Landscape and land use impacts on farm pond water quality in the Portage Plains of south-central Manitoba.

by

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Abstract

Growing intensification of agriculture in southern Manitoba has raised concern over the impacts of land use such as crop and livestock production on water quality in local surface waters. In this study 59 farm ponds across south-central Manitoba were sampled in three week rotations over two field seasons for nutrients, ions, total chlorophyll *a*, total microcystins, fecal coliforms and general chemistry and correlated with surrounding land use and landscape factors within a 250 m and 1 km radius. As well, nutrient diffusing substrata (NDS) containing the four treatments of nitrogen (N), phosphorus (P), combined N and P, or neither were deployed in a subset of 24 of the 59 ponds for three week spans throughout the sampling period to examine nutrient limitation and compare to ambient N to P ratios in the water. Multivariate analysis indicated high water quality was closely associated with high values of percent forested land within 1 km and low levels of cattle disturbance for both field seasons (~50% RDA redundancy). In particular, cattle disturbance and percent forested land within 1 km were able to predict > 50% of the variance in total phosphorus concentrations. Approximately one-third of the ponds were limited by N, co-limited by N and P or exhibited no nutrient limitation while P limitation was rare and occurred only 3% of the time. Although there were significant differences between N to P ratios among treatment effects they did not correspond consistently to Redfield N to P ratio prediction of nutrient limitation. Overall intensive agricultural land use was associated with poor water quality conditions (i.e., high nutrients and turbidity) and ambient ratios of N to P concentrations were inconsistent in predicting nutrient limitation exhibited by algal growth on NDS.

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Chapter 1: General Introduction

Hundreds of farm ponds are scattered across the agricultural region of south-central Manitoba and provide a significant opportunity to examine local, non-point influence of land use on surface water quality. These ponds play a vital ecological and economic role in a landscape that has been dramatically altered by human activities. Historically, extensive wetland systems spread throughout the plains region and provided habitat and resources for the native flora and fauna. The introduction of agricultural practices in the late 1800s prompted the drainage of vast amounts of the northern prairie wetlands to obtain viable farmland (Davies et al. 2004). For many landowners it was necessary to dig artificial farm ponds or alter pre-existing wetlands to get a permanent reliable water source. Farm ponds are still a valuable resource for farmers and present an economical means for providing drinking water and irrigation. Additionally, these ponds have become islands of biodiversity where many plant and animal species thrive in regions that have become otherwise devoid of permanent surface water sources (Oertli et al. 2002). Although farm ponds combined represent a sizeable portion of surface water there is very little research that has been accomplished on them (De Meester et al. 2005). There is, however, increasing interest in farm pond studies because of their frequency across diverse landscapes, their ecological diversity and their value as model systems of larger water bodies (Williams et al. 2004, De Meester et al. 2005). Agricultural pollution in surface waters is of growing concern and farm ponds provide a unique small scale watershed where effects of agricultural land use and intensity can be isolated out and identified. Agricultural intensity ranges from low to high levels of crop production and/or livestock density around these ponds and the water quality is poor when ponds no longer serve their agricultural purposes and/or they are limited in their biodiversity.

In North America, point sources such as urban sewage and industrial effluent have traditionally been targeted as the main source of pollutants to surface water quality. Indeed, in heavily populated areas this is normally the case and characteristic of point sources is a common, specific entry point of pollutants that is easy to regulate. However, in the sparsely populated prairie region, rich in fertile land, there is growing concern over controlling the independently negligible but collectively vast input of pollutants from non-point source agricultural activity across large watersheds. Although the task of regulating enormous tracks of land with thousands of independent operators is daunting, it is increasingly difficult to avoid as valuable surrounding surface water continues to deteriorate. Lake Winnipeg, in Manitoba, is the tenth largest freshwater lake in the world by surface area and has the second largest watershed in Canada which encompasses 953 000 km^2. This lake is relied upon extensively for commercial and recreational purposes yet has seen rapid decline in water quality over the last decade as massive algal blooms become customary for much of the open water period. Much of this decline has been attributed to agricultural runoff of nutrients from fertilizer application within the watershed.

Examining large watersheds can be overwhelming and requires tremendous resources to obtain accurate knowledge of non-point source pollution. Considering smaller watersheds within the larger watershed context can be remarkably useful in narrowing down impacts of chief concern. With this study I focused on a large subset of farm ponds varying in land use and landscape properties to establish a model of their influence on surface water quality. The primary objectives were:

Objective 1: Determine the impact of surrounding land use and landscape variables on water quality in southern MB farm ponds

Hypothesis: In areas of high agricultural intensity, water quality will be poor because of increased nutrient input and greater erosion of soil.

Objective 2: Identify the ability of surrounding land use and landscape variables to predict a full suite of water chemistry variables, including TP, a primary driver of eutrophication, which characterizes water quality in southern MB farm ponds.

Hypothesis: Farm pond water chemistry can be predicted because it is the result of local, measurable land use and landscape influences.

Objective 3: Compare the nutrient limitation prediction in farm ponds based on Redfield N to P ratios from static water chemistry values to that of an integrated *in situ* nutrient diffusing substrata bioassay that monitors algal periphytic growth response.

Hypothesis: Periphyton nutrient limitation based on static measurements of Redfield N to P ratios will be inconsistent with integrated in situ nutrient diffusing bioassays because farm ponds have dynamic water chemistry that varies spatially and temporally.

Chapter 2: Literature Review

2.1 Water Quality

2.1.1 Definition

Water quality encompasses the chemical, physical and biological character of water and is important to define for the protection of water's value and use. In essence water quality is relative and depends largely on who and what is using the water for what purpose. For instance, chlorinated water has exceptional value for drinking and swimming but it is definitely not suited for aquatic organisms. Similarly, surface water that is cold, clear and low in nutrients is ideal for fish species adapted to this environment (e.g., Rainbow Trout, *Oncorhynchus mykiss*) but difficult for species adapted to warmer, turbid waters that are nutrient rich (e.g., Channel Catfish, *Ictalurus punctatus*).

In Canada, the Canadian Council of Ministers of the Environment (CCME) is a national collaboration of federal, provincial and territorial ministers that seeks to collectively protect the environment and has an active role in regulating water quality (CCME 2008). The CCME has come up with the Canadian Environmental Quality Guidelines which includes specific water quality guidelines for human consumption, recreation, aquatic life and agriculture. Together the CCME has worked to facilitate regional and site-specific development and implementation of water quality guidelines.

In Manitoba, water quality is divided into the three tiers of Standards, Objectives and Guidelines (Manitoba Conservation 2002). Standards refer to the standards of waste discharge that can potentially impact surface waters and includes industrial, human and livestock waste. Objectives provide specific levels of variables in surface waters enforced by The Manitoba Environment Act and required to maintain adequate water quality for aquatic life and human use. Guidelines are general numerical and narrative guidelines useful in assessing the value of surface waters for a proposed use.

Although the development and regulation of water quality policy is important it can also be difficult to understand for citizens it largely affects but who lack specialized training. For instance, in recent years there have been numerous cases in Canada where native reserves (e.g., Kashechewan First Nation, 2005) and rural communities (e.g., Walkerton, Ontario, 2000; North Battleford, Saskatchewan, 2001) have had problems with drinking water contamination but have lacked the resources to diagnose and mitigate issues effectively. Similarly, many agricultural producers in Canada find their practices increasingly regulated by environmental policies that are difficult to interpret and yet potentially costly to ignore. An example in Manitoba, which affects hundreds of farmers, is new legislation called the Nutrient Management Regulation which aims to protect water resources by regulating the application and storage of materials containing nutrients (Manitoba Water Stewardship 2008). The creation of Conservation Districts, which help inform the public about environmental stewardship issues, have been helpful in bridging the gap between policy makers and agricultural producers. Furthermore, governing bodies are discovering innovative methods to make water quality accessible and understandable to the public. For example, the Province of Saskatchewan has begun using a report card system which rates water quality based on a number of important criteria such as water clarity, nutrients and the presence of disease causing pathogens (Saskatchewan Watershed Authority 2006). It is undoubtedly easier for the general public to understand an intuitive rating system than numerous values (i.e., pH, turbidity, conductivity) which can cause confusion and result in apathy or unnecessary concern.

2.1.2 What are the Issues?

Surface waters in the northern prairies are becoming increasingly threatened by cultural eutrophication (to the accelerated increase of nutrient levels in a water body caused by human activity) and the input of toxins, pathogens and soluble salts (Chambers 2001). Aquatic ecosystems, while dependent on nutrients, are also highly sensitive to fluctuation in nutrient concentration. Nitrogen and P are of greatest concern because they are the most limiting nutrients in both terrestrial and aquatic environments and therefore initially drive primary production (Wetzel 2001). In ecosystem studies, P has typically been found to be the most limiting nutrient in freshwater under natural conditions (Elsier et al. 1990) and a narrative guideline of < 0.025 mg/L total phosphorus (TP) has been set for lakes, ponds and reservoirs in Manitoba (Manitoba Conservation 2002). There is no current limit for total nitrogen (TN) in Manitoba but N in the form of ammonia, nitrate and nitrite are all considered harmful at elevated levels. Ammonia toxicity to aquatic organisms depends upon pH, temperature and length of exposure. For example, at a temperature of 20°C and pH of 8, ammonia levels < 1.76 mg/L are desirable for cool water aquatic organisms over a 30 day period (Manitoba Conservation 2002). Nitrate and nitrite are considered harmful for human and livestock consumption at levels of 10 and 100 mg/L, respectively (Manitoba Conservation 2002). Collectively, N and P enhancement increases algal growth which can subsequently decrease water clarity, reduce dissolved oxygen concentrations and release harmful algal toxins (Wetzel 2001).

Decreased water clarity is aesthetically unpleasing for recreational use and changes aquatic habitat structure by limiting plant growth and altering predator/prey strategies (Scheffer 2004). In Manitoba, the water clarity guideline for drinking water and aesthetic value has been set at 1 NTU and < 5 NTU, respectively, while the water clarity objectives for aquatic life varies with duration and background turbidity (Manitoba Conservation 2002).

Reductions in dissolved oxygen caused by decomposing algae may lead to fish kills which alters the ecosystem and often removes valuable recreational and commercial fish stock. Desired objectives for dissolved oxygen levels vary depending on life stage and adaptability of aquatic organisms, temperature and duration of time. In general dissolved oxygen levels above 5.5 mg/L are desirable for most freshwater aquatic life and wildlife (CCME 2006).

Algal toxins that target the brain and liver can be deadly to humans, wildlife and domestic animals or have long-term health effects that impede their performance (Codd et al. 2005). The Canadian drinking water limit for the algal toxin microcystin-LR is set at 1.5 µg/L (CCME 2006).

Many disease-causing viruses, bacteria and protozoa enter surface water through human, domestic livestock and wildlife waste (Jones et al. 2002). Fecal coliforms, originating from warm blooded animal feces, are used as an indicator for pathogens because of their ease of detection and high correlation with harmful pathogens. The current limit for fecal coliforms in drinking water and water for irrigational purposes is 0 CFU/100 mL and 200 CFU/100 mL, respectively (Manitoba Conservation 2002).

Soluble salts, including sulphate and chloride, can reach levels where they change the aquatic community, are unpalatable for human and livestock consumption and are harmful to plants during irrigation (Wetzel 2001, CCME 2006). The Manitoba guideline for sulphate concentrations in human and livestock consumption is < 250 mg/L and < 500 mg/L, respectively (Manitoba Conservation 2002). The Manitoba guideline for chloride concentrations in drinking water is < 250 mg/L and for irrigation purposes crops range in tolerance from < 100 to 700 mg/L (Manitoba Conservation 2002). The Manitoba conductivity objective for field and garden irrigation is < 1500 μS/cm (Manitoba Conservation 2002) and the Canadian conductivity guideline for livestock is < 4500 μS/cm (CCME 2006).

2.2 Contribution of Landscape to Water Quality

2.2.1 Hydrology

Surface water quality originates from precipitation and is then determined by its resultant hydrologic pathway controlled by climate and landscape characteristics. South-central Manitoba has a continental climate with warm wet summers and cold dry winters. The average precipitation in south-central Manitoba is around 500 mm with two thirds falling between May and September and 20 to 25% falling as snow in colder months (Blair 1996). Much of the summer precipitation falls from thunderstorm activity (Blair 1996) which can have significant erosive energy as it hits the ground (Troeh and Thompson 2005); however, 80 to 90% of surface runoff in south-central Manitoba is due to snow melt (Nicholaichuk 1967, Green and Turner 2002, Glozier et al. 2006, Sheppard et al. 2006). Snowmelt moves slower than rainfall across the land which, in turn, increases the interaction between any unfrozen surface soil layers and water. Flooding is common in south-central Manitoba because the landscape is typically level with occasional sandy ridges and valleys. The water table stays fairly constant in the winter because of frozen ground conditions but tends to increase in fall and spring due to precipitation and snow melt, respectively. During summer months in the northern prairies a high degree of evapotranspiration compared to precipitation causes the water table to subside. The combination of a lower water table and upward hydrologic pull from evapotranspiration decreases the opportunity for nutrients to leach through the soil substrate (Troeh and Thompson 2005).

2.2.2 Soil

South-central Manitoba has alkaline soils that are typically high in calcium and magnesium content and vary in soil texture. Soil texture largely determines nutrient retention, water infiltration and erosion potential (Troeh and Thompson 2005). Fine textured soils hold nutrients better due to increased surface area which allows more contact for nutrient binding (Troeh and Thompson 2005). Fine textured soils also tend to have poor water infiltration due their smaller size and subsequent tendency for soil material to pack closely together. Poor water infiltration combined with low slope can lead to flood conditions where soil water becomes anoxic and alters the chemical stability of nutrients such as P (Troeh and Thompson 2005). In New York State, Young and Ross (2001) found flooded soils increased the soluble P concentration in flood waters by up to 3.6 times. During dry conditions, however, fine textured soils are prone to cracking which can lead to rapid preferential water flow through the surface cracks. Indeed, preferential flow can be an issue in any soil texture when there is the presence of cracks, worm holes or other macropores (Leinweber et al. 2002). Dils and Heathwaite (1996) found concentrations of P > 1 mg/L in preferential flow through macropores in agricultural grasslands of the UK. Fine textured soils are detached easier than coarser soils making them vulnerable to soil erosion and subsequent loss to surface waters where they can potentially deposit their nutrient load (Nelson and Logan 1983, Haygarth and Sharpley 2000).

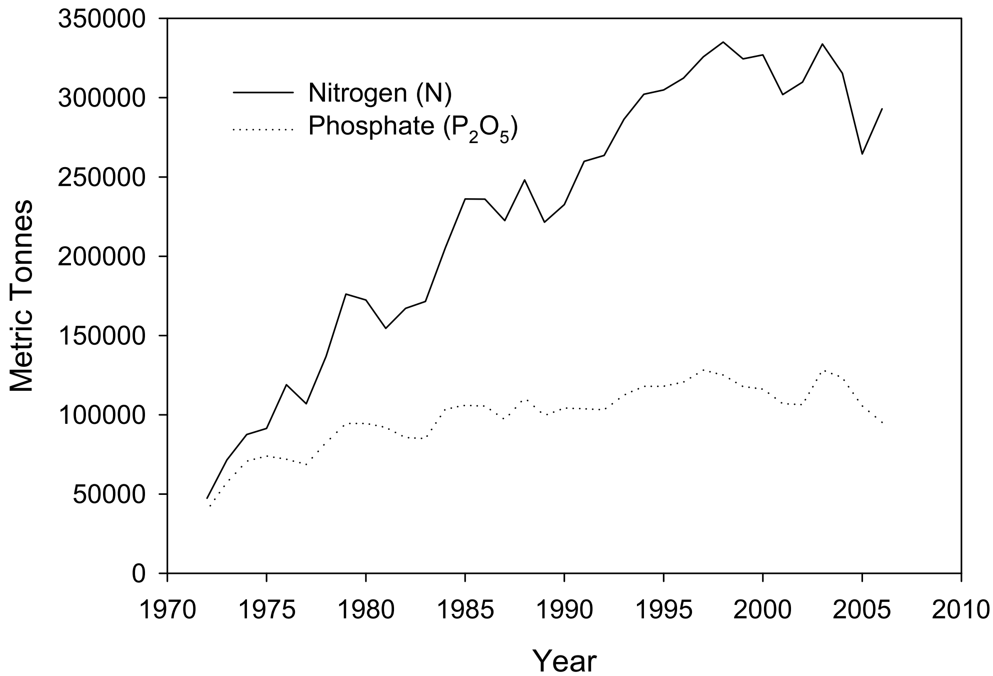
2.2.3 Vegetation

Vegetation on the landscape can influence surface water by altering surface and groundwater flow and by the direct release and uptake of nutrients (Leinweber et al. 2002). Vegetation decreases the erosive impact of precipitation by preventing rainfall from hitting the soil surface and also holding the soil together through complex root systems (Troeh and Thompson 2005). Natural prairie or forest vegetation is more preventative of soil erosion than row crops because less soil is exposed and the soil structure has not been compromised (Troeh and Thompson 2005). Cooke and Prepas (1998) in central Alberta studied watersheds in a low sloping Boreal Plain region and found agricultural watersheds contained over twice the total P load and ten times the dissolved inorganic N load as forested watersheds in stream surface waters. Similarly, Vuorenmaa et al. (2002) in Finland found runoff from agricultural watersheds had over eight times the total P load and over twice the total N load of forested watersheds. While actively growing, vegetation draws soil water up to the surface via evapotranspiration and withdraws nutrients via absorption (Nash et al. 2002). Vegetation slows the flow during surface runoff and acts as a filter to hold onto particulate matter. While erosion protection is important in humid climates it is less imperative in southern Manitoba’s semi-arid climate where snowmelt runoff over frozen soils is predominant and slope is minimal in most regions (Nicholaichuk 1967, Cooke and Prepas 1998). Indeed, in Manitoba, vegetation can be more of a nutrient source because vegetation releases nutrients into snowmelt runoff during freeze-thaw and drying conditions. Under freeze-thaw conditions in a controlled environment Bechmann et al. (2005) found that ryegrass contributed up to 9.7 mg/L of dissolved P to surface water runoff compared to 0.18 mg/L for manured soils and 0.14 mg/L for bare soils. Similarly, in a controlled environment, Miller et al. (1994) found three cover crops (ryegrass, red clover and oilseed radish) that had been dried and frozen lost biomass P and N at rates of up to 30% and 10%, respectively, in a dissolved form.

2.3 Contribution of Agricultural Land Use to Water Quality

2.3.1 Fertilizer Application

In contrast to natural nutrient cycling, industrial agricultural requires the application of mineral or manure fertilizer to maximize production and replenish exported nutrients. In Manitoba N and P are the most common fertilizers and are applied mainly as liquid pig manure, solid cattle manure or liquid and granular synthetic commercial fertilizer. In Manitoba alone, synthetic N and P fertilizer application has increased by four-fold and two-fold, respectively from 1972 to 2006 (Figure 2-1). Fertilizer application has leveled off in the last few years perhaps in part to sharp increases in fertilizer costs over the last decades (Statistics Canada 2007) and growing concern of surface water contamination (Chambers 2001).



Source: Agriculture and Agri-foods 2002, Canadian Ferilizer Institute 2007

Figure 2-1. Synthetic N and P fertilizer application in Manitoba from 1972 to 2006.

The potential for surface water contamination by fertilizers depends largely on soil conditions, quantity of fertilizer and mode and timing of application. Indeed, moderate fertilizer applications have been shown to decrease environmental nutrient loss by increasing the efficiency of plant uptake and improving the quality of the soil (Eghball and Power 1998). Soil conditions were previously alluded to and affect fertilizer loss by controlling water infiltration and nutrient binding capacity. Applying fertilizer on coarse soils can lead to leaching especially if coupled with a high water table (Sharpley et al. 2001a) which is common to southern Manitoba in spring and fall. Howarth et al. (1996) found N losses to leaching ranged from 25 to 80% for sandy soils compared to only 10 to 40% on clay and loamy soils. Fertilizer loss through preferential flow (i.e., cracks, macropores and subsurface drainage) can be substantial on any soil texture and must be taken into consideration (Simard et al. 2000, Sharpley et al. 2001a). Many studies have acknowledged a strong correlation between soil P concentrations and soil P release and a threshold soil P concentration at which the rate of P release increases substantially. This threshold value known as the "change point" differs depending on soil type and chemistry (Sharpley et al. 2001a, Leinweber et al. 2002). McDowell et al. (2001) studied soils from the USA, New Zealand and the United Kingdom and found significant correlation ($p < 0.05$) between soil test P and soil release of P and significant change points in 14 of the 18 soils. Soils where no change point was recognized were found to have either very low or high P saturation and were thus grouped below or above, respectively, the existing change point. For this reason it is important to monitor soil nutrient conditions and avoid over application of fertilizer. Applying fertilizer on the surface of the soil increases the chance of nutrient runoff, especially on frozen soils, and increases the possibility for N loss to the atmosphere via denitrification and volatilization (Sharpley et al. 2001a). Ideally fertilizer is incorporated into the soil during active plant uptake so crops can immediately benefit from them before they are lost due to leaching, chemical transformation or precipitation (Sharpley et al. 2001a). Daverende et al. (2004) observed significantly more ($p < 0.05$) TP runoff from surface applied fertilizer compared to incorporated fertilizer after one month of application.

Nitrogen is generally the most limiting nutrient for terrestrial plants and is therefore commonly applied as fertilizer. Nitrate-N is the most accessible form of N for plants to take up because it is highly soluble and does not easily bind to soil material. The high mobility of nitrate also increases the risk of environmental loss via surface and subsurface runoff because it moves readily over and through soil without being adsorbed. Both liquid pig manure and synthetic fertilizers contain high amounts of N that is either readily available to crops as nitrate or in a form that is easily transformed into nitrate-N (i.e., ammonia-N or urea-N) (Troeh and Thompson 2005). Solid manure fertilizer is high in organic N which is less susceptible to movement through the soil but consequently less readily available for plant uptake (Troeh and Thompson 2005).

Phosphorus is vital for crop production, yet its low solubility makes it difficult to obtain and requires the addition of P fertilizer to provide plant available P during initial crop growth. The low solubility of P limits the loss of soluble P through subsurface or surface pathways. For this reason, particulate P loss (granular P or P bound to soil and organic matter) via soil erosion is typically documented as the greatest threat to surface waters in regions where rainfall driven runoff events predominate (Sharpley et al. 2001a, Leinweber et al. 2002). In south-central Manitoba, however, runoff is dominated by spring snowmelt over low sloping frozen soils and soil erosion appears to have less influence (Salvano and Flaten 2006). Instead, fertilizer application on top of frozen soils and the extended soil interaction during flooded conditions seems to cause particular risk of P loss, much of which is in soluble form (Sharpley et al. 2001b). Green (1996), in central Manitoba, found surface water TP concentrations during spring runoff to be 320 to 357 times greater in fields where hog manure was spread over the snow (0.353 to 0.393 g/m^2) than fields absent of manure application (0.0011 g/m^2). In Minnesota, with a similar climate to Manitoba, Gessel et al. (2004) found fall incorporated manure applications did not increase TP levels in spring runoff but increased the proportion of dissolved phosphorous from 3% without manure application to 8 and 20% after one and two times the suggested agronomic manure application rate, respectively. There was no further difference between summer proportions of dissolved

P amongst the non-manured and manured soils. In Minnesota, Young and Mutchler (1976) found losses of orthophosphate up to 16% after manure application on frozen soils and only 4% losses were from fall application of manure that was incorporated into the soil. Phosphorus is vulnerable to loss under flooded, anaerobic conditions because its solubility increases (Sharpley et al. 2001a, Young and Ross 2001, Leinweber et al. 2002). Soluble P loss is of particular concern because it is readily available for algal uptake.

