference in annual estimates for phosphorus is between 0.02 and 0.16 kg whereas total kg of phosphorus removed from the lake during harvest is 30 to 38 kg.

Effects of aquaculture on chemicals retained in lakes

Trends in weekly rates of chemical retained by lakes 373 and 375 are presented for carbon (Figure 14), nitrogen (Figure 15) and phosphorus (Figure 16), before and following the installation of the farm in Lake 375. The variation in the weekly amount of carbon retained is similar in lakes 373 and 375 prior to the

addition of the farm to Lake 375. What was generally observed was periods of negative retention (or removal) of carbon during early spring after ice melt and during late fall when the lakes are ``turning over``. These periods of large negative retention are driven primarily by estimates of gas evasion, which dominate the carbon budgets of these lakes during these periods. The remainder of the off ice season, during the summer months, the retention of carbon remains close to zero with periodic gains and losses of carbon to the lake. At least visually, the farm has a noticeable effect on the retention of carbon in the lake. The initial addition of livestock to the lake in late May or early June results in an initial spike of carbon to the lake, which partially counters the evasion of carbon dioxide during spring melt. The constant and increasing supply of feed to the lake results in a greater than normal retention of carbon throughout the summer up until harvest, which during the fall exacerbates the removal of carbon from the system normally linked to the ``turnover`` event. The retention of nutrients nitrogen and phosphorus in lakes is tightly linked to the hydrological cycle. Large inputs are observed in both lakes early in the ice-off following spring melt and are arguably the result of large inputs of tributary inflow and erosion into the lake. Large rain events also explain the observed retention spikes through the season. The effect of aquaculture on the retention of nutrients can be seen immediately, especially for phosphorus. Retention of these two nutrients increases systematically as the farming season progresses, the result of the increasing amount of feed fed to the growing livestock. The retention of nutrients on a weekly basis is greater in the aquaculture-impacted lake than for any other week

on both lakes from 2001-2004 with the exception of a rather large input during spring runoff week of 2001. The large negative (removal) season ending spikes in Lake 375 during 2003 and 2004 are the result of the harvest, nutrients bound in fish being removed from the lake.

Effects of aquaculture on chemical stocks in lakes

Trends in lake stocks of carbon (Figure 17), nitrogen (Figure 18) and phosphorus (Figure 19) are presented for lakes 373 and 375, before and following the installation of the farm in Lake 375. Despite the larger volume of water in Lake 373, Lake 375 has historically contains more carbon, which may be a function of Lake 375 being further downstream or having a larger drainage area. Following the years of aquaculture operation it could be argued that total carbon in the water column has increased slightly more than observed in Lake 373. Total amounts of nitrogen in the water columns of lakes 373 and 375 are similar and suggest that lake drainage area may not be the only explanation for the difference we have seen in carbon between the lakes. From our initial inspection, during the years of aquaculture, it looks as is nitrogen in Lake 375 is increasing or remaining constant where nitrogen levels in lake 373 are decreasing. The same can be said for phosphorus although historical levels of phosphorus in both lakes have been greater than what was observed following the installation of the farm.

Effects of aquaculture on chemical flows within lakes

Trends in weekly concentrations of sedimenting carbon (Figure 20), nitrogen (Figure 21) and phosphorus (Figure 22) particulates in sediment traps are presented for lakes 373 and 375, before (2002) and following (2003-4) the installation of the farm in Lake 375. Weekly concentrations of chemicals collected in sedimentation traps have remained fairly stable in Lake 373 prior to (2002) and following (2003 and 2004) the installation of the farm to Lake 375. The same is not true for Lake 375, which, for all chemicals, has shown a consistent increase during the year and from year to year following the addition of the farm. Concentrations of sedimenting particulates have, as expected, been slightly higher in the near field station (closest to the farm) during the farming seasons, but not alarmingly so. Maximum weekly concentrations of particulate chemicals in sediment traps following the installation of the farm have been approximately three, three and almost four times greater for carbon, nitrogen and phosphorus respectively, when compared to sediment trap concentrations in Lake 375 prior to the farming period (i.e. in its pristine condition).

The chemical composition of the material settling below the cage is presented in Table 10. Trends in mean daily concentrations of settling carbon (Figure 23), nitrogen (Figure 24) and phosphorus (Figure 25) particulates in collectors below the farm are presented for 2003. We observed that particulates chemicals were in general concentrated near the centre of the cage. We also observed that particulate concentrations quickly approached zero beyond the perimeter of the cage. Daily concentrations of particulates generally increased

throughout the season, indicating that the flux of settleable farm waste is greatest as harvest nears, which is of little surprise. The chemical composition of the solid material collected (Table 10) was 43% carbon, 5% nitrogen and 3% phosphorus, which for carbon and nitrogen is of a lower content than in the food but for phosphorus is of higher content than observed in the food.

Trends in weekly amounts of carbon (Figure 26), nitrogen (Figure 27) and phosphorus (Figure 28) wastes discharged from the farm are presented for 2003 and 2004. Waste estimates were calculated by mass balance, subtracting estimated gains in livestock biomass from amounts of feed supplied to the farm. The same general trend can be seen for each chemical, increasing as the farming season progressed, indicating that the livestock population generally produced more waste as it grew and matured. Periodic spikes in negative waste are explained by periods when rations were reduced, often because of high temperatures, which stress fish, sometimes fatally. Fish waste also increases late in season because the decrease in water temperatures during this period is believed to be ideal for fish growth (pers. comm. M. Meeker of Meeker's Aquaculture). Negative estimates of waste imply occurred during prolonged periods of no feeding, which typically occur before harvest. This negative number suggests fish are still growing, albeit minimally, even though food is not being supplied, which means they are acquiring food from different sources, for example natural sources in the lake and the waste generated by other livestock.

Flows of carbon, nitrogen and phosphorus within lake 375 are presented; particulates sedimenting to the bottom across the lake, solids settling below the

farm, and waste generated by the farm (Table 11). This result immediately suggests that most of the chemical waste generated by the farm is not deposited directly below the farm. In fact, less than 6, 5 and 26% of respectively, carbon, nitrogen and phosphorus settles directly below the cage. In 2003, the fate of a large amount of the waste cannot be explained by an increase in sedimenting chemical particulates across the lake because waste estimates are larger than sedimentation estimates. This suggests that a large fraction of the waste remains unaccounted for. In 2004, annual sedimentation estimates for carbon, nitrogen and phosphorus increased to a level where only total amounts of sedimenting phosphorus remained below the amount of estimated phosphorus waste generated by the farm.

Evidence for short term aquaculture effects on stocks, flows and the distribution of chemicals in Lake 375

Results of the repeated measures 2-way ANOVA, testing for significant differences in chemical flows and stocks before and following the addition of the farm to Lake 375 are presented for: (1) the retention of chemicals (Table 12); (2) stocks of chemicals in the water column (Table 13); and (3) concentrations of sedimenting chemicals (Table 14). The results of these BACI-style analyses suggest that cage aquaculture has significantly altered the lake's capacity to retain nitrogen and phosphorus. The analysis also suggests that aquaculture has significantly increased stocks of particulate carbon in the water column. Finally, there is definitive and independent evidence that the rate at which carbon particulates are sedimenting is increasing.

We also test several hypotheses concerning the effect of aquaculture on the concentration of chemicals in the epilimnion, metalimnion, in deep water (below the metalimnion) and at the lake's maximum depth. Here we reported only the significant findings (Table 15), which is an increase in suspended carbon particulates and suspended nitrogen particulates in the epilimnion (Figure 29, Figure 30) and an increase in deep-water nitrogen (Figure 31).

Conclusions

Summary of findings

The addition of livestock and aquaculture feed to the lake has increased inputs of carbon, nitrogen and phosphorus to the lake by, on average, a factor of three, four and seventeen respectively. Chemical inputs to the lake were not stable but increased as the summer progressed, a function of the feed requirements of the growing livestock.

During the two production cycles, the livestock transformed an average 33, 31 and 34 percent of the carbon, nitrogen and phosphorus bound in the feed into fish biomass. Although these chemicals were removed during harvest, the remaining percentages were discharged directly into the lake.

Sinks for chemicals in Lake 375, for example discharge at the outflow, did not offset the addition of aquaculture waste and as a result, we observed an increase in the amount of carbon, nitrogen and phosphorus retained in the lake. Increases in nitrogen and phosphorus retention in particular were deemed statistically significant. The amount of phosphorus retained in lake 375 following the addition of the farm for example, was on average four times the amount observed historically. To put this in context, we compared our phosphorus budget results to a previous study (Bird and Mesnage, 1996) that also examined the effects of aquaculture on flows of phosphorus to and from a shield lake (Table 16). Following the addition of a rainbow trout farm to a tributary of Lake Heney, the lake subsequently transformed into an algal soup, forcing an end to the farming operation.

Despite the increase in chemicals retained in the lake, the accumulation of these chemicals in the water column was relatively inelastic, with the exception of carbon particulates, which increased significantly. Using Vollenweider's (1968) classic mass balance, we expected to observe a 14 kg increase in water column phosphorus following the farming season of 2003, which contrasts sharply with the observed 3 kg increase. A better alternative is Johansson and Nordvarg's model 1 (2002), which has been calibrated for fish farm emissions. This model predicted an increase of 4 kg phosphorus in the lake water column following the addition of the farm, which was closer to that observed.

The lack of a response in water column stocks of carbon, nitrogen and phosphorus to aquaculture in the short-term is not uncommon (Cornel and Whoriskey 1993; Hakansson et al. 1998). Hakansson et al. (1998) suggest that (1) direct uptake of farm waste by indigenous zooplankton and fish and (2) increased elimination processes, for example increasing rates of sedimentation, accelerate the removal of chemicals, especially nutrients from the water column.

This in fact appears to be the case. Within lake flows of sedimenting carbon, nitrogen and phosphorus particulates have all increased, which is based on an increasing trend in weekly concentrations of chemicals collected in sediment traps. We observed statistically significant increases in the rate of carbon sedimentation. The biological significance of this increase is open for debate however, as these rates are within ranges measured in un-manipulated boreal shield lakes (Elser et al. 1995; Elser and Foster 1998). Solids settling below the cage are another obvious removal process for chemicals from the

water column. Our results are interesting in that the amounts of carbon and nitrogen estimated to settle below the cage represent a very small fraction (~5%) of the total waste discharged by the farm. This relationship should be further investigated because of its management implications. Finally, the assertion that aquaculture-derived chemicals do not accumulate in the water column because of direct uptake by indigenous zooplankton and fish received moderate support. We observed an unusually large minnow population foraging around and nesting on the cage and an overall increase in the size of the native fish population (K Mills, P Blanchfield, C Podemski, pers. comm.).

Potential sources of error

We are reasonably confident in our estimates of natural sources of carbon, nitrogen and phosphorus to lakes 373 and 375 because they compare favourably to values published for un-manipulated boreal shield lakes (Schindler and Nighswander 1970; Schindler et 1976; Campbell et al 1994; Dillon and Evans 1993; Dillon and Molot 1997).

Our estimates of nitrogen and phosphorus retention in lakes 373 and 375 prior to and during the operation of the farm were within the range of values reported for un-manipulated and experimentally fertilized ELA shield lakes (Table 17). Carbon on the other hand was a different story. We often estimated lakes to be net sources of carbon during the ice-free period, which is opposite to the popular view that lakes are sinks for carbon. Our gas evasion estimates had a great deal of leverage on our carbon budgets and a review of these estimates is important. Gas exchange estimates are important because in our case, not only

did they dictate the magnitude of the flow but also the direction of the flow. These lakes were estimated to be, depending on the year and lake, either carbon sinks or carbon sources to the environment (mainly to the atmosphere). It is fair to say that alternative methods of measurement should definitely be explored as well as and an evaluation of the sensitivity of the estimate to different mass transfer functions. These budgets would also benefit from more information during spring melt and surface water chemistry up until the moment of ice-on. It is also fair to say that other chemical flows need to be explored to tighten the budgets, for example: sources such as pollen and leaf litter; and sinks such as emerging insects.

Aquaculture consequences to lake health

Lake Heney is a classic example of the impact aquaculture can have on the health of a boreal shield lake – nutrient and organic enrichment leading to blooms of obnoxious algae, eutrophication and the consumption of oxygen required to sustain aquatic life. Aquaculture has been shown to induce anaerobic conditions in deep water (Axler et al 1996; Hamblin and Gale 2002; Veenstra et al 2003).

The sedimentation and eventual decay of algae is the mechanism that leads to the depletion of hypolimnion (deepwater) oxygen (Molot et al 1992). Salmonids are sensitive to oxygen conditions and oxygenated hypolimnions are especially important to native salmonids that seek refuge in these cold habitats during the hot months of the summer.

Oxygen depletion can also stimulate internal loading in aquaculture-impacted environments, causing nutrients to be regenerated by the sediments (Wisniewski and Planter 1987). Internal loading is an example of a positive feedback system that further exacerbates eutrophication (Dillon and Molot 1996). In Lake 375, we are beginning to see increasing trends in phosphorus at the lake's maximum depth but at this point we cannot unequivocally assign this increase to the farm.

It is important to mention that the aquaculture operation in the tributary of Lake Heney was quite different from the set up in Lake 375. The farm on Lake 375 was a cage farm whereas the one located in the tributary of Lake Heney was of the run design. The difference between the two is that in the cage set up, aquaculture wastes can be discharged at a depth below or near the edge of the euphotic and mixing zones. In contrast, the farm responsible for eutrofying Lake Heney discharged wastes into the stream current, which probably enhanced the mixing of wastes and increased the dissolved component, which is more easily assimilated by algae and plants. These nutrients were also discharged into the surface water of the Lake Heney, which is exposed to more solar radiation, and ideal for algae production.

The results presented here demonstrate the short-term effects of aquaculture on the chemical conditions in Lake 375. It is important to remember that because of the significant increase in chemical retention, organics and nutrients will continue to accumulate, either at the bottom of the lake, in the water column or in the lake's biota. As stocks of these chemicals increase, the potential

for larger flows leaving the lake or larger flows within the lake increases for example, transformations of inorganic chemicals to organic chemicals or increases in volatile chemicals evading to the atmosphere.

Recommendations for management

Aquaculture increases sources of carbon, nitrogen and phosphorus to lakes. These chemicals will accumulate in lakes that have small outflow to volume ratios. Lakes with large fetch (surface areas) to volume ratios are prone to being well mixed by wind and as a result aquaculture wastes in these lakes will likely be distributed more evenly throughout the water column, which becomes an issue when these nutrients are exposed to photosynthetically active radiation. Choosing deep lakes with small fetches and large outflows could limit short-term effects although long-term implications may be disastrous.

Phosphorus is a biologically active ingredient in lakes and mitigating the amount of it discharged into any lake should be a priority. Phosphorus is an essential nutrient and important for fish growth so concentrations in feed should be optimized to minimize the difference in feed phosphorus and waste phosphorus. Theoretically, this could be achieved by developing a feed that contains the least amount phosphorus without comprising livestock yield (and taste!). A more practical solution would be not to overfeed the fish, which results in more wastes produced directly by the fish and more uneaten food pellets released into the environment. In our experiment, the rate of phosphorus discharge was at the low end of the range normally observed for freshwater trout aquaculture, which is between 7 and 25 kg of phosphorus waste per tonne of fish

produced (Yan, 2005). If however, you consider that the average cottage resident discharges approximately 0.8 kg of phosphorus annually into a lake (Dillon and Molot 1996), the total discharge from the farm would be equivalent to a hypothetical 200 residents living on Lake 375 during the same time period, which is ludicrous if you consider the size of the drainage basin.

In the context of a prospective environmental assessment, this study has provided good information for selecting leading indicators of short-term aquaculture effects at the ecosystem level. First, we have observed statistically significant increases in carbon and nitrogen particulates, most notably in the epilimnion of the lake. We can attribute this change to the farm because of the experimental design and choice of statistical test. This finding is supported by equally significant increases in sedimentation rates for carbon and nitrogen particulates. Particulate nutrient concentrations in a fresh water loch (Stirling and Dey 1990) and in an abandoned mine pits (Axler et al 1996) have also been observed to increase following the installation of a cage farm. We have also observed a statistically significant increase in hypolimnetic total dissolved nitrogen. These indicators are useful because they not only identify those parameters that respond quickly to aquaculture but also these are functional responses at the ecosystem level and are therefore of consequence to many different biological communities in the lake.

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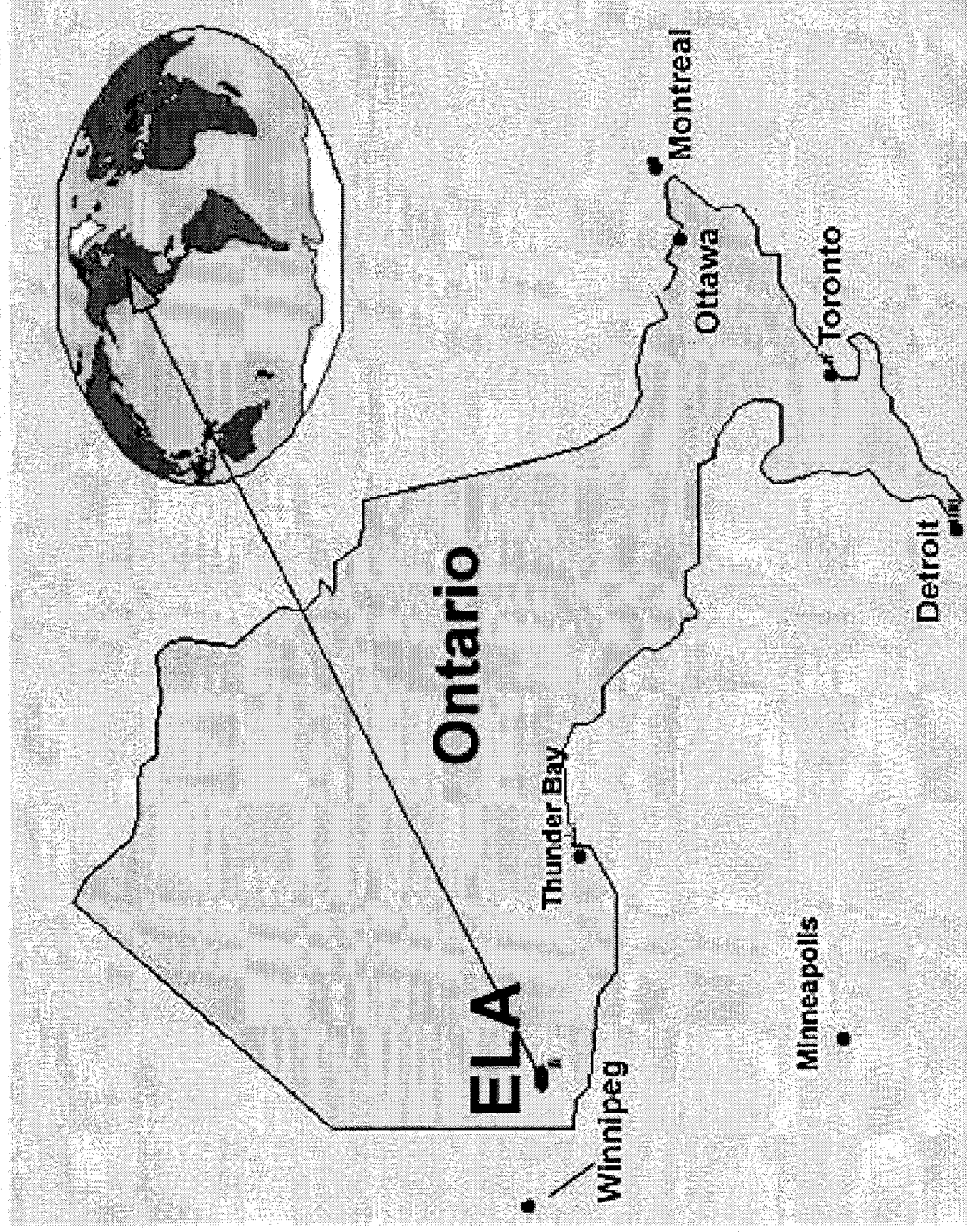


Figure 3. The Experimental Lakes Area (ELA) is located in North western Ontario, Canada.

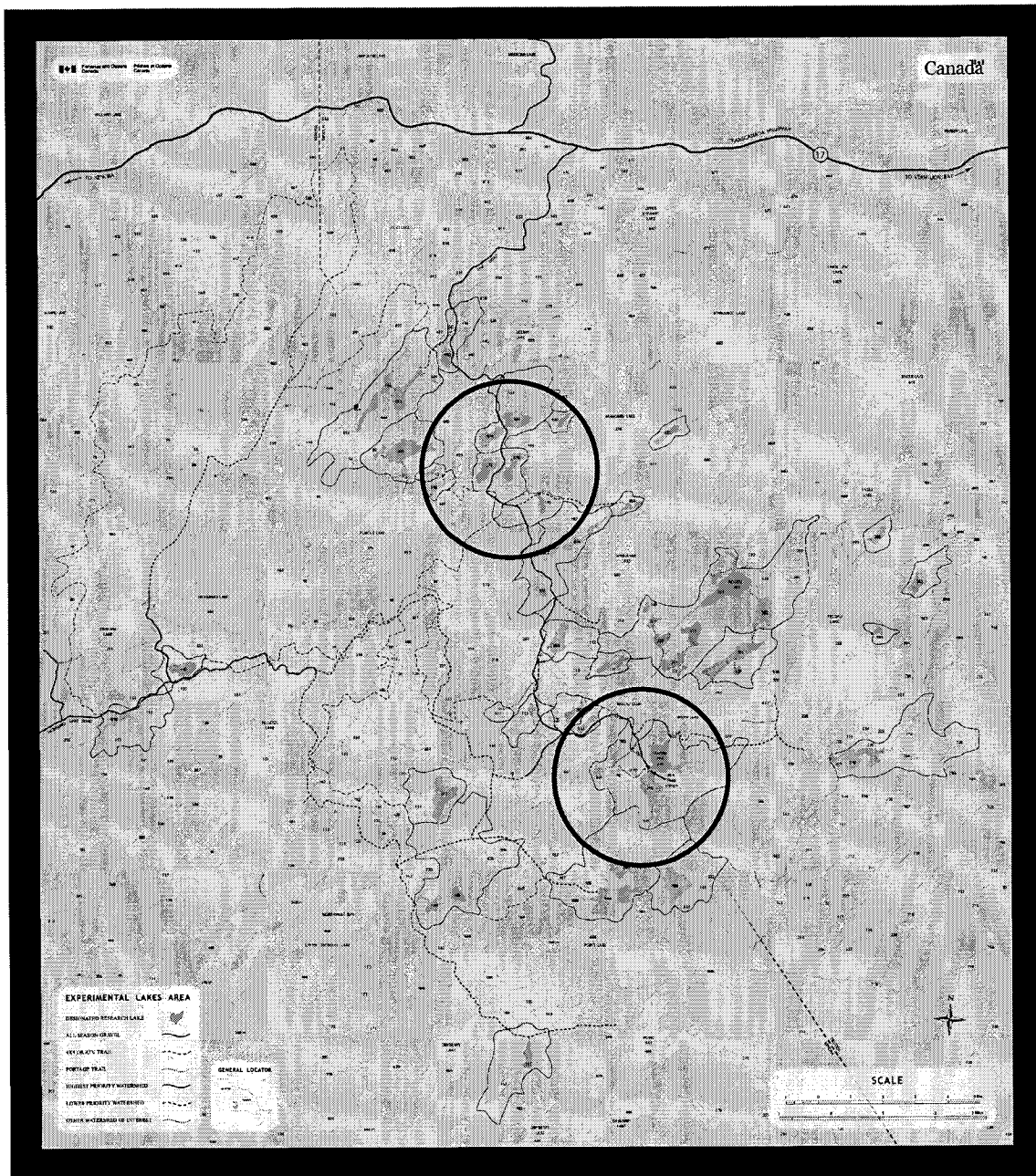


Figure 4. A map of the Experimental Lakes Area. Encircled in black are lakes 373 and 375 (top) and the ELA field station, meteorological station and Lake 239 (bottom).



Figure 5. An aerial view of lakes 375 (north and south basins), 373 and 626.



Figure 6. An aerial view of lakes 375 (north and south basins), lake 373 and Porcus Lake. Pine Road passes between lakes 375 and 373, starting at Highway 17 and ending at the ELA field station.

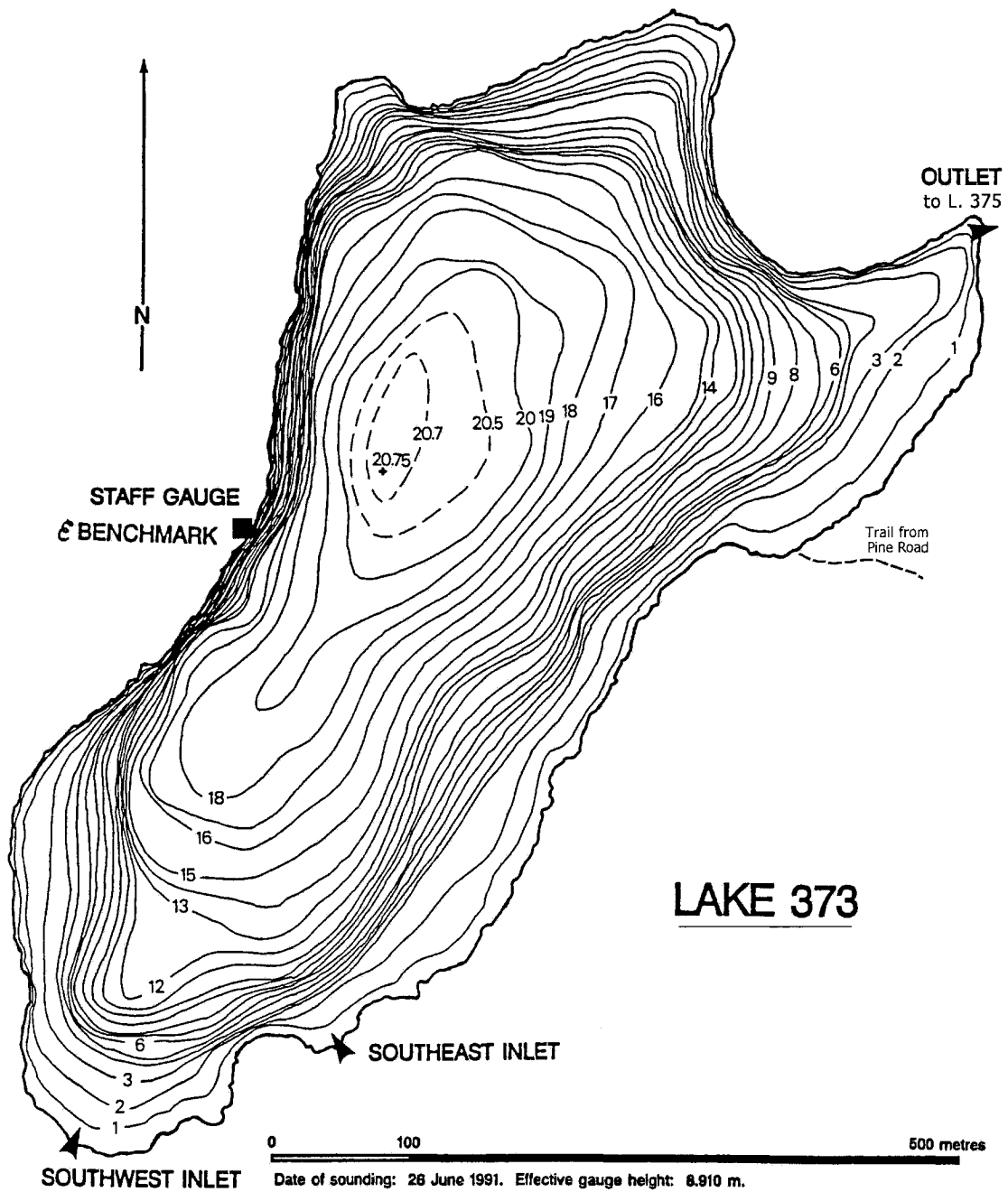


Figure 7. A bathymetric map of Lake 373.

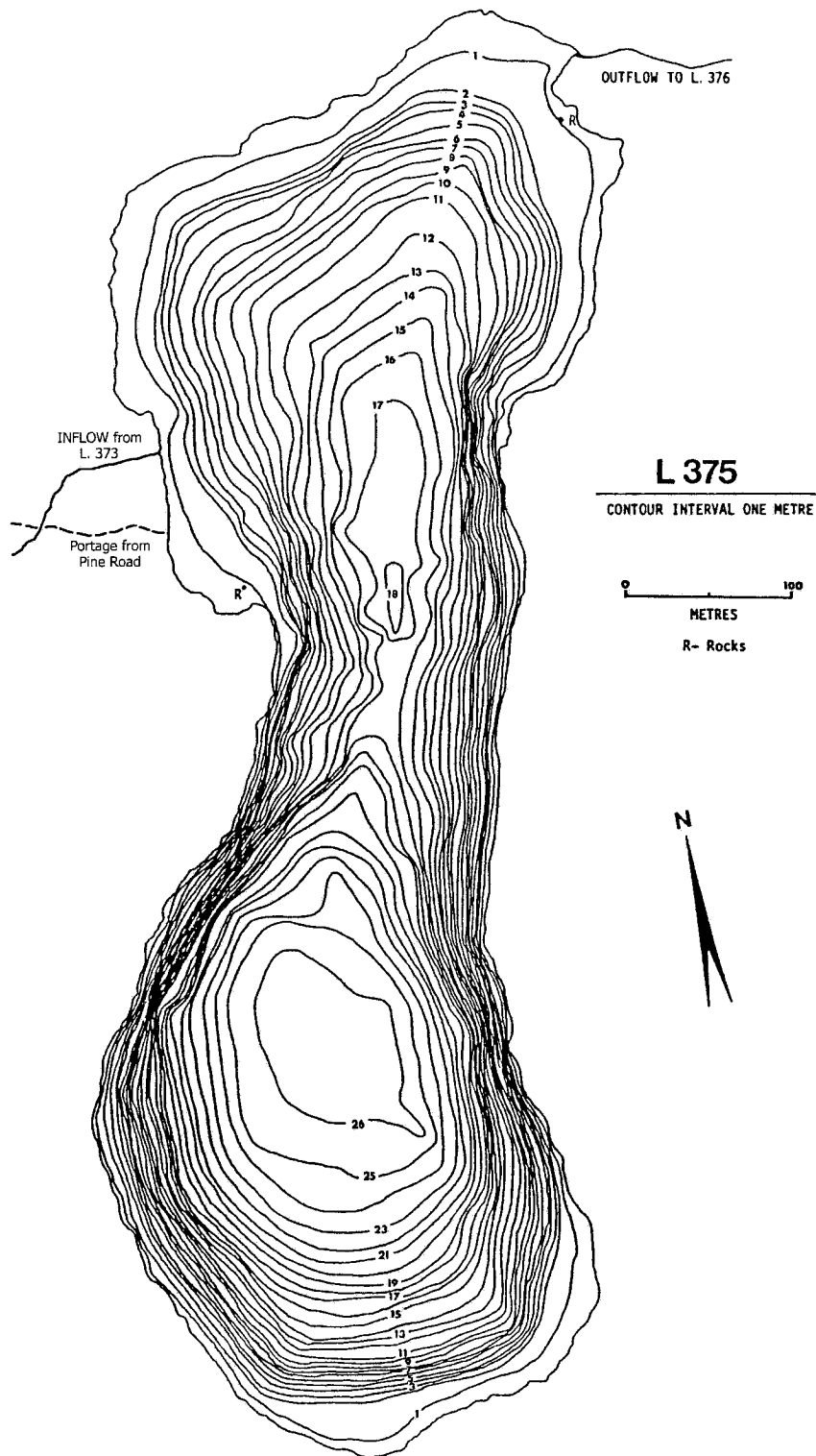


Figure 8. A bathymetric map of Lake 375.

Discharge rates from Lake 373, flows predicted by mass balance versus flows recorded at weir, April 30th to Nov 25th, 2004

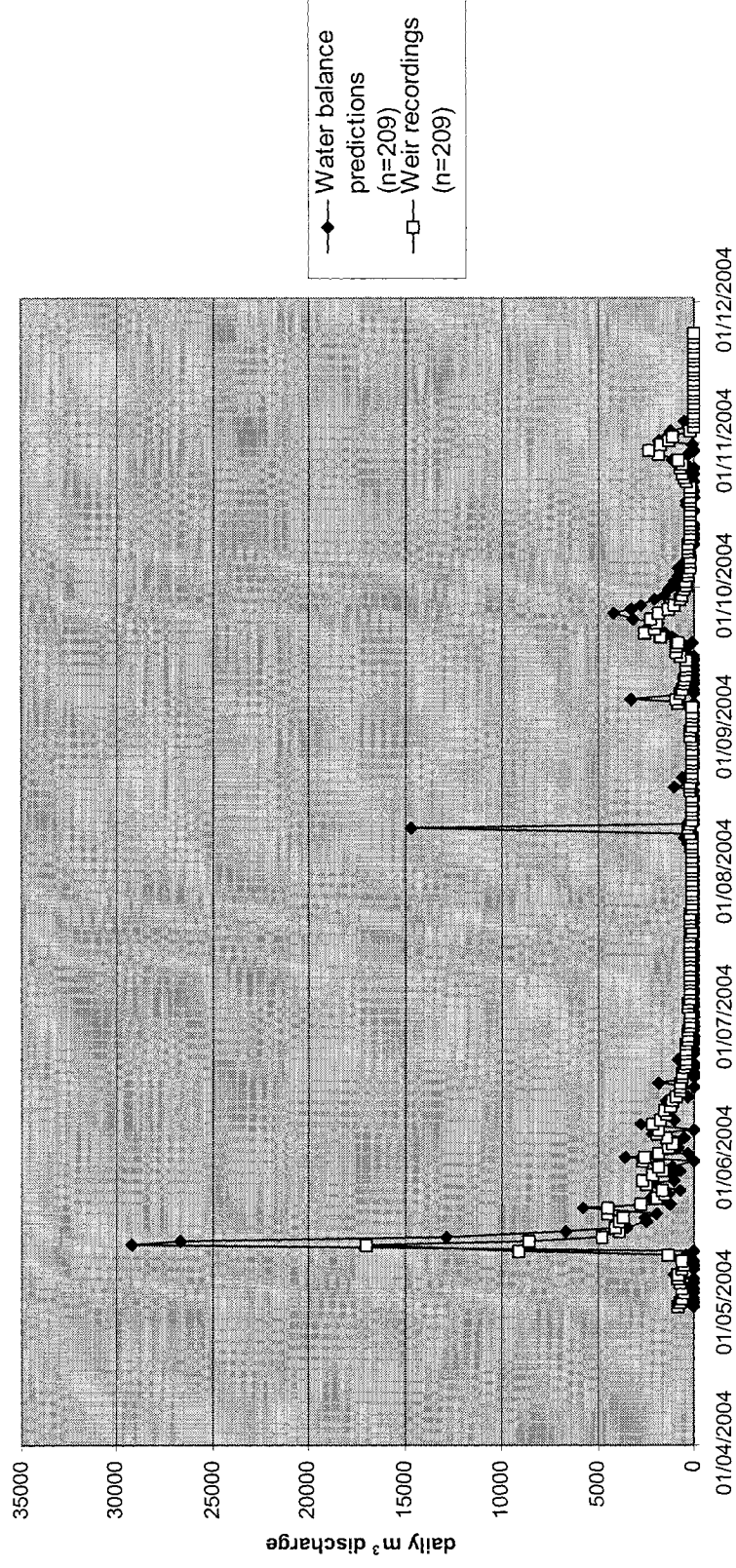


Figure 9. The accuracy of water balance predictions for the rate of daily discharge from the outflow of Lake 373, 2004.

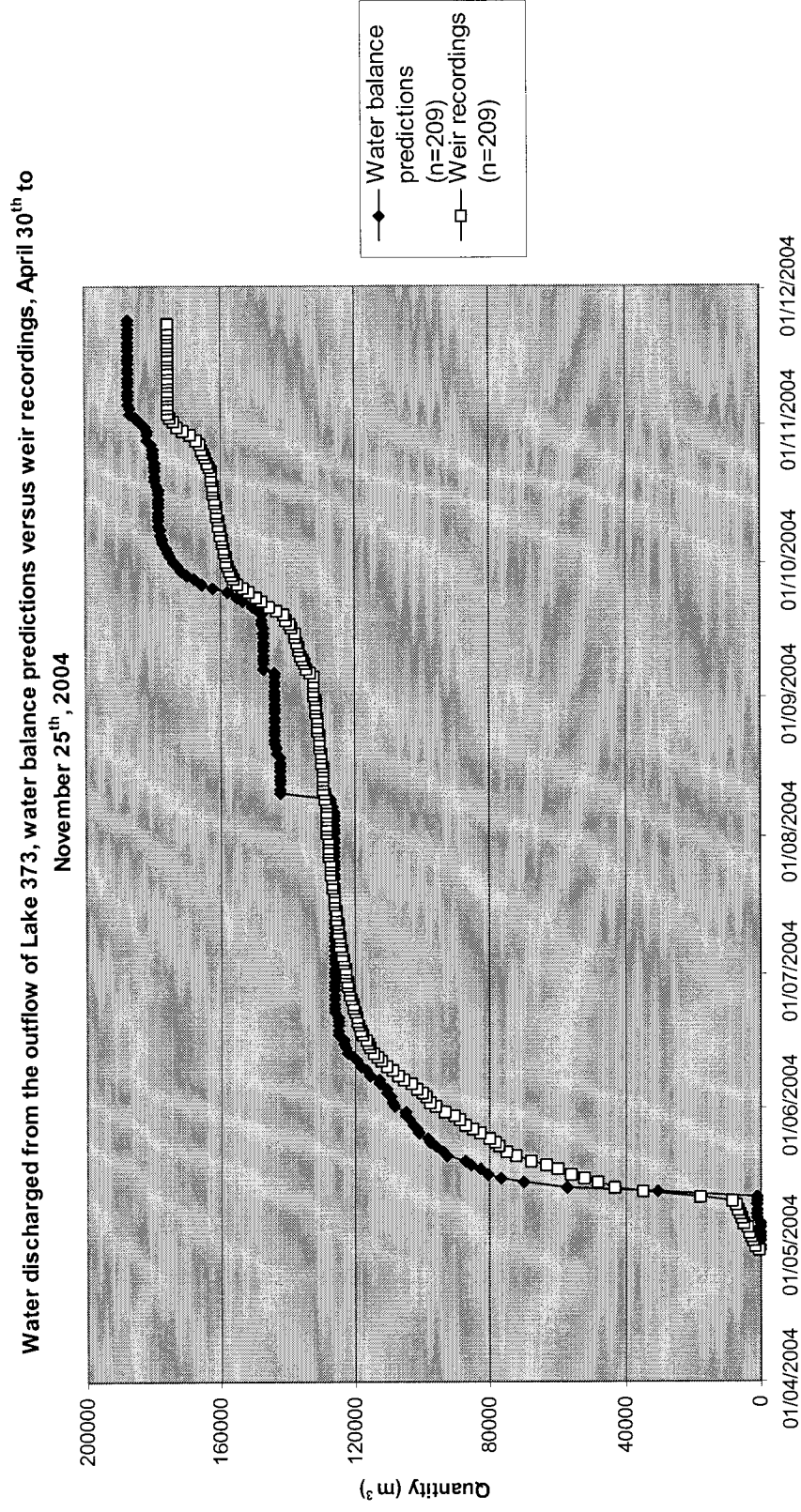


Figure 10. The accuracy of water balance predictions for the cumulative amount of water discharged from Lake 373, 2004.

Discharge rates from Lake 373, flows predicted by mass balance versus flows recorded at weir, April 22nd to Nov 24th, 2003

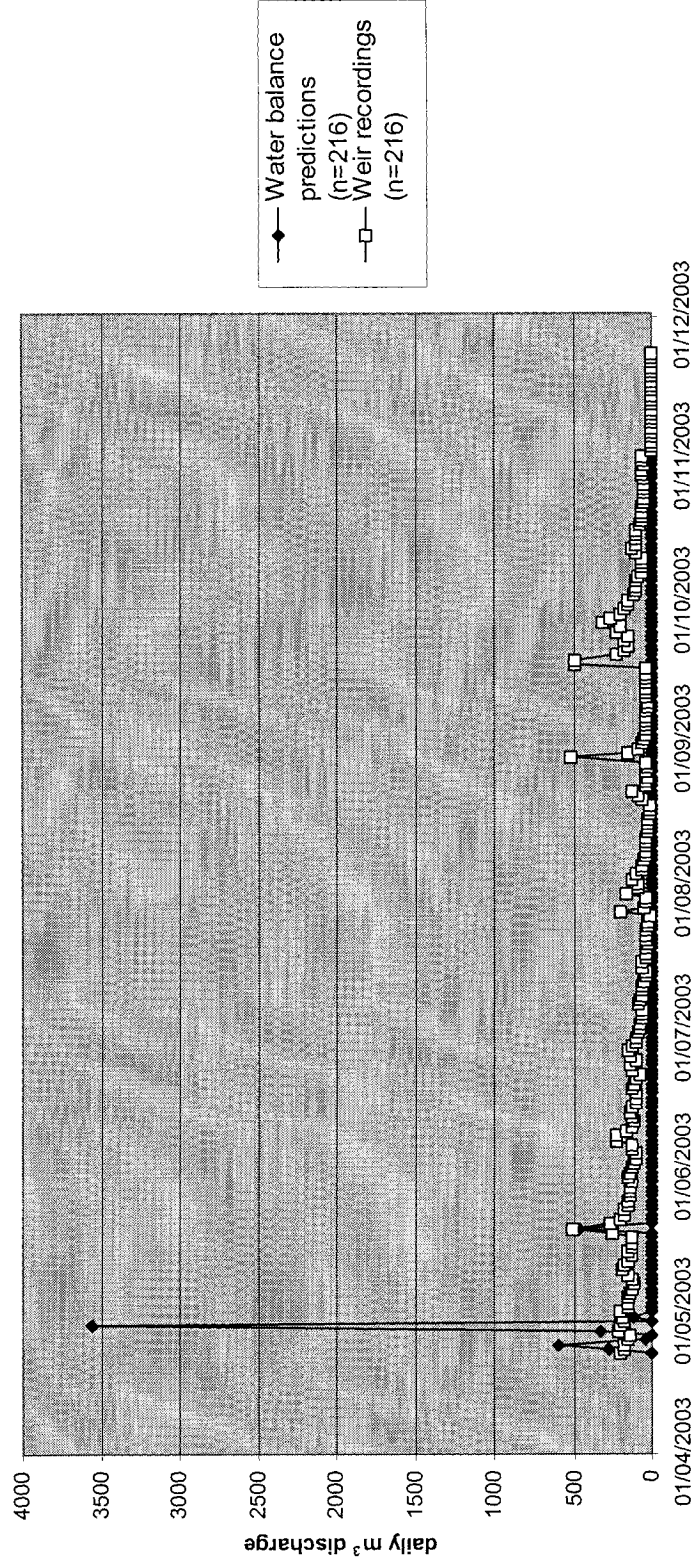


Figure 11. The accuracy of water balance predictions for the rate of daily discharge from the outflow of Lake 373, 2003.

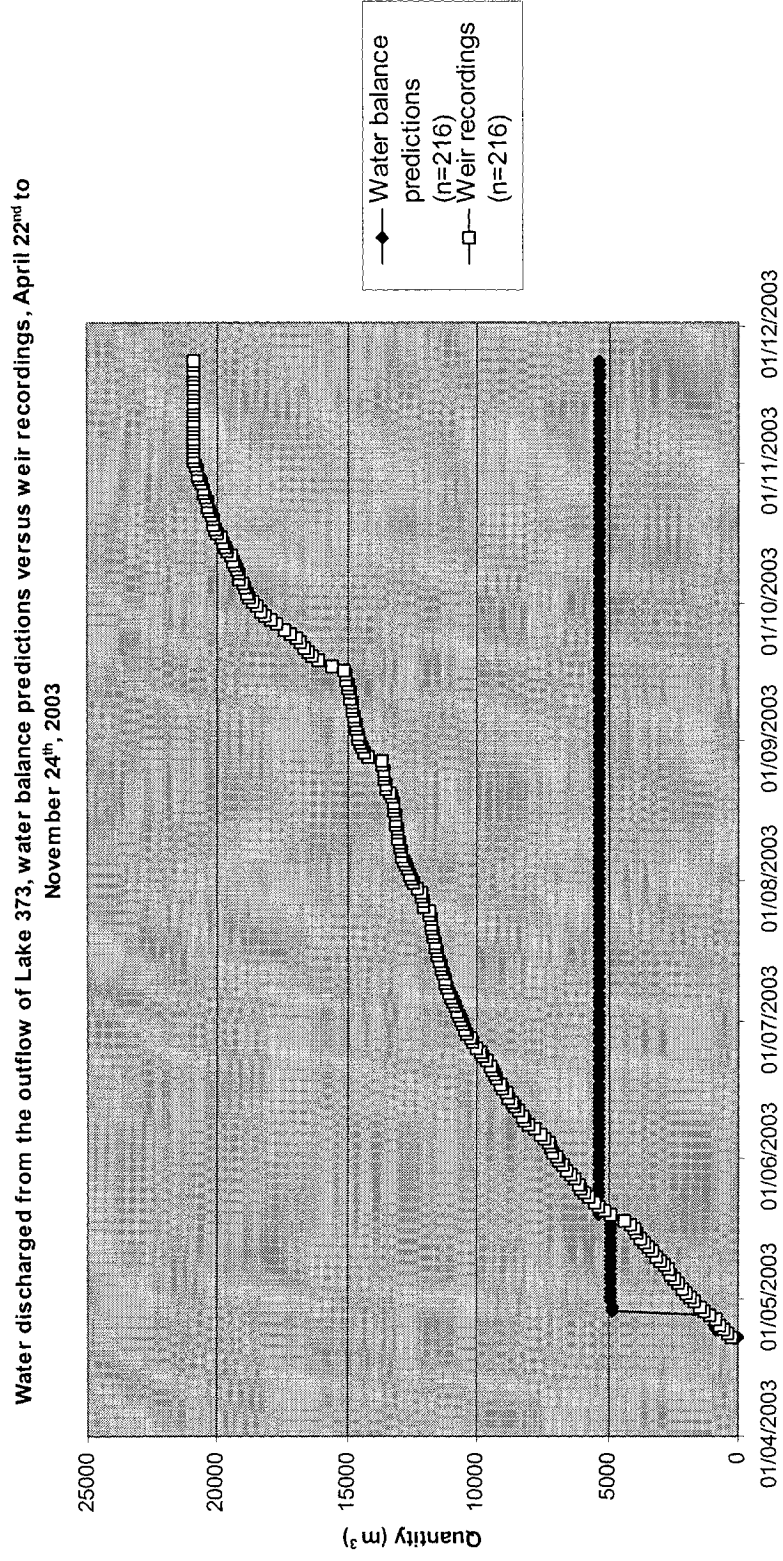


Figure 12. The accuracy of water balance predictions for the cumulative amount of water discharged from Lake 373, 2003.

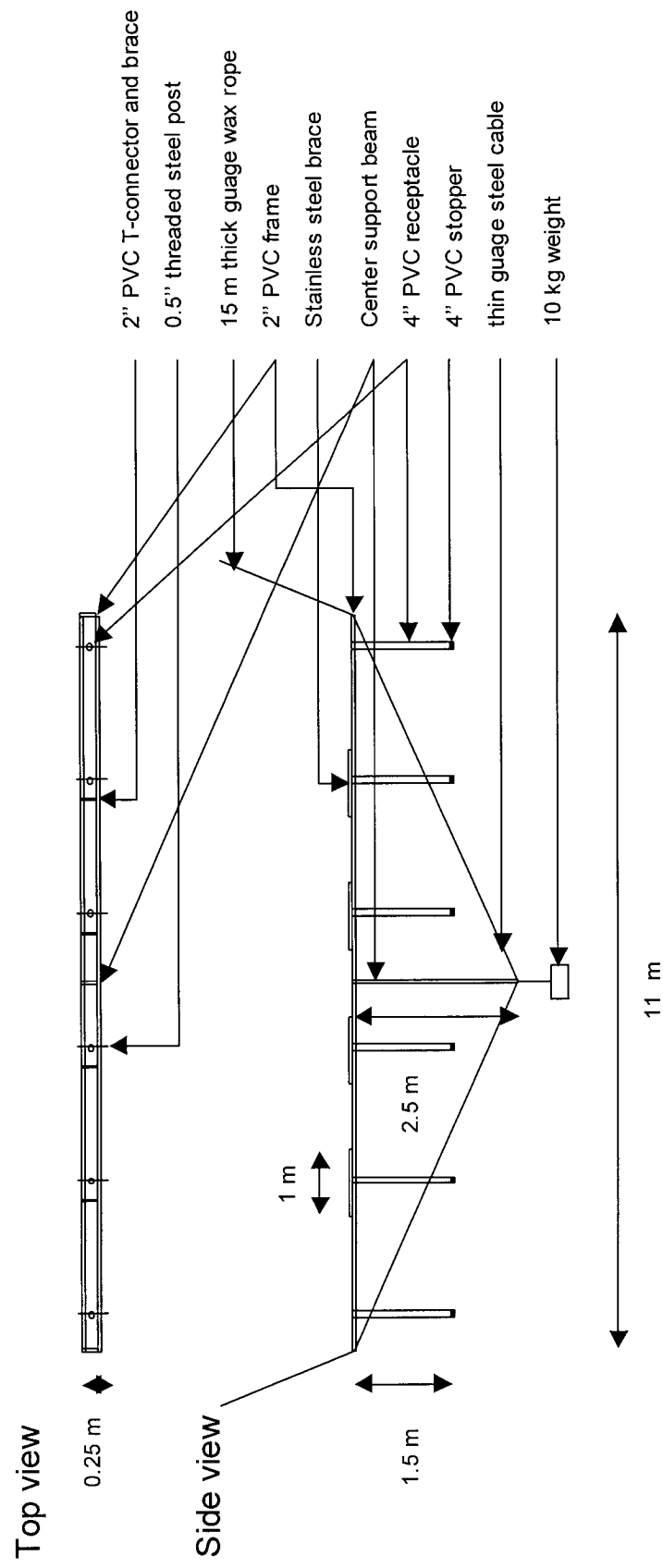


Figure 13. The apparatus used to collect solid chemicals settling below the cage farm.

Carbon retention, by lake and aquaculture installation, 2001-2005

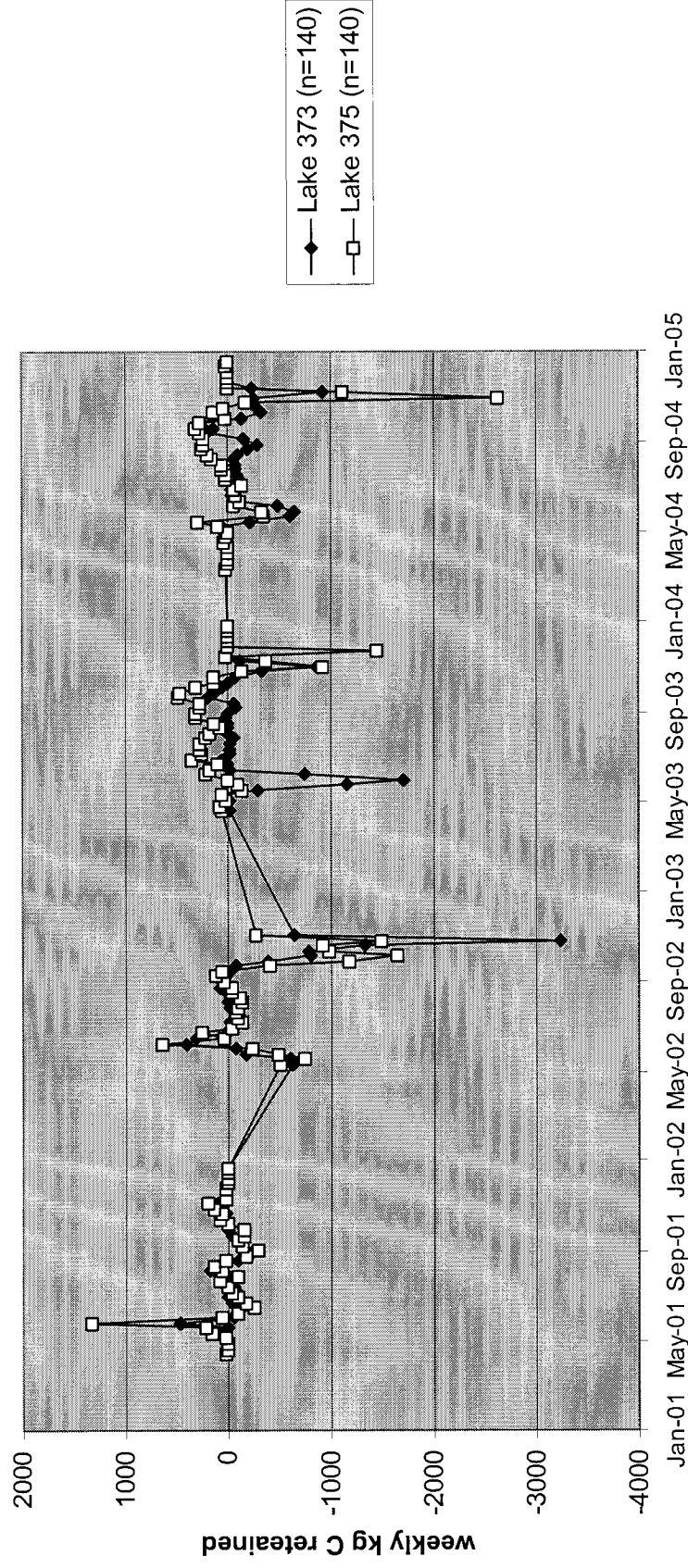


Figure 14. Weekly kilograms of carbon retained in lakes 373 and 375 before and following the installation of a cage aquaculture farm into lake 375 (June 2003).

Nitrogen retention, by lake and aquaculture installation, 2001-2005

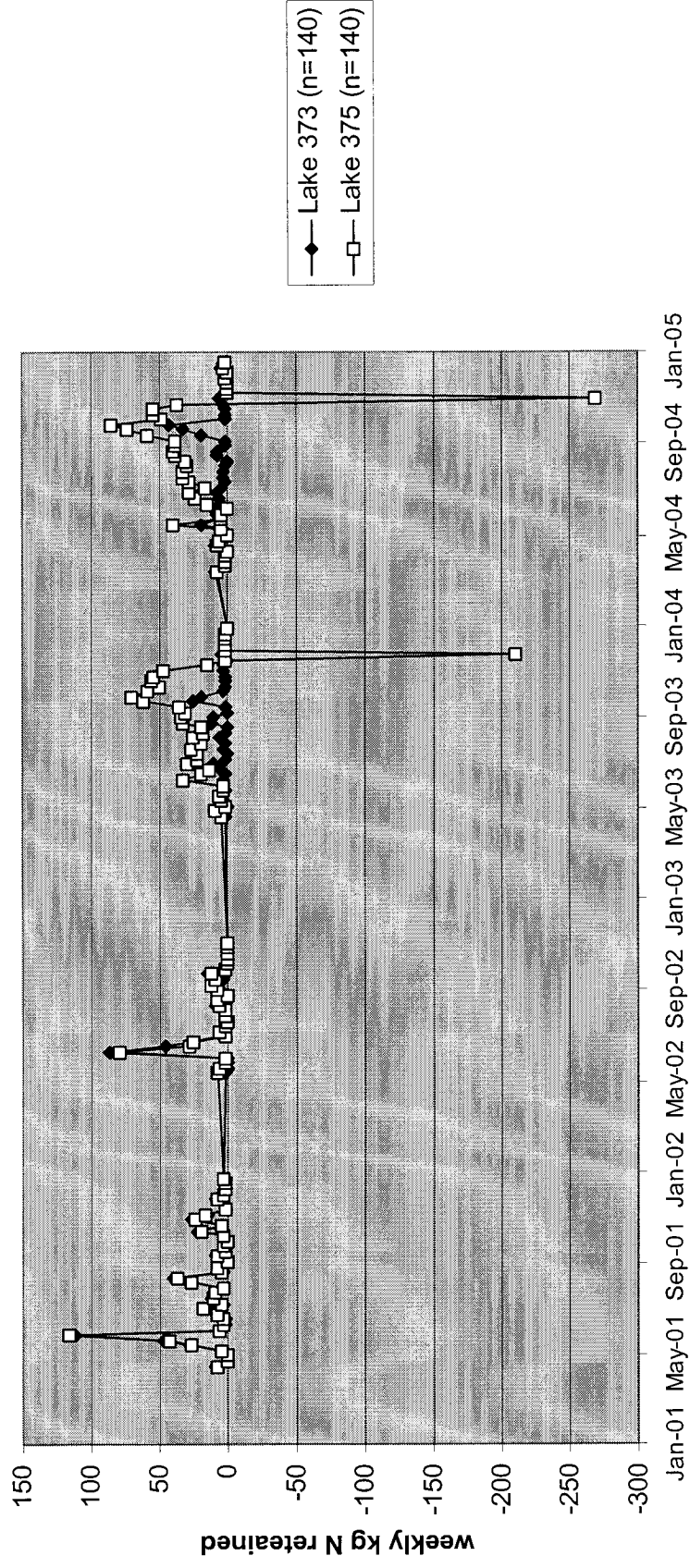


Figure 15. Weekly kilograms of nitrogen retained in lakes 373 and 375 before and following the installation of a cage aquaculture farm into lake 375 (June 2003).

Phosphorus retention, by lake and aquaculture installation, 2001-2005

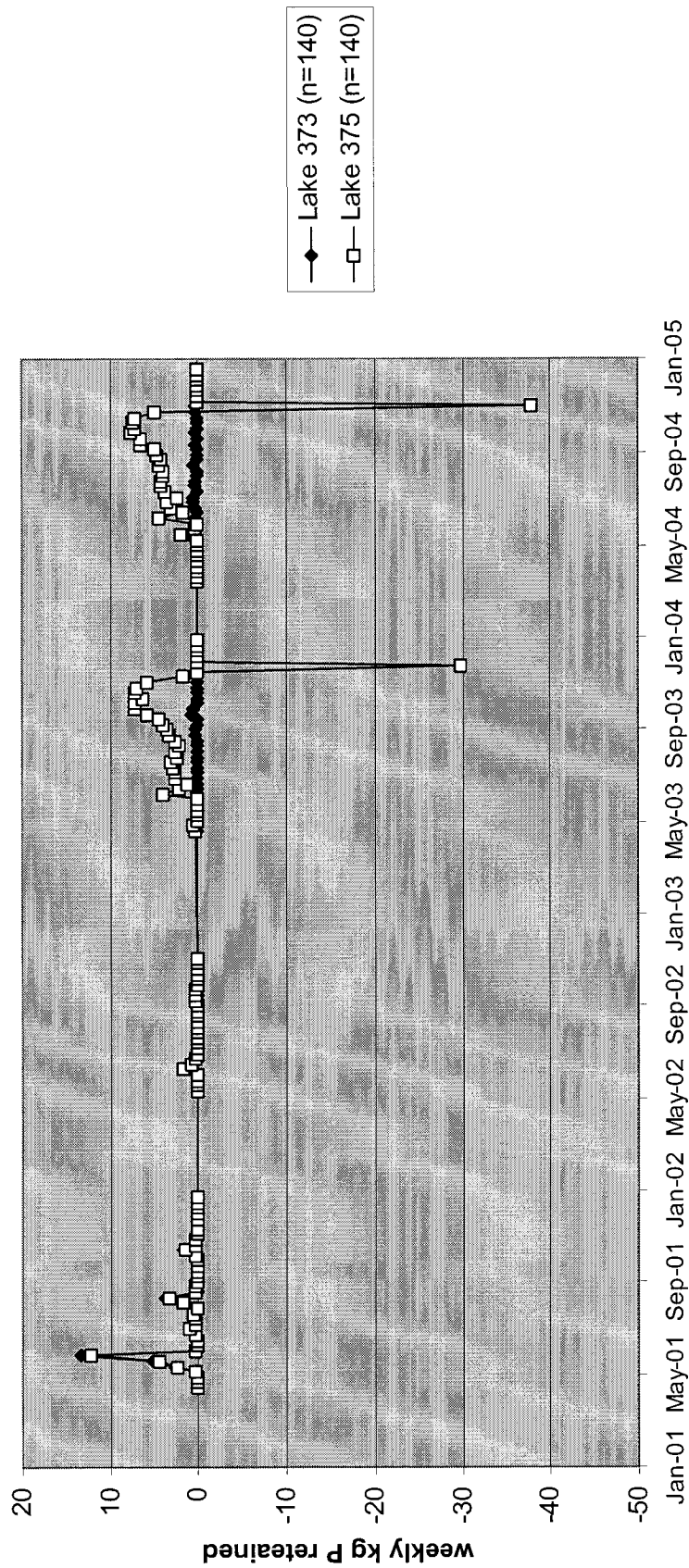


Figure 16. Weekly kilograms of phosphorus retained in lakes 373 and 375 before and following the installation of a cage aquaculture farm into lake 375 (June 2003).