Manure fertilizer poses a unique threat to surface water because of mass quantities produced and its variable nutrient content. The utilization of feed N in beef and dairy cattle is about 15 to 30% and 35 to 40%, respectively (Galloway et al. 2003) and feed P uptake of cattle in general is around 30% (Sharpley et al. 2001a) with the remaining nutrients being released again as waste. The growing intensification of livestock operations has dramatically increased the amount of manure and the need for responsible manure management. In Manitoba alone there is currently 29 million chickens, 3 million hogs and 2.1 million cattle (Statistics Canada 2007). There has been a consistent increase in hog production in Manitoba since 1975 and a similar trend in beef cattle since the 1980s (Figure 2-2).The nutrient content of manure is variable but the ratio of N to P is consistently lower than what is required for plant uptake and thus P is always added in surplus (Chadwick and Chen 2002). The common N to P ratio needed for crop uptake is 6 to 1 yet the ratio is between 2 and 4 to 1 for most livestock manures (Table 2-1) indicating an excess of P must be added to meet N requirements using manure fertilizer exclusively. Phosphorus surplus is typically not a concern because of its low solubility (Troeh and Thompson 2005); however, if manure is applied upon frozen soils, under waterlogged conditions or beyond P retention capacity there is a high likelihood of soluble P transfer to surface water (Young and Mutchler 1976, Green 1996, Chadwick and Chen 2002, Gessel et al. 2004). Manure is often applied at rates to fulfill plant N requirements and thus P levels will inevitably build to the point of saturation and become at greater risk of leaching (Chadwick and Chen 2002). In Alberta, after 16 years of feedlot manure application at varying rates (0, 30, 60, 90 Mg/ha in non-irrigated and 0, 20, 120 and 180 Mg/ha in irrigated plots), Whalen and Chang (2001) observed an increase in total soil P in the top 150 cm from 1.2 to 3.8 Mg/ha for non-irrigated plots and from 1.9 to 5.9 Mg/ha in irrigated plots. As well, over time the proportion of manure P accounted for in the top 15 cm of soil decreased and there was an increasing trend of manure P recovery in the 15 to 60 cm and 60 to 150 cm soil layers especially after higher manure applications suggesting possible leaching of manure P. In irrigated plots where 60, 120 and 180 Mg/ha of P were added, 7, 12 and 15% of manure P was unaccounted for, respectively, indicating there was possible loss of P through surface runoff or leaching beyond the 150 cm soil sample.

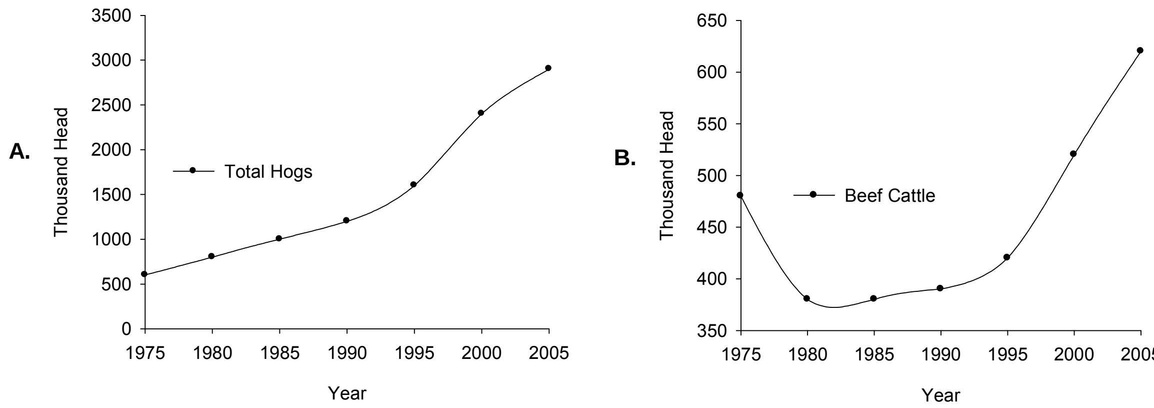


Figure 2-2. Total **A)** hogs and **B)** beef cattle present in Manitoba during five year intervals from 1975-2005.

Table 2-1. Average N and P content for various types of livestock manures (Flaten et al. 2007).

Operation Type	Dry Matter	Total N mean (range)	Ammonium-N Mean (range)	Available N	Total P mean (range)	Ratio Total N to Total P	Ratio Available N to Total P
	%		Kg/1000L		kg/1000L		
Liquid Pig (n=133)	3.4	3.1 (0.4-6.8)	1.9 (0.2-5.2)	1.2	1.0 (0.0-5.1)	3.1	1.2
Liquid Poultry (n=35)	9.1	8.0 (3.0-14.2)	5.8 (0.1-10.5)	3.8	2.8 (0.6-5.1)	2.9	1.4
Liquid Dairy (n=252)	8.9	3.4 (0.7-7.6)	1.5 (0.0-7.2)	1.0	0.9 (0.1-8.5)	3.8	1.1
Solid Beef (n=45)	26.4	6.0 (1.4-20.2)	0.6 (0.6-2.7)	0.4	1.4 (0.3-6.4)	4.3	0.3

Note: P is expressed as elemental P, not P2O5 as in fertilizer analyses; Available N (calculated for average values only) = NH4-N x 0.65 (35% average ammonia loss for incorporation within 3 days which equals loss if applied to standing crop) + 0.25 Organic N (25% of organic N); N:P calculated for average values only.
Source: Tri-Provincial Manure Application and Use Guidelines (2003)

Aside from intentional manure application, there is also the risk of water contamination from livestock grazing around surface water. Research indicates that cattle spend a proportionally high time around water sources and riparian area (Pinchak et al. 1991, Kie and Boroski 1996). In Wyoming during the grazing season, Pinchak et al. (1991) observed cattle spent 77% of their time within 366 m of water while the random expected time was 11% ($p < 0.01$). The presence of livestock around water increases the risk of harmful pathogens being transferred from livestock waste to water (Graczyk et al. 2000) and the chance of nutrient input via direct deposition or runoff from the landscape. In a controlled setting Muirhead et al. (2005) found livestock fecal patties could potentially contribute significant amounts of *E. coli* into runoff for up to 30 days. *Cryptosporidium parvum* is a harmful pathogen common to livestock and humans and transmitted via a spore stage called an oocyst. Studies by Atwill et al (2006) across a wide range of climates in the U.S. have found a range of 1.3 to 3.6 oocytes per gram of cattle feces. Line et al. (2000) detected significant reductions ($p < 0.05$) of total Kjeldahl N, TP and sediment loads of over 75% after the exclusion of cattle from a 10 to 16 m riparian corridor along a small North Carolina stream. In central Alberta, Cooke and Prepas (1998) found mixed agricultural watersheds with livestock farming had comparatively high dissolved P concentrations in surface waters compared to watersheds that were solely cropland or forested. The mixed agricultural watershed contained dissolved P levels nine times and four times the concentration of forested and cropland watersheds, respectively, on landscape very similar to southern Manitoba.

2.3.2 Physical Alteration

During agricultural production the landscape is inevitably altered and, in turn, affects surface runoff and overall water quality. In agricultural regions wetland areas are drained to reclaim land for crop production and livestock grazing. It is estimated that 70% of the original wetlands have been altered or drained in the central prairies region of Canada and approximately 85% of all wetlands in Canada were drained for agricultural purposes (Cox 1993). In low sloping landscapes, wetlands allow much of the precipitation to remain on the land and often provide a sink for nutrient uptake (Mitsch and Gosselink 2000). With the removal of these wetlands, water is diverted using extensive drainage systems which quickly move excess precipitation off the landscape. The rapid movement of water across arable land increases the potential for erosion and prevents the former uptake of nutrients via wetland systems. The erosive potential is intensified by the removal of vegetation during harvest and grazing and the poor soil structure caused by land tillage (Troeh and Thompson 2005). Green and Turner (2002) found significantly higher ($p < 0.05$) suspended solid concentrations in southern Manitoba from a conventional-till field in comparison with zero-tillage, forage and wooded land. Compaction of the soil from heavy machinery and intensive livestock grazing also limits the ability of water to infiltrate the soil (Troeh and Thompson 2005).

2.3.3 Chemical and Mechanical Manipulation

As a means of improving farm pond function landowners may use chemical and/or mechanical treatments to remove nutrients, algae and submerged macrophytes. The chemical treatments include herbicides (i.e $CuSO_4$), P precipitators (i.e., $AlSO_4$) and light interceptors (i.e., aquashade); however, none of the treatments actually remove nutrients from the pond and there is always the risk of additional toxic effects on non-target organisms (Bronmark and Hansson 1998). In contrast, mechanical treatments include raking submerged macrophytes and dredging the top layer of sediment which can effectively remove nutrients from the pond but also completely disrupt the existing ecosystem (Bronmark and Hansson 1998). In a survey of 99 farm ponds in southwestern Manitoba in 1995, 63% of landowners acknowledged using herbicides, 8% had removed macrophytes mechanically and 17% had dredged their pond (Jones et al. 1998a).

2.4 Primer on Shallow Lake Ecology

2.4.1 General Lake Ecology

The chemistry of water in lakes is influenced greatly by climate and depth of the water column. Northern temperate water bodies are usually ice covered in winter and have open water in spring, summer and fall. Larger and deeper lakes in this region are considered dimictic because the chemical constituents of the water column mix twice throughout the year driven by sudden seasonal temperature changes (Wetzel 2001). This mixing occurs in spring after ice melt and once again in fall when there is little temperature differences throughout the water column. Throughout most of the summer a thermocline (middle layer in the water column where the rate of change of water temperature is at a maximum) develops which forms an impermeable boundary for chemical mixing (Wetzel 2001). The bottom of the lake is cold water rich in nutrients and low in oxygen. The surface waters tend to be warmer, nutrient limited and oxygenated by wind mixing and diffusion from the atmosphere (Wetzel 2001). Shallow lakes differ from deep lakes in that they are polymictic (mix many times), have good light penetration to the bottom, and are normally eutrophic (nutrient rich) to hypereutrophic (very nutrient rich) (Scheffer 2004). Shallow lakes are considered polymictic because their shallow depth prevents a substantial thermocline from developing during open water seasons and allows the lake to mix during heavy wind events. This continual lake mixing cycles nutrients and oxygenates the lake bottom promoting primary growth and decomposition, respectively. Light penetration to the bottom sediment encourages rooted macrophyte growth which, subsequently, affects the influence of wind mixing. The role of periphytic (surface dwelling) algae is often more active in shallow lakes than in deeper lakes where phytoplankton (free-floating) algae completely dominate (Goldsborough and Robinson 1996, Liboriussen and Jeppesen 2003). Shallow lakes have a high ratio of surface area and perimeter area to volume and are therefore more susceptible to land use and atmospheric influences.

The past few decades have seen the development of the shallow lake theory of alternating stable state equilibria (Scheffer 2004) which explains the tendency of shallow lakes to switch between being clear with abundant submerged macrophytes covering the basin or turbid with a dominance of phytoplankton. Generally the greater the amount of nutrients available in the water column the more chance there is that the turbid, phytoplankton state will be present. The switching between states often occurs after a severe event such as a large drawdown of water level, introduction of new fish species or physical removal of macrophytes during a storm. The submerged macrophytes out compete phytoplankton by taking up nutrients from the water column, preventing resuspension of sediment nutrients and sheltering zooplankton from fish. More recently this theory has been adjusted to account for other complexities that can not be accounted for by the initial model (Scheffer and Van Nes 2007). It is now acknowledged that variation among shallow lakes in climate, nutrients, depth and lake size also contribute to alternative regimes. For instance a small, shallow lake in a northern temperate climate will be more susceptible to dramatic fish kills from low oxygen concentrations under the ice. Likewise lakes in milder, coastal climates are more susceptible to storm driven catastrophic events that remove vast amounts of submerged vegetation.

2.4.2 What is a Farm Pond?

Farm ponds are usually developed exclusively for agricultural purposes and differ from shallow lakes in that they are normally smaller and more prone to temperature driven stratification. Ponds are typically defined either as being smaller than 0.1 km^2 (Kalff 2002) or as being a water body where gentle temperature-induced mixing is more prevalent than wind driven mixing common to larger water bodies (Bronmark and Hansson 1998). Farm ponds are similar to shallow lakes; however, they are more likely to stratify because of a smaller fetch size and they have an even greater ratio of perimeter area to surface area and volume suggesting increasing vulnerability to surrounding land use impacts. Due to their shallow nature, prone to desiccation and anoxic conditions, farm ponds are unlikely to have fish in them which, subsequently, limits zooplankton predation and thereby promotes clear water conditions where submerged macrophytes can flourish. As a whole these ponds are utilized for many human purposes including human and livestock consumption, irrigation, mixing chemicals and aesthetic enhancement. Farm ponds also provide valuable habitat for a diverse group of flora and fauna (Oertli et al. 2002).

2.4.3 What are the Issues in Farm Ponds?

Water quality concerns in farm ponds is the same in surface waters collectively and includes eutrophication, algal toxins, harmful conductivity levels, high turbidity levels and disease causing pathogens. Farm ponds are particularly vulnerable to eutrophication because they are located in agricultural areas where manure and/or fertilizer are present. The build up of algae and plants in the water increases the effort of pumping and/or treating water for irrigation and consumption purposes. As well, livestock have been killed by consuming large concentrations of algal toxins. In Manitoba, the earliest records of animal death by algal ingestion were in 1951 (McLoed and Bondar 1952) where a horse and nine dogs died from drinking water out of Dauphin Lake. High conductivity levels in water affects the palatability for cattle (Petersen 1999) and reduces the value for irrigation purposes (Manitoba Conservation 2002). Turbid water is less desirable for livestock, more difficult to filter and greatly increases the ability of harmful pathogens to multiply (EPA 1999). The fixed presence of livestock and the practice of manure spreading increases the likelihood of fecal pathogens ending up in the water. A Manitoba study by Jones et al. (1998b) revealed 20% of 58 untreated dugouts and 13% of 16 recreational water bodies sampled in August had fecal coliform counts exceeding 200 CFU/100 mL.

2.5 Comparative Studies

2.5.1 General

There have been numerous large watershed studies regionally that have raised awareness of agricultural impacts on surface waters as a whole. Jones and Armstrong

(2001) identified significant trends ($p < 0.05$) of increasing N and P concentrations in most rivers draining agricultural land in southern Manitoba from the mid 190s to late 1990s. Salvano and Flaten (2006) found that TP concentrations in 14 watersheds of southern Manitoba were significantly correlated ($p < 0.001$) with soil P values and not significantly correlated with soil erosion risk. Overall, soil test P accounted for 63% of the variation in TP concentrations measured in streams draining the watersheds. Salvano and Flaten (2006) concluded that in Manitoba's landscape and climate it is vital to consider source factors such as soil P levels rather than focus heavily on transport factors such as erosion risk and runoff potential that are more of a concern in warmer humid climates. In this study TP concentrations were also found to be significantly correlated ($p < 0.05$) with agricultural capability of the land (ranked classification), agricultural land use (%), crop production (%), livestock intensity (AU/ha) and manure and synthetic fertilizer application (kg/ha). Cooke and Prepas (1998), in a low sloping Boreal region of central Alberta, found that mixed agriculture and cropland watersheds provided nine times and two times, respectively, the amount of total dissolved P (TDP) than two forested watersheds of similar size. In this study 75 and 90% of TP in runoff was TDP in mixed agriculture and cropland watersheds, respectively. In contrast, less than 50% of the TP was dissolved P (DP) in the forested watersheds. As well, the agricultural watersheds exported up to 50 times more total inorganic N than the forested watersheds. Interestingly, 98% of the total inorganic nitrogen (TIN) from the cropland was nitrate and 94% of the TIN from the mixed agricultural watershed was in the ammonia form. Green and Turner (2002) in a four year study found that nutrient runoff in southern Manitoba was largely controlled by spring snowmelt conditions. During 1998 with a large amount of spring snowmelt a field with fall surface applied and incorporated manure had over four times the nutrient loss (kg/ha) as conventional till and zero-till fields that were fertilized with injected inorganic fertilizer. However, in the three other years of study there was very little runoff from the manured field and, subsequently, little nutrient loss comparative to the conventional and zero-till fields with greater runoff volumes. A recent study by Pip (2005) looked at whether differences in surface water quality in Manitoba could be estimated by surrounding land use. This study broadly covered all of Manitoba, included lakes, rivers, streams and ponds and examined total dissolved solids, nitrate-N, Cd, Pb Cu, and ultraviolet absorption. In the southern floodplain and southwest region of Manitoba ($n = 96$) streams and ponds had the highest levels of parameters and this region had the greatest amount of agricultural land use and the least amount of minimal impact sites. In particular, surface waters in southern Manitoba were found to be high in total dissolved solids and nitrates and a significant correlation ($p < 0.001$) was found between those variables within this region.

2.5.2 Farm Pond Specific

Globally there is increasing interest in land use impacts on farm pond water quality and perhaps the largest study to date was accomplished by Declerck et al. (2006) in Belgium. Declerck et al. (2006) studied land use impacts on water quality and vegetation with 126 farm ponds evenly distributed throughout Belgium. Via multivariate redundancy analysis they found that cattle trampling and percent of surrounding crop land was negatively correlated with clear water conditions and that percent forested land was positively correlated. Multiple regression showed a further damaging impact of cattle trampling and surrounding crop land to in-pond vegetative complexity. The research of

Declerck et al. (2006) is markedly similar to this study; however, it was accomplished in a region very different in climate, landscape and anthropogenic history.

In the north temperate prairie region of Canada, farm pond water quality studies have been limited, but include intensive studies on small subsets of ponds (Reedyk et al. 2000, Leclair 2004), general surveys (Jones et al. 1998b, Pip 2005) and focused studies of herbicide (Cessna and Elliott 2004) and algal toxin occurrence (Kotak et al. 1993, Jones et al. 1998b). In 1995, a two-year survey study was undertaken by Manitoba Environment to examine surface waters in southern Manitoba (Jones et al. 1998b). In 1995, the study examined 113 farm dugouts and 16 recreational water body sites for pesticides, bacteria, algae, trace metals, nutrients and general chemistry. This was a broad survey study limited to one August water sample from each site. Of the 113 farm dugouts 58 were untreated and used for livestock and human consumption. Multivariate analysis of the water chemistry with water-use revealed the 58 untreated pond sites to be strongly associated with high nutrients and algal production (chlorophyll *a*). In 1996 the same sites were monitored for the algal toxin microcystin-LR and 70% of the dugouts had detectable levels. The maximum microcystin values found in the dugouts were 1.0 µg/L with a median value of 0.2 µg/L. In this study microcystin concentration was not found to be directly correlated with algal biomass. Reedyk et al. (2000) examined 14 untreated farm ponds in Northern Alberta that were not directly accessed by livestock but used for human and livestock consumption. The ponds were monitored over two years (at least one sample per season) and found concerning levels of fecal coliforms (present in 80% of the ponds at least once during sampling, max = 32 CFU/100mL), chlorophyll *a* (max = 104 µg/L) and total phosphorus (max = 1.220 mg/L). Kuharski (2002) sampled a farm pond near the south basin of Lake Manitoba twice in summer of 2001 and found elevated levels of total Kjeldahl nitrogen (maximum 10.5 mg/L), ammonia (maximum 4.155 mg/L), total reactive phosphorus (max = 6.675 mg/L), turbidity (maximum 26 NTU), fecal coliforms (max = 613 CFU/100 mL) and conductivity (maximum 2728 µS/cm) which then initiated a more comprehensive farm pond study in 2003 (Leclair 2004). Leclair (2004) researched 35 farm ponds in southern Manitoba affected by varying intensities of cattle access and discovered higher concentrations of nutrients, total chlorophyll, turbidity, and fecal coliforms corresponded with greater intensities of cattle access ($p > 0.05$). These regional studies (Kotak et al. 1993, Jones et al. 1998b, Kuharski 2002, Leclair 2004) have raised awareness and provided the incentive to undertake this study and further understand land use and landscape impacts on farm pond water quality.

Chapter 3: Land use and landscape prediction of farm pond water chemistry

3.1 Introduction

Surface water chemistry in farm ponds is affected primarily by surface and subsurface runoff and therefore intrinsically shaped by surrounding land use and landscape properties (Davies et al. 2004, Fairchild et al. 2005, Declerck et al. 2006). Understanding the impacts of non-point source agricultural pollution on surface water is vital in suppressing an influx of nutrients and pathogens that threaten freshwater resources (Carpenter et al. 1998, Sharpley et al. 2001a). This study examines the predictability of water chemistry from surrounding land use and landscape variables in order to apply this knowledge to both a farm and larger watershed scale (De Meester et al. 2005). The primary objectives were:

Objective 1: Determine the impact of surrounding land use and landscape variables on water quality in southern MB farm ponds

Hypothesis: In areas of high agricultural intensity, water quality will be poor because of increased nutrient input and greater erosion of soil.

Objective 2: Identify the ability of surrounding land use and landscape variables to predict a full suite of water chemistry variables, including TP, a primary driver of eutrophication, which characterizes water quality in southern MB farm ponds.

Hypothesis: Farm pond water chemistry can be predicted because it is the result of local, measurable land use and landscape influences.

3.2 Methods

3.2.1 Study Area

South-central Manitoba is mainly level landscape with occasional river valleys and sand ridges (Welsted et al. 1996). Before European settlement, south-central Manitoba was predominantly unforested prairie with abundant wetlands and the seasonal home to thousands of bison and numerous aboriginal groups (Nicholson 1996, Hanuta 2006). This region has an extreme continental climate with average daytime highs of 26 C in July and -12 °C in January (Blair 1996). Annual precipitation is approximately 500 mm with 25% of falling as snow during freezing conditions and an overall precipitation deficit (Blair 1996). The first Europeans arrived in Manitoba in the early 1600s for the fur trade, yet it was not until the 1870s that extensive European agricultural communities formed in southern Manitoba (Coates and McGuinness 1987). In the last 135 years, south-central Manitoba has seen dramatic human alteration of the landscape. Wetlands were drained, bison were eliminated and the prairies were quickly cultivated or used for domestic livestock grazing (Van Der Valk 1989, Hanuta 2006).

The study area is the La Salle-Redboine Conservation District (Figure 3-1) which covers 7000 km^2, has a population of approximately 37 000 people and the main industry is agriculture with predominant focus on beef cattle, cereal and oilseed farming (Statistics Canada 2001). This area was chosen for its proximity to the lab facilities at Delta Marsh Field Station and because of a strong working relationship with personnel of the La Salle-Redboine Conservation District and Manitoba Agriculture, Food and Rural Initiatives (MAFRI) in Portage la Prairie. Most of the ponds sampled were on private land so it was invaluable to have collaborative partners that had prior relationship with the landowners.

Some sites were selected by the La Salle-Redboine Conservation District which surveyed topographic maps and then contacted the appropriate landowners. Other sites, including six outside the La Salle-Redboine Conservation district, were selected via a MAFRI representative and chosen based on landowner interest in participating. After gaining permission from the landowners to sample their ponds we inspected the sites and chose sites that ranged widely in diversity of landscape and land use (Figure 3-2). In total, 59 ponds were sampled over two field seasons between 2005 and 2006. The ponds selected ranged in surface area from 374 to 6250 m^2 with an overall mean of 1648 m^2. Within a 250 m radius of all the ponds selected some degree of livestock activity and crop production was present in 92% and 72%, respectively. The slope around the ponds was variable, with 73% having less than 2% grade and 8% of the ponds having a slope greater than 5% grade.

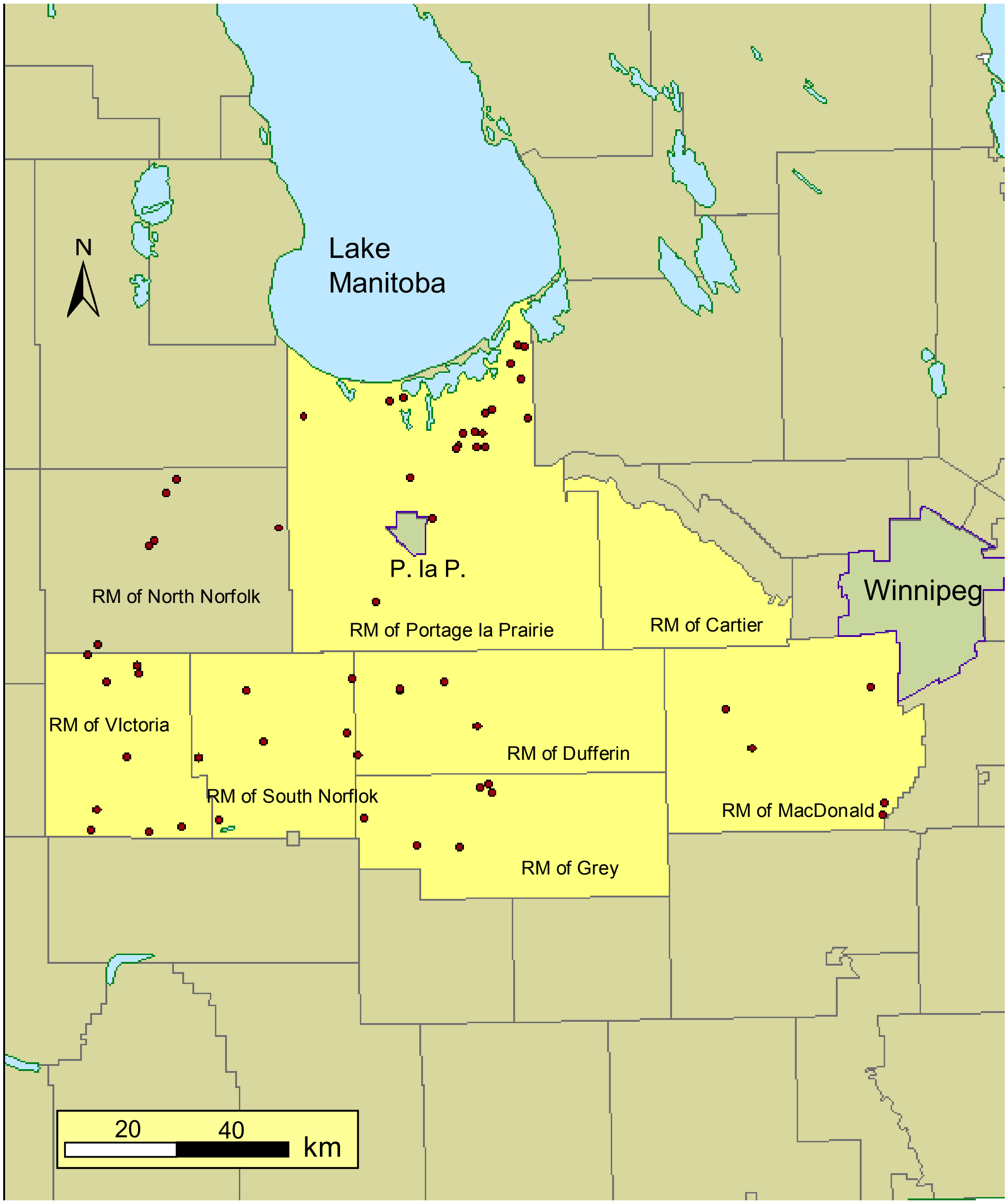


Figure 3-1. All 59 farm pond study sites (red dots) in relation to La Salle-Redboine Conservation District (central lightly shaded area). Note: For geographical coordinates of sites see Appendix B.