Total carbon, by lake and aquaculture installation, 1983-2005

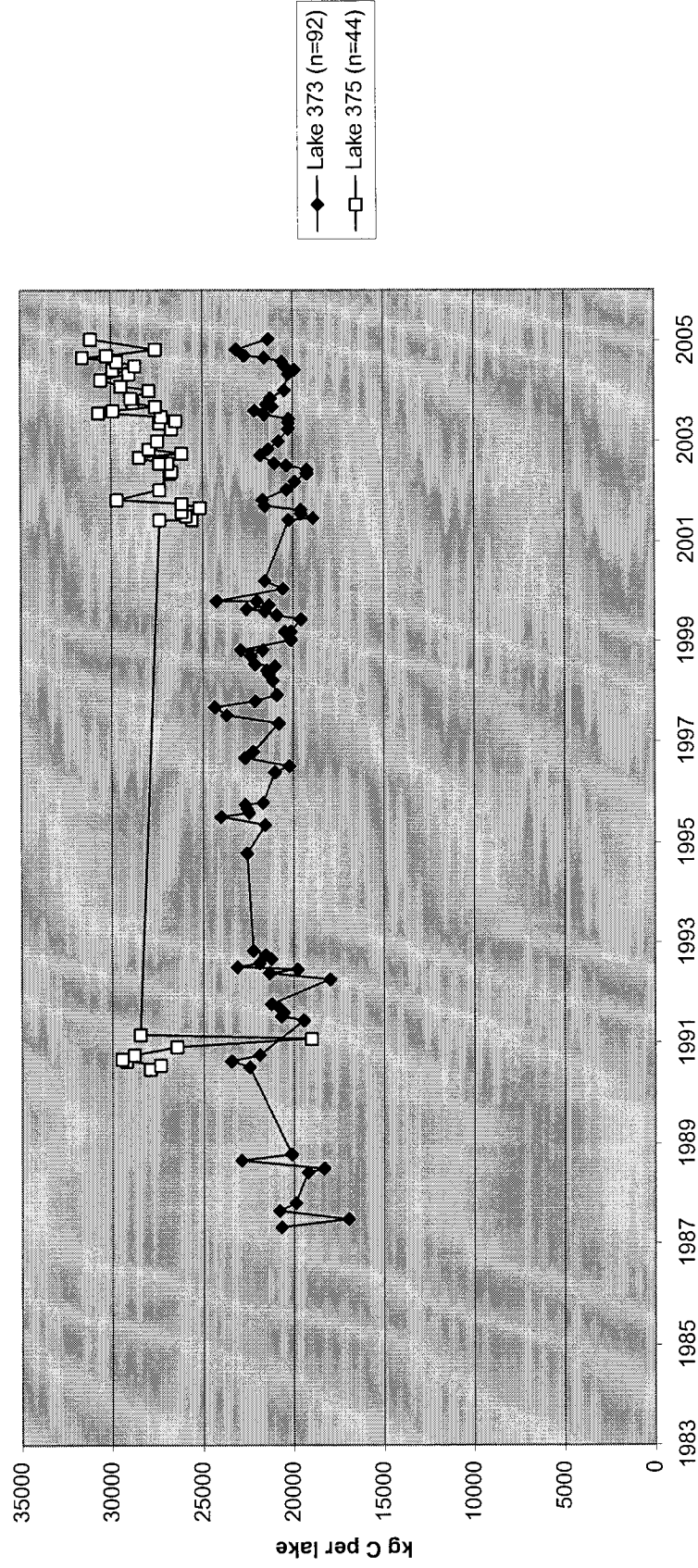


Figure 17. Total stocks of carbon in the water columns of lakes 373 and 375 before and following the installation of a fish farm into Lake 375 (June 2003).

Total nitrogen, by lake and aquaculture installation, 1983-2005

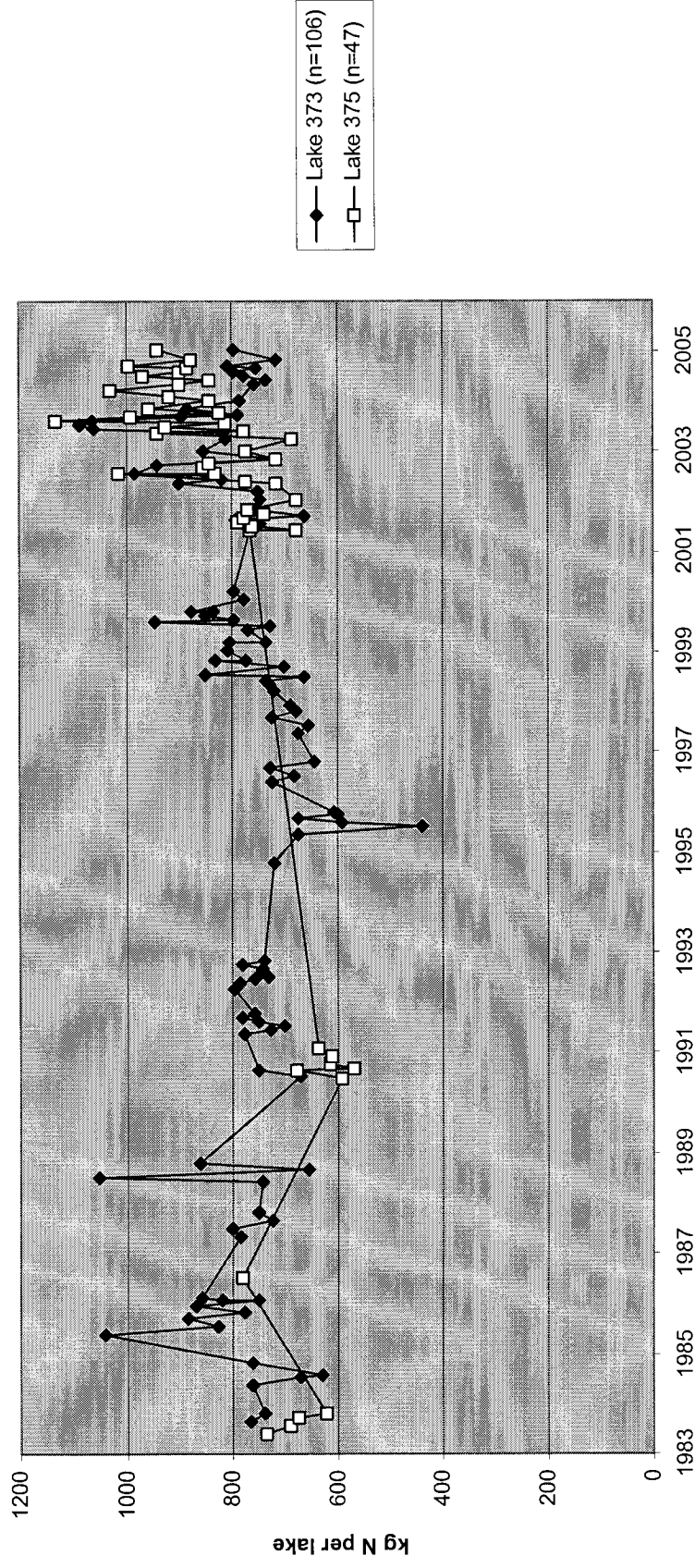


Figure 18. Total stocks of nitrogen in the water columns of lakes 373 and 375 before and following the installation of a fish farm into Lake 375 (June 2003).

Total phosphorus, by lake and aquaculture installation, 1983-2005

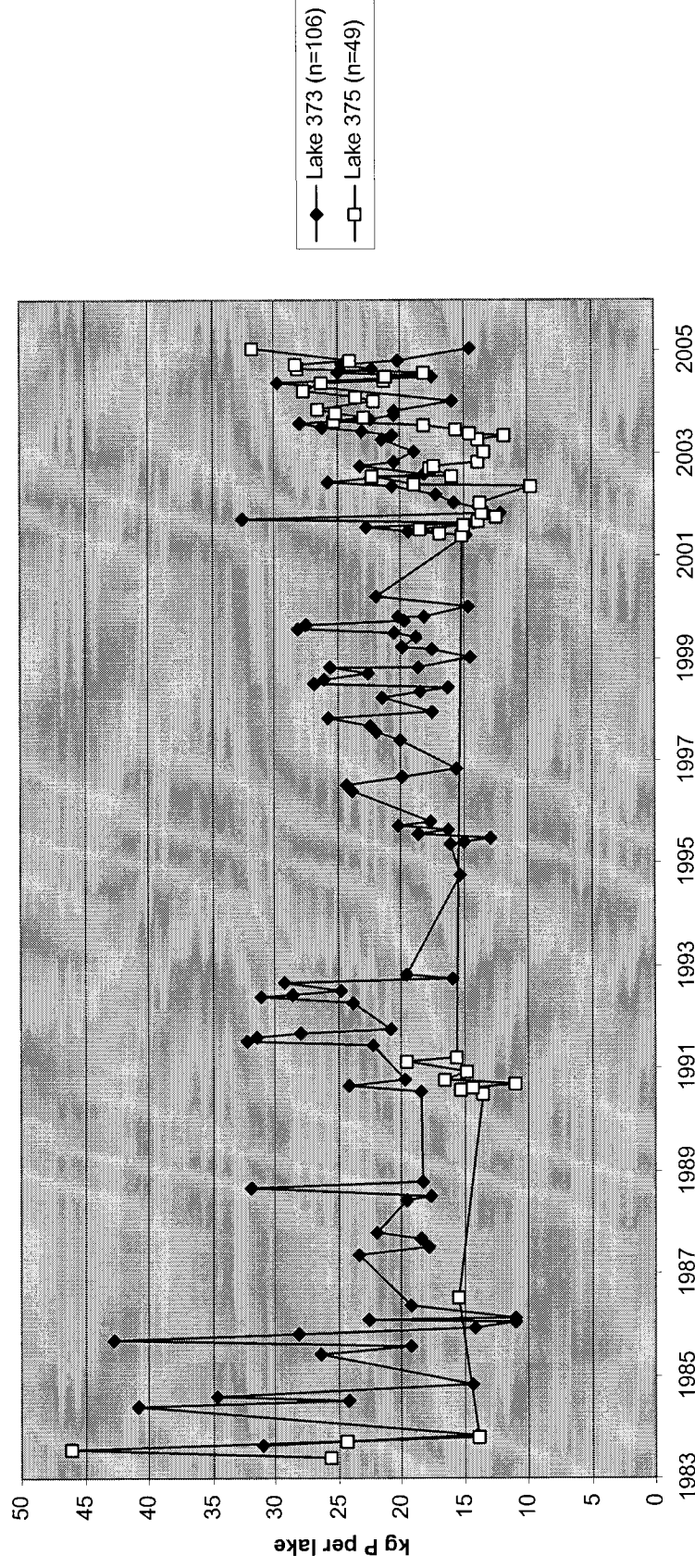


Figure 19. Total stocks of phosphorus in the water columns of lakes 373 and 375 before and following the installation of a fish farm into Lake 375 (June 2003).

Settling carbon particulates, by lake and station and aquaculture installation, 2002-2005

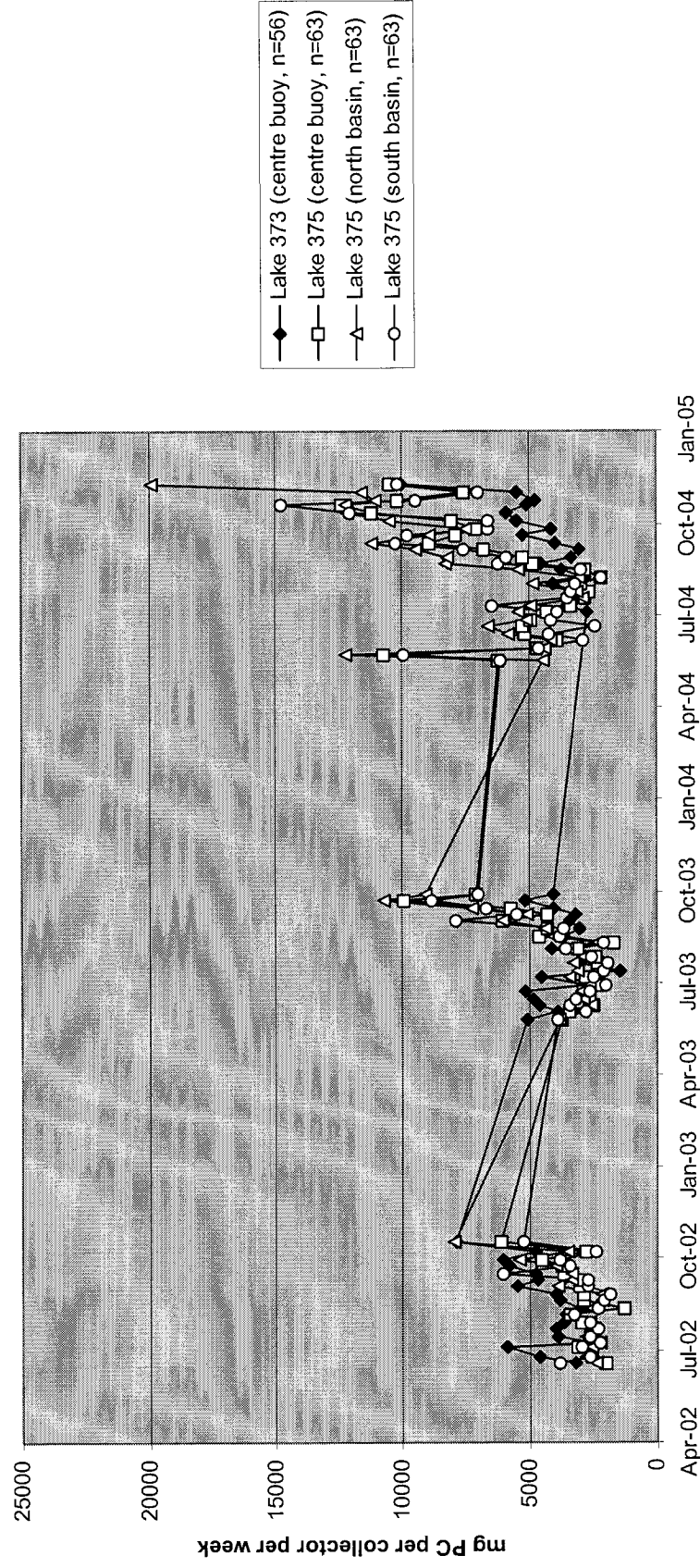


Figure 20. The weekly concentration of carbon particulates collected in sediment traps across lakes 373 and 375 before and following the installation of a fish farm into Lake 375 (June 2003).

Settling nitrogen particulates, by lake and station and aquaculture installation, 2002-2005

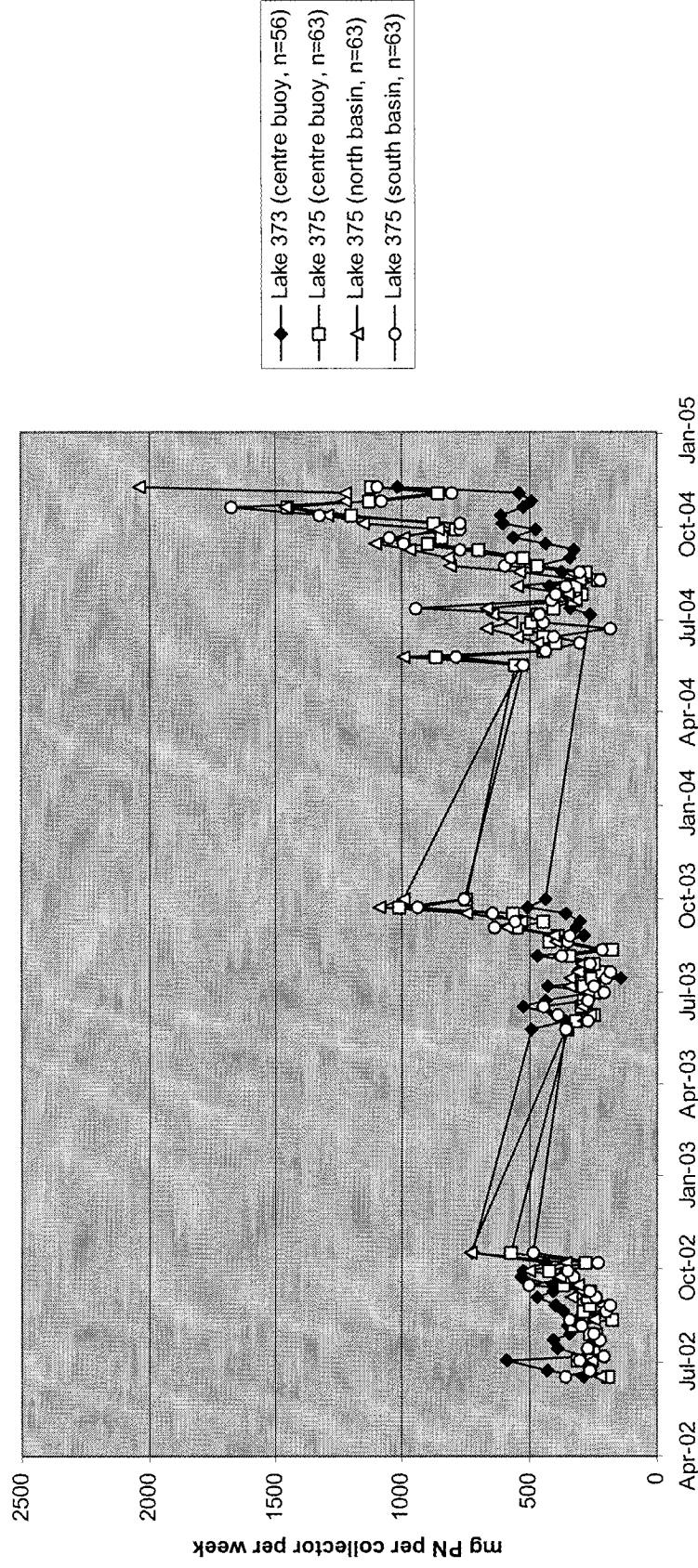


Figure 21. The weekly concentration of nitrogen particulates collected in sediment traps across lakes 373 and 375 before and following the installation of a fish farm into Lake 375 (June 2003).

Settling phosphorus particulates, by lake and station and aquaculture installation, 2002-2005

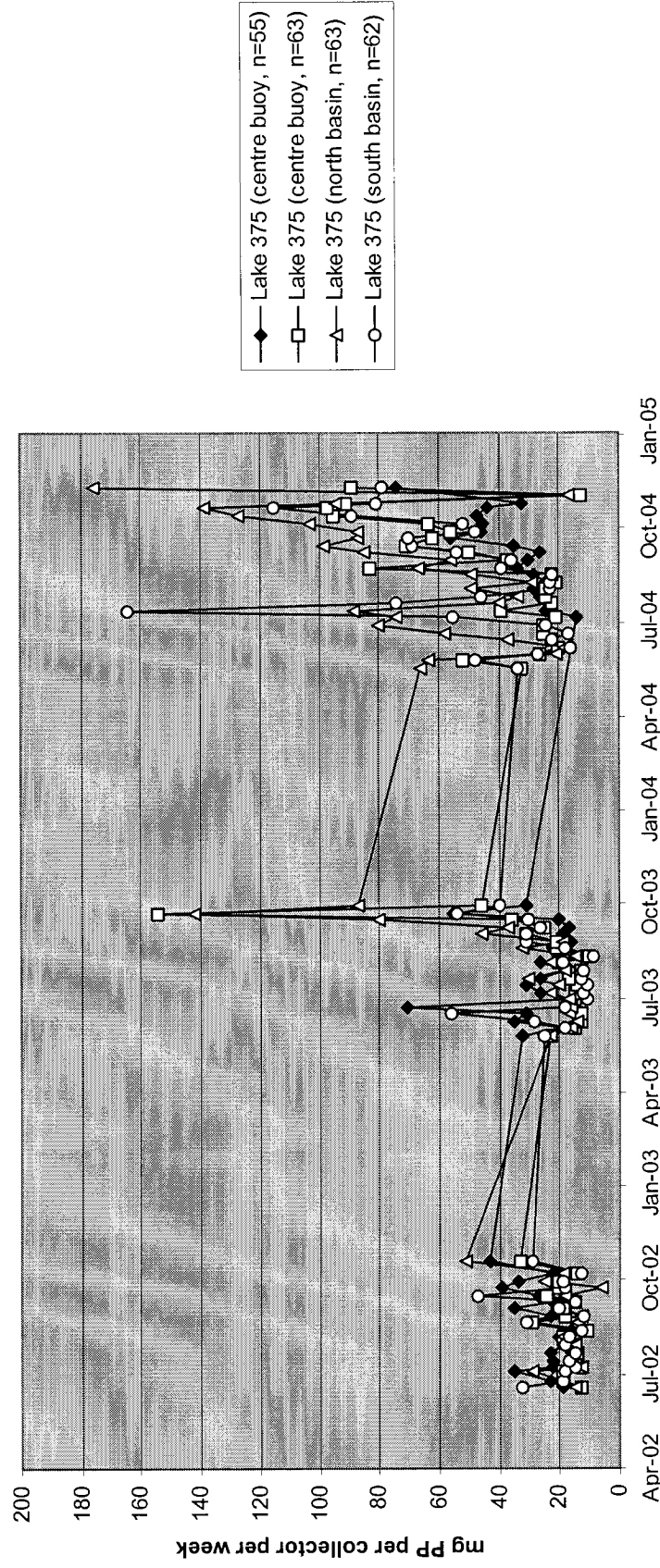


Figure 22. The weekly concentration of phosphorus particulates collected in sediment traps across lakes 373 and 375 before and following the installation of a fish farm into Lake 375 (June 2003).

Flux of carbon settling below aquaculture cage, by distance and direction from the centre of the cage, 2003-2004

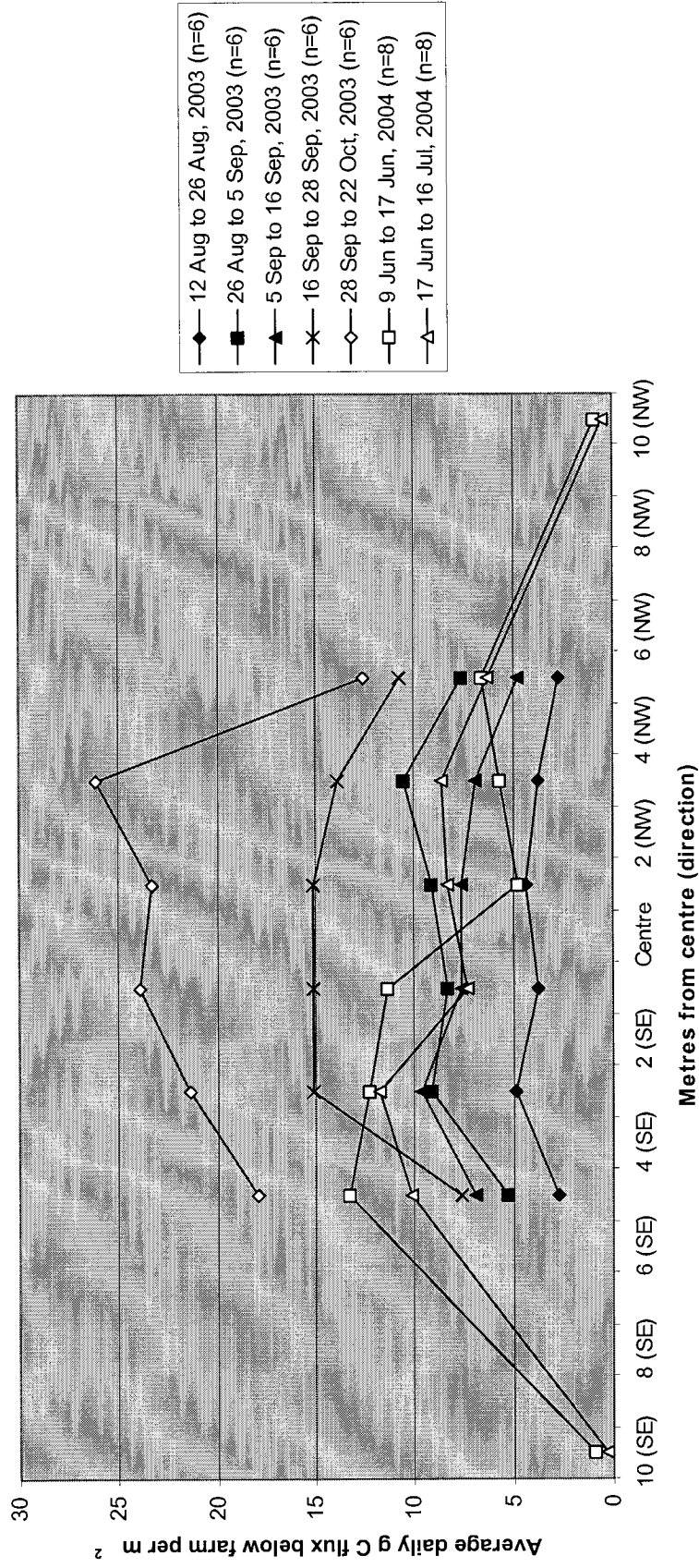


Figure 23. The average daily flux of solid carbon settling below the fish farm on Lake 375 (2003-2004).

Flux of nitrogen settling below aquaculture cage, by distance and direction from the centre of the cage, 2003-2004

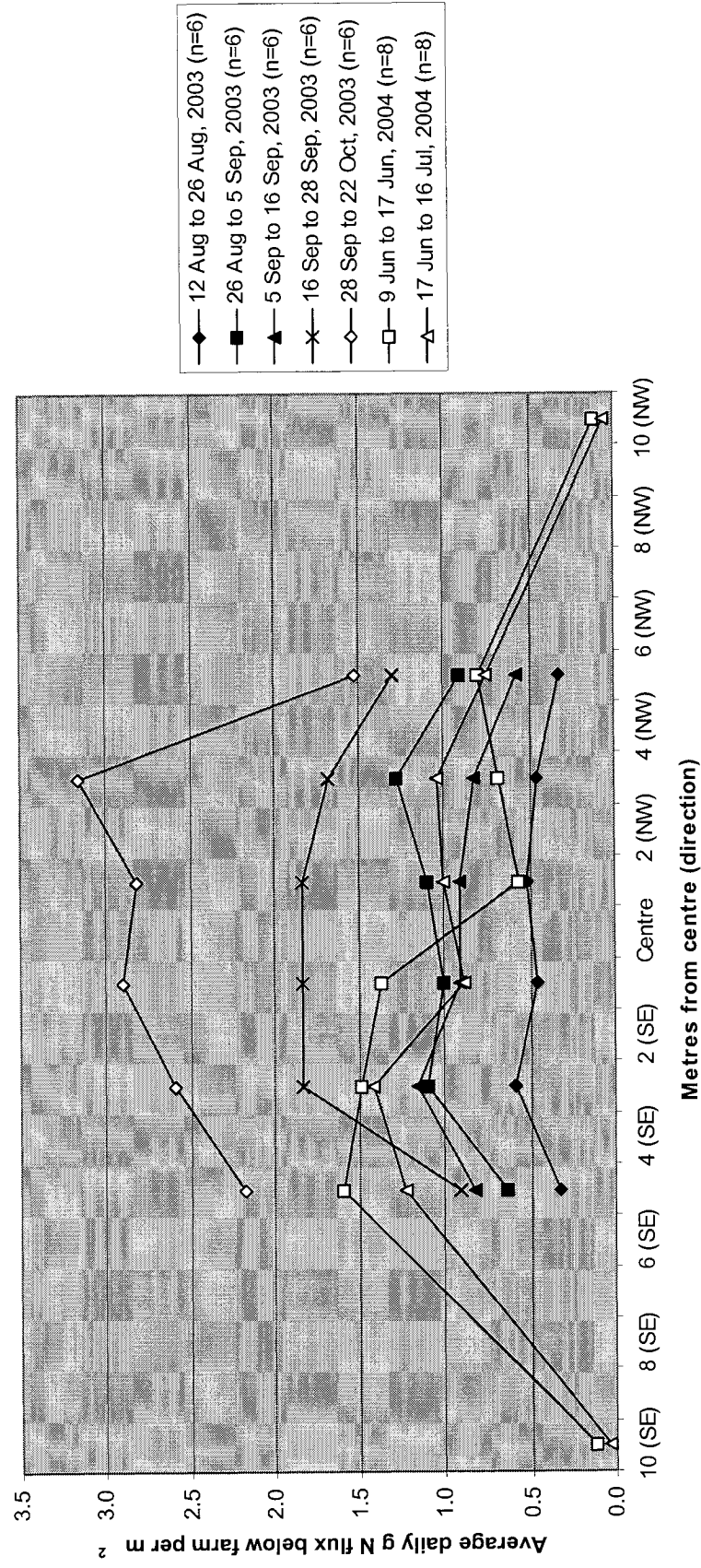


Figure 24. The average daily flux of solid nitrogen settling below the fish farm on Lake 375 (2003-2004).

Flux of carbon settling below aquaculture cage, by distance and direction from the centre of the cage, 2003-2004

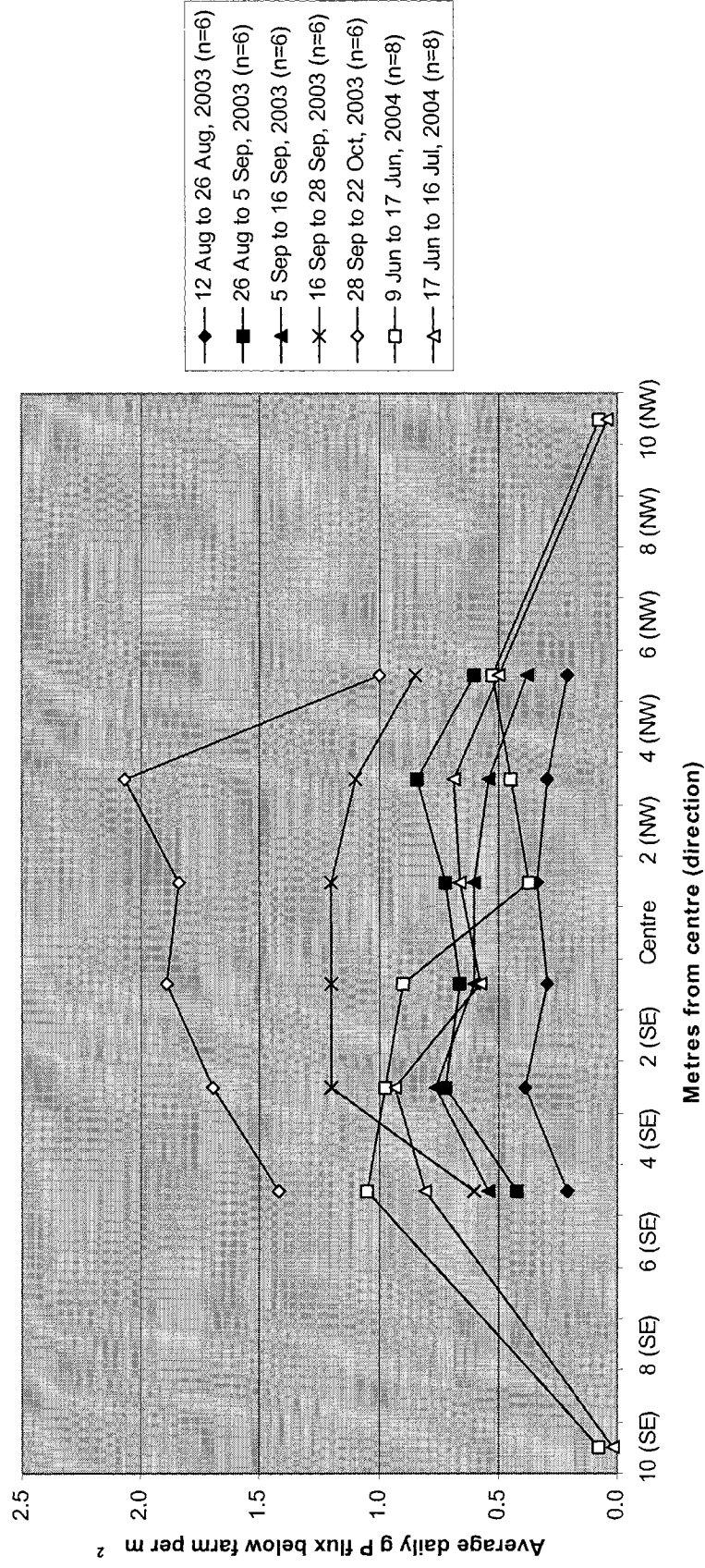


Figure 25. The average daily flux of solid phosphorus settling below the fish farm on Lake 375 (2003-2004).

Total carbon waste discharged from the farm, 2003-2004

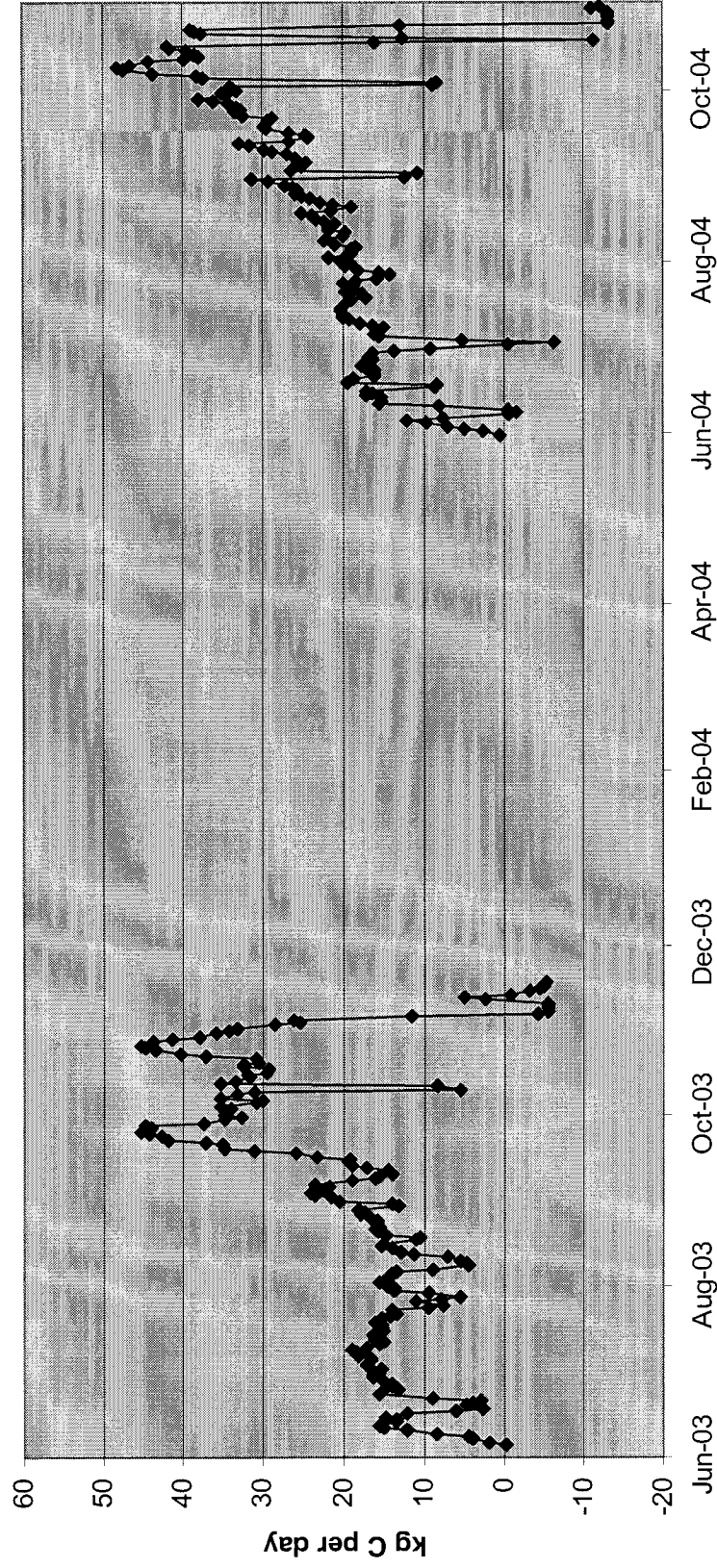


Figure 26. Daily kilograms of carbon waste discharged from the fish farm on Lake 375 during the two production cycles of 2003 and 2004.

Total nitrogen waste discharged from the farm, 2003-2004

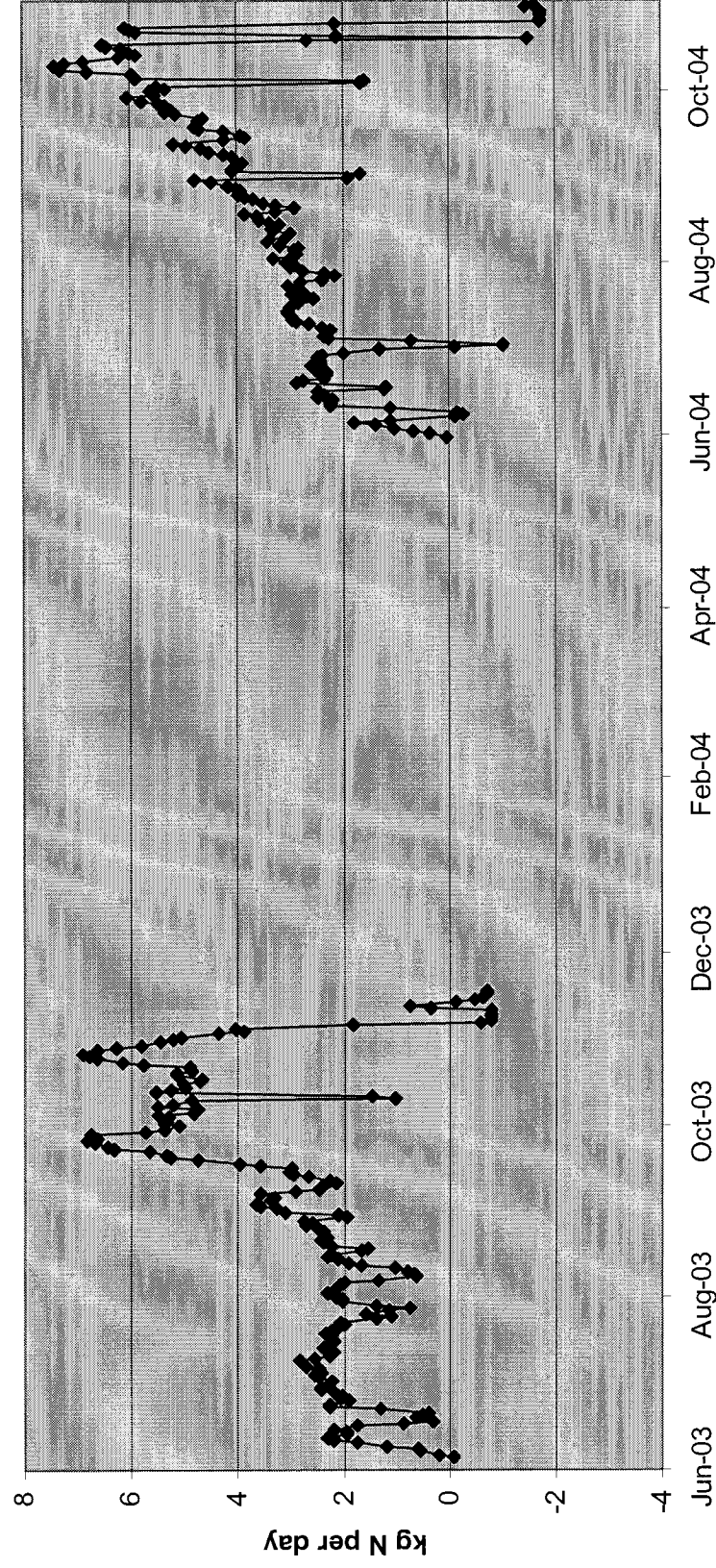


Figure 27. Daily kilograms of nitrogen waste discharged from the fish farm on Lake 375 during the two production cycles of 2003 and 2004.

Total phosphorus waste discharged from the farm, 2003-2004

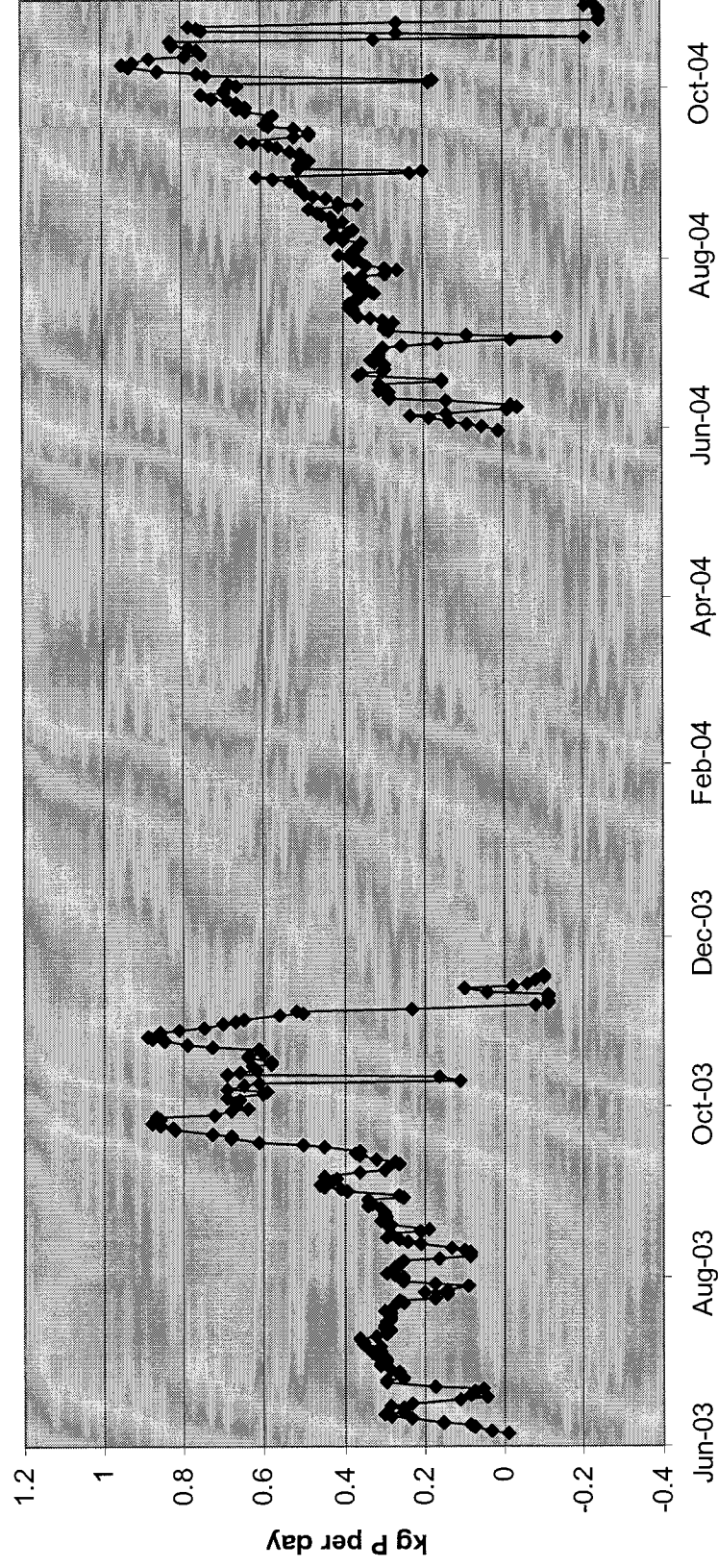


Figure 28. Daily kilograms of phosphorus waste discharged from the fish farm on Lake 375 during the two production cycles of 2003 and 2004.

Particulate carbon, by lake and basin and aquaculture installation, 1983-2005

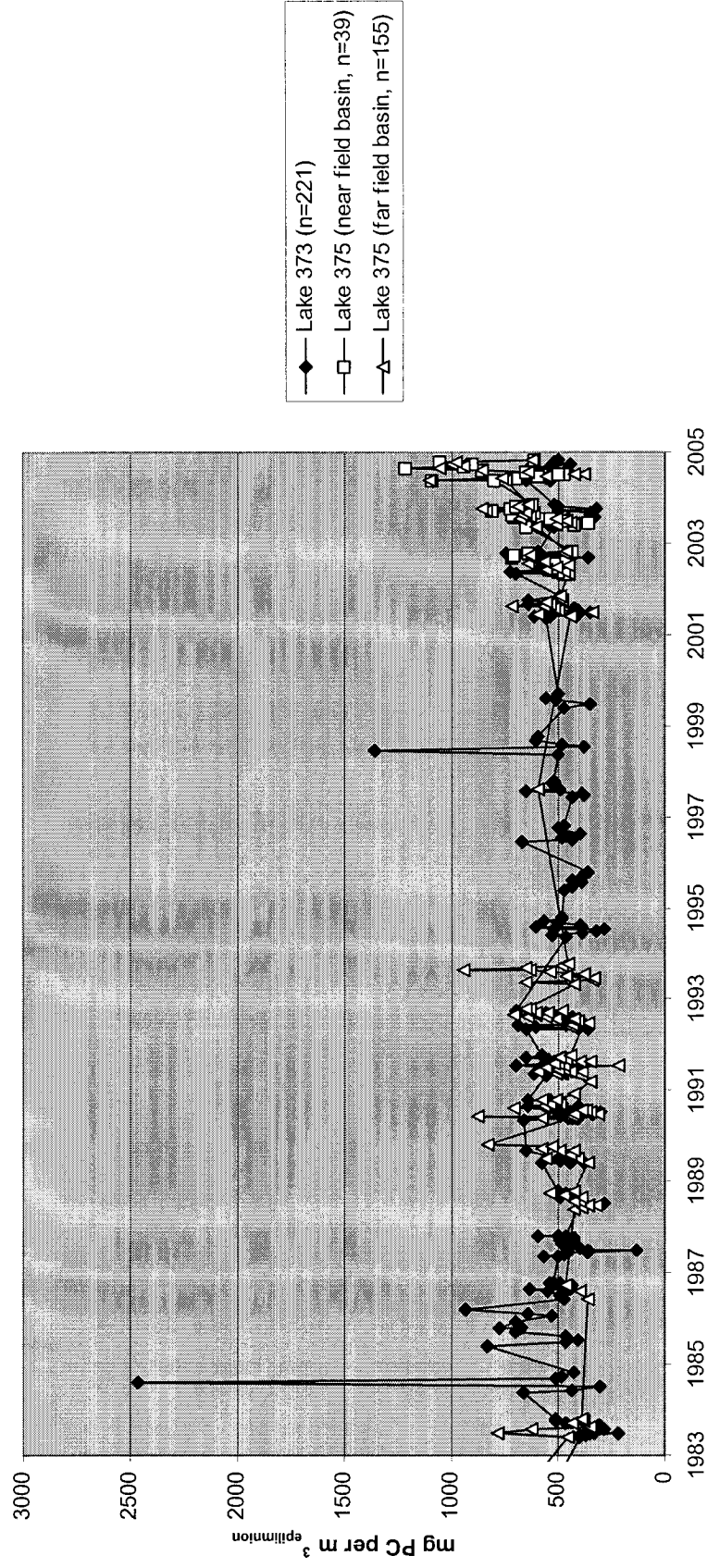


Figure 29. Historical trend in epilimnetic suspended carbon particulates in the two basins of Lake 375 and in Lake 373 before and after the installation of the fish farm into Lake 375 (June 2003).

Particulate nitrogen, by lake and basin and aquaculture installation, 1983-2005

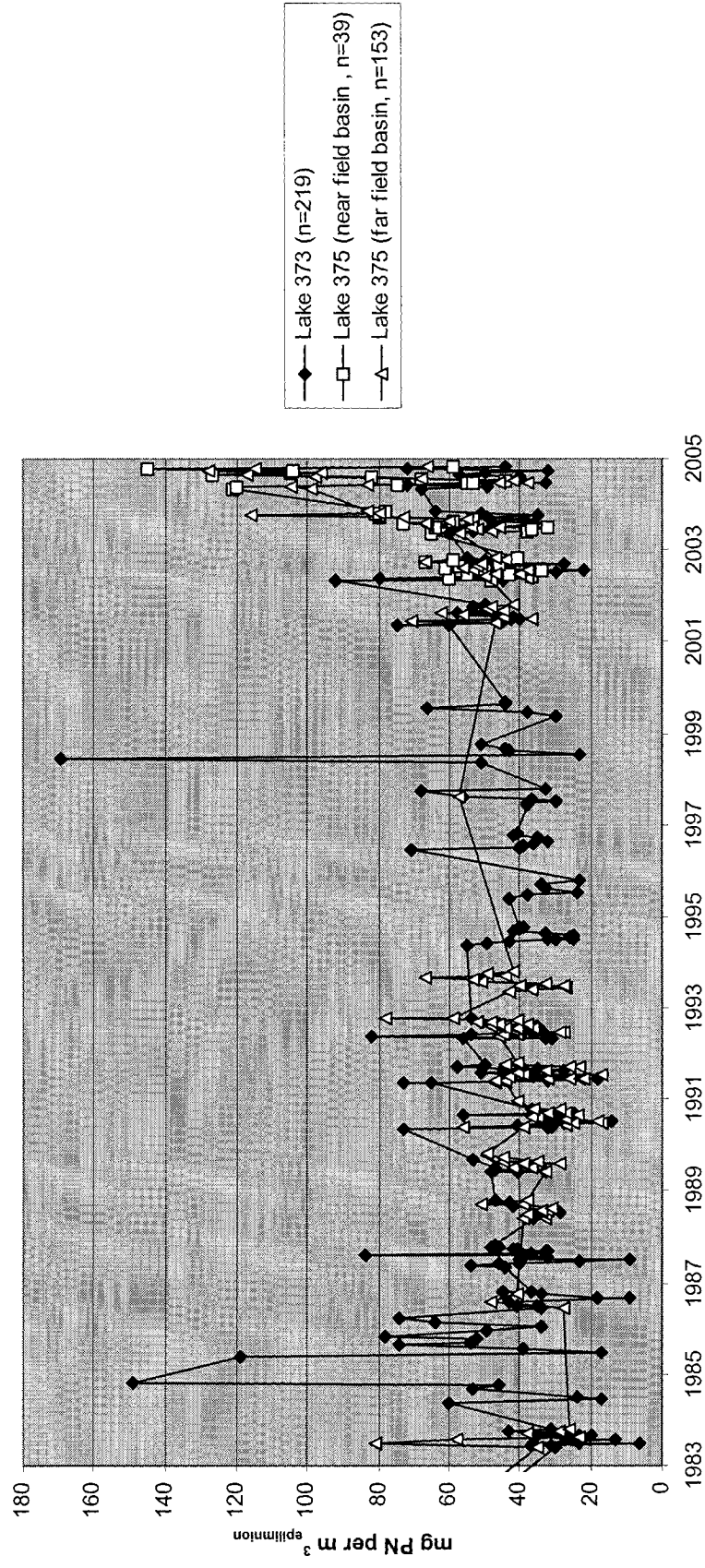


Figure 30. Historical trend in epilimnetic suspended nitrogen particulates in the two basins of Lake 375 and in Lake 373 before and after the installation of the fish farm into Lake 375 (June 2003).

Deep water total dissolved nitrogen, by lake and aquaculture installation, 1982-2005

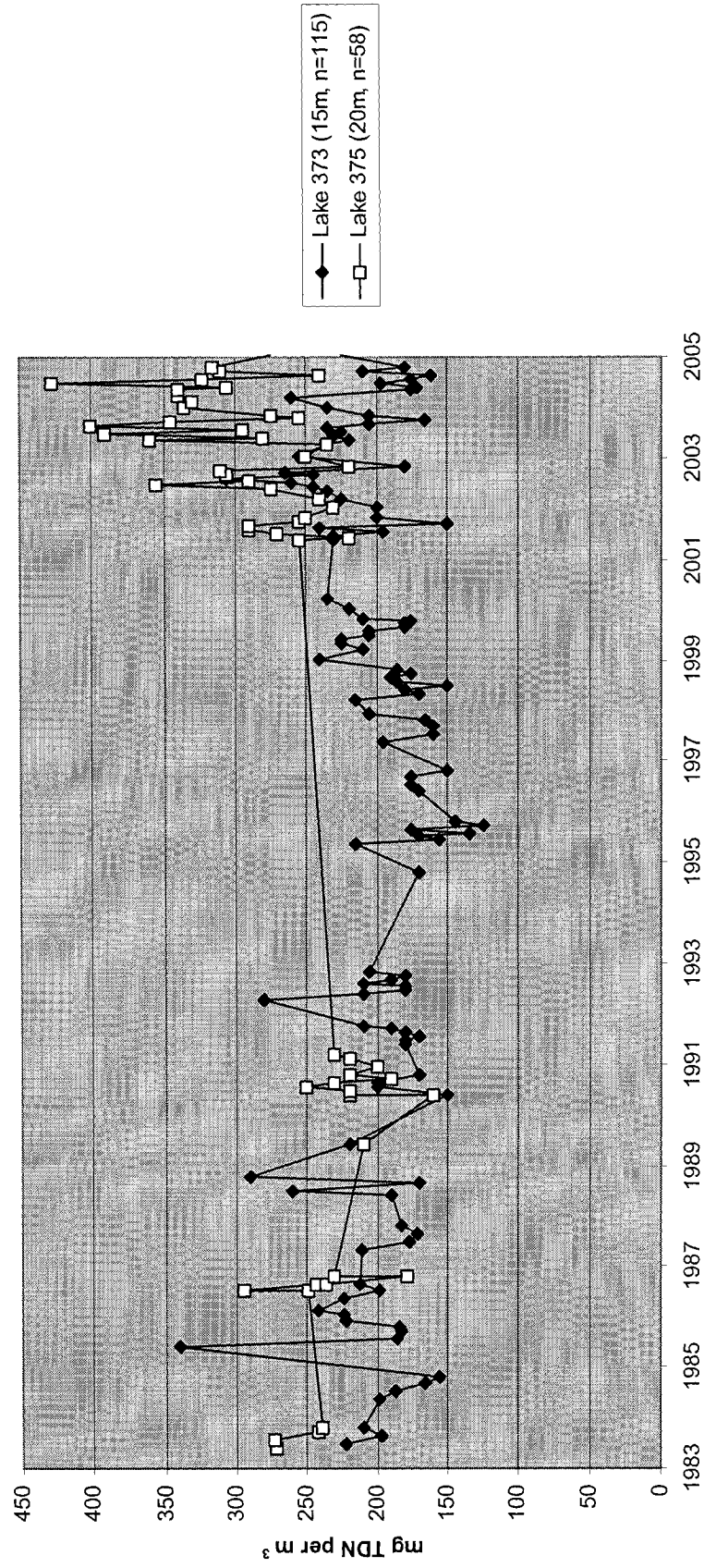


Figure 31. Historical trend in deep water dissolved nitrogen in lakes 375 and 373 before and after the installation of the fish farm into Lake 375 (June 2003).

Table 2. General basin characteristics for lakes 373 and 375.

Lake	Order	Watershed area ha	¹ Drainage area ha	Surface Area ha	Volume m ³	Mean depth m	Maximum Depth m
373	1	80.6	80.6	27.3	3012513	11.0	20.8
375	2	231.0	150.4	23.2	2695982	11.6	26.5

¹Herein sometimes referred to as catchment area.

Table 3. Farm characteristics including dates of operation, temperature conditions, size of farm and farm production.

Year	Start	Harvest	Temperature °C	g				kg
				Number of Fish _{Start}	Number of Fish _{Harvest}	Average		Estimated Biomass Gain ^a
						Individual Wet Mass _{Start}	Individual Wet Mass _{Harvest}	
2003	June 5 th	November 18 th	2-25	10640	10014	100	860	7611
2004	May 31 st	October 24 th	6-23	10227	9830	90	1090	9830

^aPopulation size at harvest multiplied by the difference in the average individual mass at the start and at harvest

^bTotal mass of feed applied to the farm divided by the estimated wet biomass gain by the fish population

Table 4. Results of the annual water budget for the ice off period including discharges at outflow estimated by mass balance, for lakes 373 and 375, 2003 and 2004.

Lake	Year	^a Ice off period	m ³	Precipitation	m ³	Runoff	m ³	^b Tributary inflow	m ³	Evaporation	m ³	Storage	m ³	^c Outflow	m ³	Start volume	m ³	End volume	m ³	year	^d RT
373	2001	Apr 28 to Dec 1	184002	184002	100002	0	167649	^e na	116432	3012513	3012437	25.9									
	2002	May 10 to Nov 16	133661	74102	0	155960	^e na	87900	3012513	2976416	33.9										
	2003	Apr 22 to Nov 24	130057	21951	0	186941	^e na	5377	3012513	2972202	552.7										
	2004	Apr 30 to Nov 25	188015	123882	0	140877	-11632	187350	3012513	3007816	16.1										
375	2001	Apr 28 to Dec 1	156368	238654	119163	143558	^e na	369177	2695982	2697434	7.3										
	2002	May 10 to Nov 16	113587	176844	91863	152900	^e na	273707	2695982	2651670	9.7										
	2003	Apr 22 to Nov 24	122821	64718	14664	166148	^e na	63677	2695982	2668360	41.9										
	2004	Apr 30 to Nov 25	159778	295644	187400	128329	-11628	530355	2695982	2691748	5.1										

^aThis roughly represents the ice-off period, for which the estimates are based on. This is the ice off period observed for nearby Lake 239.

^bTributary inflow to Lake 375 was assumed equal to outflow from Lake 373

^cOutflow = Volume + Precipitation + Runoff + Tributary inflow - Evaporation - Storage - Volume_{capacity}

^dRT is the average theoretical water renewal time in years, calculated by dividing lake volume by outflow

^ewater level data are not available for these years

Table 5. The average chemical composition of the livestock feed in mg chemical per gram of dry feed (+/- 1 standard deviation) based on three samples.

Carbon	Nitrogen	Phosphorus
528.7 ± 5.5	79.3 ± 0.9	10.35 ± 0.74

Table 6. A carbon budget for lakes 373 and 375 before and after the installation of a fish farm into Lake 375. Presented are annual estimates (kg) of sources, sinks and exchanges of carbon in lakes 373 and 375. The annual amount of carbon retained in the lake was calculated by subtracting sinks of carbon and gas evasion from sources of carbon. The average annual stock of carbon in the lake water column is also presented.

Process	Lake 373					Lake 375			
	2001	2002	2003	2004	2001	2002	2003	2004	
Sources									
Atmospheric deposition	1041	786	752	1018	884	665	639	865	
Erosion	1849	1453	404	1797	4413	3468	971	4290	
Tributary inflow	0	0	0	0	311	488	91	1254	
Livestock	0	0	0	0	0	0	161	138	
Feed	0	0	0	0	0	0	4377	4851	
Total sources	2890	2239	1156	2815	5608	4622	6239	11398	
Sinks									
Lake discharge	311	488	91	1254	1374	2615	119	5235	
Harvest	0	0	0	0	0	0	1453	1884	
Total sinks	311	488	91	1254	1374	2615	1572	7119	
Exchanges									
Gas evasion	2579	9852	6100	7560	3391	10450	2580	6468	
Retention	1	-8101	-5034	-5998	843	-8443	2087	-2190	
Stocks	20237	20406	20995	21101	26555	27183	28103	29456	

Table 7. A nitrogen budget for lakes 373 and 375 before and after the installation of a fish into Lake 375. Presented are annual estimates (kg) of sources, sinks of nitrogen in lakes 373 and 375. The annual amount of nitrogen retained in the lake was calculated by subtracting sinks of nitrogen from sources of nitrogen. The annual average stock of nitrogen in the lake water column is also presented.

Process	kg							
	Lake 373				Lake 375			
	2001	2002	2003	2004	2001	2002	2003	2004
Sources								
Atmospheric deposition	406	207	139	216	345	176	118	184
Erosion	54	44	11	69	128	105	27	107
Tributary inflow	0	0	0	0	12	21	3	46
Fish stocking	0	0	0	0	0	0	27	23
Feed	0	0	0	0	0	0	657	728
Total sources	459	251	150	286	484	302	832	1088
Sinks								
Lake discharge	12	21	3	46	39	84	4	161
Harvest	0	0	0	0	0	0	214	271
Total sinks	12	21	3	46	39	84	218	432
Retention	448	231	147	240	445	219	614	656
Stocks	749	838	917	766	754	802	881	914

Table 8. A phosphorus budget for lakes 373 and 375 before and after the installation of a fish into Lake 375. Presented are annual estimates (kg) of sources, sinks of phosphorus in lakes 373 and 375. The annual amount of phosphorus retained in the lake was calculated by subtracting sinks of phosphorus from sources of phosphorus. The annual average stock of phosphorus in the lake water column is also presented.

Process	kg							
	Lake 373				Lake 375			
	2001	2002	2003	2004	2001	2002	2003	2004
Sources								
Atmospheric deposition	32.4	3.9	3.7	6.5	27.6	3.4	3.2	5.5
Erosion	1.7	1.1	0.2	1.5	4.1	2.6	0.6	3.5
Tributary inflow	0.0	0.0	0.0	0.0	0.2	0.4	0.1	1.5
Livestock	0.0	0.0	0.0	0.0	0.0	0.0	3.7	3.1
Feed	0.0	0.0	0.0	0.0	0.0	0.0	85.7	95.0
Total sources	34.2	5.0	3.9	7.9	31.8	6.4	93.2	108.6
Sinks								
Lake discharge	0.2	0.4	0.1	1.5	0.7	1.5	<0.1	4.2
Harvest	0.0	0.0	0.0	0.0	0.0	0.0	30.0	38.1
Total sinks	0.2	0.4	0.1	1.5	0.7	1.5	30.0	42.3
Retention	34.0	4.6	3.9	6.4	31.2	4.9	63.2	66.3
Stocks	19.3	20.4	22.4	22.1	15.0	16.1	18.7	24.0

Table 9. The effect of method used to estimate outflow on annual discharges (2003 and 2004) of chemicals exiting Lake 375.

Estimate method	kg					
	2003			2004		
	C	N	P	C	N	P
Weir based	154	6.3	0.11	1088	39.8	1.35
Water budget based	91	3.4	0.09	1254	46.2	1.51

Table 10. The average chemical composition of material settling below the cage in mg chemical per gram of sample (+/- 1 standard deviation) based on six samples.

Carbon	Nitrogen	Phosphorus
430 ± 22	52.0 ± 3.9	33.65 ± 2.61

Table 11. Annual retention and within lake flows of carbon, nitrogen and phosphorus (kg) in Lake 375 during the two fish farming production cycles of 2003 and 2004.

	kg					
	2003			2004		
	C	N	P	C	N	P
Retention	2087	614.0	63.20	-2190	656.0	66.30
Within lake flows						
Total farm waste	3084	469.1	59.36	3105	479.4	60.03
Solids settling below the farm	185	22.7	15.51	-	-	-
Total amount of particulates sedimenting to the lake bottom	2262	225.9	16.06	5303	560.4	44.90

Table 12. The results of a 2-way repeated measures ANOVA testing the effect of the farm (LAKE\$*PERIOD\$) on the retention of weekly chemicals.