Site 29

Site 45

Site 7

Site 36

Site 18

Site 30

Figure 3-2. Examples typical of the farm ponds sampled during the study.

3.2.2 Water Quality

Ponds were sampled once every three weeks in a set schedule from early May to late August of 2005 and 2006 (Table 3-1). *In situ* sampling included total depth in pond center, Secchi depth, surface conductivity, dissolved oxygen concentration (2006 only), water and air temperature, and wind speed (Table 3-2). Integrated water column samples were collected from a central location in the pond using a 1.3 m clear acrylic tube (6.3 cm diameter, 1 m length) and filling a 1 L polypropylene bottle. In addition, an 80 mL surface water sample for the purpose of sodium, potassium and microcystin analysis was taken at the same location by submerging a 100 mL brown PVC bottle to a depth of about 10 cm below the surface and frozen until analysis. A subset of 24 farm ponds chosen by MAFRI was analyzed for fecal coliforms up to three times during 2005. An additional subset of 20 farm ponds, chosen randomly from sites not sampled in 2005, was sampled twice in 2006 (Table 3-2). All water samples were taken in the morning or early afternoon and stored in coolers with ice packs until they could be analyzed by late afternoon in the lab.

In the lab, the 1 L water samples were analyzed for pH, alkalinity, turbidity, total suspended solids, chlorophyll *a*, total reactive P (TRP), total P (TP), total N (TN) and ammonia-N (Table 3-2). The TRP was measured instead of soluble reactive P (SRP) due to the close relationship observed in prior research (Morris and Lewis 1988, Axler et al. 1994, Francoeur et al. 2003). A 20 mL of frozen filtrate (Whatman GF/C) sample was later analyzed in the fall for nitrate and nitrite-N, chloride and sulphate using ion chromatography (Table 3-2). In 2005 a Dionex AS4A column was used for analysis and it was replaced by a Dionex AS11 column in 2006. Data for 2005 are suspect because the changing of the columns led to some discrepancy in nitrate and nitrite-N values (see appendix A). Dissolved organic carbon (DOC) concentration was analyzed via ultraviolet spectroscopy (Table 3-2) using filtered sample (Whatman GF/C). The 80 mL samples were frozen and analyzed in the winter for potassium, sodium, and the algal toxin microcystin (Table 3-2).

Table 3-1. Range of dates corresponding to each sample round in 2005 and 2006.

Sample Round	2005	2006
1	May 24 – June 9	May 15 – 31
2	June 13 – 29	June 5 – 21
3	July 4 – 21	June 26 – July 12
4	July 25 – August 10	July 17 – August 2
5	August 15 – 30	August 8 – 22

Table 3-2. Water chemistry methods.

Parameter	Method	Reference	Detection Limit
General Chemistry and Nutrients			
Alkalinity	Acid titration colorimetric	(APHA 1998)	20 mg/L
Ammonia-N	Phenolhypochlorite colorimetric	(Stainton et al. 1977)	0.01 mg/L
Carbon– Dissolved Organic	Ultraviolet spectrophotometry	Pascal Badiou unpublished	
Chloride	Ion Chromatography; Dionex DX500ic with AS4A and AS11 column		0.1 mg/L
Conductivity	YSI model 85 portable meter		± 5% full scale
Nitrate-Nitrite-N Soluble	Ion Chromatography; Dionex DX500ic with AS4A and AS11 column		0.01 mg/L
Nitrogen-N Total	Persulphate digestion colorimetric using HACH Kit	(APHA 1998)	0.025 mg/L
Oxygen- Dissolved	YSI model 85 portable meter		± 0.3 mg/L
pH	Electrometric corning ion analyzer 250 pH Meter		0.1
Phosphorus – Total	Persulphate digestion colorimetric using HACH Kit	(APHA 1998)	0.025 mg/L
Phosphorus - Total Reactive	Acid molybdate colorimetric	(Stainton et al. 1977)	0.01 mg/L
Sulphate- Soluble	Ion Chromatography; Dionex DX500ic with AS4A and AS11 column		0.1 mg/L
Total Suspended Solids	Gravimetric	(APHA 1998)	1 mg/L
Turbidity	Nephalometric using Hach 2100A turbidimeter	(APHA 1998)	± 2% full scale
Biological Variables			
Chlorophyll-*a*	Spectrophotometric	(Marker et al. 1980, McDougal 2001)	0.1 µg/L
Microcystin (all congeners)	Protein Phosphatase Inhibition ELISA	(An & Carmichael 1994)	0.1 µg/L
Total Coliform	Membrane Filter and Multiple-tube Fermentation	(APHA 1998)	<3 CFU/100 mL
Fecal Coliform	Membrane Filtration	(APHA 1998)	<3 CFU/100 mL
E.Coli	Membrane Filter and Multiple-tube Fermentation	(APHA 1998)	<3 CFU/100 mL
Trace Ions			
Magnesium	Ion-specific electrode (Denver #300741.0)		1 mg/L
Potassium	Ion-specific electrode (Denver #300744.0)		1 mg/L

3.2.3 Sediments

Surficial sediment samples were taken during the last sampling round of 2005 and analyzed for organic and carbonate content as well as soil texture. Sediment cores were obtained by embedding a 6.3 cm diameter clear plastic tube into the sediment in a random location within 5 m from shore where the depth did not exceed 1.5 m. Suction was created on the top of the tube by wedging a rubber ball inside the top of the tube. The tube was lifted out of the water and the suction provided an intact sediment core within the tube. The tube containing the sediment was then placed on top of a wooden stake containing a rubber platform slightly smaller than the tube. The sediment was pushed up and through the plastic tube so that the top 3 cm could be removed. This procedure was carried out in two locations within each pond and the samples were mixed together to provide a representative sample. The sediment samples were then stored in 120 mL clear plastic containers at 4 °C until further analysis.

In the lab 2 cm^3 of sediment was removed from each sample using a 5 mL syringe that had been cut to provide a full diameter of the syringe. This sample was then placed in a dry, pre-weighed ceramic crucible. This was done in triplicates to reduce sampling error. The percent of organics and carbonates was then determined gravimetrically following the ignition loss method of Dean (1974).

The remaining sediment was then dehydrated and particle size was determined by using the ASTM hydrometer method (ASTM 2005) that was modified to use a stir plate, beaker and stir bar in place of stirring apparatus A or B. Percentage of sand, silt and clay was calculated using the ASTM formula provided (ASTM 2005) and then the sediment was further classified into USDA soil texture groupings (USDA 1993).

3.2.4 Soil Chemistry

Soil was sampled within a 250 m radius of each pond following a systematic sampling regime where sixteen 15 cm sub samples were taken using a Dutch auger and then pooled together for one representative 15 cm depth sample per pond. Sub-samples were taken at 100 m and 250 m in north, west, east and south directions from the pond and at 5m and 175 m in northwest, northeast, southwest and southeast directions (Figure 3-3). Samples were then air dried and pulverized for chemical analysis. Soil was sent to Agvise Laboratories (Northwood, North Dakota) to be tested for soil P, soil N, soluble salts, potassium, sulphate, chloride, pH and percent organic matter via the recommended methods for the North Central region (Table 3-3).

Table 3-3. Soil chemistry methods.

Parameter	Method	Reference	Detection Limit
Soil Chemistry			
Chloride	Potentiometric titration of Ca-Nitrate extract		1 lb/ac
Nitrogen	Cadmium reduction		1 lb/ac
Organic Matter (%)	Loss on ignition		0.1%
pH	1:1 soil:water	(Brown 1998)	0.1
Phosphorus	Olsen P ($NaHCO_3$)		1 ppm
Potassium	Ammonium acetate pH 7 extract, ICP or AA		110 ppm
Soluble Salts	1:1 soil:water		0.1 mmhos/cm
Sulfate	Turbidometric		1 lb/ac

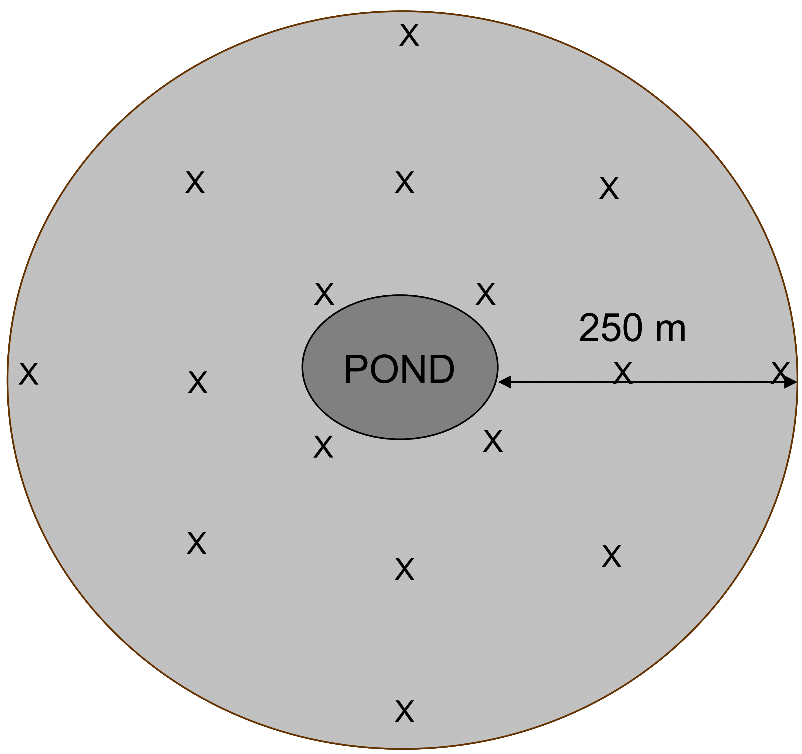


Figure 3-3. Schematic of 2006 spring soil sampling regime within a 250 m radius of the farm ponds.

3.2.5 Land use and Landscape Variables

Two measures of livestock activity were calculated to estimate cattle disturbance and impact upon pond water quality. In the first measure, referred to as Cattle Index, three general rankings quantified Cattle Access, Cattle Number and Time Around the Pond. These three general rankings were then multiplied together for each site and the resulting number was logged to obtain a normal distribution (for details see Appendix A). The second measure of cattle impact was called Cattle Trampling as it was based loosely on the research of Declerck et al. (2006) and their ranking of the same name. Cattle Trampling is a measure that ranks the perceived impact of the cattle in and around the pond. The rankings were from 0 to 4 where 0 = none, 1 = low, 2 = moderate, 3 = high and 4 = very high. Detailed protocols for the rankings are provided in Appendix A.

The percent riparian cover around each pond was determined by visual estimation (± 5%) within 10 m of the farm ponds. Aerial photos (orthophotographs) taken between 1991 to 1996 (Government of Manitoba 2007) were examined via ArcMap 8.3 to visually estimate land cover classes (± 5%) of percent forested, unforested, cropland, pasture, natural and wetland within 250 m and 1 km of ponds. The percent pasture land often included forested land because many of the pastures were heavily treed. The percent natural land included forested land and unforested land which was not used for agricultural purposes. The 2001 soil classification map databases (Government of Manitoba 2007) were used to classify land within 1 km of ponds by soil texture, slope, and agricultural capability using ArcMap 8.3. Surrounding soil texture was classified from 1 to 4 where 1 = clay, 2 = fine loamy, 3 = coarse loamy and 4 = sand. Slope rankings and corresponding degrees of slope were 1 = low (0 to 2%), 2 = moderate

(2 to 5%) and 3 = high (> 5%). There were several sites where slope from the data base did not accurately reflect slope around the ponds so the value was then adjusted accordingly based on visual observation. The source of Agricultural Capability was the Canada Land Inventory System (Library and Archives Canada 2007) where the land is ranked from 1 to 7 and 1 = land most suitable for agriculture and 7 = most poorly suited for agriculture. Surface area of the pond was calculated using a sonar distance measurer (± 1 cm) to measure pond length and width and a GPS receiver (± 6 m) was used for distances approximately > 100 m where it was difficult to measure by sonar.

3.2.6 Multivariate Analyses

Data were separated into categories of pond water chemistry variables (response) and land use and landscape variables (predictor) expected to influence water chemistry. One of the sites was eliminated from the multivariate analysis because of missing data reducing the sample size to 58. Data that were not normal in distribution were log (x + 1) transformed. UTM easting and northing values were multiplied by 0.0001 and 0.00001, respectively, because the initial values were too large to run in the multivariate analyses. Independent principal component analyses (PCA) were run using CANOCO 4.5 on both the response and predictor variables to identify the key variables and trends. Further comparison of correlation matrices and multiple regressions with the PCAs were used to eliminate cross correlations and pull out essential variables reducing response and predictor variables to nine and thirteen, respectively (Table 3-4). A redundancy analysis (RDA) was then run using CANOCO 4.5 for both years of sampling with the same predictor and response variables. The RDA was used to examine which variables in the predictor dataset proved most valuable in predicting the response water chemistry variables. The original data were then reviewed to examine whether the findings of the RDA could be supported. The site scores along the first four canonical axes in each RDA were compared with one another in a canonical correlation analysis (CANCOR) using SYNTAX 2000 to test for consistency of site placement. Additionally, multiple regressions examined the trends from the RDA and further reduced the number of variables needed to accurately predict the individual response variable TP.

Table 3-4. Transformation and abbreviations for Predictor and Response variables used in the RDA analysis

Response Variables		Predictor Variables	
RDA Abbreviation	Variable and transformation (if any)	RDA Abbreviation	Variable and transformation (if any)
COND	Log (Conductivity)	UTM_N	UTM N * .0001
TCHLa	Log (Total Chlorophyll *a*)	UTM_E	UTM E * .00001
TP	Log (TP)	TRAMP	Cattle Trampling Rank
TN	Log (TN)	CATIND	Log (Cattle Index)
DOC	Log (DOC)	AREA	Log (Area)
TURB	Log (Turbidity)	DEPTH	Depth
CARB	Log (% Carbonates)	RIP	Riparian Cover
SAND	Log (% Sand)	OM	Log (% Organic Matter w/in 250 m)
ORG	Log (% Organics)	SALT	Log (Soil Soluble Salts w/in 250 m)
		SoilN	Log (Total Soil N w/in 250 m)
		SoilP	Log (Total Soil P w/in 250 m)
		SLOPE	Slope Ranking
		TEXT	Texture Classification
		FOR1KM	Log (% Forested Land w/in 1000 m)

3.3 Results

3.3.1 Morphology

The depth of ponds was dynamic, corresponding to climatic conditions, and resulted in water levels being relatively high in 2005 and lower in 2006 (Figure 3-4). The range of maximum depth in the farm ponds varied from 11 to 488 cm. Depth of the farm ponds stayed consistently high in 2005 and only began to decline slightly by the fifth round. In 2006 there was a regular decline from the first round with a median value of around 2.5 m to the fifth round where the median value was close to 2.0 m. Pond surface area between sites ranged in values from 374 to 6250 m^2. There was some variability in pond surface area due to fluctuating depth but it was not viewed as significant and was therefore not taken into consideration.

Surface water temperatures also responded to climatic variation and values were 1 °C warmer, on average, in 2006 than in 2005 (Figure 3-5) with a combined range of temperatures from 12.1 to 30.1 °C. In both years, the temperature followed a similar pattern of increasing until the fourth round and then declining. In 2006, however, the temperature increase was more substantial and the decline after the fourth round was less abrupt than in 2005.

The sediment at most sites was sandy loam or loam with 55% and 31% of the composition, respectively (Figure 3-6 and Figure 3-7). Silt was variable in the sediment ranging from 3 to 51% while sand was consistently > 30% and clay was always < 25%. The organic content in the sediment ranged from 1 to 23% with a mean of 6% and the carbonate in the sediment ranged from 1 to 26%, with a mean of 8% (Appendix B).

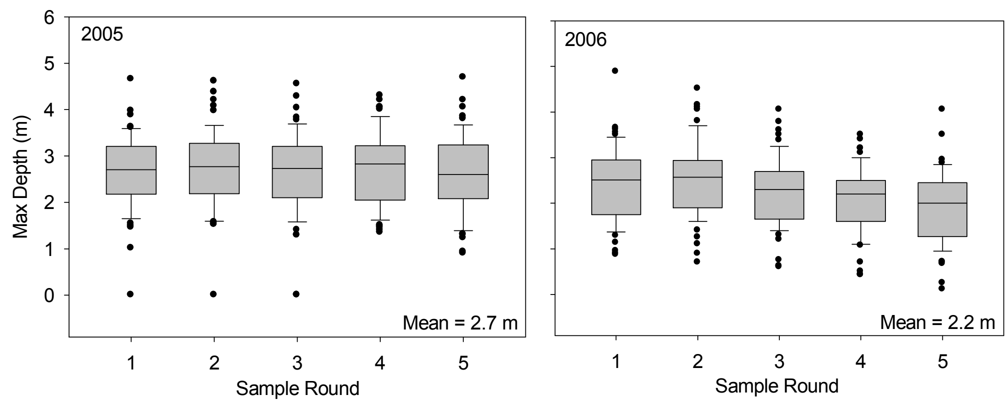


Figure 3-4. Maximum depth of all farm ponds during the five sample rounds in 2005 and 2006 (see **Table 3-1** for range of sample round dates). The above graphs are box plots where the central line signifies the median value, the two outer lines of the box are the 25th and 75th percentiles and the whiskers are the 5th and 95th percentiles.

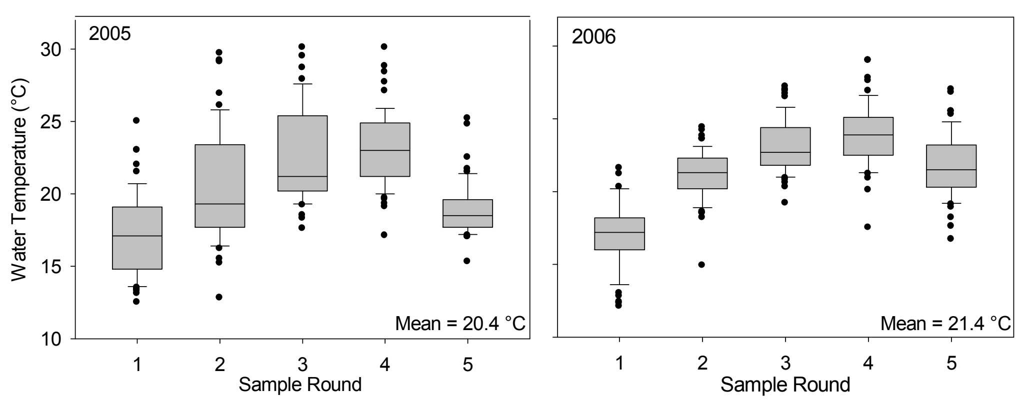


Figure 3-5. Surface water temperature of all farm ponds during the five sample rounds in 2005 and 2006 (see **Table 3-1** for range of sample round dates).

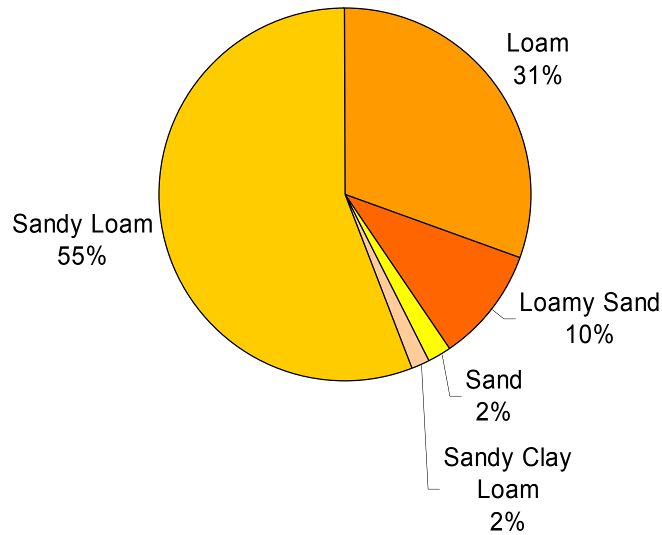


Figure 3-6. Composition of farm pond sediment texture.

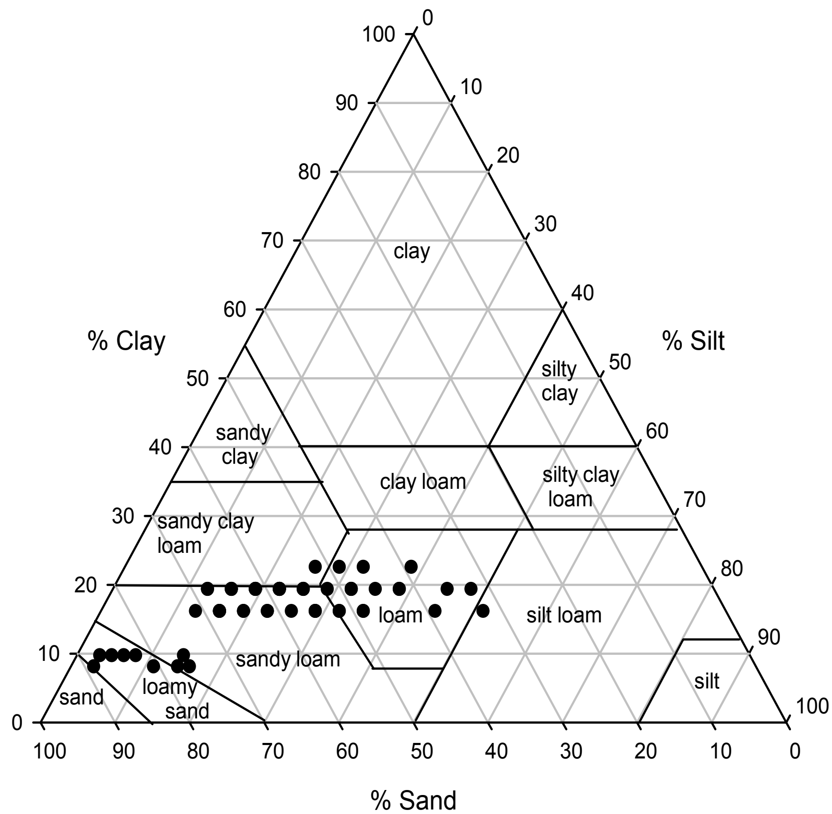


Figure 3-7. Farm pond sediment composition with overlayed USDA texture classification.

3.3.2 Nutrients

Total P concentrations in farm ponds were generally above the MB guideline of 0.025 mg/L (Manitoba Conservation 2002) and were characteristic of eutrophic (0.035 to 0.100 mg/L) to hypereutrophic (> 0.100 mg/L) bodies of water (CCME 2004). The TP levels were higher on average in 2005 than 2006 (Figure 3-8) with a combined range of < 0.03 to 4.76 mg/L across both years. In 2005 TP levels increased dramatically from the first round of sampling to the third and then leveled out while 2006 TP levels gradually increasing throughout the field season. TRP was highly correlated (R^2 = 0.86, p = < 0.001) with TP and followed the same pattern of higher values in 2005 than 2006 with a combined range of 0.01 to 3.80 mg/L. In 2005 there was a jump in the median of TRP from 0.1 in round 1 to 0.3 mg/L in round 3 and then a decrease back to 0.1 mg/L for the remaining two rounds (Figure 3-1). The TRP median values in 2006 were consistently around 0.05 mg/L throughout the field season. On average, over 50% of the TP was in the TRP form but the ratio of TRP/TP was less in 2005 than 2006 (Figure 3-8).