Retention	Source	SS	df	MS	F	P
Carbon	LAKE\$	1.78E+05	1	1.78E+05	2.90E-01	0.619
	PERIOD\$	1.40E+06	1	1.40E+06	2.30E+00	0.204
	PERIOD\$*LAKE\$	2.49E+05	1	2.49E+05	4.08E-01	0.558
	Error	2.44E+06	4	6.11E+05		
Nitrogen	LAKE\$	5.88E+03	1	5.88E+03	1.70E+01	0.015
	PERIOD\$	4.42E+03	1	4.42E+03	1.28E+01	0.023
	PERIOD\$*LAKE\$	6.31E+03	1	6.31E+03	1.83E+01	0.013
	Error	1.38E+03	4	3.45E+02		
Phosphorus	LAKE\$	1.12E+02	1	1.12E+02	2.09E+01	0.010
	PERIOD\$	9.00E+01	1	9.00E+01	1.67E+01	0.015
	PERIOD\$*LAKE\$	1.14E+02	1	1.14E+02	2.12E+01	0.010
	Error	2.15E+01	4	5.37E+00		

Table 13. The results of a 2-way repeated measures ANOVA testing the effect of the farm (LAKE\$*PERIOD\$) on stocks of different chemicals in the lake water column.

Lake Stocks	Source	SS	df	MS	F	P
Carbon	LAKE\$	5.02E+08	1	5.02E+08	4.39E+02	<0.001
	PERIOD\$	2.61E+07	1	2.61E+07	2.28E+01	0.009
	PERIOD\$*LAKE\$	3.85E+06	1	3.85E+06	3.37E+00	0.140
	Error	4.57E+06	4	1.14E+06		
Dissolved organic carbon	LAKE\$	4.71E+07	1	4.71E+07	2.49E+01	0.008
	PERIOD\$	1.18E+07	1	1.18E+07	6.24E+00	0.067
	PERIOD\$*LAKE\$	5.70E+05	1	5.70E+05	3.00E-01	0.613
	Error	7.59E+06	4	1.90E+06		
Dissolved inorganic carbon	LAKE\$	2.58E+08	1	2.58E+08	2.92E+02	<0.001
	PERIOD\$	1.15E+06	1	1.15E+06	1.30E+00	0.318
	PERIOD\$*LAKE\$	3.45E+05	1	3.45E+05	3.90E-01	0.566
	Error	3.54E+06	4	8.86E+05		
Particulate carbon	LAKE\$	2.88E+05	1	2.88E+05	1.49E+01	0.018
	PERIOD\$	3.54E+05	1	3.54E+05	1.83E+01	0.013
	PERIOD\$*LAKE\$	3.84E+05	1	3.84E+05	1.98E+01	0.011
	Error	7.73E+04	4	1.93E+04		
Nitrogen	LAKE\$	5.92E+03	1	5.92E+03	1.48E-01	0.720
	PERIOD\$	1.05E+05	1	1.05E+05	2.64E+00	0.180
	PERIOD\$*LAKE\$	9.99E+03	1	9.99E+03	2.50E-01	0.643
	Error	1.60E+05	4	3.99E+04		
Dissolved nitrogen	LAKE\$	2.00E+04	1	2.00E+04	6.07E-01	0.479
	PERIOD\$	4.26E+04	1	4.26E+04	1.29E+00	0.319
	PERIOD\$*LAKE\$	2.90E+03	1	2.90E+03	8.80E-02	0.782
	Error	1.32E+05	4	3.29E+04		
Particulate nitrogen	LAKE\$	4.16E+03	1	4.16E+03	4.60E+00	0.099
	PERIOD\$	1.40E+04	1	1.40E+04	1.55E+01	0.017
	PERIOD\$*LAKE\$	2.13E+03	1	2.13E+03	2.36E+00	0.199
	Error	3.61E+03	4	9.03E+02		
Phosphorus	LAKE\$	5.78E+01	1	5.78E+01	4.84E+00	0.093
	PERIOD\$	1.56E+02	1	1.56E+02	1.31E+01	0.022
	PERIOD\$*LAKE\$	4.38E+01	1	4.38E+01	3.67E+00	0.128
	Error	4.77E+01	4	1.19E+01		
Dissolved phosphorus	LAKE\$	1.09E+01	1	1.09E+01	2.50E+00	0.189
	PERIOD\$	1.44E+00	1	1.44E+00	3.29E-01	0.597
	PERIOD\$*LAKE\$	3.30E+00	1	3.30E+00	7.55E-01	0.434
	Error	1.75E+01	4	4.36E+00		
Particulate phosphorus	LAKE\$	1.85E+01	1	1.85E+01	1.34E+00	0.311
	PERIOD\$	1.88E+02	1	1.88E+02	1.37E+01	0.021
	PERIOD\$*LAKE\$	2.31E+01	1	2.31E+01	1.68E+00	0.265
	Error	5.50E+01	4	1.38E+01		

Table 14. The results of a 2-way repeated measures ANOVA testing the effect of the farm (LAKE\$*PERIOD\$) on the weekly concentration of sedimenting chemicals.

Sedimenting chemical particulate	Source	SS	df	MS	F	P
Carbon	LAKE\$	1.07E+06	1	1.07E+06	8.59E-01	0.452
	PERIOD\$	2.46E+06	1	2.46E+06	1.97E+00	0.296
	PERIOD\$*LAKE\$	2.11E+07	1	2.11E+07	1.69E+01	0.055
	Error	2.50E+06	2	1.25E+06		
Nitrogen	LAKE\$	4.17E+03	1	4.17E+03	1.15E-01	0.767
	PERIOD\$	6.25E+04	1	6.25E+04	1.72E+00	0.320
	PERIOD\$*LAKE\$	1.99E+05	1	1.99E+05	5.47E+00	0.144
	Error	7.28E+04	2	3.64E+04		
Phosphorus	LAKE\$	3.36E+00	1	3.36E+00	8.00E-03	0.936
	PERIOD\$	1.48E+03	1	1.48E+03	3.61E+00	0.198
	PERIOD\$*LAKE\$	1.21E+03	1	1.21E+03	2.96E+00	0.228
	Error	8.21E+02	2	4.10E+02		

Table 15. The results of a 2-way repeated measures ANOVA testing the effect of the farm (LAKE\$*PERIOD\$) on the concentration of chemicals in different stratum of the lake.

Lake stratum	Chemical	Source	SS	df	MS	F	P
Epilimnion	Particulate carbon	LAKE\$	2.98E+05	1	2.98E+05	1.14E+01	0.028
		PERIOD\$	5.00E+04	1	5.00E+04	1.92E+00	0.238
		PERIOD\$*LAKE\$	2.27E+05	1	2.27E+05	8.72E+00	0.042
		Error	1.04E+05	4	2.60E+04		
	Particulate nitrogen	LAKE\$	4.73E+03	1	4.73E+03	1.70E+01	0.015
		PERIOD\$	2.87E+03	1	2.87E+03	1.03E+01	0.032
		PERIOD\$*LAKE\$	3.19E+03	1	3.19E+03	1.15E+01	0.028
		Error	1.11E+03	4	2.78E+02		
Deep water	Dissolved nitrogen	LAKE\$	8.45E+04	1	8.45E+04	2.97E+01	0.005
		PERIOD\$	2.18E+03	1	2.18E+03	7.65E-01	0.431
		PERIOD\$*LAKE\$	1.44E+04	1	1.44E+04	5.07E+00	0.088
		Error	1.14E+04	4	2.84E+03		

Table 16. Comparing phosphorus budgets in two lakes exposed to aquaculture, lakes Heney and 375.

Components of budget	Total phosphorus (kg)	
	Lake Heney ² (1995-1996)	Lake 375 ³ (2003-2004)
Tributaries (excluding farm)	312	2
Aquaculture farm ¹	450	119
Atmosphere	186	9
Cottage septic systems	195	0
TOTAL external contributions	1143	130
Loss of P from lake	231	4
Quantity of P retained in lake	912	126

¹Wastewater inputs including metabolic wastes and uneaten food pellets.

²Lake Heney has a maximum depth of 30-33 m and a surface area of 12.4 km².

³Lake 375 has a maximum depth of 24 m and a surface area of 0.232 km².

Table 17. Weekly retention rates for carbon, nitrogen and phosphorus, by un-manipulated, aquaculture-impacted and fertilized boreal shield lakes.

Lake condition	weekly mg per m ²			Source
	Carbon	Nitrogen	Phosphorus	
Unmanipulated	Lake 375 -831 ± 1830	34 ± 39	1.5 ± 2.6	this study
	Lake 373 -468 ± 1541	27 ± 37	1.0 ± 1.8	this study
	Boreal lakes 28-161	11	0.4-1.8	Schindler and Nighswander 1970; Schindler et al. 1976; Campbell et al. 1994; Dillon and Evans 1993; Dillon and Molot 1997
Fish farm	Lake 375 289 ± 2087	131 ± 218	14.9 ± 29.3	this study
Fertilizer addition	Boreal lake -	84-224	21.7	Schindler et al. 1987

Chapter 2: Short-Term Effects of Cage Aquaculture on the Metabolism of a Boreal Shield Lake

Abstract

We conducted an experiment to determine the effect of cage aquaculture on the metabolism of a boreal shield lake. We installed a cage farm into a pristine headwater lake on the boreal shield. We used a before-after control-impact design to evaluate the weight of evidence for causal effects of aquaculture on the metabolism of the lake. We calculated the integral amount of carbon dioxide in the reference and the manipulated lakes and the changes in these amounts during the open water season. We also quantified aqueous carbon dioxide entering and exiting the lake including exchanges at the surface. By mass balance we estimated net primary production and compared these values to ^{14}C incubation based measurements of primary production. We found that both lakes were on average supersaturated with carbon dioxide during the open water season. We also found that during this period lakes were on average heterotrophic because lake stocks of carbon dioxide were relatively inelastic to the large amounts of carbon dioxide evading to the atmosphere. Based on in situ recordings of atmospheric and aqueous carbon dioxide pressure in the surface water of the aquaculture impacted lake, there was compelling evidence that suggested at least during mid summer months, carbon dioxide was drawn down into the lake resulting in periods of net autotrophy (i.e. the lake was producing more organic carbon than it was burning). Primary production increased significantly in the aquaculture-impacted lake and the period of peak productivity also shifted to later in the summer. The results of this study are discussed in the

context of consequences to aquatic life and source water and recommendations for management are provided.

Introduction

The inland cage aquaculture industry is set to expand into the boreal shield ecozone. The deep, cold, well-oxygenated lakes on the shield seem ideally suited for salmonid production. Fish farming could boost northern economies although if not managed effectively, this industry could also present a real threat to aquatic life and source water for drinking (Walker et al., 2003; Yan, 2005). In Canada, there is good evidence that farming has had consequences to lake ecology (Walker et al, 2003). Operations resulting in degraded water and sediment quality are documented (Bird and Mesnage, 1996; Boyd et al., 1998b, Boyd and Thorburn, 2001; Linqvist, 2001).

Cage farming increases the load of organic material and nutrients to an aquatic system (Beveridge 1984; Persson 1991; Axler 1996; Hamblin and Gale 2002) and this pollution has been implicated as a primary cause for elevated levels of phosphorus and primary production in lakes (Stirling and Dey 1990; Beveridge 1996; Boyd et al., 1998a; Lindquist, 2001; Guo and Li 2003)

The extreme result of an increase in primary production is eutrophication, which is a proliferation in the standing crop of algae ("a bloom"). Eutrophication events can have a number of less than desirable outcomes including: increased release of toxins from algae, which have consequences to water taste and smell; increased sedimentation rates, which smother benthic communities and fish eggs; increasing decomposition, which consumes oxygen (Hall et al 1990; Hargave et al 1993; Nickell et al 2003) and reduces the availability of habitat for lake biota (Prairie, 1994). An increase in primary production is one example of

how aquaculture can alter a metabolic component of the lake – photosynthesizing algae transform (fix) carbon dioxide to organic carbon.

Purpose of the study

In this study, we wanted to determine how the metabolic condition of the lake responded to cage aquaculture. To do this, we quantified and compared the relationship between stocks of flows of a common metabolite in the lake before and after the installation of the farm. We also tried to account for chemical transformation of the metabolite within the lake and the exchange of it at the lake surface. The metabolite we chose for this study was carbon dioxide. We selected carbon dioxide because we had a large amount of historical data for both lakes, we had many tools available to measure it and most importantly because of its importance in photosynthesis and respiration and close ties to oxygen, which is an important parameter in aquaculture and aquatic ecology. We also chose carbon dioxide because it is a dynamic substance with potential climate changing properties; it can be dissolved in water (aqueous CO₂) and volatilize to the atmosphere (atmospheric CO₂).

Farming can change the carbon dioxide balance in the lake in a number of ways. Primary production is a sink for carbon dioxide in lakes and farming may stimulate this mechanism indirectly. Algae are grazed, decomposed or mineralized, which are sources of carbon dioxide in lakes (Cornett and Rigler, 1979; Hesslein, 1980; Mattson and Likens, 1993). The difference between these metabolic sinks and sources of carbon dioxide will determine the metabolic balance in the lake, and whether indeed boreal shield lakes are autotrophic or

heterotrophic. These mechanisms are in fact difficult to measure independently but instead can be estimated by mass balance. If the change in stocks of carbon dioxide within the lake water column are known and sources to the lake and from the lake are quantified (allochthonous) then estimates of net primary production (metabolic balance) are possible.

The most accurate method to establish whether cage farming will impact lake metabolism is to conduct an experiment. A Before-After-Control-Impact (BACI) experimental design is a good method to evaluate causation in large natural settings. BACI designs can be applied when you have knowledge of conditions before and after in both the impacted (manipulated) and controlled (reference) systems (lakes). Conditions are endpoints that are relevant to lake metabolism and in this study include net primary production, primary production, the integral amount (stock) of carbon dioxide in the lake, and carbon dioxide pressure at the lake surface.

Methods

Experimental Design

We conducted an ecosystem experiment by manipulating conditions in a boreal shield lake. We installed a commercial sized cage aquaculture operation in Lake 375, which is a federally designated research lake on the property of the Experimental Lakes Area (ELA). A team of scientists' measured ecological and aquaculture-related variables on Lake 375 before and after the addition of the farm. Similar measurements were also made on a nearby "reference" lake, Lake 373. Conclusions about effects of aquaculture on ecosystem components were drawn by comparing the results from these two lakes before and after the installation of the farm.

The study site

The Experimental Lakes Area (ELA) is located in a remote region of northwestern Ontario, Canada (49° 34' - 49° 47' north latitude, and 93° 36' - 93° 52' west longitude) (Figure 1). Approximately 58 lakes in this area have been reserved for experimental studies. ELA lakes are ideally suited for manipulation experiments because they are located in headwater region of the Canadian Shield, which limits the possibility of other "un-natural" inputs confounding the results of the manipulation experiment. ELA lakes are also well suited for lake budget and mass balance studies because their granite basins and thin soils reduce the need to account for ground and subsurface water seeping into or out of a lake.

Numerous limnology-related laboratories are located at the ELA field station including: hydrology, analytical chemistry, contaminants, isotopes, phytoplankton, zooplankton, aquatic invertebrates and fish laboratories. A meteorological station has been operated continuously from 1969 and data from this station has been used for lake budget, mass balance studies and modeling studies. Subcatchment and catchment outflow and lake levels are monitored for a number of lakes. Routine field sampling occurs throughout the ice-off period and periodic sampling occurs during winter visits.

As mentioned, the ELA is located on the Canadian Shield, specifically a pink granodiorite batholith outcrop (Davies and Pryslak, 1967) where upland soils are thin and prone to leaching, which explains why groundwater inputs are minimal (Brunskill and Schindler, 1971). Lakes in this region can be generally characterized as soft-water lakes because atmospheric deposition on exposed bedrock results in relatively small inputs of chemicals weathered into the lake (Brunskill et al, 1971).

The historical climate of the ELA was summarized by Beaty and Lyng (1989). The terrestrial vegetation is dominated by Boreal sub climax forests that include pine, spruce, aspen and birch (Rowe 1959).

The experimental lake and the reference lake

The present study involves the single basin headwater (1st order) Lake 373 and the double-basin 375 into which lake 373 drains and which itself drains into Lake Winnange from the northeast (Figure 4, Figure 5, Figure 6). Both lakes are ice-free for 6 to 7 months each year, and both are typical of many of the deep

lakes in the ELA region insofar as they are (1) dimictic and stratify thermally in the summer and winter; and (2) dilute and oligotrophic resulting in a relatively high light transmission. Because Lake 375 is downstream of Lake 373, Lake 375 has a larger overall watershed area (Table 2). Compared to Lake 375, Lake 373 has a smaller drainage (catchment) area (ha), which means inputs from erosion are likely to be larger. Lake 373 also has a larger surface area and volume.

The farm

The cage farm that was installed in Lake 375 was designed to yield approximately 10 tonnes of rainbow trout (*Oncorhynchus mykiss*) per harvest. Suspended from a 100 m² square frame was a 760 m³ nylon mesh net with 5 cm² openings. The net was suspended to a depth of approximately 10 meters. The farm was moored in the center of the north basin, over 15 meters of water. The fish were fed conventional feed pellets (Profishent®) at a rate monitored by a commercial operator (Meeker's Aquaculture). The start and harvest dates in 2003 and 2004 were similar; the 2004 season started 1 week and finished 4 weeks earlier (Table 3). The range of water temperatures in this lake between the start and harvest dates ranged from 2 to 25°C. The population size of 2003 livestock was greater than in 2004. The total biomass gained by 2003 livestock was less than in 2004, which is partly explained by the greater amount of total feed applied to the farm in 2004. The feed conversion ratio is often used in the aquaculture industry as an indication of the economy of the farm. The Feed Conversion Ratio (*FCR*) is calculated by dividing the quantity of feed applied to

the farm (F) (kg) by quantity of wet weight gained by the livestock (ΔL) (kg) (Equation 1).

$$FCR = F / \Delta L \quad (1)$$

Net primary production and lake metabolism

We used net primary production as an indicator of the metabolic balance in a lake. Positive net primary production suggests lakes are autotrophic whereas negative values imply lakes are heterotrophic. When a lake is considered autotrophic for example, we can infer that photosynthesis exceeds respiration and the lake is a sink for carbon dioxide. It is difficult however to measure photosynthesis and respiration directly so instead we estimated net primary production indirectly, using a mass balance for carbon dioxide. The change in lake carbon dioxide (kmoles) was assumed equal to net primary production, when corrected for sources of carbon dioxide from outside the lake, sinks of carbon dioxide leaving it and exchanges such as carbon dioxide evasion at the air water interface (Equation 2, Equation 3)

$$\Delta CO_2 = Sources^{CO_2} - Sinks^{CO_2} - GE^{CO_2} - NPP \quad (2)$$

$$NPP = Sources^{CO_2} - Sinks^{CO_2} - GE^{CO_2} - \Delta CO_2 \quad (3)$$

Water and carbon dioxide budgets for lakes

To estimate net primary production we needed to build a carbon dioxide budget for the lake. The carbon dioxide budget presents a comprehensive set of estimates for quantities (stocks) of water (m^3) and carbon dioxide (kmoles) within a lake and flows of water (m^3) and carbon dioxide (kmoles) entering or exiting a

lake over periods of days, weeks or years. Mass balance equations, which are formulated based on the principle of conservation of mass, are sometimes used to estimate stocks and flows indirectly.

Stocks of water and carbon dioxide in lakes

Stocks of carbon dioxide in the water columns of lakes 373 and 375 were assumed to be the concentration of the carbon dioxide multiplied by the volume of water in the lake. Because carbon dioxide, like heat, stratify in dimictic lakes, the stock of a carbon dioxide in the lake S (kmol) is calculated by multiplying the area A_z (m^2) at depth z (m) by the concentration of the chemical C_z (mmol/ m^3) at depth z integrated dz (m) from depths zero to the lake's maximum depth Z_{max} (Equation 4).

$$S = \int_0^{z_{max}} A_z C_z dz \quad (4)$$

To make this calculation we had to take samples at numerous depths, which we referred to as a chemical profile. The depth specific volumes required to calculate the stocks were acquired using bathymetric maps for lakes 373 (Figure 7) and 375 (Figure 8), which show the relationships between lake depth, area and volume. It was assumed that carbon dioxide diffuse almost instantaneously across the horizontal plane of the lake and as such the equation used to determine the stock needed to be only two dimensions.

Flows of water and chemicals in lakes

Flows of water and carbon dioxide have been estimated for a number of lake processes. *Sources* are processes that direct carbon dioxide flows into the

lake and in this study we consider atmospheric deposition (wet and dry or bulk), erosion (such as weathering and runoff) and tributaries (stream influent). Flows directing substances out of the lake, called *sinks*, include discharge at the outflow. We also estimated exchanges, which depending on conditions can either be a source to or a sink from a lake. Air-water gas exchange is an example of such a bi-directional flow, where depending on conditions in the lake and across the interface, carbon dioxide can move into or out of the lake.

In lakes, chemical flows are often linked to the movement of water into or out of a lake through processes such as wet atmospheric deposition (precipitation), erosion, tributary inflow and discharge. For example, the amount of carbon dioxide entering a lake by a tributary is the product of the rate at which water is entering the lake and the carbon dioxide concentration of the influent. In this study, a new V-notch weir was installed at the outflow of Lake 373 (a tributary of Lake 375) in 2003 to measure the rate of discharge, the same year the fish farm was installed in Lake 375. Because we were interested in comparing the carbon dioxide budgets of Lake 373 and Lake 375 before and after the installation of the farm, we decided not to use the weir results, but instead standardize our method of estimation and calculate tributary inflows and outflows using a mass balance for water. We did however use the results of the weir to check the accuracy of the discharge estimates generated by the mass balance.

Mass balances for water in lakes

We estimated daily discharges at the outflows of lakes 373 and 375 (m^3) using a mass balance for water. At any moment in time, we assumed that the discharge O^D (m^3) of water at the outflow of a lake is calculated by subtracting the capacity of the lake V^C (m^3) from the volume of the lake V (m^3) plus the net inflow of water, which is calculated by subtracting outflows due to evaporation O^{Ev} (m^3) and water storage O^S (m^3) from combined inflows of direct precipitation I^P (m^3), runoff I^R (m^3) and tributaries I^T (m^3) (Equation 5).

$$O^D = V + I^P + I^R + I^T - O^{Ev} - O^S - V^C \quad (5)$$

The net amount of water entering the lake was calculated by subtracting the amount of water lost by evaporation and the amount stored by the lake (sometimes referred to as antecedent storage) by the cumulative amount of all inflows including precipitation, runoff and tributaries. The capacity of lakes 373 and 375 are presented in Table 2. Water lost by evaporation and storage can theoretically exceed water gained by precipitation, runoff and tributaries. If these conditions persist, the volume of water in a lake can fall below the capacity of the lake, resulting in zero discharge, sometimes for extended periods of time.

The daily flow of water directly onto a lake from precipitation I^P (m^3) was calculated by multiplying the surface area of the lake A^S (ha) by the rate of precipitation p (mm/day) (Equation 6).

$$I^P = A^S * 10000 * p * 0.001 \quad (6)$$

The precipitation rate is measured and recorded daily at a meteorological station about 15 km south of the two lakes.

Erosion is a general term used for inputs to the lake from weathering and runoff. We estimated daily flows of runoff water to Lakes 373 and 375 by extrapolating the results of weir-recorded runoff rates from the eastern subcatchment of nearby Lake 239. A number of considerations were taken into account before extrapolating this data to the drainage areas of lakes 373 and 375. For one, the subcatchments of only two lakes in the area are monitored with weirs. Secondly, water from this subcatchment is sampled and analyzed regularly for chemical constituents, which was crucial for our chemical budgets. Another important consideration was we knew the areas for all three catchments and therefore could normalize the flow of Lake 239 runoff and scale these rates according to the catchment sizes of lakes 373 and 375. Finally, the eastern subcatchment of Lake 239 is large and typical of most subcatchments in the area, including the drainage areas of lakes 373 and 375 (K. Beaty pers. comm.). The daily amount of runoff from the subcatchment into the lake I^R (m^3) can be calculated by dividing the weir- determined average daily discharge rate from the eastern subcatchment of Lake 239 r (m^3 /second) by the drainage area of that subcatchment $A^{D(239)}$ (ha) then multiplying it by either the drainage area A^D (ha) of Lake 373 or Lake 375 (Equation 7).

$$I^R = \frac{r * 60 * 60 * 24}{A^{D(239)} * 10000} * A^D * 10000 \quad (7)$$

Lake 373 is a headwater lake so there are only small tributaries from the catchment area, which we have designated to runoff. The only tributary to Lake 375 is the outflow discharged from Lake 373.

Daily evaporation (m^3) was calculated by multiplying the surface area of the lake (ha) by an evaporation coefficient (mm/day). The evaporation coefficient was determined using a mass transfer equation, which is a function of surface water temperature ($^{\circ}C$), air temperature ($^{\circ}C$), relative humidity, wind speed (m/second), and an empirically determined mass transfer coefficient based on historical water balances for Lake 239 (K. Beaty pers. comm.). The daily amount water evaporating off the lake O^{Ev} (m^3) is calculated by multiplying the surface area of the lake A^S (ha) by the monthly evaporation rate ev (mm/month), which is a function of average daily wind speed w (m/second), relative humidity RH , temperatures for water Tw and air Ta ($^{\circ}C$) and an empirically determined mass transfer coefficient K^C (Equation 8)

$$\begin{aligned}
 O^{Ev} &= A^S * 10000 * ev * 0.001 / 30 \\
 ev &= (1 + 0.06 * (\frac{w * 60 * 60}{1000})) * (es1 - ea) * K^C \\
 es1 &= (EXP(52.57633 - (6790.4985/(Tw + 273.15)) - 5.02808 * LOGN(Tw + 273.15))) * 7.5006 \\
 ea &= es2 * RH \\
 es2 &= (EXP(52.57633 - (6790.4985/(Ta + 273.15)) - 5.02808 * LOGN(Ta + 273.15))) * 7.5006 \\
 K^C &= 10
 \end{aligned} \tag{8}$$

Air temperature, relative humidity and wind speed are measured and average daily at the meteorological station. Temperatures are recorded at the surface of each lake every two weeks during the ice-off period.

The daily amount of water stored in the lake basin (m^3), for example by plants, woody debris and soils, is a measure of a basin's capacity to sponge water from the lake. The daily amount of water removed from the lake and stored in the basin O^S (m^3) is calculated by multiplying the surface area of the lake A^S (ha) by the daily change in water level ΔL (m) (Equation 9).

$$O^S = A^S * 10000 * \Delta L \quad (9)$$

Storage can be negative, indicating that during heavy rainfall events the basin can become over saturated and an additional source of water to the lake.

Assessing the accuracy water discharge estimates

In 2003 and 2004, we compared our mass balance predictions of daily discharge from Lake 373 to those recorded at the weir. In 2004 (Figure 9, Figure 10), balance predictions and weir recordings are in good agreement. 2003 predictions are however less accurate (Figure 11, Figure 12). The summer of 2003 was unusually hot and dry. For extended periods, runoff estimates were zero because there were no measured flows draining from the Lake 239 subcatchment. As a result, our estimates of evaporation often exceeded the sum of all water inputs, causing a gradual reduction of water in both the lake. This depletion kept the lake well below its capacity resulting in no overflow and thus no discharge. The discrepancy between our prediction and the weir observations can be perhaps explained by alternative sources of water to the tributary, for example, groundwater seepage from wooded areas adjacent to the stream or direct runoff to the stream during rain events. The implication of this potential underestimate is further discussed in the proceeding chapters, as it relates to sources of error in the chemical budget.

The annual discharge (m^3) of water from Lake 375 is greater than in Lake 373, which is not unusual given that Lake 375 is downstream of Lake 373 (Table 4). The hydraulic residence time RT (years) is calculated by dividing the volume

of the lake V (m^3) by the annual amount of water discharged at the outflow O^D (m^3) (Equation 10).

$$RT = \frac{V}{O^D} \quad (10)$$

The residence time of Lake 375 is shorter than that of Lake 373 indicating water molecules on average spend less time in this lake before discharged at the outflow.

Software used for budget calculations

Stocks and flows of water and chemicals were calculated using the modeling software STELLA 7.0.3 Research©. We used Euler's integration method to make daily calculations ($dt=1$) during the off-ice period. Observations were not always available on a daily basis but estimates were still obtainable because the software interpolates values between observations.

Lake sampling

We sampled water and measured temperature, secchi depth and light transmission on lakes 375 and 373. During this time, we also collected integrated water samples for primary production estimates and phytoplankton and zooplankton enumeration. The physical and chemical properties of these lakes are well known; both lakes have been monitored extensively dating back to 1983. Temperature and concentrations of major ions, nutrients and metals have been measured a number of times over the past years and done so at different depths. Historically, continuous measurements have been made at one sampling station

on each lake. The locations of these stations have not changed from their original positions anchored over the deepest points in each lake.

We chose to use these stations and continue sampling previously selected depths. We sampled depths of 1, 5, 10, 15, 20 and 24m on Lake 375 and 1, 5, 10, 15 and 20 on Lake 373. We decided to add a third station in 2002, to the north basin of Lake 375, to see if what effect distance from the farm had on our ability to detect changes in water chemistry. Sampling depths at this station were 1, 5, 10 and 15m (maximum depth). The original station on Lake 375 lies about 400m to the south of the farm whereas the new station rests only 25m to the south of the farm.

Surface water samples and physical measurements were made bi-monthly during the ice off period. Using a peristaltic pump, water was pumped up a plastic tube into 250 mL Nalgene® labelled according to location, station and depth. The surface water was sampled more frequently.

Meteorological sampling

Meteorological conditions at the ELA have been monitored since 1969. Climate monitoring and air and precipitation chemistry monitoring is supported by the Meteorological Service of Canada (MSC). MSC protocols are followed and precipitation (bulk rain and bulk snow), air temperature and wind speed are recorded at least once a day at a meteorological station located approximately 15 km south of lakes 373 and 375.

Hydrological sampling

Runoff to Lake 239, outflow from Lake 373 and water levels on lakes 373 and 375 are recorded at permanent stations, which are calibrated throughout the ice-free season. Discharge rates are recorded every minute from v-notch weirs and water levels are recorded every hour.

Chemical analyses

Samples were processed at the analytical water chemistry laboratory of the ELA within 24 hours. Using methods described in Stainton (1979), samples were analyzed for dissolved inorganic (DIC), chlorophyll A (mg/m^3) and pH.

Carbon dioxide measurements

Carbon dioxide is a species of inorganic carbon that can dissolve in solution and volatilize to the atmosphere, which is important when building budgets that include gas exchange at the air-water interface of a lake. Following the method of Hesslein (1990), surface water was collected in a serum bottle, equilibrated then analyzed for carbon dioxide partial pressure ($p\text{CO}_2$) (ppm). Once the pressure was measured, the concentration of carbon dioxide (mg/m^3) was determined by multiplying the pressure by Henry's constant adjusted for lake temperature and salinity (Harned and Scholes, 1941; Harned and Davis, 1943).

Samples were collected in 160 ml Wheaton glass serum bottles. Prior to sampling, 8.9 g of KCl (a preservative to inhibit microbial activity) was added to each bottle, then evacuated, sealed (with Vacutainer® stoppers) and backfilled with 10 mL of N_2 to create the head space. To collect a sample, the bottle was

submersed just below the surface (<30 cm) and filled by puncturing the cap with a needle. Bottles were filled to a capacity (leaving only the head space) then shaken vigorously until the salt dissolved completely.

In the laboratory, bottles were placed in a wrist action shaker for 10 minutes to equilibrate dissolved gases with N₂. Head space *p*CO₂ was then measured using a LICOR LI-800 GasHound CO₂ Analyzer®.

Using formulae derived by Harned and Scholes (1941) and Harned and Davis (1943) we used dissolved inorganic carbon (*DIC*) (mmol/m³), pH and temperature (*T*) (°C) measurement data at depth to generate estimates for stocks of carbon dioxide CO₂ (mmol/m³) in the water column of the lake (equation 11).

$$CO_2 = \frac{DIC}{(1 + K1 / H^+ + \frac{(K1 * K2)}{(H^+)^2})}$$

$$H^+ = 10^{-pH}$$

$$K1 = 10^{\left(\frac{3404.71}{T_K} + 14.8435 - 0.032786 * T + 0.05\right)}$$

$$K2 = 10^{\left(\frac{2902.39}{T_K} + 6.741 - 0.02379 * T + 0.2\right)}$$

$$T_K = T + 273.15$$
(11)

Statistical method

A repeated measures ANOVA was used in this study to test lake by period interaction, with lake (lakes 373 and 375) and period (before and after installation of the farm) representing the fixed factors and time as the repeated factor (weeks or months) and *n*=4 years (2001 to 2004).

Carbon dioxide budgets for lakes

We built budgets to compare stocks of carbon dioxide within and between lakes 373 and 375 and the flow of carbon dioxide through these lakes, before and after the installation of the farm into Lake 375. Schindler and Nighswander (1970), Schindler et al (1976), Dillon and Rigler (1974 and 1975) and Kirchner and Dillon (1975) used variations of these budgets to calculate the retention of chemicals in lakes and build models to predict the accumulation of chemicals in the water column.

We quantified stocks of carbon dioxide (kmoles) in lakes 373 and 375 by integrating the product of chemical concentration (mmol/m^3) and lake area (ha) over depth (m) (Equation 4). We identified the major processes that move carbon dioxide into and out of lakes and attempted to quantify these flows. Once a process was identified, it was categorized, depending of the direction of the flow, into one of three categories. Sources, sinks and exchanges were the categories used to indicate whether the process behind the flow moved chemicals respectively, into the lake, out of the lake or in either direction. To further develop our understanding of the fate of these chemicals, we also quantified some flows within lakes.

Sources: flows of chemicals into lakes

We identified and quantified three sources of chemicals to lakes 373 and 375. These sources were atmospheric deposition (bulk rain and bulk snow), erosion (weathering and runoff) and tributaries.

The weekly amount of bulk aqueous carbon dioxide falling directly on the lake from atmospheric deposition (AD) (kg) was equal to the product of the weekly rate of precipitation (I^P) (m^3) and the weekly concentration ($mmol/m^3$) of carbon dioxide collected in the bulk deposition collector (C^{AD}) at the ELA meteorological station (Equation 12).

$$AD = I^P * C^{AD} * 10^{-6} \quad (12)$$

Bulk samples were collected for chemical analyses and we considered this bulk amount a combination of wet and dry deposition.

The weekly amount of aqueous carbon dioxide erosion to the lake (E) (kg) was equal to the weekly runoff from the catchment (I^R) (m^3) (Equation 7) multiplied by the concentration of chemical ($mmol/m^3$) in a weekly sample of runoff water (C^E) (Equation 13).

$$E = I^R * C^E * 10^{-6} \quad (13)$$

Runoff water was chemically analyzed from the nearby and compositionally similar eastern subcatchment of Lake 239.

The weekly amount of chemical entering a lake by a tributary (T) (kg) was calculated by multiplying the weekly volume of water inflowing from the upstream catchment (I^T) (m^3) by the concentration of aqueous carbon dioxide ($mmol/m^3$) in a weekly sample taken from the inflow (C^T). The concentration of chemical in the surface water of the upstream lake was used as a proxy for C^T (Equation 14).

$$T = I^T * C^T * 10^{-6} \quad (14)$$

Sinks: flows of chemicals out of lakes

We identified one sink of aqueous carbon dioxide from lakes 373 and 375. This sink was the discharge at the outflow. The weekly amount of chemical discharged at the outflow (D) (kmol) was calculated by multiplying the weekly volume of water discharged at the outflow (O^D) (m³) (Equation 3) by the aqueous carbon dioxide concentration of the discharge (C^O) (mg/m³) (Equation 15).

$$D = O^D * C^D \quad (15)$$

In this study case, we use the chemical concentration of the surface water of the lake instead of the concentration at the outflow.

Exchanges: bi-directional flows of chemicals into or out of lakes

We identified one bi-directional flow of chemicals to and from both lakes, which was gas exchange at the air-water interface of the lake.

The weekly exchange of a carbon dioxide either dissolving into the lake or volatilizing to the atmosphere (kmol) was calculated using the Stagnant Film Model (Liss and Slater, 1974). This model describes diffusive gas exchange (or flux) across the stagnant film or boundary layer at the air-water interface. The flux is proportional to the difference in chemical concentration (mmol/m³) measured in the water and at the top of the boundary layer. The boundary layer is considered to be in equilibrium with the atmosphere. If chemical concentrations in the surface water exceed those in the boundary layer, the chemical will evade from the lake. If the opposite is true, the chemical will invade the lake from the atmosphere. The velocity of this movement is dependent on the thickness of the boundary layer, which is related to the wind shear across the top of the lake. An

equation for mass transfer velocity at the interface of lakes (m/second) is published by (Cole and Caraco, 1998). In summary, the weekly amount of volatile chemical evading from the lake by gas exchange (GE) (kg) was calculated by taking the difference between weekly measures of the equilibrated atmospheric chemical concentration in the boundary layer and the aqueous concentration in the water ($C^{AQ}-C^{EQ-ATM}$) (mg/m^3) and multiplying this difference by the area of the lake (A^S) (ha) and a mass transfer velocity (k) (m/second). The mass transfer coefficient is a published equation dependent on wind speed (w) (m/second) (Equation 16).

$$GE = (C^{AQ} - C^{EQ-ATM}) * A^S * 10000 * k * 60 * 60 * 24 * 7$$

$$k = 2.07 + 0.215 * w^{1.7}$$
(16)

The boundary layer concentration of the chemical was considered in equilibrium with the atmosphere. In the case on carbon dioxide the boundary concentration was determined by applying Henry's constant to an atmospheric pressure held constant at 375 μatm (Keeling and Whorf, 2004).

Pelagic primary production and estimates of community respiration

Daily primary production (mg C fixed) was estimated using the method of Fee (1990). Integrated samples from the mixed and euphotic layers were collected monthly using a device described by Shearer (1978). Samples were returned to the laboratory and incubated in light and temperature conditions similar to those observed in the field. Each sample was spiked with radioactive carbon ($\text{NaH}^{14}\text{CO}_3$) and uptake rates were calculated by difference. The rate of uptake was assumed to represent primary production, as opposed to net primary

production, because of the short incubation periods (~45 minutes). Daily primary production was interpolated using the monthly uptake values, continuous observations (Li-Cor LI-190SR quantum cell) of incident photosynthetically active radiation (PAR) recorded from the meteorological station and bi monthly measurements of PAR attenuation (light extinction) in the lake.

Results

Lake budgets for carbon dioxide

Annual flows and stocks of carbon dioxide are presented in budget format for lakes 373 and 375, before (2001-2) and following (2003-4) the installation of the farm in Lake 375 (Table 21). The change in carbon dioxide in the water column during the off ice period is also presented, as are estimates of annual net primary production. The most striking result from the carbon dioxide budget is that during the ice-free periods of 2001 and 2004, both lakes are net sources of carbon dioxide to the atmosphere. Since allothchonomous contributions of aqueous carbon dioxide to these lakes are minimal relative to gas evasion (4-11%), and changes in stocks of carbon dioxide throughout the ice-free season are moderate (9-20% change), estimates of net primary production are negative. These negative values imply that heterotrophic processes dominate the metabolic balance in lakes, and respiration in general outpaces photosynthesis.

The sensitivity of gas evasion estimates to methods and coefficients of mass transfer

Trends in surface water carbon dioxide were measured using two different methods; samples collected in serum bottles, equilibrated then analyzed in the lab (Figure 42) and in-situ automated recordings using infrared analysis (Figure 43). Gas evasion estimates for Lake 375 in 2004 were compared using the results of these two methods and also two different mass transfer coefficients (Table 22).

For both lakes, surface water carbon dioxide concentrations were regularly above equilibrated values for atmospheric carbon dioxide in the boundary layer of the lake. The seasonality of carbon dioxide concentrations were similar in both lakes and within lake 375; there were signs of elevated concentrations following the ice-off period of spring, at times exceeding the summer average by a factor of nearly 15. Concentrations also begin to increase late in the fall and are synchronous with a period when the lake becomes well mixed thermally.

Our automated *in-situ* recordings of surface water and atmospheric carbon dioxide pressure measured at the air-water interface of Lake 375 during the farming cycles show that the variation in aqueous carbon dioxide is much greater than that observed for atmospheric carbon dioxide. These results also show that for extended periods throughout the summer, carbon dioxide pressure in the surface water is less than in the atmosphere, implying a net invasion of carbon dioxide into the lake, which is contrary to the previous results. The automated recordings do however; show a marked increase in late season aqueous carbon dioxide pressure, which again follows the onset of the fall mixing event.

The disparity between the results both methods of carbon dioxide determination in the surface water have large implications with respect to the estimation of gas evasion (or as shown invasion) and carbon dioxide and carbon budgets for lakes in general. The choice of two established mass transfer coefficient also has an effect on estimate, albeit small, in comparison to the choice of data used for generating the gas exchange estimate.

Effects of aquaculture on stocks of carbon dioxide in lakes

Trends in stocks of carbon dioxide in the water columns of lakes 373 and 375 are presented before and following the installation of the farm in Lake 375 (Figure 44). Prior to the installation of the farm, Lake 375 has had on average, despite its smaller size, one and one-half times the amount of carbon dioxide of that in the water column of Lake 373. Amounts of carbon dioxide in both lakes have fallen rather inconsistently since 2001. Stocks of carbon dioxide in lakes were on average greater during the winter and during early spring and late fall.

Effects of aquaculture on the metabolic balance in lakes

Trends in weekly net primary production in lakes 373 and 375 during the off ice period are presented before (2001) and following (2004) the installation of the farm in Lake 375 (Figure 45). Most of the weekly estimates for net primary production are negative, implying that heterotrophic processes generally dominate autotrophic processes. Both lakes, before and after the installation of the farm have demonstrated parallel results for net primary productivity; suggesting that aquaculture effects are not limited to only one trophic group. Although seasonal patterns in NPP are not presently obvious there seems to be a spike in the month of August.

Effects of aquaculture on the magnitude of metabolic processes in lakes

Trends in weekly primary production derived from ^{14}C incubations are presented for lakes 373 and 375 during the off ice period before and following the installation of the farm in Lake 375 (Figure 46). Stocks of chlorophyll A, a positive

indicator of primary production, are also presented for lakes 373 and 375 before and after the installation of the farm (Figure 47).

Historically, daily primary production in Lake 373 has been on average greater than or equal to that observed in Lake 375. For non-aquaculture years, peaks in daily primary productivity are most often observed in late May, June and early July. During the years of aquaculture, primary production in Lake 375 was consistently above that observed in Lake 373. Peaks in primary production in Lake 375 during this aquaculture periods were in mid to late July and early August. There was also a noticeable change in primary production estimates between the 1983-1993 periods and the 2001-2004 periods. Stocks of chlorophyll A in lakes 373 and 375 have been similar historically although there have been on occasion extreme amounts (up to ten times normal amounts) of chlorophyll A in Lake 373. Lake chlorophyll A has been stable in Lake 375 if not increasing slightly upon the installation of the farm.

Using Bureau's metabolic model (2003) for rainbow trout in cage culture operations, we presented trends in weekly fish respiration (g O₂ consumed per fish) in 2003 and 2004 (Figure 48). Weekly oxygen consumption (or alternatively carbon dioxide production) of individuals increased exponentially as the growing season progressed. This rate of increase in fish respiration in 2004 was greater than in 2003. Late in the 2003 season the rate of respiration decreased, which can be partially explained by the stoppage in feed applied to the farm and the drop in water temperature to near freezing conditions.

Flows of carbon dioxide within lakes are compared within and across lakes 373 and 375 during 2004 (Table 23). The metabolic balances within these lakes are derived from estimates of net primary production, primary production and livestock respiration. Our estimates show that the annual fixation of carbon dioxide (inorganic carbon) to organic carbon in these lakes can anywhere from 2 to 5 times the average stock of carbon dioxide in a lake. This level of primary production can only be supported by an allochthonous production of carbon dioxide from lake respiration that exceeds it by 12 to 35%. During the production cycle of 2004, the livestock produced about 9% of the total carbon dioxide generated by respiration in Lake 375. Annual estimates of primary production and lake respiration were greatest for Lake 375 in 2004, during the second season of farming.

Evidence for short-term aquaculture effects on lake primary production

Results of the repeated measures 2-way ANOVA, testing for significant differences in metabolic condition before and following the addition of the farm to Lake 375 (Table 24) are presented for: (1) the concentration of carbon dioxide in the surface water; and (2) ^{14}C estimates of weekly primary production. The BACI-style analyses demonstrate that aquaculture has already had a significant effect on primary production in Lake 375. Conversely, surface water carbon dioxide concentrations have not changed in response to the farm.

Conclusions

Summary of findings

During the ice-free period of 2001 and 2004, lakes 373 and 375 were almost invariably supersaturated with carbon dioxide. As a result, these lakes were almost always a source of carbon dioxide to the atmosphere. The small change in lake stocks of carbon dioxide and the relatively small input of aqueous carbon dioxide from allochthonous sources suggest these lakes must be heterotrophic; carbon dioxide produced by respiration is greater than that fixed by photosynthesis. Although some have suggested that boreal lakes are on average autotrophic systems (Carignan et al 2000), a larger body of research (Cole et al. 1994, del Giorgio and Peters 1994, Dillon and Molot 1997 and Prairie et. al 2002) supports the alternative; un-manipulated boreal lakes are predominantly heterotrophic systems and are supersaturated with carbon dioxide.

During the second year of farming, the manipulated lake demonstrated heterotrophic tendencies and continued to be a source of carbon dioxide to the atmosphere. This result is consistent with at least one experiment; Cole et al.'s (2000) experimental addition of nutrients and piscivorous fish to a small lake. The metabolic balance in our farm-impacted lake did however begin to move towards autotrophy, at least during the summer months.

Autochthonous sinks of carbon dioxide are processes that consume carbon dioxide in lakes. Primary production for example, is the result of a process (photosynthesis) that transforms (fixes) inorganic carbon such as carbon dioxide to organic carbon. We observed an increase in pelagic primary

production during aquaculture, which explains the shift in metabolism towards autotrophy. The increase in primary production in Lake 375 was statistically significant and attributable to the farm. Chlorophyll A concentrations have also increased, albeit marginally, which further supports the notion that primary production is increasing in the manipulated lake. There is preliminary evidence that aquaculture has not only amplified production but also shifted the period of peak primary production from earlier to later in the summer.

Although an increase has been observed, primary production remains within normal ranges for un-manipulated boreal lakes (Fee et al 1992, Del Giorgio and Peters 1993 and 1994, Carignan et al 1998 and 2000, Kelly et al 2001, Prairie et al 2002). The increase in primary production in the open water of the farm-impacted lake was in fact, less than predicted, given the amount of phosphorus added to the lake and the sensitivity of these lakes to nutrient additions. The annual load of phosphorus to Lake 375 was almost as great as amounts added to artificially fertilized lakes at the Experimental Lakes Area (Table 25). Phosphoric acid injections into the epilimnion of two experimental lakes (Schindler et al 1978) induced a far greater increase in primary production than did the addition of the farm to Lake 375. The aquaculture installation has increased primary productivity to a rate that is approached what was observed in Lake 302 during a period of experimental injections of phosphoric acid directly into the lake hypolimnion (Schindler et al 1980).

Given the total amount of phosphorus loaded into the system, classic eutrophication models (e.g. Schindler et al 1978) over predict responses in

chlorophyll concentrations by a factor of six. The lack of a response in gross primary production could be related to the amount of phosphorous available to phytoplankton (Hakansson et al 1998) and/or an increase in zooplankton and fish herbivory (Schindler et al 1997; Cole et al 2000). Of the total phosphorus farm waste discharged into the lake, Bureau et al. (2003) estimate that approximately 20-25% of it is available in dissolved form, which a fraction of is excreted below the euphotic zone of the lake.

Sources of error

Gas evasion was the predominant pathway of carbon dioxide leaving the system and as such had a great deal of leverage on our estimates of net primary production. We therefore explored two different techniques to measure carbon dioxide in the surface water of Lake 375. We also assessed the sensitivity of our gas exchange estimates to two different mass transfer coefficients. The results of different methods are in good agreement that mid summer carbon dioxide concentrations in the surface water are less than averages for the open water season. Secondly, both methods suggest that during spring ice off and fall turnover, lakes are sources of carbon dioxide to the atmosphere. What is less clear is the relationship between mid summer surface water and atmospheric carbon dioxide pressures. The results of our equilibrated serum bottle analyses suggested surface water pressures were greater than atmospheric whereas our automated in-situ recordings suggested the opposite, and as a result carbon dioxide was drawn down into the lake. Draw down of atmospheric carbon has

been previously documented for an oligotrophic lake fertilized with nitrogen and phosphorus (Schindler et al., 1972).

This finding has implications to our estimates of net primary production. If we substitute the gas invasion estimate generated by the second estimate and substitute this value into our budget we find that in fact Lake 375 was autotrophic at least from late May to early November 2004. Although this is interesting, this estimate does not include the evasion of carbon dioxide immediately following ice-off, which is the period where carbon dioxide pressures in lakes are the greatest (Kelly et al., 2001). This occurs because carbon dioxide builds up in the ice covered lake during winter, when photosynthesis is irrelevant. We still maintain that Lake 375 is on average heterotrophic during the open water season but there is evidence that during the summer aquaculture impacted lakes may sequester atmospheric carbon. Regardless, we found that our many estimates of gas exchange fell within the ranges previously published for shield lakes (Kelly et al., 2001; Prairie, 2002).

There exists some uncertainty surrounding our estimates of community respiration. These values were calculated by subtracting net primary production from pelagic primary production. Pelagic primary production does not account for photosynthesizing epilithon and aquatic plants in the littoral zone and the inclusion of these processes would inflate our respiration estimates. Organic carbon degradation in the epilimnion (Curtis and Schindler 1997; Tranvik and Kokalj 1998; Gennings et al 2001) is an important mechanism of carbon dioxide production in lakes and including this process would lower our estimate of

community respiration. For Lake 375, we would expect this degradation process to produce between 200 and 300 kmol based on a 200-day open water season (Curtis and Schindler 1997).

Following two years of aquaculture production, monthly oxygen conditions at depths of both the cage bottom and manure pile have remained stable. We also did not see a change in the areal hypolimnetic oxygen deficit (AHOD, in daily mg/m²) (Lasenby 1975), a measure that has increased in previous cage aquaculture studies (Axler et al 1996; Hamblin and Gale 2002; Veenstra et al 2003).

Implication for the health of the lake

Since the onset of the aquaculture operation, we have observed a decrease in net primary production suggesting an increase in heterotrophy in the lake and an overall increase in carbon dioxide evasion to the atmosphere during the open water season. We have also observed an increase in primary production and possibly a change in the seasonality and magnitude of gas exchange.

An increase in primary production can reduce water quality with consequences for aquatic life and sources of drinking water. Increases in primary production can result in blooms of odour and toxin producing algae. An increase in primary production can also lead to an increase in sedimenting organic carbon, which upon decomposition at the bottom of the lake will consume more oxygen and eventually result in greater concentrations of carbon dioxide in the hypolimnion (Hanson et al 2003; Houser et al 2003; Sobek et al 2003). As

oxygen concentration decrease, anaerobic processes will become more important and reduced compounds such as methane, ammonium and hydrogen sulphide will begin to appear.

These natural gases will be exposed to the surface water and expelled to the atmosphere upon lake mixing events, for example during spring and fall turnover, which has climate change and air quality implications. In the meantime, cool water fishes and benthic organisms will be subjected to these changing conditions and it is probable that their community structure will change. For example sensitive benthic organisms such as ephemeroptera, plecoptera and tricoptera will be replaced with resilient tubificids (worms).

Recommendations for management

Primary production estimates can be costly and require a great deal of technical expertise. Surface water carbon dioxide measurements could be used as a leading indicator for system-wide impacts from farming operations. At this time, it is difficult to determine which response is more elastic to aquaculture, surface water carbon dioxide pressure or deep-water oxygen. We would recommend the use of both these parameters in terms of developing an environmental effects monitoring (EEM) program for short –term cage aquaculture effects. To properly assess if future farm are indeed affecting lake ecology (as opposed to climate), we suggest monitoring conditions before installation, so a before-after impact-control (BACI) type monitoring design can be implemented.

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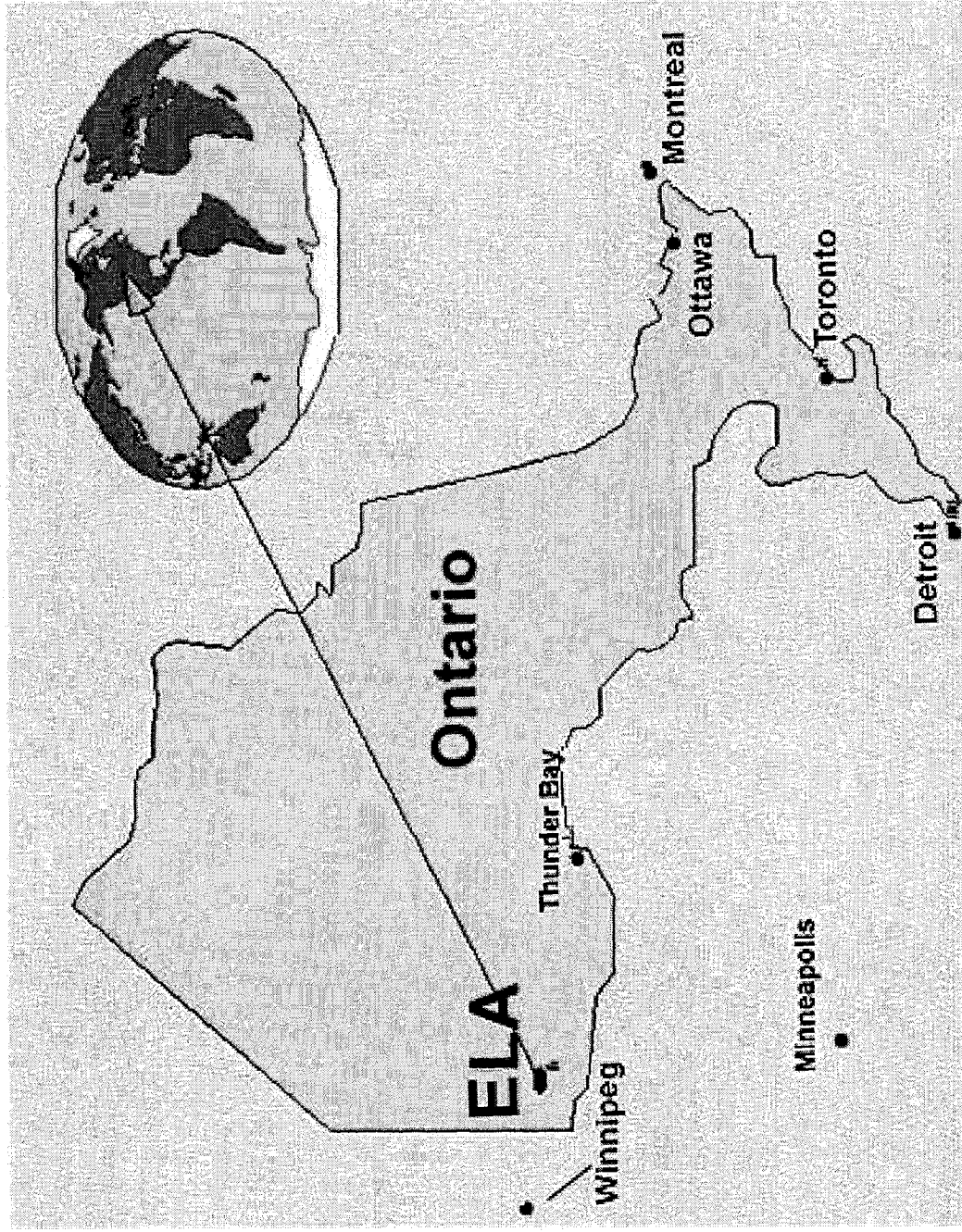


Figure 32. The Experimental Lakes Area (ELA) is located in North western Ontario, Canada.

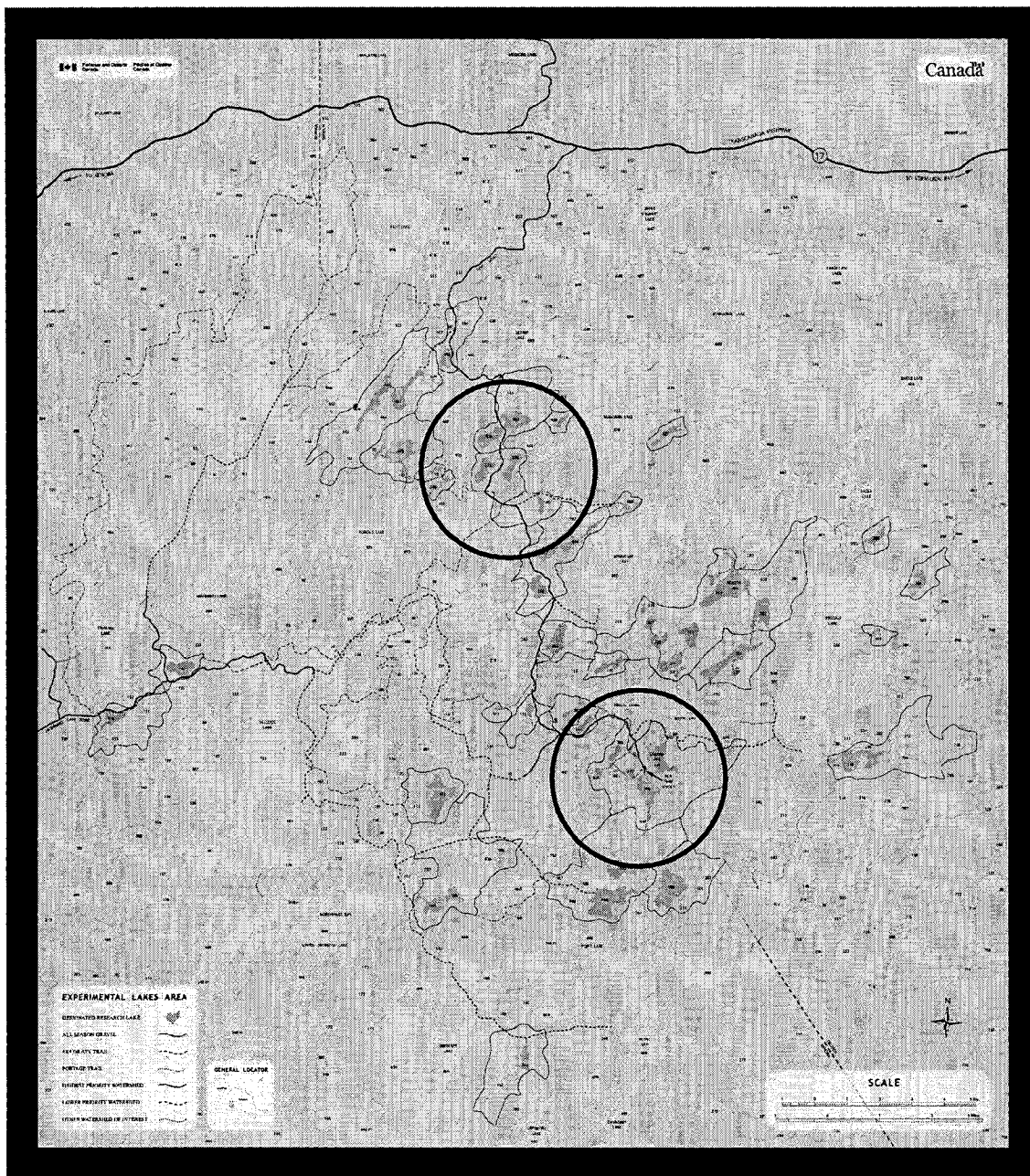


Figure 33. A map of the Experimental Lakes Area. Encircled in black are lakes 373 and 375 (top) and the ELA field station, meteorological station and Lake 239 (bottom).



Figure 34. An aerial view of lakes 375 (north and south basins), 373 and 626.



Figure 35. An aerial view of lakes 375 (north and south basins), lake 373 and Porcus Lake. Pine Road passes between lakes 375 and 373, starting at Highway 17 and ending at the ELA field station.