Total N values were usually > 1 mg/L (approximately 10% in dissolved form) and ammonia levels in several ponds consistently reached levels considered toxic to cool water aquatic life (e.g., > 1.76 mg/L at 20 °C and pH 8.0 for a 30 day duration, see section **2.1.2** for more details)(Manitoba Conservation 2002). Total N values were higher on average in 2006 than in 2005 (Figure 3-9) with a combined range of < 0.03 to 114 mg/L. In 2005 TN values remained fairly constant whereas in 2006 there was an increasing trend in TN values over the field season. The last round of sampling in 2006 had a high overall median value of 3.36 mg/L but also many values below the 25th percentile which were below the detection limit of 0.025 mg/L. Total nitrate and nitrite-N levels were considerably higher in 2005 than 2006 (Figure 3-9) but this was due, in part to an analytical error (see Appendix A). The overall combined range for nitrate and nitrite-N was < 0.01 to 1.54 mg/L. Ammonia-N levels were higher on average in 2006 than in 2005 (Figure 2-1) with a combined range of < 0.01 to 5.60 mg/L. Ammonia-N levels in 2005 stayed relatively constant while in 2006 there was a large increase in ammonia-N concentrations from the first to last round. The dissolved inorganic nitrogen values (DIN) were higher for 2005 than 2006 (Figure 3-9) but again possible analytical errors in 2005 must be considered (Appendix A). The combined range of DIN in both years was from 0.01 to 5.60 mg/L. In 2006 there was a noticeable trend in increasing DIN over the sampling season due to increasing ammonia values (Figure 3-9).

Median values of DOC were always greater than 15 mg/L, reflecting high organic content. DOC generally increased throughout the field seasons with a 2 mg/L higher average concentration in 2006 than 2005 (Figure 3-10) and a combined range of 6.7 to 71.8 mg/L.

Dissolved oxygen concentrations ranged from anoxic condition of < 0.1 mg/L to super saturated conditions of > 20.0 mg/L (present during algal blooms). DO was only measured in 2006 and was much higher on average during the later sampling rounds of the field season (Figure 3-11) when frequent algal blooms were observed.

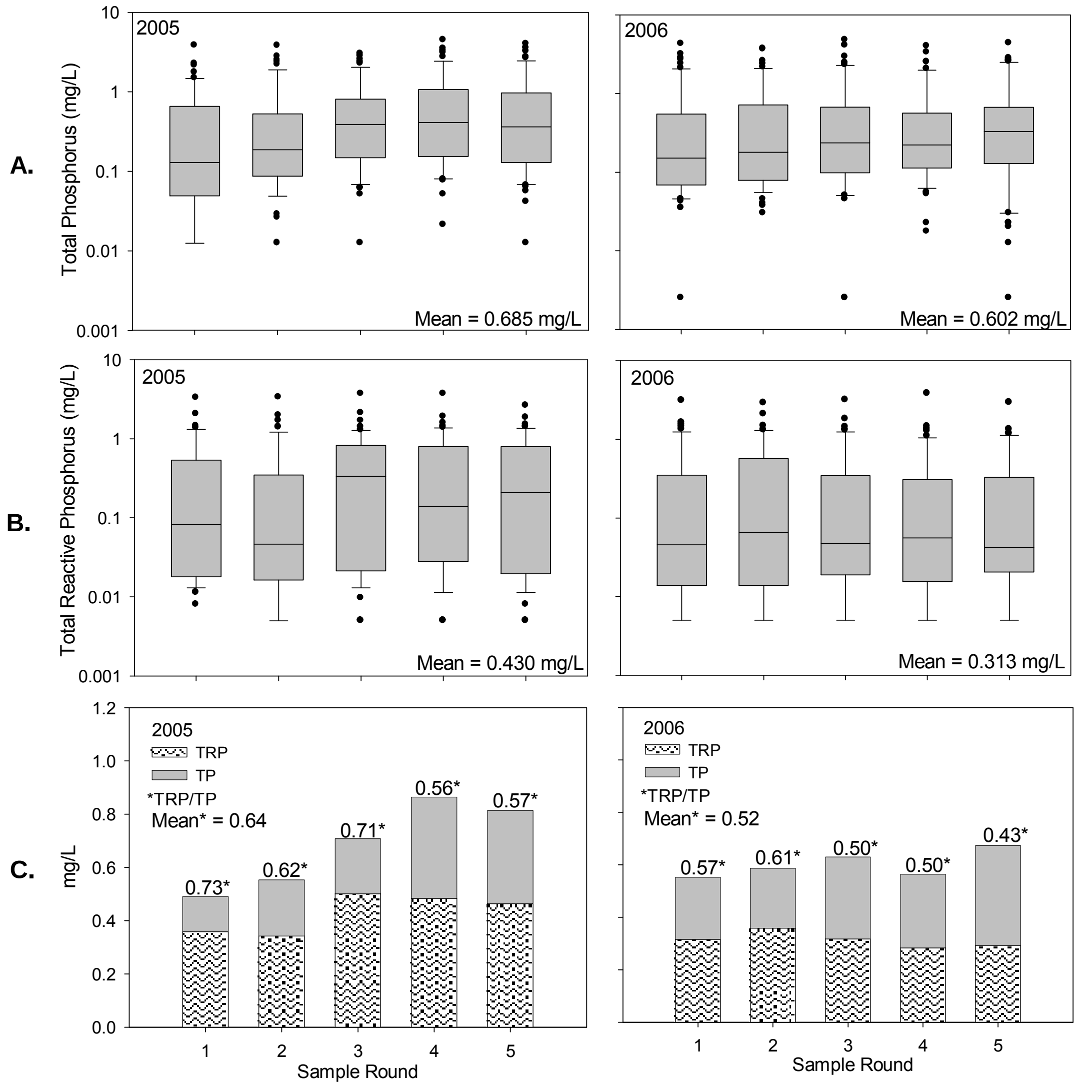


Figure 3-8. Phosphorus in farm ponds over the five sample rounds in 2005 and 2006 with A) TP concentration, B) TRP concentration and C) Ratio of TRP to TP (see **Table 3-1** for range of sample round dates).

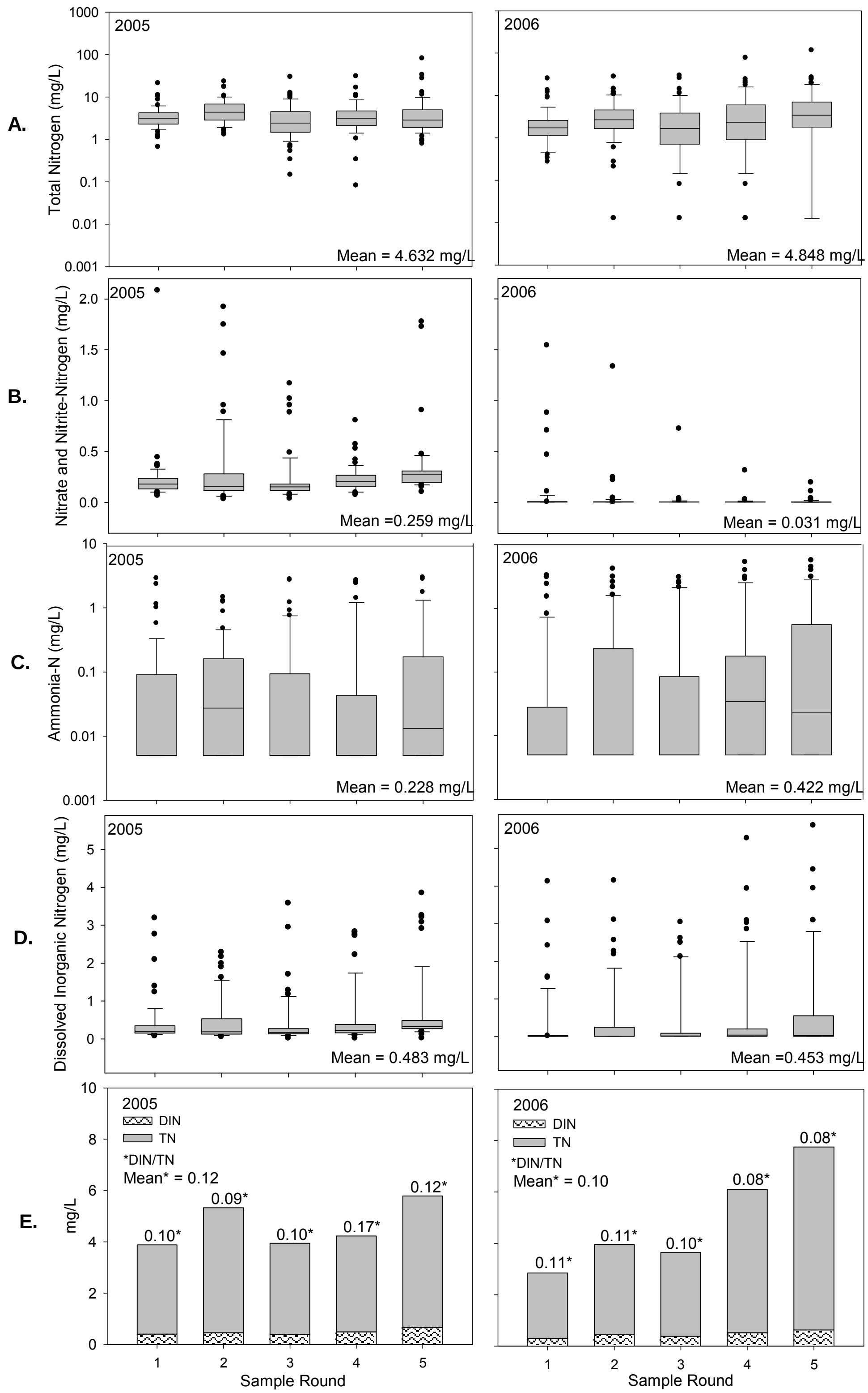


Figure 3-9. A) TN, B) Ammonia, C) Nitrate and Nitrite-N, D) DIN and E) Ratio of DIN to TN in farm ponds over the five sample rounds in 2005 and 2006 (see **Table 3-1** for range of sample round dates).

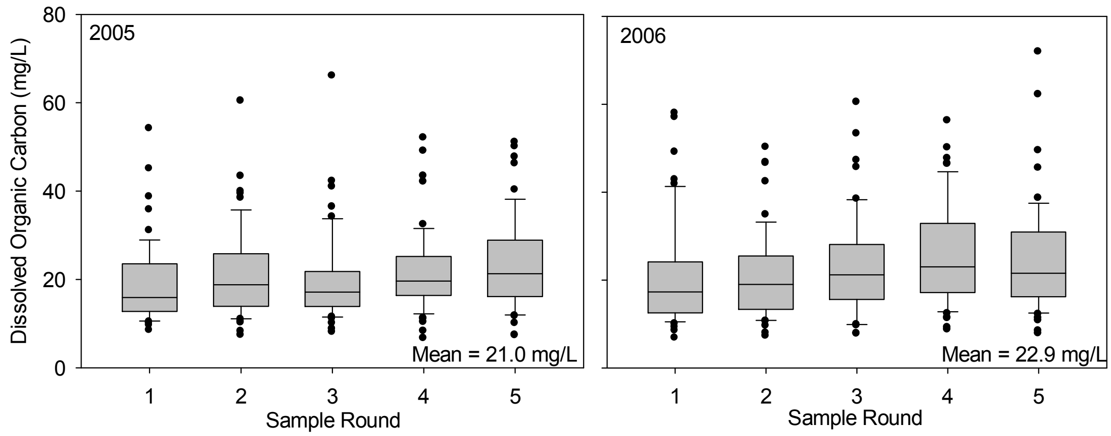


Figure 3-10. Dissolved organic carbon concentrations of all farm ponds during the five sample rounds in 2005 and 2006 (see **Table 3-1** for range of sample round dates).

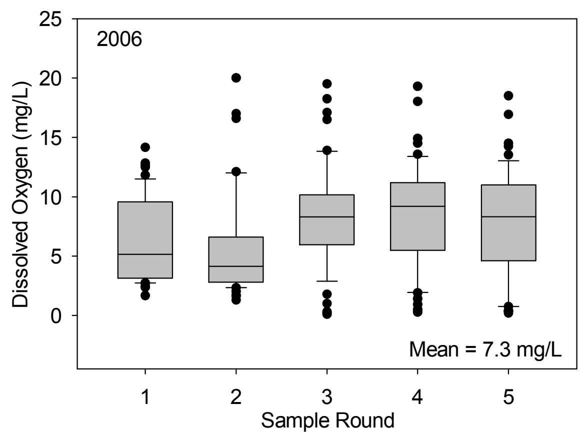


Figure 3-11. Surface dissolved oxygen concentrations of all farm ponds during the five sample rounds in 2006 (see **Table 3-1** for range of sample round dates).

3.3.3 Ions

Average conductivity values reflected brackish conditions (> 500 µS/cm) in most farm ponds with values occasionally exceeding suggested irrigation levels of < 1500 µS/cm (Manitoba Conservation 2002) but rarely higher than the suggested livestock consumption limit of 4500 µS/cm (CCME 2006). Conductivity levels were higher on average in 2006 than 2005 (Figure 3-12) with an overall combined range of conductivity values from 153 to 4970 µS/cm.

Sulphate and chloride concentrations varied considerably across the region with some ponds exceeding one or more MB water quality guideline for irrigation and human and livestock consumption. Sulphate ranged in concentrations from 0.1 to 643.1 mg/L (Table 3-5) with 13% and 4% of ponds on average exceeding guidelines for human (< 250 mg/L) and livestock (< 500 mg/L) consumption, respectively (Manitoba Conservation 2002). Chloride ranged in concentrations from 0.2 to 1247 mg/L (Table 3-6) with 8% of ponds exceeding human drinking water guidelines of > 250 mg/L and 12 % of ponds exceeding the irrigation standard for chloride sensitive crops of < 100 mg/L (Manitoba Conservation 2002).

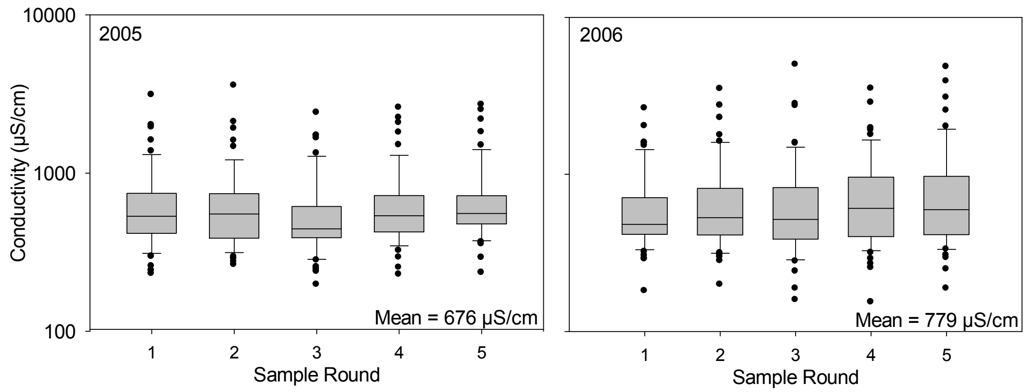


Figure 3-12. Conductivity in all farm ponds during the five sample rounds of 2005 and 2006 (see **Table 3-1** for range of sample round dates).

Table 3-5. Average sulphate concentrations and statistics in all ponds for 2005 and 2006 sampling.

	Min (mg/L)	Max (mg/L)	Median (mg/L)	Mean (mg/L)	Samples above MDWG[1] (%)	Ponds with ≥ one value over MDWG[1] (%)	Samples above MLDWG[2] (%)	Ponds with ≥ one value over MLDWG[2] (%)
2005	0.3	643.1	19.8	61.1	8	15	1	3
2006	0.1	609.6	24.2	80.7	10	10	2	5
Mean				70.9	9	13	2	4

[1] MDWG - Manitoba sulphate drinking water guideline of < 250 mg/L for human consumption
[2] MLDWG - Manitoba sulphate livestock drinking water guideline of < 500 mg/L

Table 3-6. Chloride concentrations and statistics in all ponds for 2005 and 2006 sampling.

	Min (mg/L)	Max (mg/L)	Median (mg/L)	Mean (mg/L)	Samples above MDWG[1] (%)	Ponds with ≥ one value over MDWG[1] (%)	Samples above IG[2] (%)	Ponds with ≥ one value over IG[2] (%)
2005	0.2	704.3	7.9	37.2	4	7	10	12
2006	0.6	1246.8	13.0	64.1	7	9	12	12
Mean				50.7	6	8	11	12

[1] MDWG - Manitoba chloride drinking water guideline of < 250 mg/L for human consumption
[2] IG - Manitoba chloride irrigation guideline of < 100 mg/L for chloride sensitive crops

3.3.4 Water Clarity

Water clarity variables (turbidity, Secchi depth, TSS) were all significantly correlated ($p = 0.05$). Sites varied from being primarily clear to highly turbid from organic and/or inorganic suspended solids. Turbidity and TSS were nearly twice as high, on average, in 2006 than in 2005 (Figure 3-13). The combined range for turbidity and TSS was < 1 to 487 NTU and < 1 to 1040 mg/L, respectively. In 2005, turbidity levels remained fairly constant with the median values consistently falling around 10 NTU. In contrast, there was a temporal increase in 2006 median turbidity values from close to 4 NTU in the first round to around 15 NTU by the end of the field season. As well, in 2006 there were noticeably high outliers detected for both turbidity and TSS. On average, the organic suspended solids (OSS) and inorganic suspended solids (ISS) made up 70% and 30%, respectively, of TSS in farm ponds over both years (Figure 3-13). Secchi depth could not be measured at some sites because, in clear water conditions, the disk could be seen on the bottom of the sediment. A highly significant correlation coefficient of -0.71 and -0.91 was found between Secchi depth and turbidity for detectable values in 2005 and 2006, respectively.

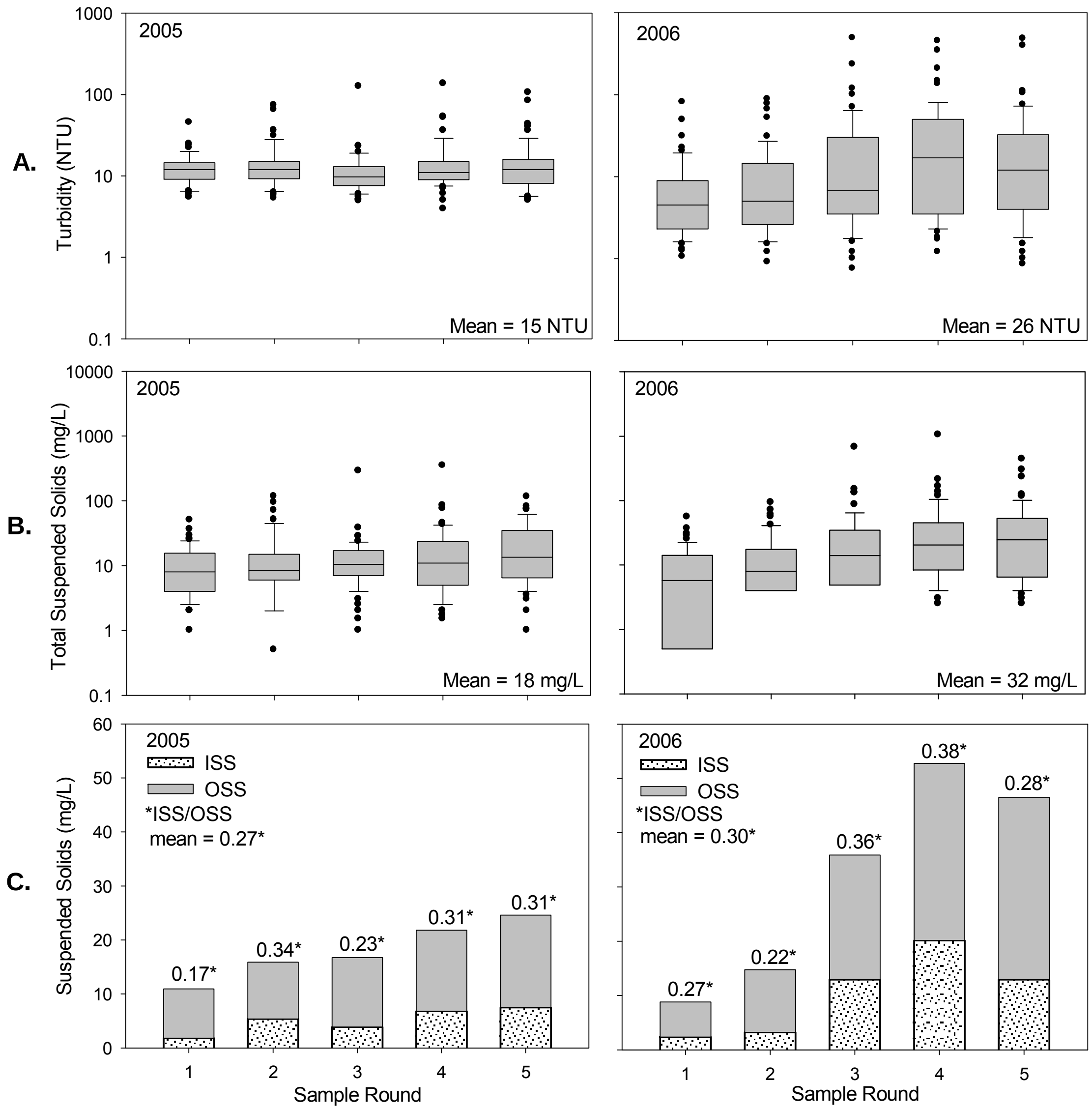


Figure 3-13. A) Turbidity, B) TSS and C) ratio of ISS to OSS of all farm ponds during the five sample rounds of 2005 and 2006 (see **Table 3-1** for range of sample round dates).

3.3.5 Biological Variables

Average total chlorophyll *a* concentration were indicative of hypereutrophic (> 25 µg/L) conditions but values ranged from oligotrophic (< 3.5 µg/L) upward to > than 1000 µg/L (Nurnberg 1996). Total chlorophyll *a* concentrations were twice as high on average in 2006 than 2005 (Figure 3-14). Median total chlorophyll *a* values in 2005 increased gradually from around 10 µg/L to near 40 µg/L by the last round. In contrast 2006 median total chlorophyll a values increased more rapidly from around 10 µg/L to close to 75 µg/L by the fourth round and then 55 µg/L by the fifth round.

Greater than 50% of the farm ponds showed detectable levels of total microcystin (> 0.01µg/L) at least once during the sampling although only 3% of the ponds exhibited total microcystin levels greater than the Canadian drinking water guideline of 1.5 µg/L (Table 3-7). Overall, there was little inter-annual difference in total microcystin values between 2005 and 2006 (Figure 3-15). Total microcystin was found to be significantly correlated ($p < 0.05$) to nutrient and water clarity parameters for both seasons (Table 3-8).

With respect to bacterial content, almost all of the farm ponds exceeded human drinking water guidelines at all times and over 40% exceeded irrigation standards at least once during this project (Table 3-9). The total range in fecal coliform samples was from below detection to 4300 CFU/100mL. Mean values were slightly higher in 2006 than in 2005 (Table 3-9 and Figure 3-16). In general, high fecal coliform counts were associated with farm ponds with open access to cattle and low counts were associated with ponds with no cattle access (Figure 3-16). However, these results should be interpreted cautiously. Fecal coliform testing lacked replication, and different subsets of farm ponds were sampled in each field season.

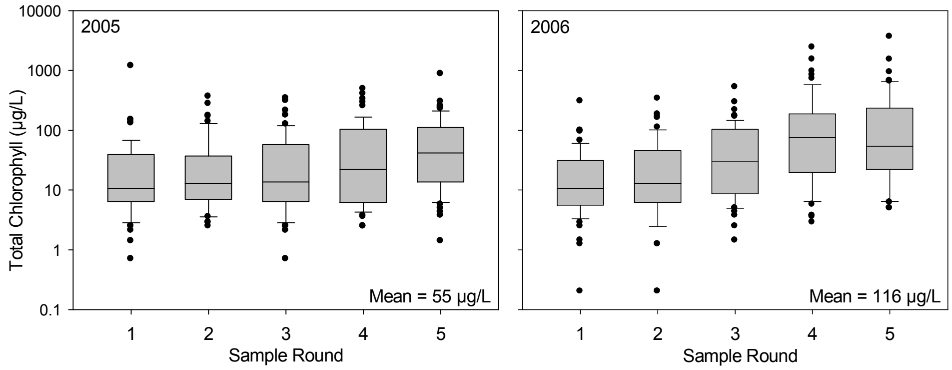


Figure 3-14 Total chlorophyll *a* concentrations from all farm ponds during the five sample rounds in 2005 and 2006 (see **Table 3-1** for range of sample round dates).

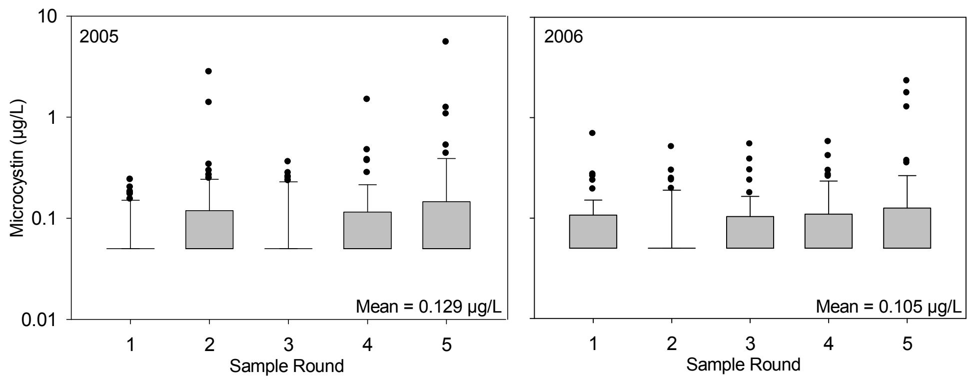


Figure 3-15. Total microcystins from all farm ponds during the five sample rounds in 2005 and 2006 (see **Table 3-1** for range of sample round dates).

Table 3-7. Summary of total microcystin concentration statistics in all farm ponds over the two field seasons of 2005 and 2006.

	Min (µg/L)	Max (µg/L)	Median (µg/L)	# of ponds	# of Microcystin samples	% of samples above detection (0.01 µg/L)	% of samples above CDWG[1] (1.5 µg/L)	% of ponds with ≥ one detectable level	% of ponds with ≥ one value over CDWG[1]
2005	<.01	5.47	<.01	59	236	33	<1	56	3
2006	<.01	2.3	<.01	59	234	35	<1	58	3

[1]CDWG - Canadian drinking water guideline of < 1.50 µg/L

Table 3-8. Correlation coefficient of microcystin with water clarity and nutrient variables in 2005 and 2006 (all data were log transformed before correlation).

		Turbidity	TSS	TP	TRP	TN	DOC	Conductivity
Microcystin	2005	0.40**	0.32*	0.39***	0.33**	0.43***	0.22*	0.29**
	2006	0.39**	0.36**	0.45***	0.43***	0.46***	0.50***	0.30**

*, **, *** significant at p < .05, .01, and .001, respectively

Table 3-9. Summary of fecal coliform concentration in a subset of ponds over the two field seasons of 2005 and 2006.

	Min (CFU/100 mL)	Max (CFU/100 mL)	Median (CFU/ 100 mL)	# of ponds	# of fecal coliform samples	Samples above MDWG[1] (%)	Ponds with ≥ one value over MDWG[1] (%)	Samples above IG[2] (%)	Ponds with ≥ one value over IG[2] (%)
2005	0	4300	32	24	63	92	96	21	43
2006	0	1490	48	20	34	94	100	28	40

[1] MDWG - Manitoba drinking water guideline of 0 fecal coliform units/100 mL
[2] IG - Manitoba Irrigation guideline of 100 fecal coliform units/100 mL

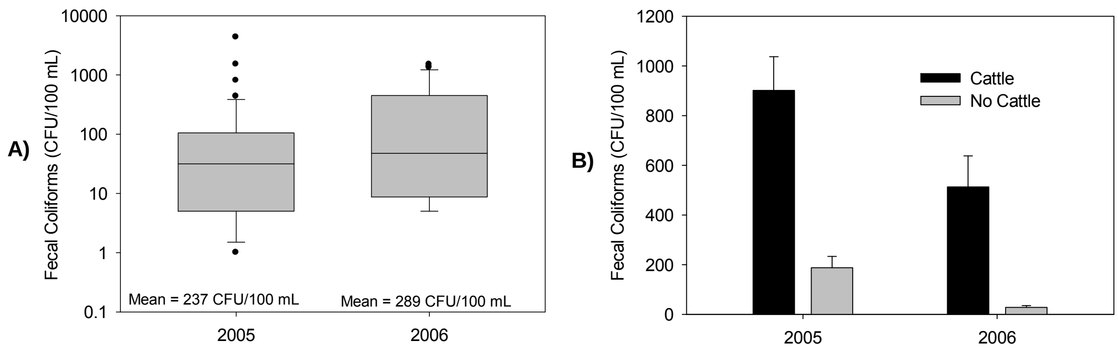


Figure 3-16. Fecal coliform concentrations in 2005 and 2006 including A) concentrations in a subset of farm ponds in 2005 (n = 24, sampled up to three times from early summer to mid-fall) and 2006 (n = 20, sampled once in early summer and once in late summer) and B) summary results for sites with cattle (n = 18 in 2005 and n = 15 in 2006) and sites with no direct cattle access (n = 6 in 2005 and n = 5 in 2006).

3.3.6 Soil Chemistry near Farm Ponds

Overall, soil chemistry from 0 to 15 cm samples near ponds appeared typical for southern Manitoba when compared with Agvise Laboratory statistics of 2007 fall sampling (Agvise Laboratories website) and Johnston (2006). The median values of soil N, sulphur and chloride values were 16, 128 and 59 kg/ha, respectively (Table 3-10). The median P concentration (Olsen) was 19 ppm, which was 25% higher than the median for soil P (Olsen) in Manitoba for 2005 which was 14 ppm (Johnston 2006), converted from Bray P using formula in Kumaragamage et al. (2007). The median for potassium concentration was 317 ppm, which was 35% higher than the median for soil K in Manitoba which was 207 ppm (Johnston 2006). The median for soluble salts, percent organic matter and pH was 650 µS/cm, 4.5% and 7.9, respectively. Overall there was little correlation between surrounding land use and soil chemistry variables (Table 3-11). Soil nitrogen, however, was positively correlated with percent cropland ($p < 0.01$) and negatively correlated with percent pasture ($p < 0.05$) and wetland ($p < 0.01$). Soil salinity was negatively correlated with percent forested ($p < 0.01$) and percent natural land ($p < 0.001$). Soil phosphorus was correlated with Cattle Trampling in 2005 ($p < 0.05$).

Table 3-10. Soil chemistry within 250 m radius of each pond in 2006.

	Min	Max	Median	Mean
Phosphorus[1] (ppm)	9	132	19	32
Nitrogen (kg/ha)	4	84	16	21
Potassium (ppm)	58	1279	317	393
Sulphur[2] (kg/ha)	29	>134	128	>104
Chloride (kg/ha)	3	1307	59	116
Salts (µS/cm)	80	3320	650	761
Organic Matter (%)	1.6	13.1	4.5	5.5
Soil pH	7.1	8.4	7.9	7.8

[1] Phosphorus was measured using the Olsen P method
[2] the lab reporting limit for sulphur was 134 kg/ha so the max and mean were probably much higher.

Table 3-11. Correlation between soil chemistry and percent land use within 250 m radius of farm ponds.

	% Forested (250m)	% Crop (250m)	% Pasture (250m)	% Natural (250m)	% Wetland (250m)	Trampling (2005)	Trampling (2006)
Soil pH	0.18 ns	-0.11 ns	0.19 ns	0.20 ns	0.13 ns	0.19 ns	0.24 ns
Organic Matter (%)	-0.04 ns	-0.29 *	0.05 ns	-0.27 *	-0.12 ns	-0.17 ns	-0.01 ns
Salts (µS/cm)	-0.37 **	0.11 ns	-0.18 ns	-0.45 ***	-0.17 ns	-0.10 ns	-0.09 ns
Nitrogen (kg/ha)	-0.15 ns	0.38 **	-0.29 *	-0.19 ns	-0.39 **	0.02 ns	-0.14 ns
Potassium (ppm)	-0.31 *	0.06 ns	-0.07 ns	-0.48 ***	-0.29 *	0.14 ns	0.09 ns
Sulfur (kg/ha)	-0.25 ns	0.05 ns	-0.09 ns	-0.23 ns	-0.12 ns	-0.04 ns	-0.05 ns
Chloride (kg/ha)	-0.34 **	-0.03 ns	0.09 ns	-0.33 *	-0.26 *	0.20 ns	0.13 ns
Phsophorus (ppm)	-0.21 ns	0.39 **	-0.10 ns	-0.20 ns	-0.36 **	0.28 *	0.08 ns

*, **, *** significant at p < .05, .01, and .001, respectively. ns not significant.

3.3.7 Land use near Farm Ponds

The percent forested land within 1 km of each pond was significantly negatively correlated ($p < 0.001$) with percent unforested land and percent cropland and significantly positively correlated ($p < 0.001$) with percent pasture, wetland and natural area (Table 3-12). The percent forested within 250 km had similar results with the exception of an insignificant correlation with percent natural area. The percent forested land typically increased around each pond with the level of agricultural capability ranking (lower ranking signifies higher capability) (Figure 3-17).

Table 3-12. Correlation table of land use with 1 km and 250 m of farm ponds and percent forested land. All data were log-transformed.

	% unforested within 1 km	% cropland within 1 km	% pasture within 1 km	% wetland within 1 km	% natural within 1 km
% forested within 1 km	-0.81***	-0.65***	0.58***	0.19***	0.64***
	% unforested within 250 m	**% cropland within 250 m**	**% pasture within 250 m**	**% wetland within 250 m**	**% natural within 250 m**
% forested within 250 m	-0.78***	-0.43***	0.26*	0.41***	0.16[ns]

*, **, *** significant at p < .05, .01, and .001, respectively. [ns] not significant.

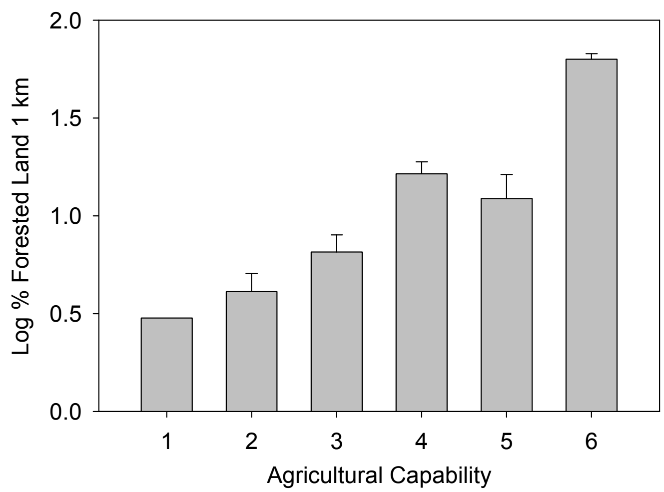


Figure 3-17. Log of percent forested land within 1 km corresponding to the Agricultural Capability (1 = highest capability for agriculture, 6 = lowest) around all the farm ponds (See section **3.2.5** for more details on Agricultural Capability).

3.3.8 Multivariate Model

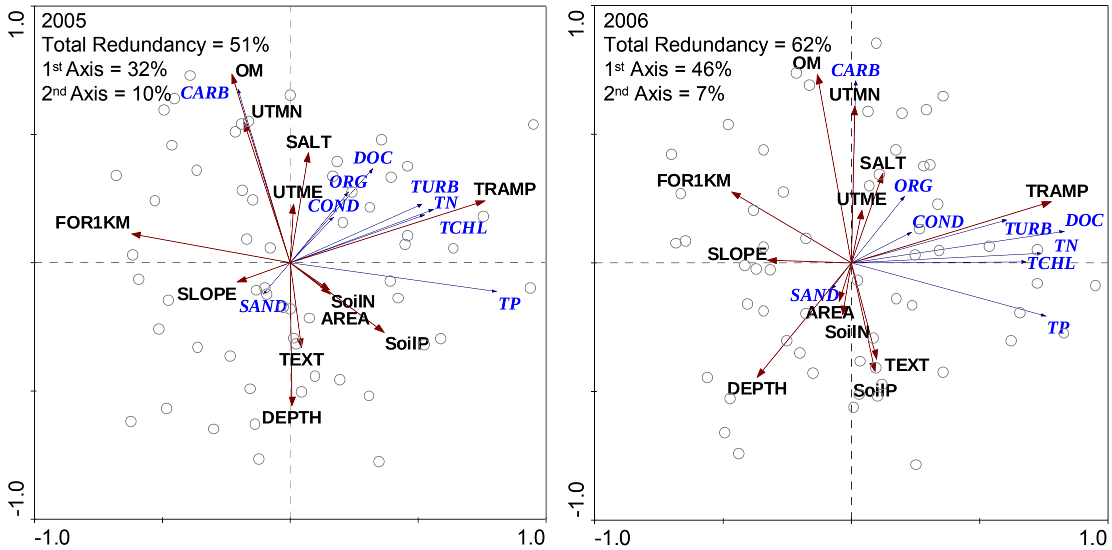
The land use and landscape predictor variables in the RDAs for both 2005 and 2006 were associated with approximately 50% of the variance in farm pond water chemistry. The RDAs using Cattle Trampling revealed 48% redundancy with 28% along the first axis and 10% along the second in 2005 (Figure 3-18) and 60% redundancy with 45% along the first axis and 7% along the second in 2006. Similarly, the 2005 RDA using Cattle Index and riparian cover revealed 49% redundancy with 29% along the first axis and 9% along the second axis and in 2006 it revealed 54% redundancy with 37% along the first axis and 7% along the second axis. A Monte Carlo test run on all RDAs separately gave the same p-value of 0.002 for the first canonical axis eigenvalue and all other canonical axes combined (See Appendix C). The CANCOR, which compared the first four RDA axis coordinate positions of the farm pond sites in 2005 with the positions in 2006, revealed high correlation between site placements within both RDAs with correlations around 0.80 for the first two axes and a highly significant ($p < 0.001$) chi-square (See Appendix C). The CANCOR demonstrates that the position of the farm ponds within the RDAs, which was determined by the values of the predictor and response variables for each pond, did not fluctuate much relative to one another over the two years of sampling. Therefore, the multivariate RDA representation of the farm ponds in relation to the predictor (landscape and land use) and response (water chemistry) variables was consistent and predictable over two years, even despite considerable variation in weather.

The variables explaining most of the variation in the RDA (28 to 45%) were along the first axis and in both 2005 and 2006 included the predictor variables cattle impact and percent forested land within 1 km and the response variables of nutrients, ions and water clarity (Figure 3-18 and Figure 3-19). Higher values of cattle impact were associated with high nutrients, ions and turbidity which are indicative of poor water quality conditions. Conversely, the more forested land within a 1 km radius of the ponds, the more likely the water had low nutrient, ion and turbidity values. Although similar trends were evident in the RDA analysis using both cattle impact measures, there was a clearer association with water chemistry and more variability accounted for when using Cattle Trampling rather than Cattle Index.

Two predictor variables that were dominant along the first axis in the RDA for only one field season were soil P within a 250 m radius, pond depth and slope of landscape around the pond. During 2005, when there was a large amount of precipitation and runoff, high values of soil P within 250 m of the pond were associated with high TP concentrations in ponds. Conversely, in the drier conditions of 2006, soil P was less associated with TP and low values of pond depth and landscape slope were closely associated with poor water quality conditions including high nutrients, ions and turbidity.

The variation in water chemistry accounted for by the second RDA axis (7 to 10%) in 2005 and 2006 was explained mainly by the predictor variables percent soil organic around the pond (within 250 m) and the UTM northing coordinates and the response variable percent carbonates (Figure 3-18). Both percent organic matter and UTM northing trended in the same direction as high percent carbonate levels in pond sediment.

A. Using Cattle Trampling



B. Using Cattle Index and % Riparian Cover

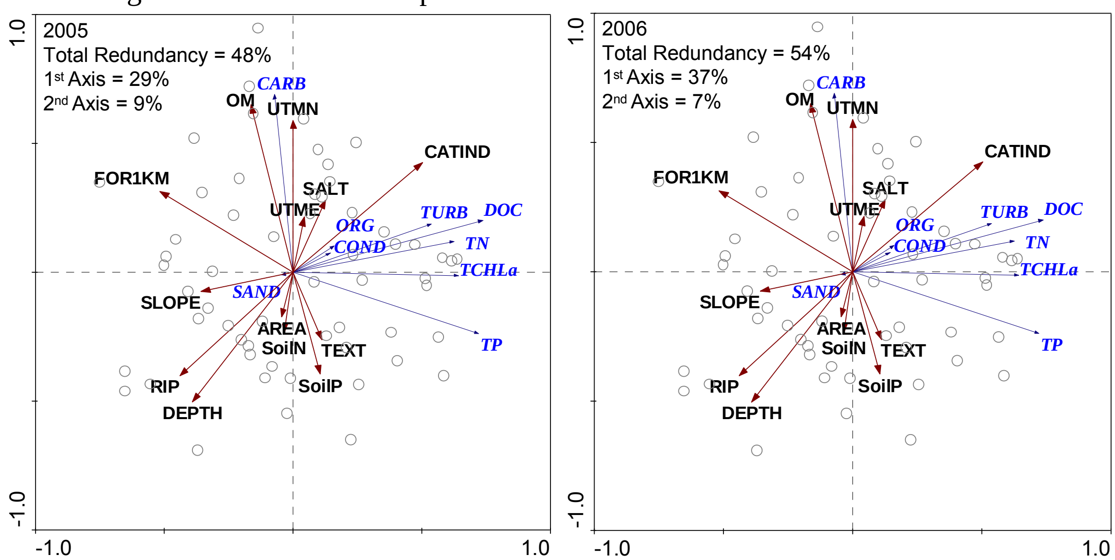


Figure 3-18. The 2005 and 2006 RDAs where water chemistry is the response variables and land use and landscape is the predictors. As an indicator of cattle disturbance A) uses Cattle Trampling and B) uses Cattle Index and percent Riparian Cover.

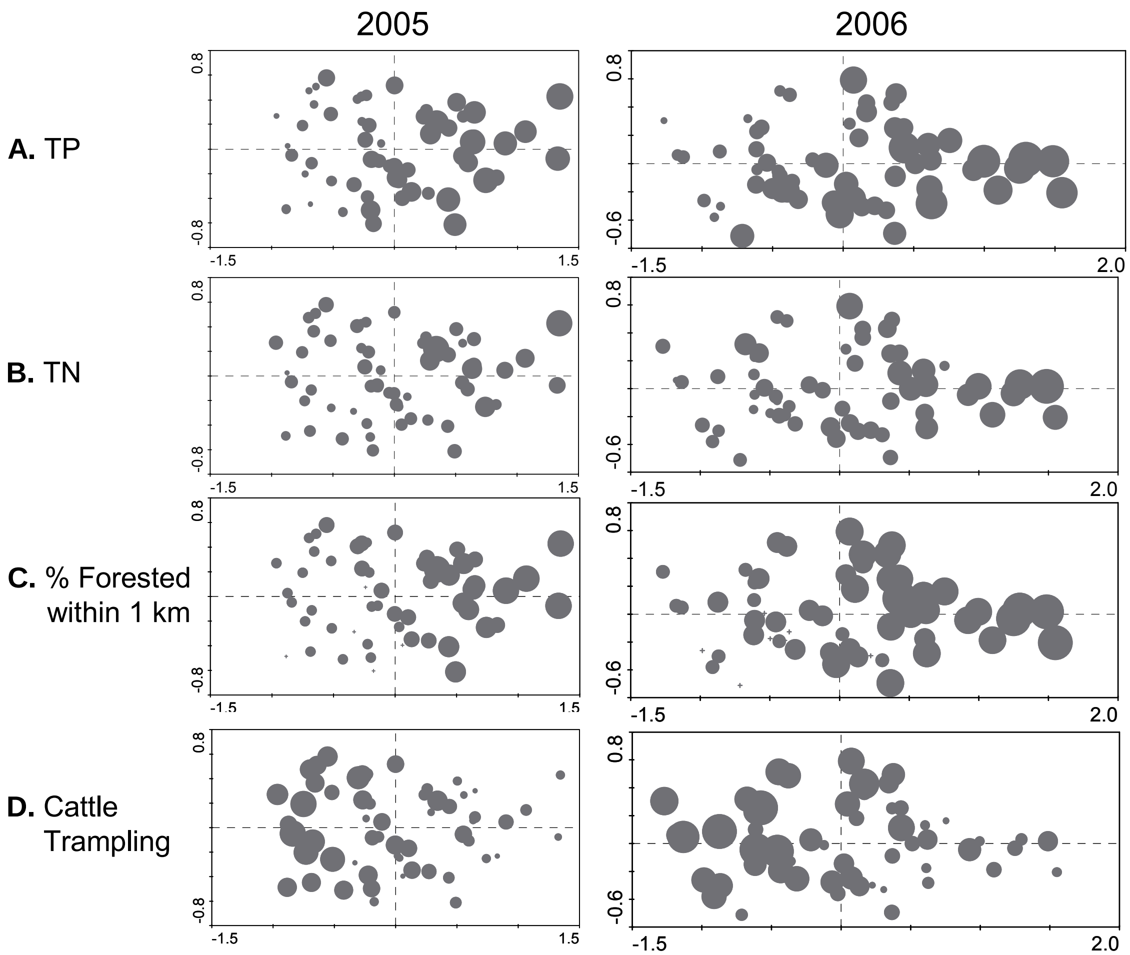


Figure 3-19. Attribute plots created from the RDA where the dots are the farm pond sites in the same position as in the RDA (Figure 3-19A.) and the size of the dots vary depending on the average value in each pond of the specific variable A) TP, B) TN, C) percent forested land within 1 km of the ponds and D) Cattle Trampling.

3.3.9 Multiple Regression

Stepwise multiple regression analysis of all predictor variables against TP as a response revealed cattle impact variables and percent forested land accounted for approximately 50% of the variance on average. Using Cattle Trampling as the cattle impact variable led to a prediction of 57% of the variance in both 2005 and 2006 (Table 3-13). The resulting predictive equations for 2005 and 2006, respectively were as follows:

Formula (1) TP = 0.260(TRAMP) - 0.596(FOR1KM) + 2.666 2005

Formula (2) TP = 0.271(TRAMP) - 0.644(FOR1KM) + 2.539 2006

Using the Cattle Index as the cattle impact variable accounted for 46 and 48% of the variance in 2005 and 2006, respectively (Table 3-14). The resulting predictive equations for 2005 and 2006, respectively were as follows:

Formula (3) TP = 0.563(CATIND) - 0.804(FOR1KM) + 2.839 2005

Formula (4) TP = 0.632(CATIND) - 0.789(FOR1KM) + 2.690 2006

Table 3-13. Multiple regression statistics for 2005 and 2006 using Cattle Trampling and percent forested land as predictors for TP concentrations in farm ponds.

Regression and ANOVA Statistics

		2005	2006
	Multiple R	0.762	0.767
	R^2	0.581	0.588
	Adjusted R^2	0.566	0.573
	Standard Error	0.356	0.356
	Observations	59	59
df	Regression	2	2
	Residual	56	56
	Total	58	58
Regression	F	38.8	39.9
	Significance F	2.70E-11	1.70E-11
Coefficients	Intercept	2.666	2.539
	TRAMP	0.260	0.271
	%FOR1K	-0.596	-0.644
Standard Error	Intercept	0.14	0.14
	TRAMP	0.04	0.04
	%FOR1K	0.11	0.11
t Stat	Intercept	19.4	18.6
	TRAMP	6.4	6.8
	%FOR1K	-5.6	-6.1
P-value	Intercept	1.49E-26	1.18E-25
	TRAMP	3.79E-08	6.74E-09
	%FOR1K	6.05E-07	1.14E-07

Table 3-14. Multiple regression statistics for 2005 and 2006 using Cattle Index and percent forested land as predictors for TP concentrations in farm ponds.

Regression and ANOVA Statistics

		2005	2006
	Multiple R	0.677	0.686
	R^2	0.459	0.470
	Adjusted R^2	0.439	0.451
	Standard Error	0.404	0.404
	Observations	59	59
df	Regression	2	2
	Residual	56	56
	Total	58	58
Regression	F	23.7	24.8
	Significance F	3.46E-08	1.89E-08
Coefficients	Intercept	2.839	2.690
	%FOR1K	-0.804	-0.789
	CATIND	0.564	0.633
Standard Error	Intercept	0.15	0.15
	%FOR1K	0.13	0.13
	CATIND	0.13	0.13
t Stat	Intercept	19.1	18.1
	%FOR1K	-6.4	-6.3
	CATIND	4.3	4.9
P-value	Intercept	3.07E-26	4.73E-25
	%FOR1K	3.44E-08	5.15E-08
	CATIND	6.12E-05	9.12E-06

3.4 Discussion

3.4.1 Climatic Variability

The two sampling years of study were highly variable in climatic conditions with 2005 being very wet and cold and 2006, conversely, hot and dry. This variability allowed us to examine land use and landscape impacts together with extremes in climate conditions which, collectively, are fundamental drivers behind primary production and surface water runoff. Likewise, this variability enabled us to study how consistently farm pond water quality could be predicted despite large weather and precipitation fluctuation. Overall, despite climatic variability in the field seasons, there was little change in the multivariate models (revealed in the RDAs) of land use and landscape impacts on water chemistry. This demonstrates that amid large fluctuations in summer precipitation the interaction of land use and landscape variables with water chemistry remains constant and predictable.