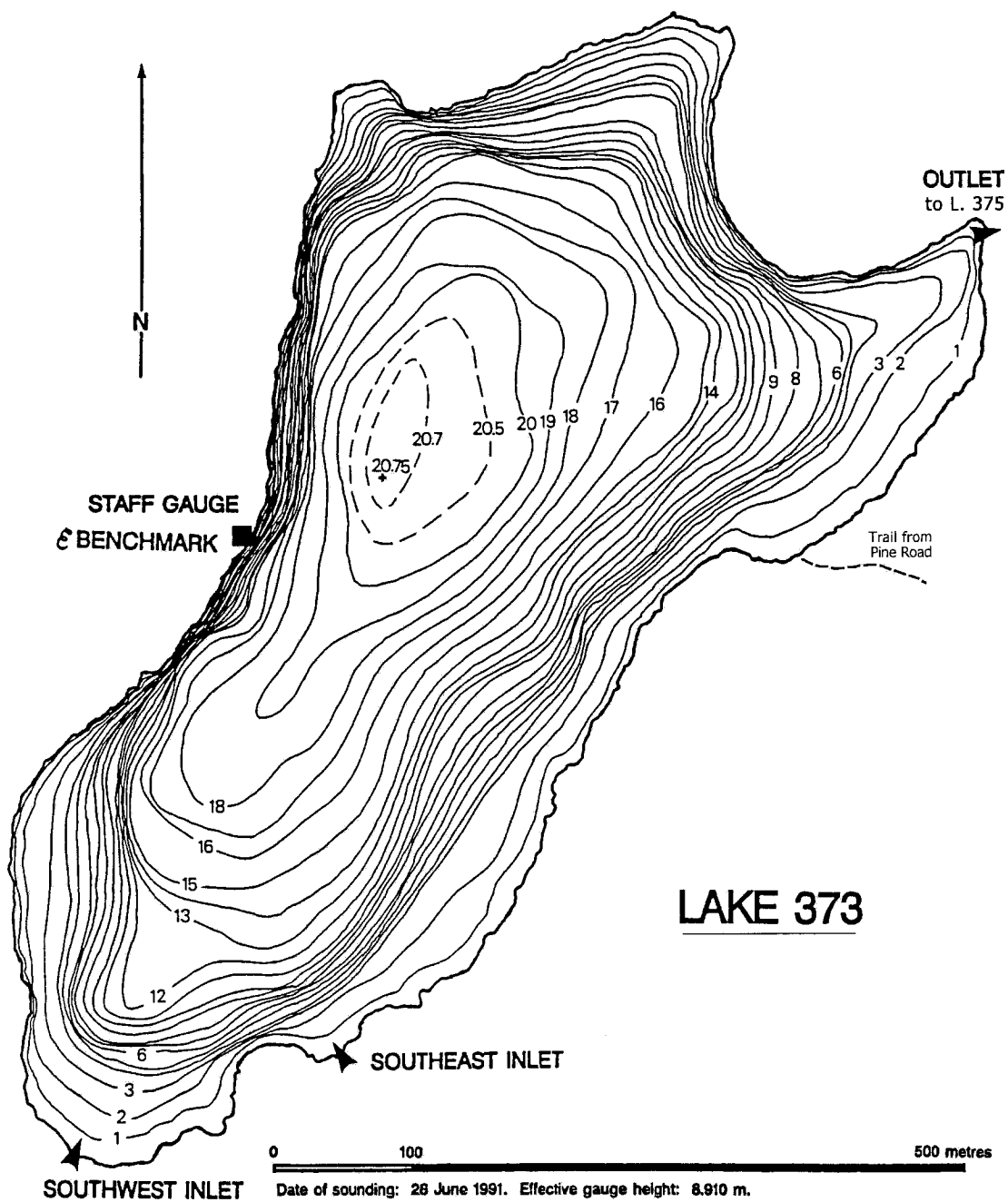


Figure 36. A bathymetric map of Lake 373.

Discharge rates from Lake 373, flows predicted by mass balance versus flows recorded at weir, April 30th to Nov 25th, 2004

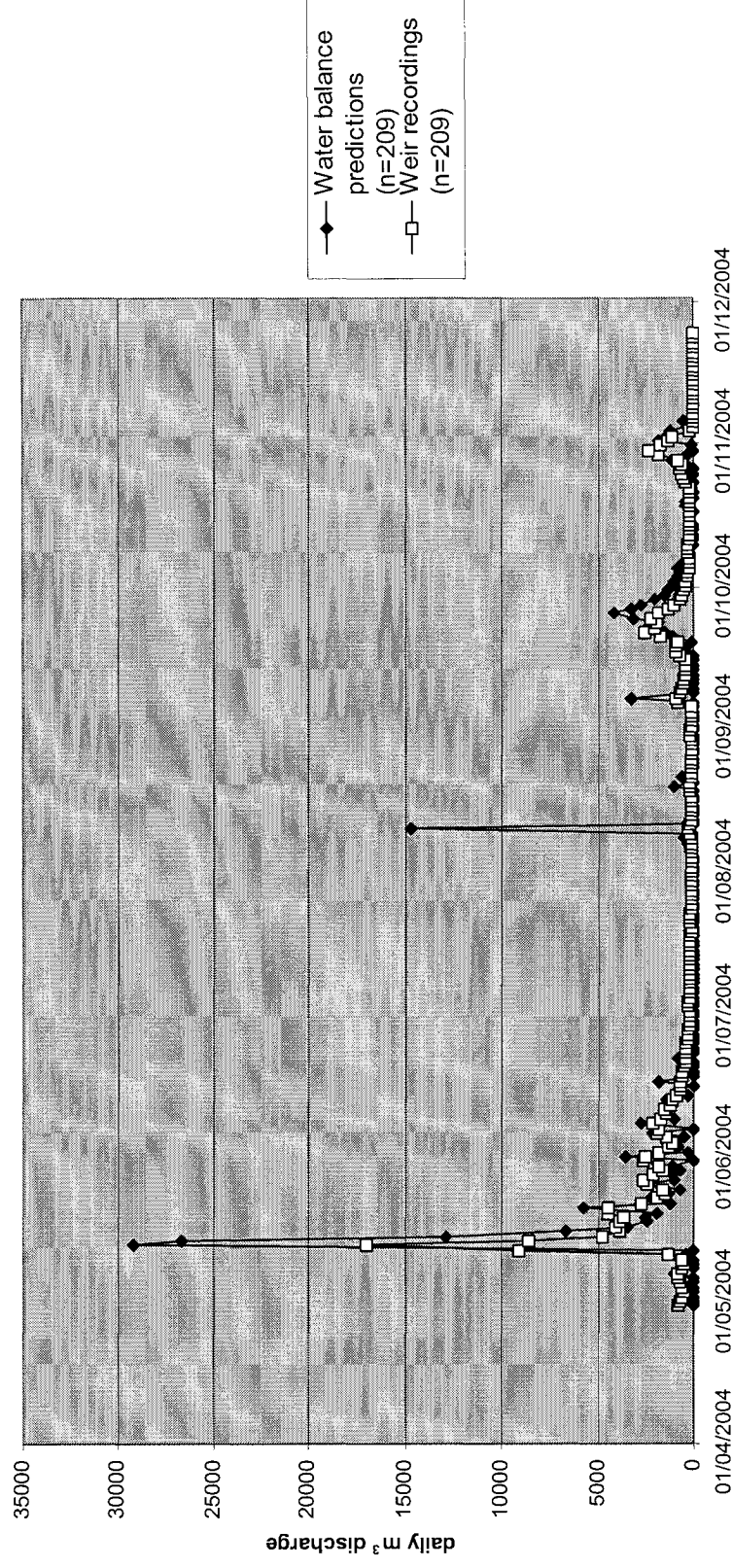


Figure 38. The accuracy of water balance predictions for the rate of daily discharge from the outflow of Lake 373, 2004.

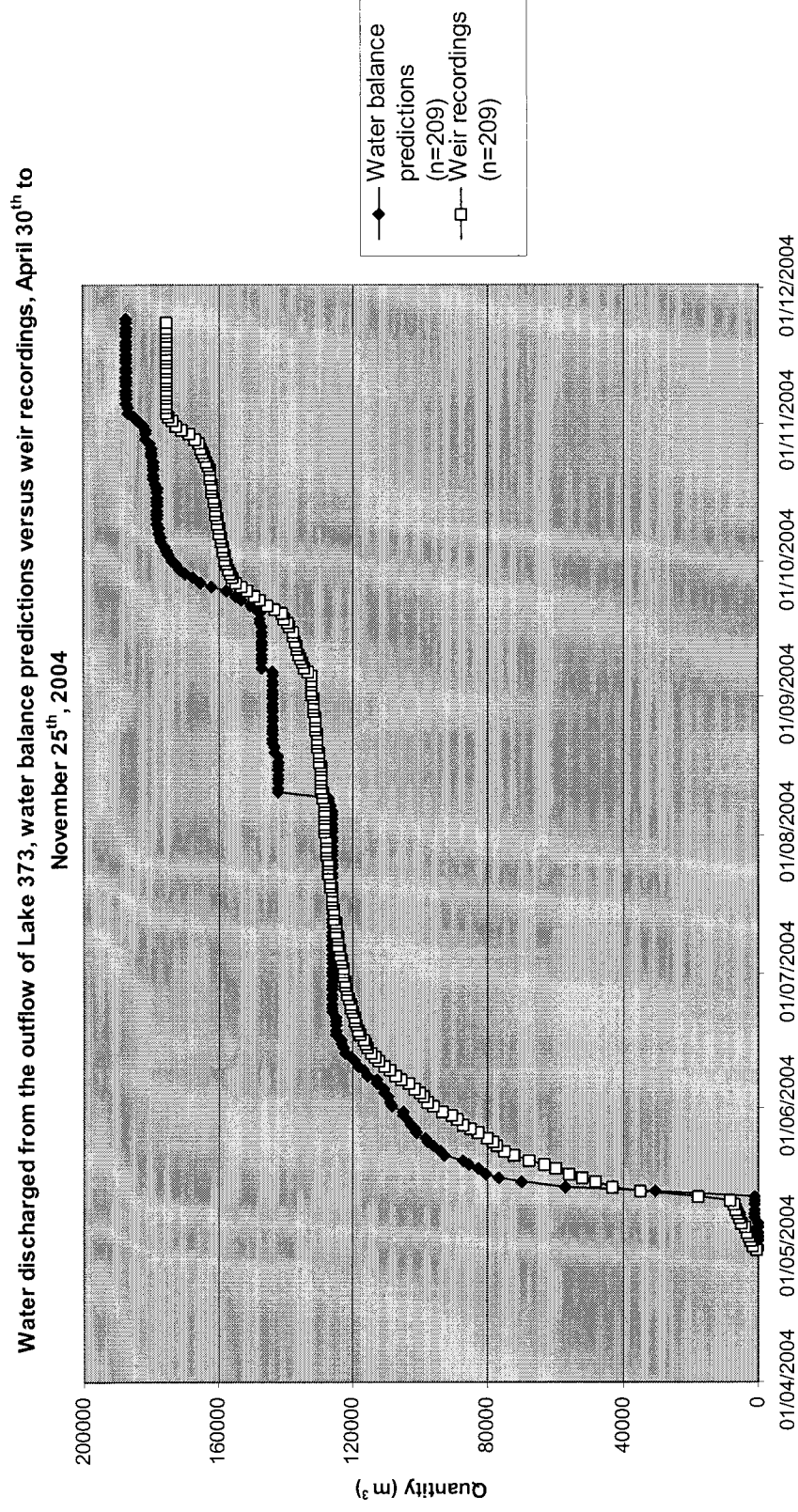


Figure 39. The accuracy of water balance predictions for the cumulative amount of water discharged from Lake 373, 2004.

Discharge rates from Lake 373, flows predicted by mass balance versus flows recorded at weir, April 22nd to Nov 24th, 2003

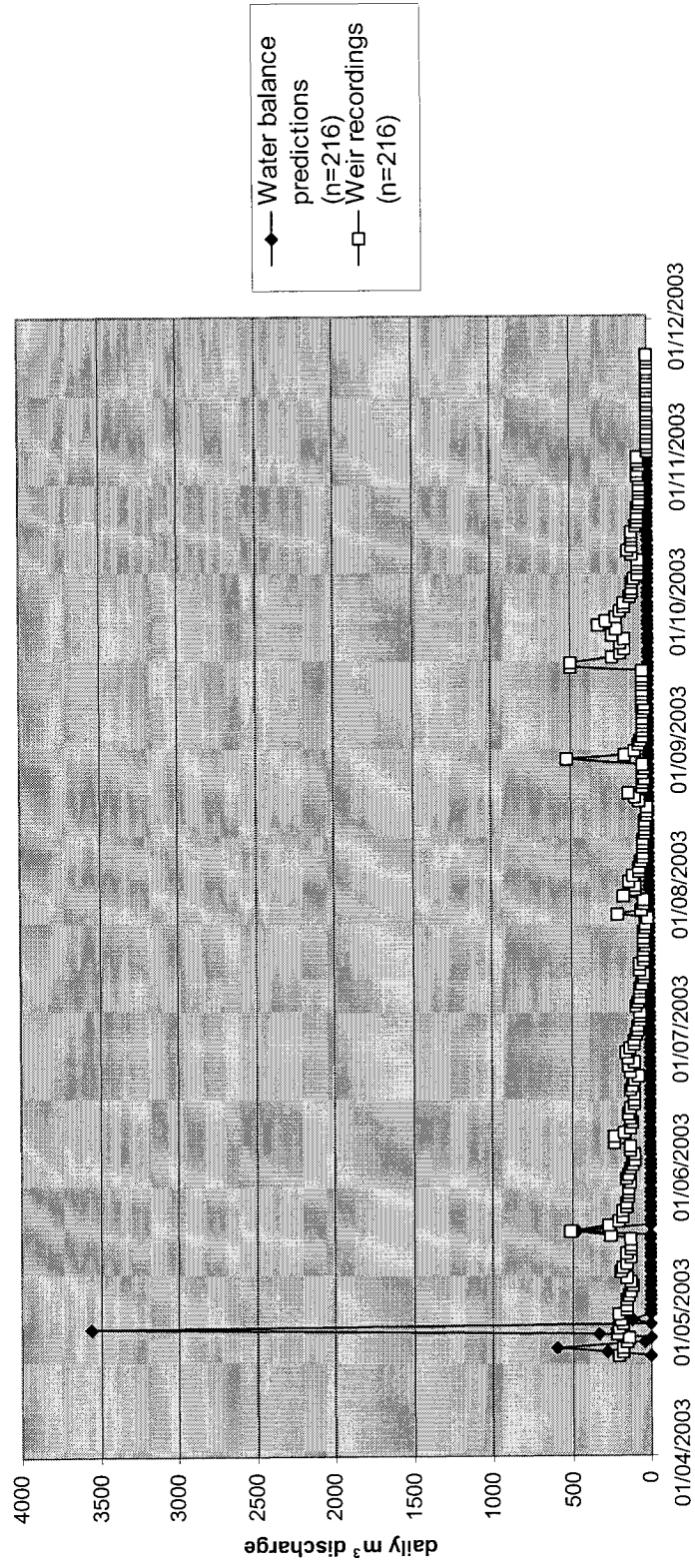


Figure 40. The accuracy of water balance predictions for the rate of daily discharge from the outflow of Lake 373, 2003.

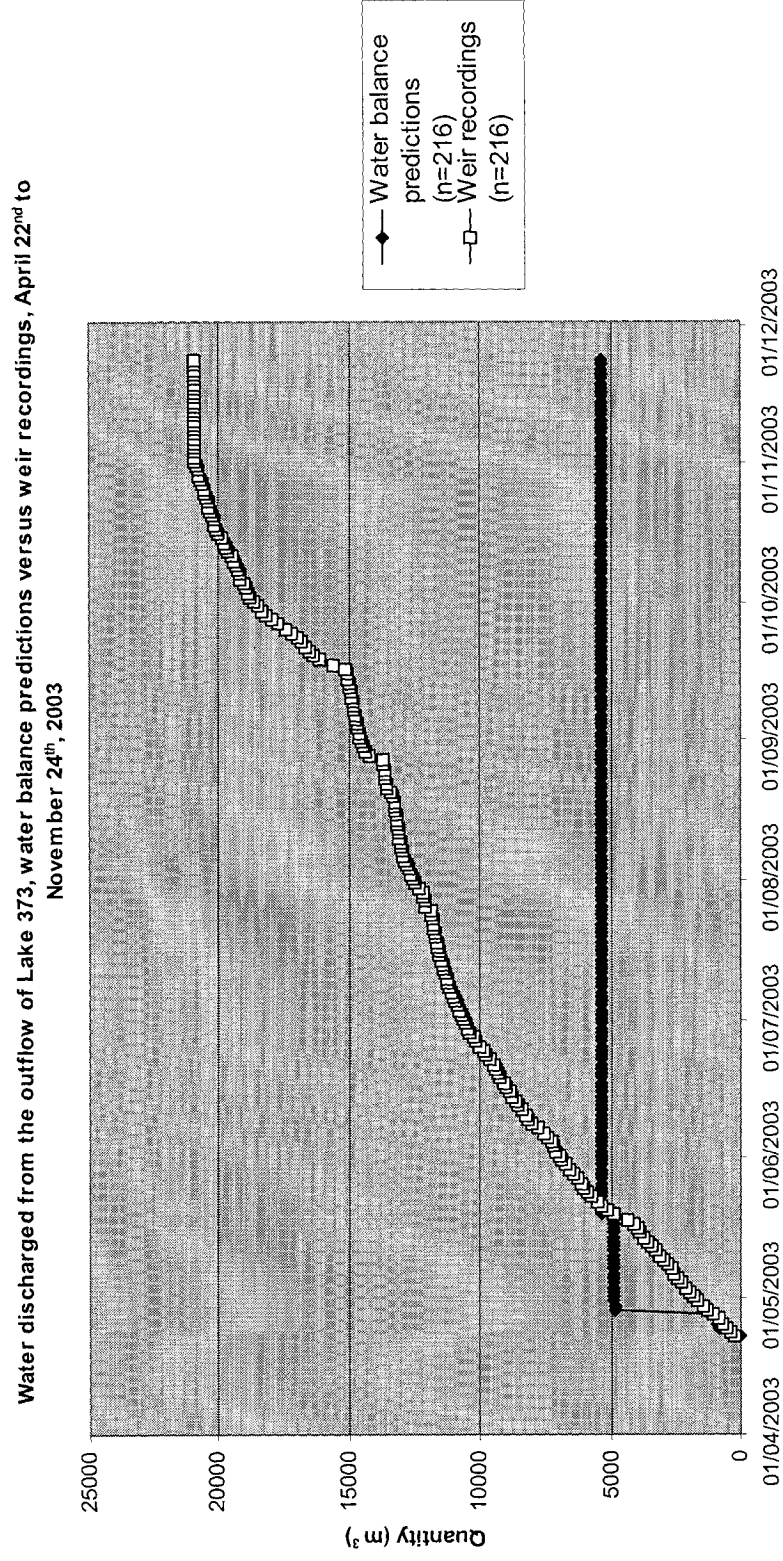


Figure 41. The accuracy of water balance predictions for the cumulative amount of water discharged from Lake 373, 2003.

Surface water carbon dioxide, by lake and basin and aquaculture installation, 2001-2005

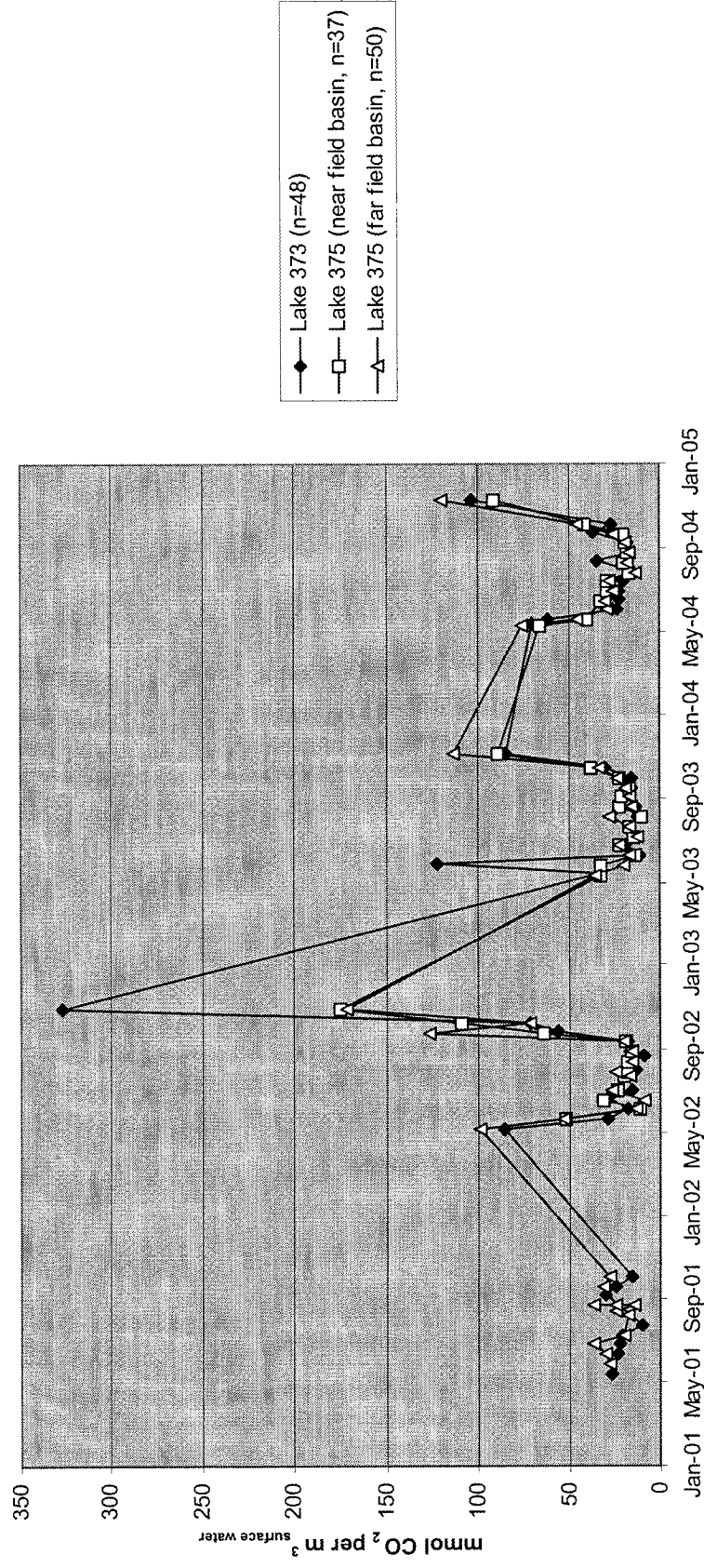


Figure 42. Trends (2001-2004) in surface water carbon dioxide concentration (mmol/m^3) in lakes 373 and 375 before and after the installation of a fish farm into Lake 375 (June 2003 and 2004). Samples were collected in serum bottles then equilibrated and analyzed in the laboratory.

Lake 375 air-water interface carbon dioxide pressure, aqueous or atmospheric, 2003-2005

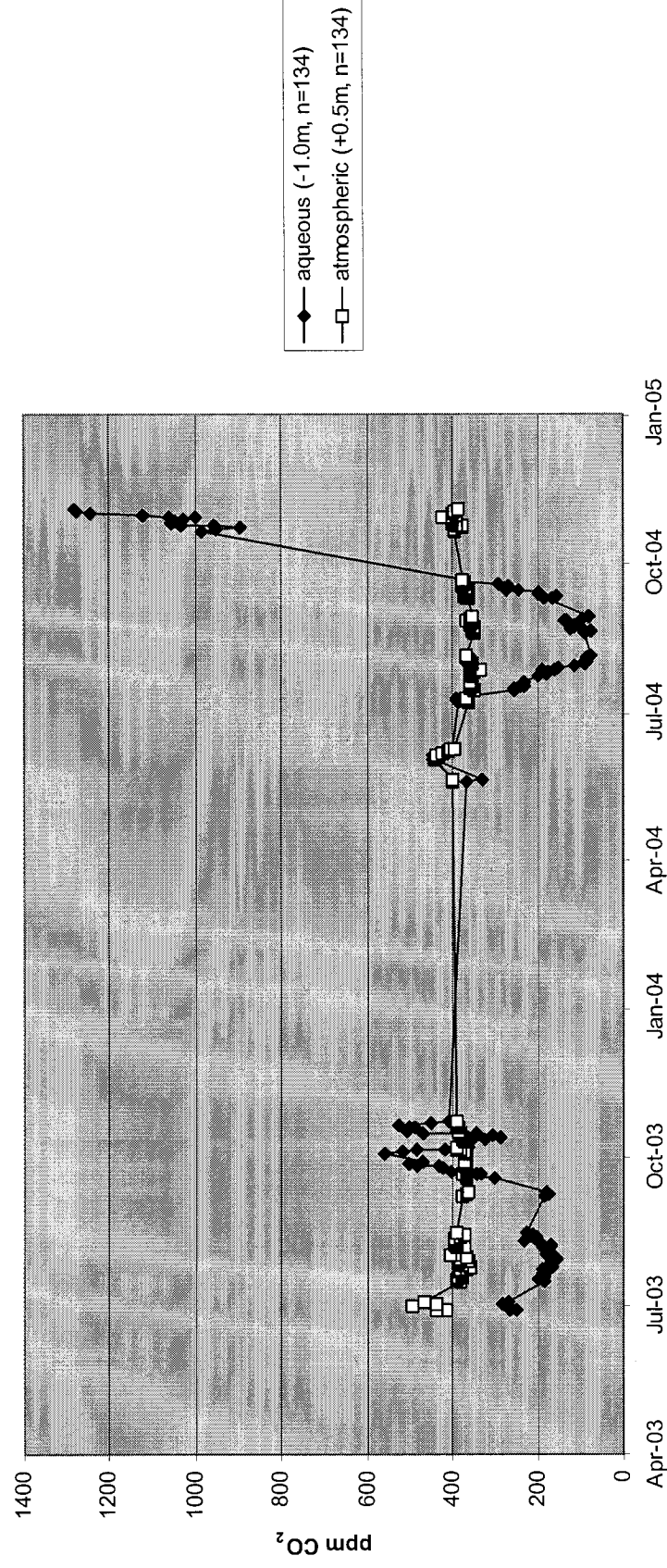


Figure 43. Trends (2003-2005) in carbon dioxide pressure (ppm) at the air water interface of lake 375 during the first two production cycles of cage aquaculture. Samples were recorded *in-situ* using an automated infrared gas analyzer.

Total carbon dioxide, by lake and aquaculture installation, 1985-2005

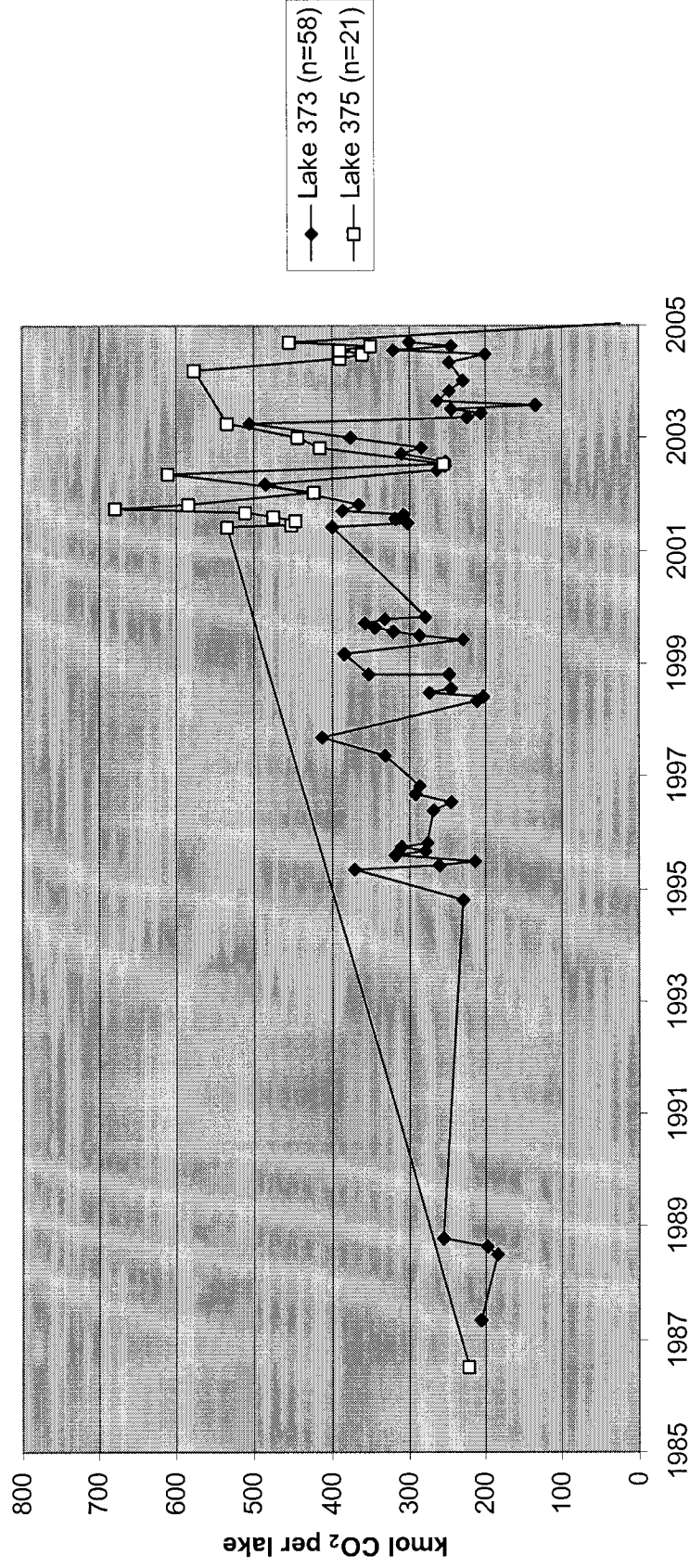


Figure 44. Trends (1985-2005) in total stocks of carbon dioxide (kmol) in the water columns of lakes 373 and 375 before and after the installation of a fish farm into Lake 375 (June 2003).

Net primary productivity, by lake and aquaculture installation, 2001 and 2004

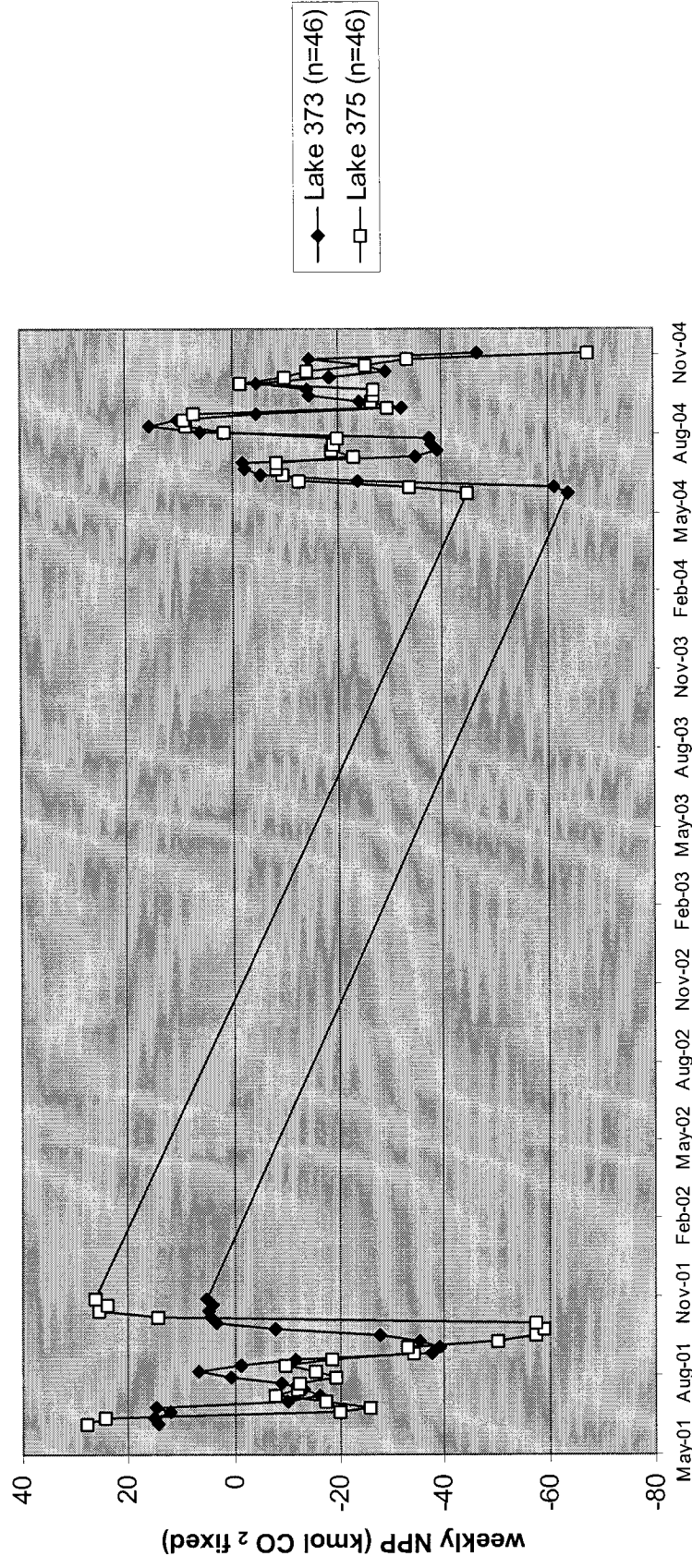


Figure 45. Trends (2001 and 2004) in estimates of weekly net primary production (kmol CO₂ fixed) in lakes 373 and 375 before and following the installation of a fish farm into Lake 375 (June 2003 and 2004).