The large quantity of precipitation in 2005 increased the inorganic and organic runoff into the ponds and initially diluted pond water. This dilution was evident in the decreasing levels of DOC and conductivity by sample round three of 2005. In contrast, 2006 results showed a dry season pattern of increasing DOC and conductivity over the open water season due to evaporative concentration.

3.4.2 Measuring Cattle Impact on Water Quality

Cattle Trampling and the Cattle Index showed similar results but Cattle Trampling seemed most accurate in assessing cattle impact because it captured much of the variability intrinsic to wide ranges of topography, land use and climatic fluctuation.

Cattle Trampling took into consideration actual disturbance of pond shoreline, indicating cattle disturbance and it incorporated the potential for manure flow during snowmelt runoff. Monitoring the frequency of cattle access to each pond was logistically difficult and time consuming. By ranking the disturbance of the shoreline along the pond we were able to capture the cattle access at a coarser but more manageable scale. In Cattle Index, cattle access to each pond was taken into account with a ranking scale but there was no consideration of other water supplies in the pasture where cattle may have frequented and even preferred. With the Cattle Index there was the assumption that open access indicates that the pond is the primary water source, though I observed this was not always the case. Not only were there alternate water sources in some pastures, but in the wet 2005 field season, numerous fields were inundated. Likewise, a low ranking of cattle access in the Cattle Index implies little cattle disturbance but does not consider the potential for manure runoff. In reality, however, there was considerable build up of manure around several ponds that was susceptible to runoff, particularly during spring snowmelt and regardless of direct cattle access. Cattle Trampling, on the other hand, has potential runoff contamination built-in to the ranking so it is able to capture more of the variability.

In the multivariate analysis, when comparing to Cattle Trampling, Cattle Index did not trend as well with nutrient and turbidity levels in 2005. This would be expected considering that the Cattle Index did not account for the increase of water sources around the ponds. However, when Cattle Trampling was used as a predictor in the RDAs it was consistently associated with nutrients and turbidity during both years possibly because it was a more pliable measure that could account for changes in water sources and potential manure runoff. Therefore, for this study design which encompasses diverse land use and topography, Cattle Trampling appears to be the more accurate representation of cattle impact and further multivariate discussion will be limited to the RDA models using Cattle Trampling. In a study design where there was additional control over pasture size, number of open water sources and manure runoff potential, the Cattle Index might be appropriate due to its more objective and quantitative formulation.

3.4.3 Model Implications

In both field seasons an increase in Cattle Trampling trended strongly with increasing pond nutrient levels, turbidity and algal production (chlorophyll *a*). Cattle Trampling took into consideration cattle disturbance around the pond and potential for manure runoff. Multiple regressions with the individual response variables showed that Cattle Trampling had a higher correlation with nutrient concentrations than did any one cattle disturbance variable (i.e., cattle access, cattle number etc.). The increase in nutrient level with increasing cattle impact was expected because of the potential for direct input of nutrient-rich livestock waste into the pond as well as the indirect runoff of nutrients from cattle waste on the landscape. Indeed, ponds that were around areas of over-wintering livestock seemed to have higher levels of nutrients, especially if they were susceptible to runoff from concentrated livestock waste such as winter shelters and manure piles. There were 14 ponds near (within 250 m) over-wintering livestock and they all had surrounding soil P values higher than the median of 19 ppm and 70% of these ponds were above the 75^{th} percentile of 43 ppm. Cooke and Prepas (1998) observed a large pulse of nutrient levels in spring snowmelt from a mixed agricultural watershed containing over wintering livestock compared to watersheds containing strictly crop production and forested land. As well, cattle trampling the vegetation around ponds would promote erosion of nutrient-rich soil and reduce plant uptake of nutrients that would otherwise enter the pond (Troeh and Thompson 2005). Aquatic macrophytes prevent sediment from being resuspended by wind and waves and also take up much of the nutrients in the water and sediment that would otherwise by used by algae. Therefore, if these aquatic macrophytes are removed by livestock disturbance, there would be a decrease in competition for the nutrients and, as a result, algae may begin to dominate (Scheffer 2004). Thus, cattle can impact turbidity directly by stirring up sediment and indirectly by promoting soil erosion (due to bank instability) and algal blooms (due to nutrient resuspension and addition).

The positive correlation of percent forested land with increasing water quality (decreased levels of nutrients, turbidity and algal production) implies that agriculture decreases water quality because most agricultural land is deforested. Indeed, in south-central Manitoba, where agriculture dominates the landscape, it is reasonable to assume most land suitable for agriculture is without forested cover. This agricultural land is used for either crop or livestock production depending on the capability of the land and landowner preference. The cattle disturbance measure was able to capture the influence of livestock on pond water quality and, similarly, the percent forested land around each pond encapsulates some of the same influence of livestock land use (i.e., most pastures are deforested) and all of the influence of crop production (i.e., all cropland is deforested). It is important to note, however, that naturally fertile land is often used exclusively for crop production while less desirable land (e.g., infertile and/or rough terrain) tends to be used for livestock production. Therefore, there would be a tendency to underestimate cattle impact due to low background concentrations of nutrients and, conversely, overestimate crop production influence because of high background concentrations of nutrients. The primary impact of crop production would be runoff of fertilizer and the erosion of nutrient rich soil into the pond.

The multivariate analysis closely correlated agricultural land with poor water quality, but it is important to consider the agricultural practices themselves along with inherent qualities of the landscape (e.g., nutrient, ion and organic content) which contribute to background water quality level. Agriculture will be maximized on lands that are naturally fertile and facilitate high yields and it is therefore imperative not to assume agricultural practices themselves are the sole contributor. Without background knowledge of water quality before historical agricultural production began it is difficult to quantify the agricultural impact. Understandably, fertile lands have much higher potential for nutrient and ion input into surface waters than infertile lands regardless of agricultural land use practices. Nevertheless, studies such as Jones et al. (2001) which examined historical N and P concentrations in southern Manitoba rivers in the last three decades, confirmed an increasing trend consistent with increasing intensification of agricultural land use. As well, there is a large body of international research confirming the pollution arising from agricultural practices and highlighting the primary mechanisms (Carpenter et al. 1998, Sharpley et al. 2001a).

Declining depth of ponds (due to evaporation and groundwater recharge) concentrates nutrients and ions, increases temperature fluctuations and alters biological activity. The 2005 field season was cold and wet so farm pond depths did not fluctuate considerably. In this year there was a slight trend of increasing pond depth correlating with decreasing nutrient levels. The year 2006, however, had a hot and dry summer which dropped the water levels and increased the concentration of nutrient and ions and the potential for wind-driven nutrient cycling within the ponds. This rapid drop in water level is probably why depth of the ponds has more of a significant weighting along the first RDA axis for 2006 than in 2005 in the multivariate analysis. Deeper ponds in summer tend to stratify along a temperature gradient where warmer water lies on top of colder water (Bronmark and Hansson 1998). This stratification can be permanent for many days, depending on the depth and amount of surface area exposed to wind mixing. The stratification causes an impermeable barrier between the nutrient rich sediments and the upper water column where most planktonic algae would be developing. Shallow ponds, on the other hand, are susceptible to wind-mixing and do not generally stratify permanently (Fairchild et al. 2005). Therefore sediment nutrients in shallow ponds are often cycled back into the water column and remain available for algal growth. This susceptibility to wind mixing can therefore increase the turbidity from sediment suspension and promote algal growth as a result of nutrient cycling.

Ponds with higher organic matter in the surrounding soil tended to occur in more natural, undisturbed environments with very little surrounding crop production. This trend was recognized by the RDA where percent organic matter trended strongly along the second axis. In a disturbed agricultural environment much of the vegetation is removed either by harvesting or grazing and less organic matter is left to build up in the soil (Troeh and Thompson 2005). High percent organic matter corresponded with northern sites which were not ideal for farming because they were stony, poorly drained and saline, in part, due to their close proximity to Lake Manitoba.

Soil P levels within 250 m of the ponds appeared to have more influence on water quality during the wet 2005 field season than the much drier field season in 2006. High soil P levels in 2005 trended strongly in the direction of increasing TP within the ponds. This rise in TP was probably due to increased soil erosion from heavy rainfall events and also related to soluble P release during flooded, anaerobic soil conditions (Young and Ross 2001).

Interestingly, ponds in flatter landscapes, which made them more prone to flooding, tended to have higher TP values. This is contrary to more humid southerly climates, such as the Midwest of the United States, where increasing slope is usually associated with increasing phosphorus runoff due to erosion (Sharpley et al. 2001a). In cooler temperate climates such as southern Manitoba, the mechanism of P loss from land to water is not well understood but it is thought most attributable to soluble P movement across frozen soil during spring snow melt. This soluble P is obtained from decaying vegetation and animal waste that is at or above the soil surface (Green 1996, Bechmann et al. 2005) as well as from soil release (Little et al. 2007) that can be amplified during anoxic conditions (Sharpley et al. 2001a). Therefore, the combination of frozen, impermeable soil, level landscape and large quantities of snowmelt promotes soluble P loss which then contributes to the overall TP load.

3.4.4 Multiple Regression Analysis

Cattle Trampling and percent forested land (within 250 m of the pond) were able to account for 57% of the TP concentration consistently over both years. This is a significant amount of predicted variance considering the difference in climatic conditions over both years which would have affected surface runoff and subsequent P input into the surface water. The 2005 field season received approximately four times the amount of rain (434 mm in 2005 and 135 mm in 2006) and was over 1 °C colder than the 2006 season (Portage Southport Station, Environment Canada). Studies by Glozier et. al. (2006) and Nicholaichuk (1967) suggest climatic variability, namely snow melt, are the main drivers in runoff of nutrients from the land in the northern prairies. Perhaps the differences in climate conditions over the summer were insignificant considering that snowmelt is the main contributor to runoff. Indeed, total snowfall prior to the 2005 and 2006 field seasons was 133 and 173 cm, respectively (Portage Southport Station, Environment Canada) which suggests the 2006 runoff was larger than 2005. Alternatively, there may have been little difference in explained variance over the two field seasons because the build up of P in the pond sediment acted as a buffer that reduced interannual differences in P input. As well, TP values could have responded equally proportional to climatic conditions which would then not alter the predictive power of percent forested land and cattle disturbance.

3.4.5 General Findings

Average water quality in many of the ponds was consistent with previous studies of shallow water bodies in southern Manitoba (Jones et al. 1998a, Jones et al. 1998b, Leclair 2004, Pip 2005) where ponds with substandard quality were largely influenced by intensive agricultural land use and/or groundwater infiltration. Nutrients rarely appeared to be a growth limiting factor to algae in any farm pond, especially in fertile areas with an abundance of surrounding crop production. In some ponds ion concentration exceeded water quality standards and was, in most cases, probably due to the discharge of high conductivity groundwater. Several of the ponds with high ion concentrations were near to

Lake Manitoba and it is likely they were influenced by surface aquifers along a coarse sand vein. Low concentrations of total microcystin occurred commonly in farm ponds and were associated closely with nutrient and water clarity parameters. Thus, from the multivariate model I could infer cattle disturbance and percent forested land to be positively and negatively associated, respectively, with microcystin concentrations. Fecal coliform testing confirmed previous regional farm pond studies detecting high counts in ponds associated with open cattle access (Jones et al. 1998a, Reedyk et al. 2000, Leclair 2004).

My first initial hypothesis was that water quality would be poor in areas of intensive agriculture production. The hypothesis was supported because I found that poor water quality, typified by higher nutrient levels, algal toxins and fecal coliforms and lower water clarity, was associated with agricultural sites where crop production and/or cattle density was high.

My second hypothesis was that general farm pond water chemistry could be predicted because it is the result of local, measurable land use and landscape influences. The RDA and CANCOR multivariate analysis confirmed that, despite a wide range in climatic conditions, farm pond water chemistry can be predicted with a reasonable level of accuracy. The dominant predictors of farm pond water chemistry were cattle disturbance, percent of forested land within 1 km radius, pond depth and percent organic matter within a 250 m radius.

3.4.6 Further Consideration and Research

On a study of this scale, with a large number of independent landowners, it is vital to consider management history of the ponds as a possible source of water quality variation. Management history of particular influence to water quality is the time of farm pond excavation or dredging because older ponds had the potential to build-up P and organic matter in the sediment. As well, the practice of pumping large volumes of water into ponds from well water or surrounding ditches would compromise land use and landscape correlations especially if the source of water was characteristically different. In particular, one dugout had a tenfold increase in conductivity when the landowner had added local well water to prevent the pond from drying up. Recent unaccounted changes of livestock intensity (i.e., changing level of access or stocking number) around the ponds could also have affected pond water quality. Some ponds that were used extensively in the grazing season for 2004 were rarely used in 2005 due to the extremely wet weather. Some ponds that had open cattle access one or two years prior were fenced off by the time of this study. Therefore, it is likely that some of the variability in nutrient levels was due to historical management and not entirely to current conditions.

Greater detail and understanding of pond morphology such as volume and surface area change over time would be ideal to elucidate the entire spectrum of water chemistry influences. Preliminary multivariate analysis after the first field season showed little influence of pond surface area; however, pond volume and surface area fluctuated considerably over the two years of study and it could have been monitored in more detail.

Additionally, it would be interesting to compare soil nutrient levels near the pond (e.g., within 50 m radius of pond) to soil nutrient levels further away (e.g., between 50 and 250 m from pond) to examine if nutrients build up around the pond due to cattle spending disproportionate amounts of time there (Kie and Boroski 1996) or perhaps from nutrients being retained in the riparian zone (Sheppard et al. 2006). This could have been achieved, for example, by isolating a subset of soil sample from within 10 m of the pond and comparing it to the 250 m radius soil sample.

Measuring microcystin concentration on the leeward side of ponds, where algae would build up following wind events, might be better suited for landowners and/or researchers concerned with the maximum concentrations of microcystin toxin that could potentially be consumed by livestock and other water users. In contrast, this study focused on finding the average characterization of the entire water body so microcystin samples were intentionally taken in the middle of the pond.

It would be interesting to expand this study over a larger area such as an ecozone to have a predictive model that is accurate to a broader region sharing similar characteristics. I would incorporate climatic measures such as average temperatures and precipitation because of the higher variability across a broader region and the known importance of climate in driving hydrologic mechanisms.

Further knowledge of nutrient levels in the sediment, pond water before and after spring runoff, and runoff water itself would be beneficial for establishing a level playing field of comparison among ponds. While obtaining samples for sediment analysis would require minimal effort, collecting pond water before and during runoff events would be a major undertaking for a study of this magnitude and may require focusing more intensively on fewer ponds.

Knowing the level of groundwater influence on the ponds would help in determining the source and variability of nutrient and ion concentrations. New stable isotope methodology involving oxygen-18 and deuterium (Clark and Fritz 1997, Kendall and McDonnell 1998) makes this information easier to gather than traditional methods based on well-water monitoring.

The coarse scale (> 1 m) of the current digital elevation model available publicly for southern Manitoba made it impractical to delineate watersheds around ponds in a nearly level landscape. For future studies regionally or elsewhere it would be ideal to have finer scale digital elevation data (< 0.5 m) that can allow easier access to small-scale watershed mapping.

3.4.7 Suggestions for Agricultural Producers

In reviewing farm pond management literature and policy it is clear that there are excellent resources and clear regulation standards for new farm pond construction (Alberta Agriculture and Food 2002, Fairchild and Velinsky 2004, MWSB and PFRA 2006). In talking to individual landowners it is apparent that many producers are knowledgeable of current best management practices for pond management yet lack the time and money to repair or sustain ponds to an ideal level. For this reason, in new construction of such ponds it is vital that proper planning of pond size, location and maintenance are all taken into consideration. In particular, landowners should pay special attention to the proximity of livestock manure storage, especially during the spring melt when runoff over frozen soils is prevalent. The farm ponds that were impacted the greatest were in farm yards where livestock over-wintered.

Considering the importance of water supply for most farm operations and the dynamic nature of water quality I would advise individual landowners to test their farm ponds at least annually. Obviously the need for testing will depend on the frequency of farm pond use, what it is used for and surrounding landscape and land use characteristics.

It would be ideal to obtain a characterization of the pond nutrients (TN, TP, DOC, DO), ions (conductivity, sulphate, chloride etc.) and general parameters (pH, alkalinity) to have some foundational knowledge of the potential for exceeding water quality guidelines. The best time to sample the farm pond would probably be mid-spring after snowmelt because the majority of runoff would have entered the pond and the water column would not be stratified (i.e., temperatures would still be moderate). Sampling the pond after the main runoff event could also be helpful in determining the potential source of abiotic and biotic constituents in the water. For example, several ponds I sampled had very high ammonia levels in spring which was indicative of contamination from livestock waste or nitrogen fertilizer; based on the surrounding land use and soil texture it was usually obvious where the source of the ammonia was coming from. In addition it would be beneficial if landowners themselves were trained to visually recognize water quality threats and use low cost techniques, such as using pH strips or a Secchi disk, which could enable them to monitor basic pond water on a more frequent basis (e.g., bi-weekly or monthly).

3.4.8 Suggestions for Policy Developers

The percent forested cover, and its relation to agricultural land, was a reliable and quickly attainable coarse estimate of water quality which could be utilized to examine watersheds on a large scale with minimal effort. It would be interesting to evaluate the predictability of forested land on water quality around larger surface waters by considering all land within varying distance of the water body or within the watershed (including contributing streams and rivers) using GIS software and a land use database. The impact of point sources such as urban and industrial waste could be alleviated by subtracting out their known concentrations of pollutants. While this model would be simplistic it could facilitate an inexpensive and quick surrogate to understanding non-point source pollution in southern Manitoba while more complex and accurate models are being developed.

3.4.9 Conclusion

Overall this research provides a clear and descriptive model of the interaction between land use and landscape variables and farm pond water chemistry in southern Manitoba. Water quality is impacted negatively by increasing agricultural utilization, particularly the influence of intensive livestock use. The easily attainable measures of percent forested land and Cattle Trampling accounted for the largest amount of water chemistry variation. In addition, the land use and landscape interaction with water chemistry was largely unaffected by considerable variation in temperature and precipitation over the two field seasons. The study confirms it is valuable to consider pond placement relative to surrounding land use for the protection of surface water quality.

Chapter 4: Periphyton Bioassay of Farm Pond Water Quality

4.1 Introduction

Periphyton (algae attached to solid surfaces) is an important part of primary production in shallow water bodies (Goldsborough and Robinson 1996) and due to its clear response to nutrient manipulation (McDougal et al. 1997) it is used commonly in bioassays of nutrient limitation. One such assay is the use of nutrient diffusing substrata (NDS) which release known concentrations of nutrients across a porous substratum where periphyton can grow and their production can be quantified. Nutrient diffusing substrata have been used extensively in a wide variety of freshwater environments including lakes (Fairchild et al. 1985, Barnese and Schelske 1994), ponds (Smith and Lee 2006), wetlands (Scott et al. 2005), rivers (Carr et al. 2005) and streams (Francoer et al. 1999, Tank and Dodds 2003). Although there are numerous other methods for examining nutrient limitation (Healey and Hendzel 1980) I found NDS to be well suited for the study design of this research. One benefit of using NDS is that a treatment can be deployed in a water body and left virtually unmonitored for several weeks before being taken in and analyzed for periphytic response. This was ideal for this study where 59 farm ponds were sampled over three week rotations in remote conditions where I had limited time to sample each pond. Another benefit to NDS was the ability to obtain an integrated algal response over three weeks which took into consideration the variability of available nutrient levels throughout that time. Other nutrient limitation analyses such as N:P ratios provide a static glance of nutrient concentrations at one particular moment in the water body but are not necessarily a good reflection of nutrient limitation over time. Static nutrient limitation methods are particularly ineffective in highly dynamic environments such as shallow water bodies where there is a continual resuspension of sediment nutrients. Weithoff and Walz (1999) suggest static measures of nutrient limitation are more suitable for deeper stratified water bodies where the surface water is less likely to receive influxes of nutrients from lower water levels.

Natural freshwater systems are typically associated with P limitation based on N to P ratios; however, many nutrient enrichment bioassays have shown that algae do not always respond according to chemical prediction (Elser et al. 1990). The traditional N to P ratio used is that of Redfield (1958) based on research demonstrating aquatic algae, on average, have ideal total cellular N and P requirements at a molar ratio of 16 to 1. Phosphorus is thought to be limiting above the ideal ratio of 16:1 and N is considered limiting below the ratio of 16:1. In actuality, however, alga species may vary in nutrient requirements and also the external ratio of nutrients in the water is not always identical to the internal ratio of nutrients within alga cells. Thus, if the molar N:P ratio is close to 16 there may be some periphyton species limited by N while others are limited by P. This variability has led researchers to develop a range of external N to P ratio that is more flexible (Rhee and Gotham 1980, Schanz and Juon 1983, Guildford and Hecky 2000). For example, a common range suggested by both Schanz and Juon (1983), for periphyton in streams, and Healey and Hendzel (1980), for phytoplankton in lakes, is TN:TP molar ratios < 10 indicate N limitation, > 20 indicate P limitation and between 10 and 20 could be either N or P limitation or co-limitation. NDS are normally colonized by many species of periphyton which would thus have a range of optimum N:P ratios (Fairchild et al. 1985) and, over a three week duration, each species may switch between N and P limitation. Thus, bioassays using NDS can be useful in evaluating the actual average nutrient limitation of periphyton production in comparison to what the perceived nutrient limitation might be based solely on one-time water chemistry ratios of N and P.

External water chemistry ratios (outside algal cells) of TN:TP are not always accurate representations of bioavailable N and P, nor are they necessarily consistent with internal ratios of TN:TP within algae. The ratio of TN:TP within a water body represents the total nutrients potentially available for algal production; however, dissolved forms of nutrients are usually more readily accessible than particulate (inorganic and organic) forms. Due to the discrepancy between total nutrients and bioavailable nutrients, researchers often examine several N:P ratios including TN:TP, DIN:TP and DIN:TRP to examine whether dissolved forms of N and P are more representative of what algae are consuming. Measures of TN:TP and DIN:TRP are comparative with the Redfield ratio of 16, however, with DIN:TP the ideal ratio is closer to 3 (Higgins et al. 2006). As well, published values of N and P concentrations that have been identified as thresholds under which algal growth is limited may also be useful in elucidating algal response to NDS treatments (Tank and Dodds 2003). Overall, my goal was to compare periphyton response on NDS to ambient water chemistry, predominantly N and P concentrations, to improve the current understanding of nutrient dynamics and algal response in shallow water bodies of southern Manitoba.

Objective 3: Compare the nutrient limitation prediction in farm ponds based on Redfield N to P ratios from static water chemistry values to that of an integrated *in situ* nutrient diffusing substrata bioassay that monitors algal periphytic growth response.

Hypothesis: Periphyton nutrient limitation based on static measurements of Redfield N to P ratios will be inconsistent with integrated in situ nutrient diffusing bioassays because farm ponds have dynamic water chemistry that varies spatially and temporally.

4.2 Methods

4.2.1 Nutrient Diffusing Substrata

The NDS were deployed in 24 randomly selected farm ponds to test for the benthic algae response to N and P enrichment. The same ponds were sampled four times over two field seasons in 2005 and 2006 which corresponded with the timing of the larger study in chapter 3. The NDS consisted of four 2% agar treatments which included: 1) a control with no N or P, 2) 0.05 mol/L P added, 3) 0.05 mol/L N added, 4) 0.05 mol/L of both P and N added. These concentrations were chosen because of prior success with these nutrient levels in local nutrient enrichment experiments (McDougal 2001). The chemical form of P and N was potassium phosphate (K_2HPO_4) and sodium nitrate ($NaNO_3$), respectively. The dry chemical solutes (i.e., agar and any nutrient additives) and deionized water were mixed in an Erlenmeyer flask and then autoclaved at 121 °C. Circular, porous silica frits (Leco Instruments, Mississauga, ON # 528-042) the same diameters as a 50 mL plastic centrifuge vials were also autoclaved. After sterilization, the agar solution was poured into the centrifuge vials and just enough room was left in the vials to place the silica frit over the opening. Vials were stored at 4 °C prior to use. Studies by Bortoluzzi (thesis in prep.) in a controlled environment have shown that the nutrient treatments release consistent concentrations of nutrients in water for an average duration of one month. Three replicates of each treatment were placed in a 30 x 60 cm PVC frame at a depth of 10 cm below the surface of the water and held floating with two foam floats positioned lengthwise along the frame (Figure 4-1). Although more replicates would have resulted in greater statistical power I decided that three would be adequate considering the large number of sites and limited time constraints. The 10 cm depth was chosen because of prior studies by Bortoluzzi (thesis in prep.) which indicated at this depth light would rarely be limiting or inhibitory. Foam floats were wrapped in duct tape to protect them from photolytic breakdown and disturbance from wildlife (e.g., waterfowl gnawing on them). One frame was placed centrally in each pond and anchored to the bottom with rope and a plastic jug filled with sand. Each frame was deployed during the first sampling round and then, three weeks later at each subsequent sampling, the treatment tubes were removed and replaced with new tubes (Figure 4-2). The silica frits from the old tubes were then removed by squeezing the neck of the tube with needle-nose pliers and placed individually in labeled brown glass jars (Figure 4-3) that were then frozen for a minimum of 24 hours. The jars were then taken out of the freezer, spiked with 90% methanol and stored in a dark drawer for a further 24 hours. The resulting methanol extract was then analyzed for chlorophyll *a* and pheophytin via the same methods as for phytoplankton (see Chapter 3) and calculated in $\mu g/cm^2$ based on the surface area of the silica frit.

Figure 4-1. Nutrient diffusing substrata frame in farm pond (deployment of nutrient treatments in the frame was random).

Figure 4-2. Four different NDS treatments and their corresponding algal response.

Figure 4-3. Treatment tube being squeezed by pliers to remove silica frit for storage in the brown glass jar.

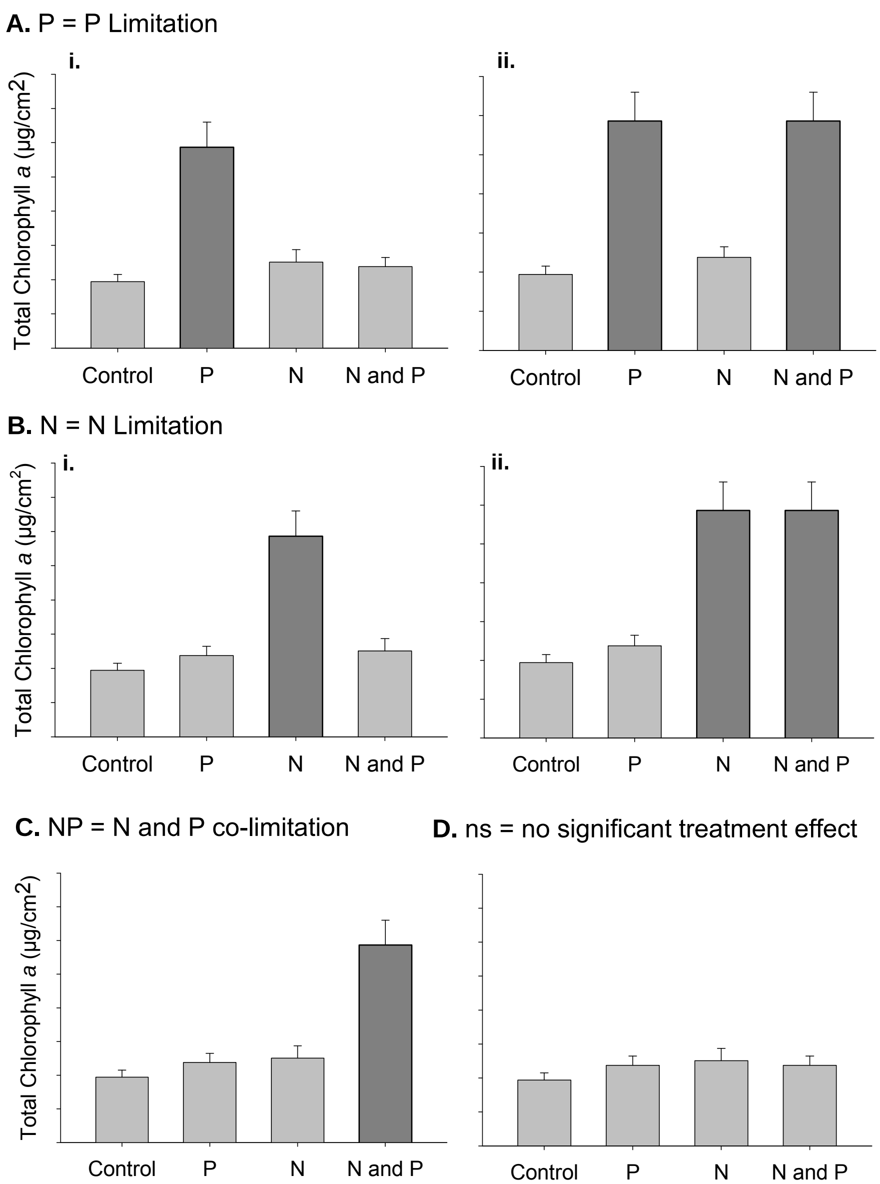


Figure 4-4. The four treatment response categories expected from the results which includes A) P (P-limitation) = P treatment has significantly more growth alone (i.) or together with the N and P treatment (ii), B) N (N limitation) = N treatment has significantly more growth alone (i.) or together with the N and P treatments (ii), C) NP (N and P co-limitation) = N and P combined treatment has significantly more growth than other treatments and D) ns (no nutrient limitation) = no significant growth on any treatment comparative to the control.

4.2.2 Analysis of Nutrient Diffusing Substrata

Differences in algal chlorophyll concentration between treatments were analyzed via one-way ANOVA using JMP IN 5.1 statistical software then the treatment means at each site were further compared to the control using Dunnett's method. When a nutrient treatment increased algal growth significantly compared to the control, it was presumed to contain the limiting nutrient in the water column during that three week sampling time. The four possible results were: no significant response (ns), N limitation (N), P limitation (P) and N and P co-limitation (N and P). When more than one treatment was found to be significantly different ($p = 0.05$) from the control, Tukey-Kramer HSD was used to examine whether there was significant differences amongst those treatments. For example, if both N and combined N and P treatments were considered significantly different from the mean then Tukey-Kramer HSD evaluated whether N and combined N and P were significantly different from each other. If there was a significant difference between the N and combined N and P treatment, and the N and P treatment had the highest mean of algal biomass, then the pond would be considered co-limited by N and P. On the other hand, if there was a significant difference between the N and combined N and P addition treatment, and the N treatment had the highest mean algal biomass, then the pond was considered N limited. If there was no significant difference between the N and combined N and P treatments, the pond would be considered N limited.

After ponds were grouped by their nutrient response to the treatment (i.e., ns, N, P or NP) by year, additional information including water quality variables, N to P ratios and ratios of treatment algal biomass to control algal biomass were gathered for each pond and then averaged across the groupings. For example, if three ponds in 2005 were found to be P limited then average water quality values across all three ponds was calculated to give an average value for the group. The pond water quality variables I chose to compare amongst the NDS treatment results were turbidity, total chlorophyll *a*, TP, TN, TRP, and DIN because I thought they would best represent nutrient and light availability. I used the ratios of TN:TP, DIN:TRP and DIN:TP because each has been found valuable in previous NDS experiments when assessing nutrient limitation (Dodds 2003, Smith and Lee 2006). The mean algal biomass of the N, P and combined N and P treatment from each pond during each sampling time were divided by the algal biomass of the control treatment to provide a relative magnitude of the algal response to nutrient enrichment (Francoeur 2001, Tank and Dodds 2003). Therefore, each sampling time of one pond resulted in three ratios: N treatment algal biomass to control algal biomass, P treatment algal biomass to control algal biomass, and N and P combined treatment algal biomass to control algal biomass. If the ratio of the nutrient enriched treatment to control equaled 1, then there was no nutrient treatment effect. If the ratio was > 1 there was a positive nutrient effect, and if the ratio was < 1 there was an inhibitory nutrient effect.

A chi-square analysis was run using the predicted N or P limitation based on Redfield N:P ratios (N limitation < 16 > P limitation) and the actual observed limitation based on the NDS treatment response. The ratios of external TN:TP and DIN:TRP in the water were used because the internal cellular TN:TP in algae is what Redfield's ratio was originally based on and DIN:TRP is often used as a surrogate to TN:TP because it is thought to represent actual bioavailable nutrients (Stelzer and Lamberti 2001).

A canonical correspondence analysis (CCA) was run using CANOCO 4.5 with the four NDS response outcomes ns, N, P and NP as response variables and TP, TN, DIN and turbidity as predictor variables. There was high correlation between TP and TRP ($r^2 > 0.85$, $p < 0.0001$) so only TP was used in the analysis. The response variables were given a 1 or 0 if they were present or absent, respectively, in a particular pond sampling. All predictor variables were log transformed and checked for normality in distribution. Several outlier turbidity and TP values in 2005 were reduced so as not to skew the analysis.

4.3 Results

Pond bioassays most frequently (> 30%) exhibited no NDS treatment effect while limitation by N and co-limitation by N and P were also common (> 27 and > 19%, respectively) and P limitation was rare (3%) (Figure 4-5). In 2005, 51% of pond bioassays exhibited no treatment effect and N limitation, N and P co-limitation and P limitation were exhibited in 27%, 19% and 3%, respectively. In 2006 there was approximately equal distribution of ponds with no NDS treatment effect, N limitation and N and P combined limitation while P limitation was again only exhibited in 3% of the assays. There was significantly less algal growth on nutrient treatments relative to the control treatment in 8% of the ponds and, in those cases, 80% were with P treatments and 20% were with N treatments.

In N or P limited assays, the limiting nutrient treatment had, on average, three times the algal growth of the non-limiting nutrient treatment and the control while in N and P co-limited ponds, the combined N and P treatment had three times the single nutrient addition N and P treatments and six times that of the control treatment (Table 4-1). Even in ponds considered N or P limited, there was equal or more algal growth on the combined N and P treatment. Interestingly, there was a tendency for P treatments in N limited ponds to have less algal growth than the control. During significant N and P co-limitation the single nutrient addition N and P treatments showed, on average, 50 to 100% more algal growth than the control.

Ponds in which there was no NDS treatment effect tended to be nutrient rich and turbid whereas N- or P-limited ponds typically had low concentrations of the limiting nutrient in respect to the nutrient that was not limited. Ponds with no treatment effect had average TP, TN, TRP and DIN values of 0.91, 6.77, 0.61 and 0.81 mg/L, respectively and average total chlorophyll *a* and turbidity of 148 µg/L and 28 NTU, respectively. The average TN/TP ratio for ponds exhibiting no treatment effect was 30 while DIN/TRP and DIN/TP were 16 and 5.7, respectively (Table 4-1). Due to a high variability of values, the few P-limited ponds were not shown to be significantly different in total chlorophyll *a*, turbidity and nutrient values when compared to ponds exhibiting other treatment effects. The P-limited sites had TN:TP, DIN:TRP and DIN:TP averaging > 100 in both years. Additionally, N limited ponds were typically low in DIN (average 0.18 mg/L) and had the lowest N to P ratios (average 27, 4 and 1.2 for TN:TP, DIN:TRP and DIN:TP, respectively). Ponds co-limited by N and P had TP and TRP concentrations less than half of the amount for the other treatment effect ponds and DIN values equivalent to the N limited treatment ponds but four times less than P limitation and no treatment effect ponds. The average DIN:TP ratio in N and P co-limited ponds was 2.5.

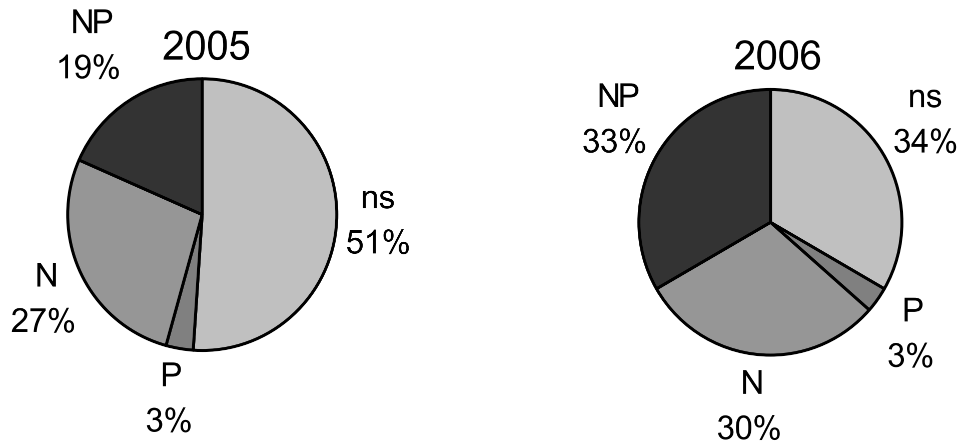


Figure 4-5. Distribution of significant ($p < 0.05$) treatment response across all NDS experiments in 2005 and 2006. P = P limitation, N = N limitation, NP = N and P co-limitation and ns = no significant treatment response.

Table 4-1. Mean biomass ratios, limnological variables and N to P ratios that correspond to established NDS treatment effects on ponds.

	2005				2006			
Significant Treatment	ns	P	N	NP	ns	P	N	NP
# of occurrences	49	3	26	18	32	3	29	32
P:Control	bc 0.9	a 2.6	c 0.7	b 1.4	b 0.9	a 2.7	b 0.8	a 1.8
N:Control	b 1.4	b 1.0	a 3.5	b 1.9	b 1.2	ab 1.0	a 3.5	a 1.5
NP:Control	c 1.4	abc 2.6	b 2.9	a 5.7	c 1.2	abc 3.9	b 3.1	a 6.3
Turbidity (NTU)	a 19	a 18	a 14	a 18	a 42	ab 10	b 13	b 12
Total Chlorophyl *a* (µg/L)	a 76	a 36	a 64	a 46	a 258	ab 65	b 99	b 84
TP (mg/L)	a 0.80	a 1.00	a 0.42	a 0.44	a 1.12	ab 0.09	a 0.64	b 0.16
TN (mg/L)	a 5.50	a 5.30	a 3.53	a 4.87	a 8.71	ab 1.62	b 3.21	b 2.49
TRP (mg/L)	a 0.60	a 0.51	a 0.24	a 0.27	a 0.63	ab 0.02	a 0.37	b 0.03
DIN (mg/L)	ab 0.65	a 1.50	c 0.23	bc 0.40	a 1.06	ab 0.31	b 0.13	b 0.03
TN:TP (mol)	b 33	ab 104	ab 32	a 64	b 25	ab 93	b 22	a 71
DIN:TRP (mol)	b 15	a 97	b 8	a 34	a 18	a 135	b 1	a 7
DIN:TP (mol)	bc 7.4	a 30.0	c 1.9	b 5.0	ab 3.1	a 48.0	c 0.6	bc 0.9

note: ns = none significantly different, P= Phosphorus treatment, N = Nitrogen treatment, NP = Nitrogen and Phosphorus treatment.

Groupings related via Tukey Kramer HSD statistics where treatments within a group with the same letter are not significantly different at the 5% level.

P:Control, N:Control, NP:Control all represent nutrient treatment biomass:Control treatment biomass ratios.

There was little correspondence between prediction of N or P limitation based on Redfield N:P ratios (N limitation if N:P < 16, P limitation if N:P > 16) and the actual results observed on the NDS frames (Table 4-2 and Table 4-3). All chi-square tables with TN:TP ratios and DIN:TRP ratios showed a highly significant difference ($p < 0.0001$) from the expected results.

The CCA analysis confirmed that sites with no treatment effect were high in nutrients and turbidity, N limited sites were low in N and high in P and P limited sites were low in P and high in N. The N and P co-limited sites tended to be low in both N and P. The N and P concentrations and turbidity had more of an influence on treatment response in 2006 than 2005. This is evident because twice as much treatment response variance was accounted for by the nutrients and turbidity in 2006 than in 2005 and there was considerably greater trending along the first and dominant axis. According to a Monte Carlo test both the 2005 and 2006 CCAs had significant results ($p < 0.002$) over all canonical axes.

Table 4-2. Chi-Square table for predicted N and P limitation based on TN:TP ratios (N limitation if N:P < 16, P limitation if N:P > 16) and observed N and P limitation based on NDS frames.

	2005				2006			
	P	**no P**	**N**	**no N**	**P**	**no P**	**N**	**no N**
Observed	2	94	10	86	2	94	15	81
Expected	60	36	36	60	63	33	33	63
$(O-E)^2$	3364	3364	676	676	3721	3721	324	324
$(O-E)^2/E$	56.1	93.4	18.8	11.3	59.1	112.8	9.8	5.1
X^2	**149.5**		**30.0**		**171.8**		**15.0**	
p	**< 0.001**		**<0.001**		**< 0.001**		**< 0.001**	

Table 4-3. Chi-Square table for predicted N and P limitation based on DIN:TRP ratios (N limitation if N:P < 16, P limitation if N:P > 16) and observed N and P limitation based on NDS frames.

	2005				2006			
	P	**no P**	**N**	**no N**	**P**	**no P**	**N**	**no N**
Observed	2	94	22	64	1	95	29	67
Expected	25	71	71	25	12	84	84	12
(O-E)2	529	529	2401	1521	121	121	3025	3025
(O-E)2/E	21.2	7.5	33.8	60.8	10.1	1.4	36.0	252.1
X^2	**28.6**		**94.7**		**11.5**		**288.1**	
p	**< 0.001**		**< 0.001**		**< 0.001**		**< 0.001**	

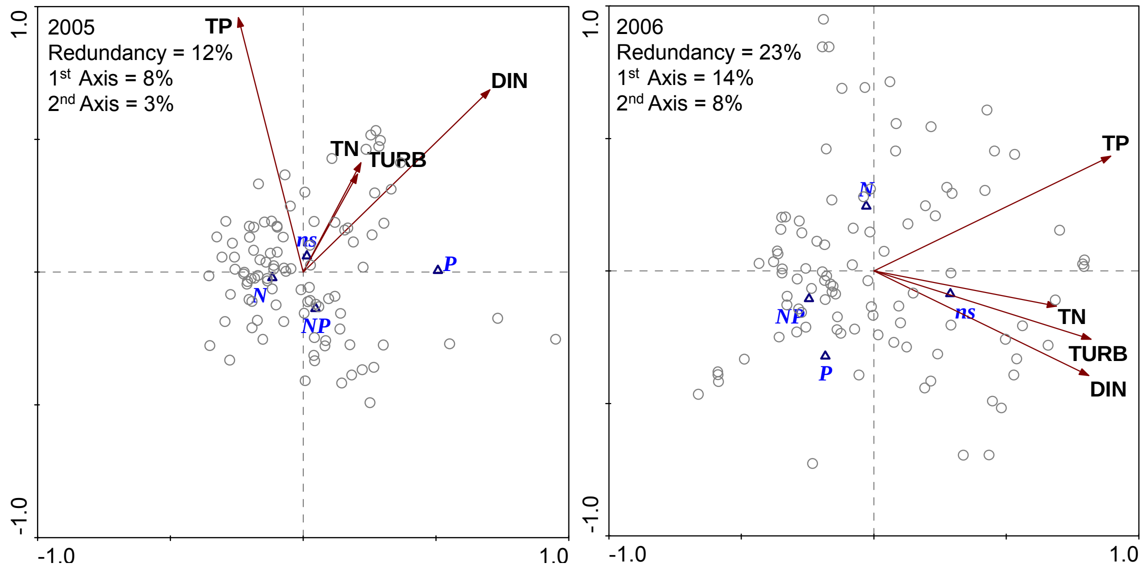


Figure 4-6. The 2005 and 2006 CCAs where significant treatment response is the response variable (triangles) and nutrients and turbidity are the predictors (arrows).

4.4 *Discussion*

In general, most NDS treatments showed either no treatment effect, N limitation or N and P co-limitation with unreliable correlation with the Redfield N:P ratio. Ponds where there was no treatment effect were noticeably high, compared to other treatment effects, in total chlorophyll, turbidity and nutrients; however, the difference was only significant in 2006. Nutrient inputs from the NDS treatments would become less important if the ambient nutrient levels were at a point where there was already no nutrient limitation to growth (Borchardt 1996). In fact, the average nutrient levels within ponds with no treatment effect were well above published threshold nutrient levels where algae are considered to be nutrient-replete (Table 4-4). Dodds (2003), however, warns that low dissolved nutrient levels (SRP < 0.1 mg/L and DIN < 1 mg/L) may be deceiving because they are static and do not consider high rates of biological turnover that can quickly make nutrients available. He notes that oligotrophic waters (i.e., low nutrient) and eutrophic waters (i.e., high nutrient) sometimes have similar low dissolved nutrient concentrations despite the fact that in eutrophic waters nutrients are abundantly available which is evident by their high productivity. On the other hand, Dodds (2003) notes that high dissolved nutrients (SRP > 0.1 mg/L and DIN > 1 mg/L) are usually a strong indication there is no nutrient limitation. TRP (SRP plus particulate reactive P) and DIN at my sites were, on average, 0.61 and 0.81 mg/L, respectively for both years in ponds with no treatment effect. High chlorophyll concentrations in the water indicate greater abundance of phytoplankton that contribute to turbidity levels and effectively shade out periphytic growth on the treatment. Minimal periphytic growth was observed in ponds with excessive suspended material (~ > 20 NTU), probably due to light limitation.

Combined N and P co-limitation was observed in ponds that were close to or below the highest published threshold of nutrient limitation for dissolved N and P (TRP < 0.008, DIN < 0.100) which suggests that, regardless of N:P ratios, the periphyton may have required both nutrients for growth (Tank and Dodds 2003). Overall, N and P co-limitation was common and occurred greater than 19% of the time. Similarly, Smith and Lee (2006) observed high incidence of N and P co-limitation in 12 coastal kettle ponds in the Eastern U.S. despite TN:TP ratios averaging 71. Francoer et al. (2001) and Elser et al. (2007) found N and P co-limitation to be common across most published nutrient enrichment bioassay studies in freshwater. Despite variability in TN:TP ratio in this study, N limitation was observed at an average TN:TP ratio of 27 which was considerably higher than the Redfield ratio of 16. The average DIN levels in ponds exhibiting N limitation were near previous published threshold levels of 0.100 mg/L where N was thought to be limiting (Table 4-4). The average N:P ratios for P limited sites were > 30 for both years although because P limitation was rare the averages of N:P ratios in 2006, in particular, were heavily influenced by an outlier (Appendix D, Table D-4).

Table 4-4. Published N and P threshold limits in freshwater below which algae have been found growth limited. (Adapted from Glozier et al. 2006)

Reference	TP (mg/L)	TN (mg/L)	Type of Water body	Type of Algae
Borchardt (1996)	--	0.035	Lotic	Periphyton
Bothwell (1989)	0.005 (TDP)	--	Lotic	Periphyton
Cash et al. (2004)	0.008 (ortho-P)	0.080 ($NO_3 + NO_2$)	Lotic	Periphyton
Chambers and Guy (2004)	0.003 (TDP)	0.065 (DIN)	Lotic	Periphyton
Dodds. et al. (2002)	0.030	0.040	Lotic	Periphyton
Dodds et al. (1997)	0.055	0.470	Lotic	Periphyton
Horne and Goldman (1994)	--	0.100 (DIN)	Lentic	Phytoplankton
Lohman et al. (1992)	0.021	0.250	Lotic	Periphyton

The high frequency of N and P co-limitation detected in ponds could have been a result of multiple species of periphyton with differing nutrient requirements (Francoeur 2001) or temporal changes in nutrient limitation after one nutrient requirement was satisfied. The Redfield TN:TP ratio of 16:1 is merely an average of nutrient requirement ratios amongst algae and researchers have observed considerable variability among freshwater species (Healey and Hendzel 1979, Rhee and Gotham 1980). Thus, because periphyton species may thrive at different N:P ratios, one species could be limited by N while another species on the same substratum is limited by P and both requirements could then be met by a combined N and P enriched treatment. However, the further away the ambient N:P ratio is from the average of 16 the more consistent the nutrient response for different algal species. For example, most freshwater algae have optimum N:P ratios well below 100 so any algae present in water with a ratio above 100 would likely be P limited (Hecky and Kilham 1988). Another reason for abundant algal growth on the N and P combined treatment is that as the requirements for the initial limiting nutrient, for example P, are met, there may be a shift to the other nutrient, for example N, being limiting (Smith and Lee 2006). Thus, the presence of both N and P in a treatment may allow periphyton to grow virtually uninhibited by nutrients because the limiting nutrient is always supplied by either the N or P.

Interestingly, 8% of the ponds had significantly less algal growth on an N or P treatment in comparison to the control. This phenomenon has been observed by other researchers with NDS treatments but to my knowledge the causes are still speculative and there has been no conclusive explanation (Fairchild et al. 1985, Tank and Dodds 2003).