Gross primary productivity, by lake and aquaculture installation, 1983-2005

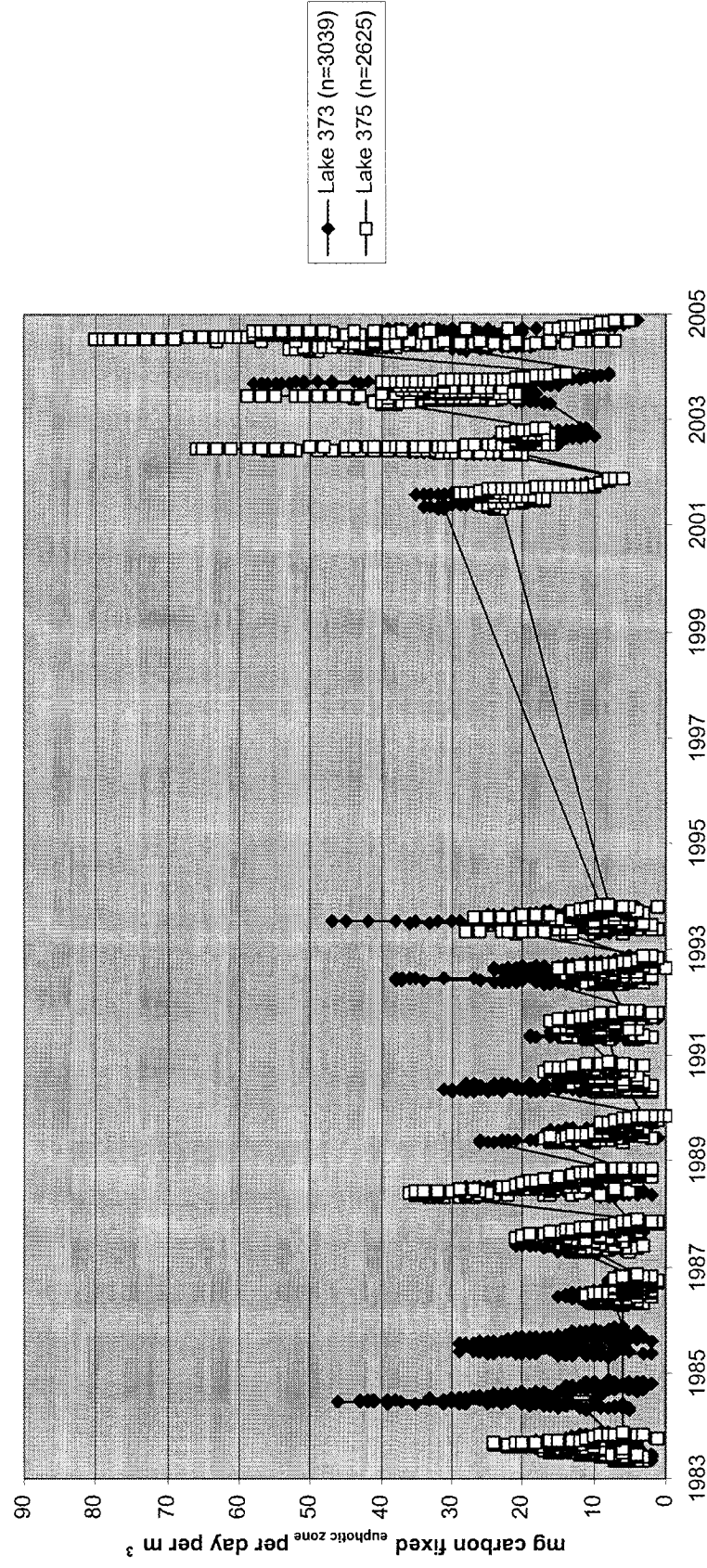


Figure 46. Trends (1983-2005) in daily pelagic primary production (mg C fixed per m³) in lakes 373 and 375 before and following the installation of a fish farm into Lake 375 (June 2003).

Total chlorophyll A, by lake and aquaculture installation, 1983-2005

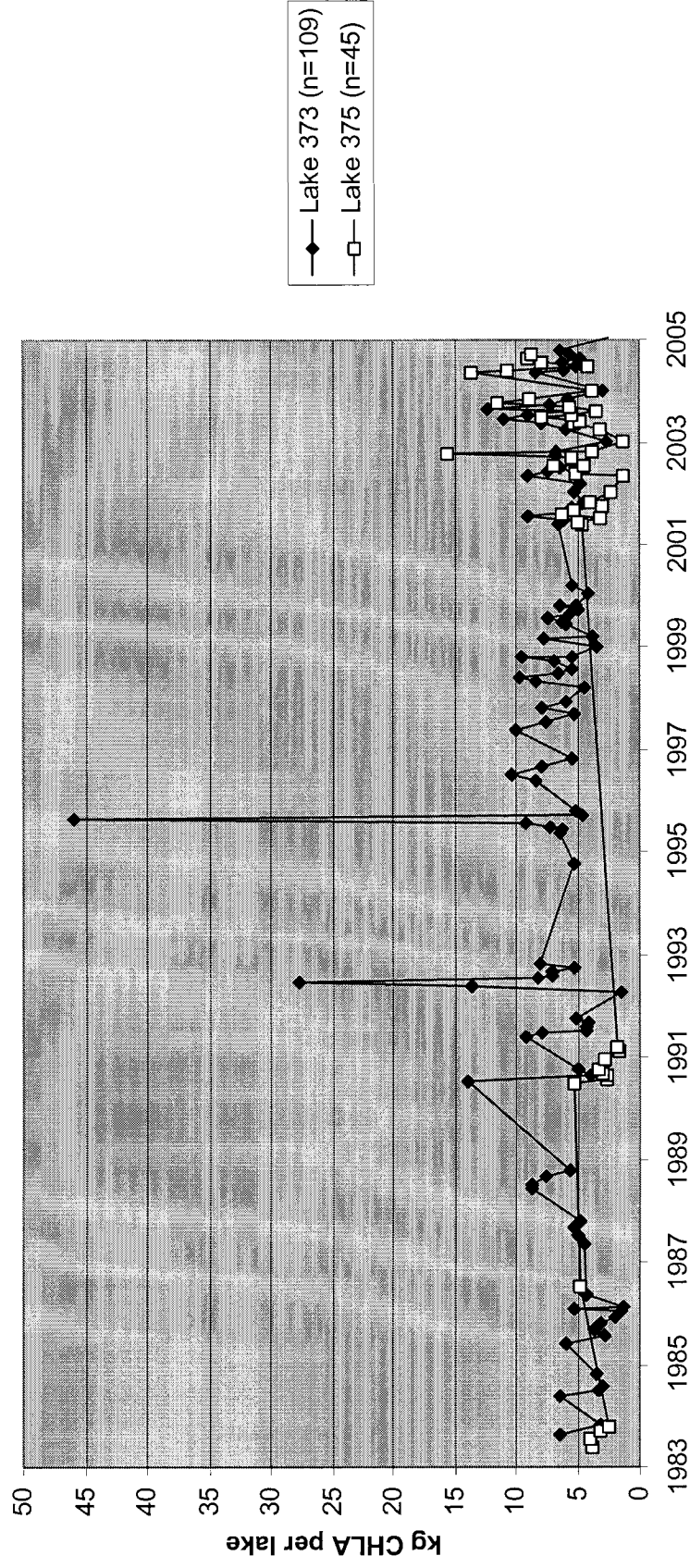


Figure 47. Trends (1983-2005) in chlorophyll A (kg) in the water columns of lakes 373 and 375 before and following the addition of the fish farm into Lake 375 (June 2003).

Livestock respiration, 2003 and 2004

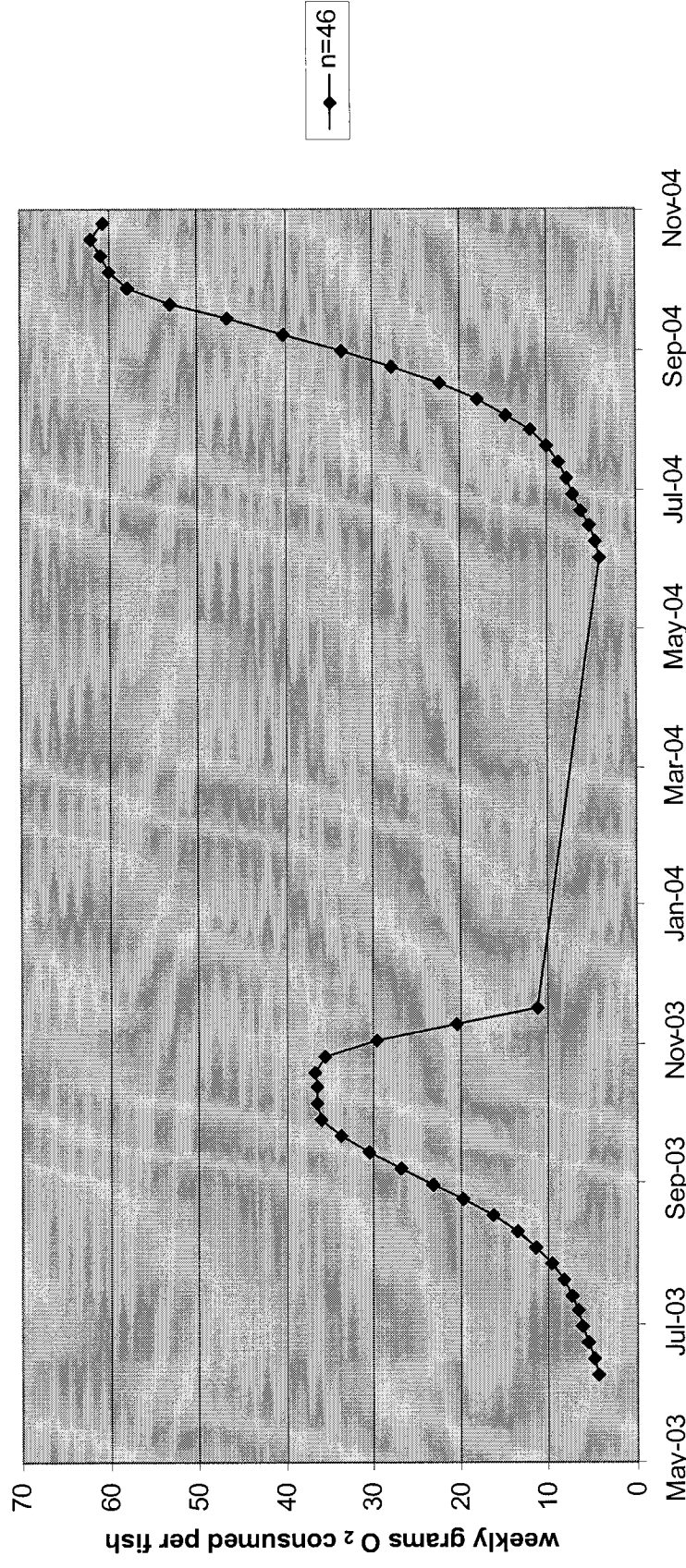


Figure 48. Trends (2003-2004) in weekly livestock respiration (g oxygen consumed per fish) during the first two production cycles in Lake 375. The estimates were based on an energetics model (Bureau et al., 2003) calibrated for rainbow trout cage aquaculture.

Table 18. General basin characteristics for lakes 373 and 375.

Lake	Order	Watershed area ha	¹ Drainage area ha	Surface Area ha	Volume m ³	Mean depth m	Maximum Depth m
373	1	80.6	80.6	27.3	3012513	11.0	20.8
375	2	231.0	150.4	23.2	2695982	11.6	26.5

¹Herein sometimes referred to as catchment area.

Table 19. Farm characteristics including dates of operation, temperature conditions, size of farm and farm production.

Year	Start	Harvest	Temperature °C	g		g		kg
				Number of		Average		
				Fish _{Start}	Fish _{Harvest}	Individual Wet Mass _{Start}	Individual Wet Mass _{Harvest}	Estimated Biomass Gain ^a
2003	June 5 th	November 18 th	2-25	10640	10014	100	860	7611
2004	May 31 st	October 24 th	6-23	10227	9830	90	1090	9830

^aPopulation size at harvest multiplied by the difference in the average individual mass at the start and at harvest

^bTotal mass of feed applied to the farm divided by the estimated wet biomass gain by the fish population

Table 20. Results of the annual water budget for the ice off period including discharges at outflow estimated by mass balance, for lakes 373 and 375, 2003 and 2004.

Lake	Year	^a Ice off period	m ³	Precipitation	m ³	Runoff	m ³	^b Tributary inflow	m ³	Evaporation	m ³	Storage	m ³	^c Outflow	m ³	Start volume	m ³	End volume	m ³	year	^d RT
373	2001	Apr 28 to Dec 1	184002	184002	100002	0	167649	^e na	116432	3012513	3012437	25.9									
	2002	May 10 to Nov 16	133661	74102	0	155960	^e na	87900	3012513	2976416	33.9										
	2003	Apr 22 to Nov 24	130057	21951	0	186941	^e na	5377	3012513	2972202	552.7										
	2004	Apr 30 to Nov 25	188015	123882	0	140877	-11632	187350	3012513	3007816	16.1										
375	2001	Apr 28 to Dec 1	156368	238654	119163	143558	^e na	369177	2695982	2697434	7.3										
	2002	May 10 to Nov 16	113587	176844	91863	152900	^e na	273707	2695982	2651670	9.7										
	2003	Apr 22 to Nov 24	122821	64718	14664	166148	^e na	63677	2695982	2668360	41.9										
	2004	Apr 30 to Nov 25	159778	295644	187400	128329	-11628	530355	2695982	2691748	5.1										

^aThis roughly represents the ice-off period, for which the estimates are based on. This is the ice off period observed for nearby Lake 239.

^bTributary inflow to Lake 375 was assumed equal to outflow from Lake 373

^cOutflow = Volume + Precipitation + Runoff + Tributary inflow - Evaporation - Storage - Volume_{capacity}

^dRT is the average theoretical water renewal time in years, calculated by dividing lake volume by outflow

^ewater level data are not available for these years

Table 21. A carbon dioxide budget for lakes 373 and 375 before and after the installation of a fish into Lake 375. Presented are annual estimates (kmol) of sources, sinks, and exchanges carbon dioxide in lakes 373 and 375. The annual estimate of net primary production during the off ice period was calculated by subtracting sinks, exchanges and changes in stocks of water column carbon dioxide from sources of (allochthonous) carbon dioxide. The annual average stock of aqueous carbon dioxide in the lake water column is also presented.

Process	kmol			
	Lake 373		Lake 375	
	2001	2004	2001	2004
Sources				
Atmospheric deposition	9	7	7	6
Erosion	13	19	24	36
Tributary inflow	0	0	1	2
Total sources	21	26	32	45
Sinks				
Lake discharge	1	2	3	17
Total sinks	1	2	3	17
Exchanges				
Gas evasion	215	629	282	539
Stocks				
ΔStocks	347	262	526	387
	-32	53	52	65
Net primary production	-162	-658	-305	-576

Table 22. A comparison of the effect method and choice in mass transfer coefficient on annual estimates of carbon dioxide evasion (kmol) during the two production cycles of fish farming on Lake 375.

Year		Date	n	CO ₂ evasion (kmol)	
				k ₁ ^a	k ₂ ^b
2003	serum bottle samples	May 13 to November 5	13	215	171
	in-situ automated recordings	June 27 to October 23	1462	-45	-28
2004	serum bottle samples	May 11 to November 8	13	539	430
	in-situ automated recordings	May 19 to November 4	1452	-82	-53

^ak₁=2.07+0.215w^{1.7} (Cole and Caraco, 1998)

^bk₂=0.168+0.228w^{2.2} (Crusius and Wanninkhof, 2003)

note:

k is mass transfer velocity (cm/hr)

w is average daily windpeed (m/sec)

Table 23. Annual within lake flows of carbon dioxide (kmol) in lakes 373 and 375 before (2001) and during (2004) the second fish farming production cycle. Lake respiration was calculated by mass balance, subtracting net primary production and livestock respiration from primary production.

Process	kmol			
	Lake 373		Lake 375	
	2001	2004	2001	2004
Net primary production	-162	-658	-305	-576
Sinks				
Primary production	1152	1215	902	1689
Sources				
Livestock respiration	0	0	0	195 ^a
Lake respiration	1314	1873	1206	2070

^aBased on Bureau et al. (2003)

Table 24. The results of a 2-way repeated measures ANOVA testing the effect of the farm (LAKE\$*PERIOD\$) on lake primary production and surface water carbon dioxide concentration.

Metabolic indicator	Source	SS	df	MS	F	P
Primary production	LAKE\$	8.19E+04	1	8.19E+04	2.58E+00	0.123
	PERIOD\$	1.13E+06	1	1.13E+06	3.57E+01	<0.001
	PERIOD\$*LAKE\$	9.90E+04	1	9.90E+04	3.11E+00	0.091
	Error	6.99E+05	22	3.18E+04		
Surface water $p\text{CO}_2$	LAKE\$	1.07E+02	1	1.07E+02	1.16E+00	0.342
	PERIOD\$	1.61E+02	1	1.61E+02	1.75E+00	0.257
	PERIOD\$*LAKE\$	3.00E-03	1	3.00E-03	0.00E+00	0.995
	Error	3.68E+02	4	9.20E+01		

Table 25. Estimates of primary production in boreal shield lakes that have been artificially fertilized using different methods. Rate limiting factors such as mean mixing depth, penetrating photosynthetically active radiation (PAR) and rate of phosphorus addition are provided for comparison.

	Year	annual mg per m ² Phosphorus addition	m Mean mix depth	daily mg C fixed per m ³ Euphotic layer	Mixed layer	mE per m ² per minute		Source
						Mean PAR	Mixed layer	
Epilimnion injection Lake 226 (NE) ¹ Lake 227	1973-1980	346 ± 13	4.7 ± 0.4	104 ± 45	146 ± 72	6.5 ± 0.6		Schindler et al. 1978
	1973-1993	452 ± 18	2.7 ± 0.4	203 ± 94	366 ± 192	6.4 ± 0.9		Schindler et al. 1978
Hypolimnion injection Lake 302 (N) ²	1973-1976, 1978	526 ± 11	5.4 ± 0.4	58 ± 11	71 ± 12	7.3 ± 0.5		Schindler et al. 1980
Cage aquaculture Lake 375	2003-2004	288 ± 21	6.8 ± 0.4	34 ± 3	50 ± 4	7.7 ± 0.8		this study

¹Lake 226 is a double basin lake that was divided by a curtain, phosphorus was added to the North East (NE) basin

²Lake 302 is a double basin lake that was divided by a curtain, phosphorus was added to the North (N) basin

General conclusion

We conducted an experiment to investigate the impacts of cage aquaculture on flows and stocks of chemicals in a boreal shield lake. We also wanted to examine the metabolic response of the lake to farming. We felt that in answering these two questions, we would provide some fundamental knowledge that would improve the management of water resources, the productiveness of cage farms and the protection of aquatic life and source water.

The first objective of this study was to quantify the relationships between flows and stocks of chemicals in boreal shield lakes. The second objective was to determine how cage aquaculture impacted these relationships. The third objective of the study was to quantify the effects farming had on ecosystem functions within lakes, such as the transfer, distribution and transformation of chemicals in the water column. The variables we selected to measure are presented in Figure 49. The chemicals we chose to focus on were carbon, nitrogen and phosphorus. These three chemicals are both environmentally and nutritionally important to respectively, lake ecology and livestock production.

The design of our experiment allowed us to confidently draw conclusions about many potential short-term effects cage aquaculture could have on the ecology of boreal lakes. First, the scope of the experiment was realistic; we added a commercial size farm to a boreal shield lake. Second, we had a large amount of control; the farm was installed in a pristine lake in a headwater region within the confines of a research area restricted to public access. Third, we had historical information on the ecology of the lake we were installing the farm in.

Finally, we had a reference lake of similar size nearby that could be compared to the manipulated lake before, during and after the installation of the farm.

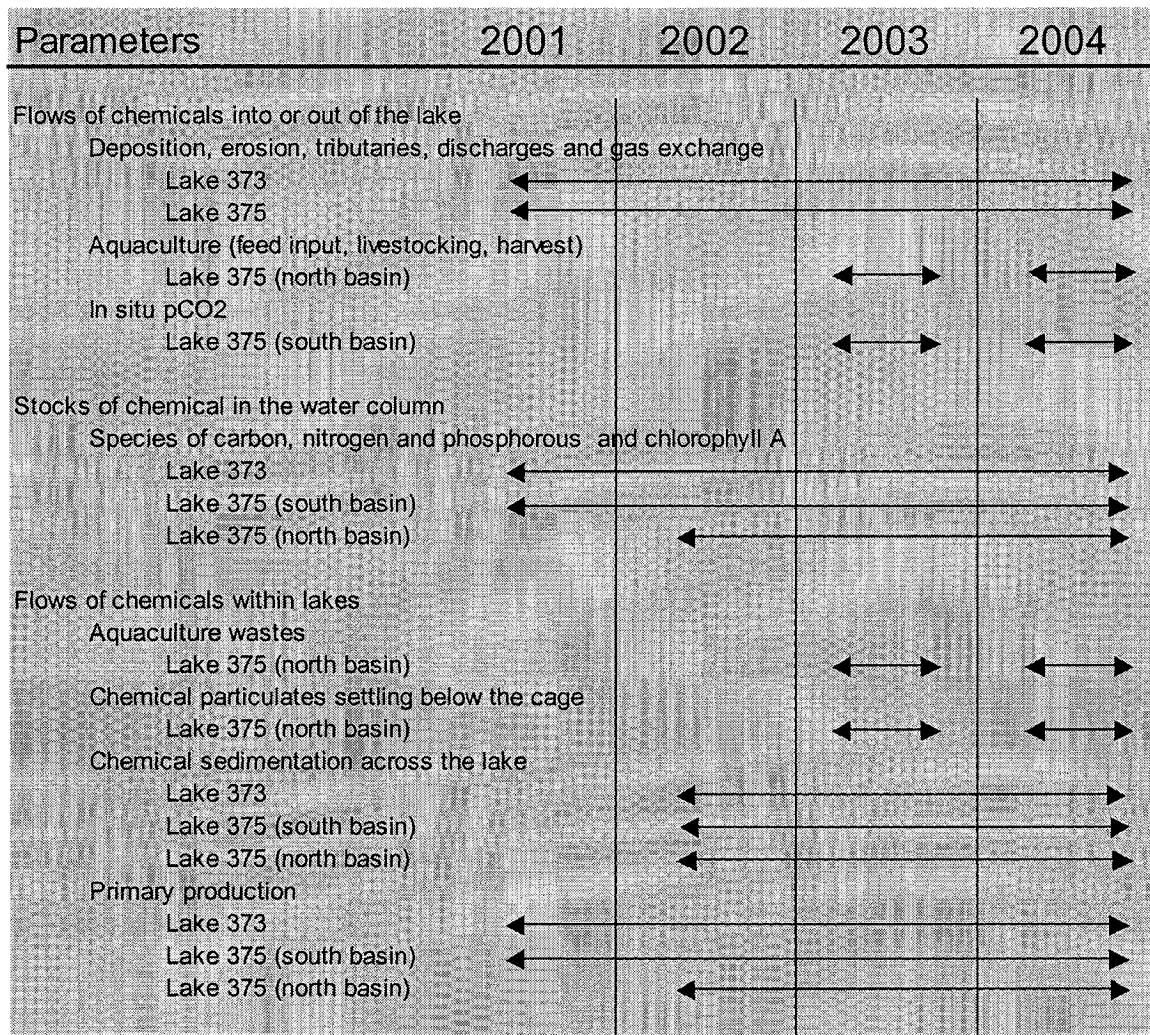
The results of the experiment demonstrate that in the short term, the farm had significant effects on many functional properties of Lake 375 (Table 26), which in our minds could be extrapolated to other lakes on the boreal shield. The aquaculture industry could use this study as rationale to further develop practices that reduce their ecological footprint, for example by producing “greener” phosphorus reduced feeds and optimizing feed conversion ratios, resulting in “leaner farms”, which could also be cost effective. These results could also be used to develop national monitoring guidelines for fish farms in small to moderately sized boreal shield lakes.

Towards developing a risk assessment model for cage aquaculture

The results from this study and others like it will be instrumental in developing a good risk assessment tool for aquaculture in boreal lakes. This tool would be a useful way to evaluate the suitability of a lake for aquaculture and would give the aquaculturalist the means to mitigate risk associated with polluting the lake and maintaining a sustainable farming operation. The information we suggest would be important to developing such a tool is presented in Table 27 and includes the number of consecutive farming years, the cumulative amount of phosphorus retained in the lake since the onset of farming and a preliminary number of ecology and aquaculture relevant endpoints. From this information, a risk landscape could be developed, allowing one the means to predict the level of risk associated with installing any size of farm in any size of lake for any period of

time (Figure 50). We think this would be a valuable tool and one that should be developed before expanding this industry into valuable boreal shield lakes.

Figure 49. A timeline for this experiment, illustrating the variables we measured or estimates, in what lake and lake basin, and for how long.



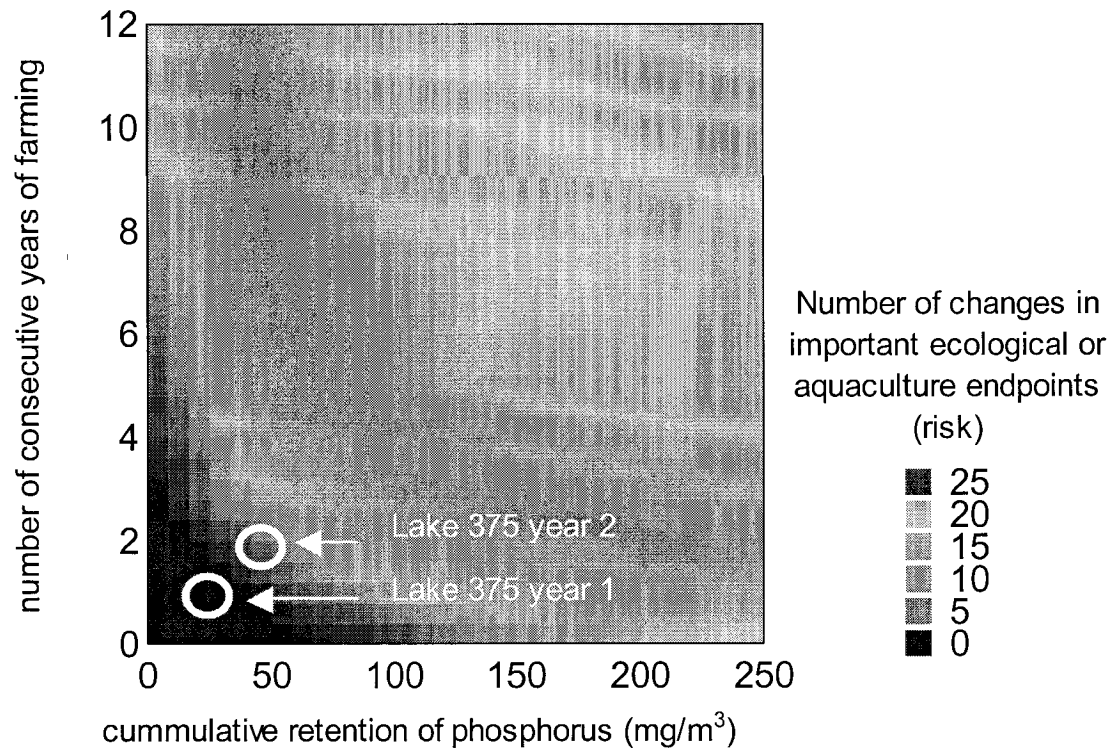


Figure 50. An example of a hypothetical risk landscape for cage aquaculture in boreal shield lakes. The results of this study and others are used to develop the empirical relationship between the (1) number of consecutive farming seasons, (2) the cumulative retention of phosphorus since the onset of the operation and (3) the number of important or negative changes to ecological or aquaculture endpoints (risk). The cumulative phosphorus retention results are placed on the model to generate a prediction of risk.

Table 26. A summary of the weight of evidence supporting the conclusions drawn from the results of this study, regarding the effects of aquaculture on functional properties of Lake 375.

Indicator	Target	Endpoint	WOE ¹
Lake function	Chemical accumulation in lakes	Chemical retention increasing	strong
	Chemical accumulation in the water column of lakes	Particulate chemicals increasing Dissolved chemicals increasing	good fair
	Increasing rates of chemical transfer in lakes	Sedimentation rate of particulate chemicals increasing	strong
	Increasing rates of chemical transformation in lakes	Increase in primary production Increase in chlorophyll a	good fair

¹Weight of evidence (WOE) that aquaculture has had a causal effect on lake function.

Table 27. Information requirements for the development of an empirical risk model for cage aquaculture in shield lakes: Incidence of change in important ecological and aquaculture endpoints, the cumulative retention of phosphorus in the lake since the onset of the farm and the number of consecutive farming years.

Indicator	Target	Endpoint	change in endpoint						
			Year 1	Year 2	Year 3	Year 4	Year 5	Year 10	
Lake function	Accumulating nutrients and organics	Particulate	no	yes					
		Settleable	yes	yes					
		Dissolved	no	no					
	Reduction in water quality	Transparency	no	no					
		Acidity	no	yes					
		national guideline exceedances	no	no					
Reduction of air quality	Odour	no	yes						
Lake structure	Increased evasion of climate altering compounds	GHG ¹ production	no	no					
		Oxygen conditions	no	yes					
		Ammonia conditions	no	yes					
	Habitat alteration	Incidence of winter fish kill	no	no					
		Increase in biological production	Primary production	no	yes				
			Secondary production	no	no				
Fish	no		yes						
Farm health	Incidence of parasitism		no	no					
		Incidence of disease	no	no					
		Species extirpation	no	no					
	Farm productivity	decrease in FCR	no	no					
		Livestock health	Frequency of antibiotic use	no	no				
		Fish meat quality	Color of meat	no	no				
Fish contamination	Taste of meat	no	no						
	PCB/mercury levels	no	no						
	Livestock mortality	critical increase	no	no					
	Total		1	8					
Cumulative phosphorus retention (mg/m ³)			23	48					
1 Greenhouse gas (GHG)									

¹Greenhouse gas (GHG)