The inability of N:P ratios to consistently reflect periphyton limitation, as indicated by the NDS, suggests that algal nutrient limitation in farm ponds is complex and difficult to summarize with a water chemistry sample taken once every three weeks. Indeed, the great value of using bioassays over an extended period of time is to account for fluctuating chemical concentrations, the influence of biota and changing weather conditions. Chemical fluctuations are frequent in shallow water bodies because nutrients, released by the sediments during intensive decomposition and subsequent anoxic conditions, are frequently mixed throughout the water column during windy weather (Scheffer and Van Nes 2007). Biota can influence the response of periphyton on a bioassay in numerous ways including grazing on the periphyton (e.g., snails), competing for inorganic nutrients (i.e., fungi and bacteria), and shading by aquatic and terrestrial plants and metaphyton. In addition, each periphyton species that colonizes the NDS has unique nutrient requirements, growth rate and morphology, which can contribute to assemblage variability by affecting the ability of periphyton to adapt to diverse physiochemical conditions. If the conditions on an NDS treatment are ideal for a periphyton species with a high growth rate it may affect the amount of biomass accumulated on the treatment and may not be directly comparable to periphyton growth from other species on NDS treatments. Fairchild et al. (1985) observed that periphyton species assemblages on NDS changed in response to different enrichment concentrations. Therefore, it is also likely that periphyton species composition on NDS will vary when the treatment concentrations remain the same but ambient nutrient concentrations in each pond is different. Morphological differences between periphyton taxa can affect their relative ability to remain attached to NDS because, as the periphytic cell grows away from the substratum, it becomes more vulnerable to be sloughed off via turbulent water and being grazed.

I hypothesized that NDS algal growth would be inconsistent with predicted nutrient limitation from static measurements of chemical N to P ratios of ponds because pond water chemistry is dynamic temporally and spatially. The hypothesis was accepted by this study because the algal response to the NDS, although often congruent with high and low N and P levels in the ponds, was variable and not always predictable by traditional Redfield molar ratios of N and P (TN:TP and DIN:TRP) where greater than 16 indicates P limitation and less than 16 reveals N limitation. The range of nutrient limitation where < 10 is N limitation, > 20 is P limitation and in between is variable (could be N, P or co-limited) was also inaccurate for these results (Healey and Hendzel 1980, Schanz and Juon 1983). The TN:TP was probably the best ratio to compare with the NDS results because it represented a more stable total nutrient pool; conversely, DIN:TRP and DIN:TP included the nutrient forms, DIN and/or TRP, which are liable to change rapidly over time depending on the turnover rate of nutrient supply (Dodds 2003). Unlike DIN and TRP, the total measure of nutrients in TN and TP takes into consideration nutrients that are available for both uptake and remineralization. During this study the DIN values were so low comparative to TP values that there was not a lot of information given by the DIN:TP ratio and many of the DIN:TP ratios were less than 1. There were times, however, when comparing the DIN:TP ratio with the TN:TP ratio gave additional information that helped in understanding the NDS. For instance, sometimes the periphyton responded mostly to N enrichment when the TN:TP ratio was greater than 50 but the DIN:TRP and DIN:TP was less than 10. If only the TN:TP ratio was considered there would be little correspondence with the NDS results but the additional information of DIN:TRP and DIN:TP suggested dissolved nitrogen concentrations were very low comparative to available phosphorus despite higher TN values overall.

4.4.1 Further Consideration and Future Research

Internal N:P concentrations of algae, nutrient deficiency based on physiological assays and algal taxonomy would be valuable in further clarifying nutrient limitation and the algal response to ambient water chemistry. Internal N:P concentrations of algae would be useful to compare with external water chemistry to see if there is correlation between them. If internal and external N:P ratios are quite different it may be an indication that algae have physiological adaptations, such as the ability to luxury consume P in times of abundance, which enable them to overcome times of nutrient limitation. Physiological measures of nutrient deficiency, such as monitoring the alkaline phosphatase activity (APA) in algae, can further clarify the actual status of nutrient supply. For example, if algae are producing high concentrations of APA it implies that P is in short supply and thus confirms that the algae are probably P limited. Specific knowledge of individual periphyton growing on the NDS, combined with knowledge of their life history characteristics and physiological N:P ratios, would clarify the resulting biomass response on nutrient treatments. For instance, if a periphyton species identified on the NDS was known to have a normal N:P ratio of 30:1 and a high growth rate it would not be surprising to find it growing abundantly on the N enriched treatment in a pond with an N:P ratio of 20:1. Better knowledge of individual species response on the NDS may help to explain a large response on the N treatment despite an apparently high N:P ratio relative to the Redfield ratio.

4.4.2 Conclusion

Overall, this research demonstrates the difficulty in predicting nutrient limitation in small, shallow, eutrophic water bodies using NDS and external N:P ratios and highlights the importance of monitoring both N and P. In this study of farm ponds it was common for static and integrated nutrient limitation measures to give conflicting results where N appeared limiting in one measure and P appeared limiting in the other. This is not surprising because in deeper stratified lakes where nutrient levels are considered more stable (less influenced by sediment and nutrient rich bottom water) Guildford and Hecky (2000) also found that different nutrient limitation measures (i.e., internal and external N:P ratios and physiological assays) contradicted each other. It is also apparent from this study that nutrient levels in many farm ponds are at such an elevated level that nutrient limitation is perhaps no longer an issue. The evident lack of nutrient limitation in many ponds is a strong indication that nutrient levels are high and other factors such as light and grazing is what predominantly limits algal growth. This is especially clear in ponds with above average nutrient levels and less applicable in sites where growth was severely limited by turbidity levels compared to the other sites (~ > 20 NTU). This lack of response to NDS treatments suggests their value may be limited in turbid and eutrophic conditions and that alternative measures such as physiological assays (i.e., APA) and internal N:P ratios may be more useful. Furthermore, periphyton in many of these ponds are clearly responding more to N addition or N and P addition combined than P addition alone; thus, it is perhaps an indication that P is enriched to such an extent that it is no longer growth limiting. From a management perspective this highlights the need to regulate and monitor N along with P to fully protect water quality in this region (Smith and Lee 2006).

Chapter 5: Research Synthesis

This research was important in elucidating anthropogenic influences on surface waters in south-central Manitoba and understanding the present status of algal nutrient limitation. Manitoba's waterways are becoming increasingly vulnerable to agricultural inputs as the level of agricultural intensity increases and more land is being utilized for a maximum output of production. The consequences are apparent in the frequency and magnitude of algal blooms across Lake Winnipeg and in the inconspicuous, but equally telling, confines of rural farm ponds. The focus of this study on small ponds with limited watersheds gave us confidence that measured water quality within the ponds was impacted primarily by immediately surrounding land use and landscape variables. Indeed, over 50% of characteristic water chemistry was consistently predicted over two field seasons of study by land use and landscape variables. The amount of water chemistry variation predicted was impressive and gives confidence in further potential for understanding and predicting surface waters using readily accessible land use and landscape measures such as percent forested land and cattle disturbance (Cattle Trampling). The impacts of land use on water quality extends over enormous tracts of land and it is far easier and cost effective to monitor using coarse scale measures rather than sampling hundreds of surface water locations on a continuous basis.

The prediction of water chemistry from land use and landscape variables was consistent over two field seasons with different extremes of precipitation implying that the predictive model itself was accurate over a variety of conditions. This is important because it suggests the results of the analysis are stable and could potentially be used to predict water chemistry over multiple years rather than being re-examined annually. In particular, the prediction of TP using percent forested land and Cattle Trampling was so similar over the two years that it is possible it may even apply to a broader region.

The clear association between land use and water quality observed in this study demonstrates to agricultural producers and policy makers the value of allocating resources to monitor and protect farm ponds. In addition, the ability to explain large portions of water chemistry variance in these farm ponds using easily attainable, coarse scale measures has encouraging potential for monitoring larger regions of study. For example, measures such as percent forested land and Cattle Trampling could be used to estimate the contribution of individual regions to a particular watershed. This contribution could be verified by sampling drainage or streams flowing out of the specified regions.

The model of water chemistry and land use/landscape interaction can be used by future policy makers and researches to identify important predictors of individual water chemistry parameters of interest. For example, in this study I chose to find out specific parameters that best predict TP concentrations because of the important role P has in driving eutrophication in surface water. Similarly, if someone was interested they could use this data set to examine what parameters might best predict chloride or N concentrations. Otherwise, they could simply examine the multivariate model (RDA) and evaluate which predictor variables they correspond most strongly with. Many variables, such as chloride, were not used directly in the multivariate analysis, however, they were highly correlated with actual variables in the analysis (i.e., chloride was highly correlated with conductivity).

While the concentration of N and P that is released into surface water is of concern it is often vital to consider the ratio of N:P to determine how great an impact the nutrient addition will actually have. In this study, however, the number of ponds exhibiting no significant algal response to nutrient addition (> 1/3) and the overall high level of nutrients suggested that nutrient ratios were of limited use because nutrient concentrations were no longer limiting. Therefore, algae had become more limited by physical parameters such as light, temperature and grazing. For this reason it is challenging to use nutrient ratios to predict nutrient limitation unless there is further knowledge of the threshold nutrient concentrations where N and P are no longer limiting. However, threshold nutrient concentrations are difficult to obtain in these shallow, eutrophic ponds where nutrient concentrations, biota and physical parameters (e.g., turbidity) are very dynamic. In contrast, the algal growth response on NDS is better at demonstrating algal nutrient limitation because it occurs over several weeks and takes into consideration the changing ambient conditions. Ideally, physiological assays (e.g., APA) of algal growth could be used to compliment NDS studies and confirm actual algal nutrient limitation. Physiological assays are more integrated than static nutrient concentrations because they exhibit algal response to nutrient uptake over a period of days. As well, physiological assays are dealing with actual algal nutrient uptake, not the uptake implied by external nutrient concentrations which are subject to spatial and temporal variability.

Ponds that were limited by nutrients were primarily N limited or co-limited by N and P. From a management perspective this poses the question of whether it is most beneficial to regulate N or P. Clearly much of the algal response was to N input which implies regulation of N is important, however, it may also indicate that P inputs have become so consistently high that they are no longer limiting. Much of the P in the ponds could be bound up in the sediment and available to algae through resuspension of sediment, anoxic release or decomposition of macrophytes and sediment dwelling periphyton. Phosphorus remains the primary nutrient to regulate because, unlike N, it has low solubility and is therefore easier to control and it has no significant pathway for removal once it has entered surface waters. Thus while both N and P should be monitored and regulated, management of P in particular is crucial.

Overall, these farm ponds were fascinating to study because of their wide range in physical, chemical and biological attributes and surrounding land use and landscape. There is great potential for understanding land use and landscape impacts on water chemistry by using these ponds and even further opportunity to understand the range of physical and chemical conditions that specific biota inhabit. Studies of these ponds can be broadened to cover a larger region such as an ecoregion in order to increase the relevancy of the data. In addition the depth of information collected in and around each pond could be increased (i.e., watershed delineation, hydrology, species richness) in order to enhance the understanding of these ponds and increase the amount of predictable water chemistry variation. Studying these ponds provides tangible information for both individual landowners and broader public policy groups to make valuable economic and environmental decisions that affect the future of the northern prairie region.

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Appendix A. Further clarification of select methods

<u>Nitrate and Nitrite-N</u>

The nitrate and nitrite-N values obtained from the new 2006 AS11 ion chromatographic column were considerably different from 2005 values using an AS24 ion chromatographic column. After running the same samples using both columns I was still unable to get a clear correlation between the two data sets. As a result the 2005 data are suspect and I believe it to be inaccurately high.

<u>Cattle Intensity Index (CATIND)</u>

I expected that together all three rankings of Cattle Access, Cattle Number and Time Around the Pond would give an accurate picture of Cattle Intensity (CATIND), more so than any of the rankings on its own. For this reason I multiplied the three rankings together to form a pseudo-variable of Cattle Intensity for each site. Cattle access was ranked from 0 to 2 where 0 = no access and no cattle in vicinity, 1 = restricted/fenced off access, 2= open access. For Cattle Number the cattle were ranked from 0 to 3 where 0 = no cattle, 1 = 1 to < 20 head, 2 = 20 to 50 head, 3= > 50 to 100 head and 4 = >100 head. Most of the cattle were beef cow/calf pairs with only 4 sites containing dairy cattle. Calves were considered one head equally with cows. Annual time around pond was ranked from 0 = cattle never present, 1 = cattle present < 3 months, 2 = cattle present 3 to 8 months and 3 = cattle present > 8 months (over winter). Again, the rankings for time around the pond were based upon common grazing periods for our sample. The ranking categories for cattle number and time around pond were decided upon after examining the distribution of the data in a Gaussian plot and observing natural breaks which would best differentiate between groups.

Cattle Trampling

The Cattle Trampling ranking was designed to encapsulate cattle impact of both:

1) Physical disturbance – Determined by observation of livestock presence such as hoof prints, trampled vegetation in or around pond, and livestock fecal matter.

2) Potential disturbance – Consideration of cattle fecal matter around pond and potential risk of runoff, particularly relevant at sites where physical disturbance around pond was minor (i.e., pond was fenced off), yet potential for disturbance was still a possibility.

Ranking:

0 = None = no cattle disturbance in vicinity of pond

1 = Low = exhibits both of the criteria below

- □ Riparian area within 5 m of pond remains primarily undisturbed
- □ Low probability of significant manure runoff
    - ▪ i.e., cattle primarily down slope from pond
    - ▪ i.e., pasture has low density grazing

2 = Moderate = exhibits at least one of the criteria below and none from higher rankings

- □ Riparian area within 5 m of pond was frequently trampled by a low density of cattle relative to pond size
    - ▪ i.e., much of the riparian vegetation would still be intact
- □ Moderate probability of significant manure runoff
    - ▪ i.e., range area sloped toward pond with moderate livestock density during the growing season
    - ▪ i.e., range area sloped toward pond with high livestock density during the growing season for a short period of time

3 = High = exhibits only one of the criteria below

- ☐ Riparian area within 5 m of pond was frequently trampled by a moderate to high density of cattle relative to pond size
    - ▪ i.e., most of the riparian would be trampled including the shoreline submerged macrophytes
- ☐ High probability of significant manure runoff
    - ▪ i.e., range area high livestock density sloped toward pond throughout the growing season
    - ▪ i.e., range area with moderate livestock density sloped toward pond throughout the year (over the winter also)
    - ▪ i.e., range area with high livestock density over the winter sloped toward pond

4 = very high = exhibits both of the below criteria

- ☐ Riparian area within 5 m of pond was frequently trampled by a moderate to high density of cattle relative to pond size
    - ▪ i.e., most of the riparian would be trampled including the shoreline submerged macrophytes
- ☐ High probability of significant manure runoff
    - ▪ i.e., range area with high livestock density sloped toward pond throughout the growing season
    - ▪ i.e., range area with moderate livestock density sloped toward pond throughout the year (over the winter also)
    - ▪ i.e., range area with high livestock density over the winter sloped toward pond

Appendix B. Additional Results

Table A-1. Pond attributes and sediment variables for 2005 and 2006.

Site	UTM E	UTM N	Surface Area (m^2)	% Riparian Cover (2005)	% Riparian Cover (2006)	Macrophyte Rank (2005)	Macrophyte Rank (2006)	Sediment Texture Class	Sediment Organics (%)	Sediment Carbonates (%)
1	562544	5551287	1440	70	70	1	1	Sandy Loam	3	18
2	534108	5553948	2268	70	70	2	2	Loam	5	9
3	550027	5556901	800	95	95	5	5	Sand		
4	501606	5517453	1650	95	95	9	9	Sandy Loam	4	1
5	499746	5515689	1265	95	95	5	5	Sandy Loam	9	4
6	501276	5491000	1320	75	75	7	7	Loam	6	1
7	514638	5488401	2244	65	65	8	8	Loam	7	14
8	512233	5541668	1092	40	40	1	1	Sandy Loam	5	3
9	564109	5554925	1525	80	80	8	8	Sandy Loam	7	15
10	562965	5554522	1260	70	70	3	3	Sandy Loam	7	15
11	562129	5494615	800	90	90	4	4	Loam	3	5
12	562162	5494646	750	80	60	0	0	Sandy Loam	8	6
13	563931	5493755	2450	60	50	0	0	Loam	23	11
14	569211	5565053	825	70	70	4	4	Loam	3	20
15	567993	5565129	1196	50	50	1	1	Sandy Clay Loam	4	14
16	624302	5510504	950	0	0	2	2	Sandy Loam	7	3
17	626361	5492143	1200	100	100	5	5	Sandy Loam	10	3
18	561720	5504395	648	100	100	8	8	Sandy Loam	2	3
19	552186	5485273	1035	80	80	4	4	Loamy Sand	1	2
20	549385	5509969	2100	90	90	1	1	Sandy Loam	2	3
21	549388	5510183	2600	75	75	3	3	Loam	3	11
22	601106	5506982	882	45	20	6	6	Sandy Loam	8	4
23	517402	5499327	5500	95	95	7	7	Loam	4	2
24	541947	5511986	2015	90	90	1	1	Loamy Sand	4	2
25	520710	5489408	374	80	80	1	1	Loam	2	15
26	506066	5499554	1800	95	95	2	2	Loamy Sand	2	1
27	558916	5485199	1166	80	70	2	2	Loam	7	4
28	525048	5509977	2240	95	95	6	6	Loam	10	10
29	547823	5556384	500	65	55	1	1	Sandy Loam	12	5
30	540901	5503258	1040	65	45	0	0	Sandy Loam	5	5
31	561415	5551332	1210	90	70	10	10	Sandy Loam	7	11
32	558745	5549329	3150	90	80	1	1	Sandy Loam	10	14
33	509548	5487488	1323	50	50	2	6	Sandy Loam	12	5
34	626181	5490228	1250	90	90	7	7	Sandy Loam	11	2
35	626072	5490149	6250	80	80	2	2	Sandy Loam	9	2
36	507801	5513978	1800	100	90	1	1	Loam	12	16
37	507922	5512811	1000	100	90	5	5	Loam	13	20
38	500371	5487772	1404	65	65	6	6	Sandy Loam	7	6
39	569674	5553500	2275	100	90	6	4	Sandy Loam	7	16
40	542787	5499845	1500	60	50	1	1	Sandy Loam	4	5
41	556469	5511394	1792	90	70	5	5	Sandy Loam	7	4
42	510319	5533974	1200	95	95	6	6	Loam	6	6
43	509615	5533173	1500	75	75	1	1	Sandy Loam	5	5
44	605299	5500711	1000	60	60	1	1	Sandy Loam	11	3
45	502756	5511242	1250	85	75	9	9	Loamy Sand	4	2
46	563038	5549031	1944	80	60	7	7	Sandy Loam	6	16
47	561496	5548869	3400	80	60	5	5	Sandy Loam	6	17
48	563484	5494981	1250	30	30	1	1	Sandy Loam	1	3
49	545640	5524186	1872	100	100	10	10	Loamy Sand	1	1
50	527752	5501815	893	95	95	3	3	Loam	8	6
51	543689	5489644	800	60	60	1	1	Loamy Sand	1	4
52	567013	5562318	500	60	50	1	1	Sandy Loam	7	18
53	551092	5544156	3375	100	100	1	1	Sandy Loam	4	6
54	559436	5551157	1098	90	90	10	10	Sandy Loam	7	12
55	558330	5548598	2800	95	85	5	5	Loam	7	5
56	514022	5543790	476	40	40	2	2	Sandy Loam	7	7
57	568607	5559788	1600	30	30	1	1	Loam	1	26
58	530035	5536123	2400	65	65	2	2	Sandy Loam	2	2
59	554521	5537664	1972	50	50	5	5	Loam	4	7
Min	**499746**	**5485199**	**374**	**0**	**0**	**0**	**0**		**1**	**1**
Max	**626361**	**5565129**	**6250**	**100**	**100**	**10**	**10**		**23**	**26**
Mean	**548391**	**5520891**	**1648**	**76**	**71**	**4**	**4**		**6**	**8**

Table A-2. Seasonal mean of field and water chemistry variables for farm ponds, 2005.

Site	Air Temp (°C)	Water Temp (°C)	Conductivity (µS/cm)	Max Depth (m)	Secchi (cm)	Turbidity (NTU)	TSS (mg/L)	ISS (mg/L)	OSS (mg/L)	Alkalinity (mg/L)	pH	Microcystin (µg/L)	Total Chlorophyll (µg/L)
1	23.8	22.6	1832	3.04	100	13	9.4	2.6	6.8	172	7.9	0.10	10
2	17.5	19.6	508	3.33	61	12	15.2	5.8	9.4	230	7.6	0.17	30
3	17.5	19.5	2354	2.13	99	9	13.1	2.3	10.8	734	8.1	0.26	9
4	18.1	18.6	443	2.75	146	9	4.7	0.0	4.7	266	7.5	0.20	7
5	17.7	18.9	414	3.06	124	11	5.1	0.5	4.6	195	7.2	0.14	28
6	19.2	19.7	925	2.77	93	9	9.0	1.0	8.0	209	8.0	0.05	61
7	17.5	19.0	657	2.14	130	10	3.9	1.7	2.2	394	8.1	0.05	5
8	17.4	16.7	794	3.03	33	24	33.8	15.5	18.3	400	7.3	0.17	61
9	21.1	20.5	513	1.44	81	10	6.4	1.2	5.2	255	7.3	0.05	11
10	22.1	21.1	560	1.69	71	10	9.3	1.9	7.4	254	7.4	0.08	49
11	24.0	23.8	480	2.81	114	10	9.1	0.5	8.6	218	8.6	0.05	53
12	23.9	25.2	678	1.52	41	24	32.1	8.1	24.0	304	8.2	1.42	77
13	25.3	25.6	1757	2.39	6	85	164.2	65.0	99.2	419	8.0	0.30	117
14	17.1	18.6	610	1.81	109	10	7.0	1.1	5.9	276	7.9	0.05	6
15	17.8	19.6	1419	2.27	195	10	5.6	0.5	5.1	223	8.2	0.05	3
16	22.6	22.8	263	2.85	70	22	27.7	12.1	15.6	108	8.5	0.05	34
17	24.2	22.4	319	2.67	138	9	18.6	2.0	16.6	154	7.4	0.07	68
18	23.6	23.0	393	2.77	215	7	7.1	0.6	6.5	209	7.8	0.05	13
19	15.7	18.3	412	1.67	46	16	25.4	2.4	23.0	214	8.1	0.05	188
20	18.4	18.9	505	4.01	151	11	9.0	0.6	8.4	222	7.7	0.05	56
21	18.5	19.9	457	4.02	117	10	6.1	0.1	6.0	226	7.8	0.05	6
22	25.9	22.1	452	3.66	140	8	21.0	7.8	13.2	151	7.3	0.08	77
23	17.2	18.4	675	3.57	243	11	4.6	0.8	3.8	148	7.5	0.11	5
24	17.6	20.5	679	2.93	152	10	10.3	2.8	7.5	213	7.8	0.27	50
25	17.9	18.0	491	2.58	204	11	14.1	7.9	6.2	240	7.8	0.05	9
26	18.2	19.9	304	3.53	102	10	13.1	2.1	11.0	159	7.5	0.05	38
27	16.7	18.7	469	3.49	60	17	11.5	0.0	11.5	211	7.8	0.06	44
28	15.9	18.0	632	3.69	234	9	7.1	0.3	6.8	349	7.9	0.05	14
29	24.0	22.9	2607	1.53	39	21	22.8	8.1	14.7	310	7.9	0.12	43
30	14.4	17.4	573	3.19	84	12	15.7	5.9	9.8	296	7.5	0.05	16
31	23.3	21.6	360	2.04	71	9	20.0	2.8	17.2	186	7.6	0.06	122
32	22.2	21.2	417	1.02	48	15	27.8	12.4	15.3	205	7.4	0.05	87
33	17.1	18.5	1181	1.42	52	15	17.3	3.6	13.7	377	8.2	0.11	51
34	25.2	21.8	928	3.41	87	10	21.8	0.0	21.8	156	7.6	0.12	149
35	24.4	23.8	435	4.51	37	24	32.6	5.6	27.0	122	8.9	0.62	166
36	17.5	19.9	610	2.51	73	16	17.4	0.6	16.8	306	7.8	0.05	68
37	18.1	18.8	419	2.33	118	11	6.9	0.0	6.9	208	7.5	0.05	24
38	19.2	19.6	616	3.23	68	12	16.7	2.1	14.6	215	8.4	0.32	52
39	18.7	19.5	564	3.18	81	8	7.4	0.3	7.1	254	7.7	0.09	25
40	14.5	17.5	686	2.18	28	37	25.3	5.4	19.9	362	7.8	0.09	268
41	22.5	22.3	467	3.84	131	11	14.9	2.8	12.1	252	8.0	0.05	42
42	19.7	19.5	689	2.52	112	8	7.9	0.4	7.5	276	7.8	0.06	9
43	19.2	19.6	748	1.88	67	14	14.0	1.5	12.5	329	7.7	0.05	206
44	25.5	24.7	342	3.27	170	12	13.9	1.2	12.7	146	7.9	0.10	50
45	18.1	20.3	399	2.74	200	7	4.3	0.6	3.7	217	7.8	0.05	11
46	19.0	20.4	391	1.94	61	13	19.0	3.8	15.2	192	8.4	0.12	64
47	19.2	20.2	489	2.44	45	19	35.5	13.0	22.5	242	8.1	0.08	159
48	25.7	26.3	461	2.78	103	10	13.0	1.4	11.6	181	8.9	0.07	58
49	21.2	22.0	440	2.23	177	7	22.0	7.8	14.2	185	8.0	0.05	21
50	20.4	19.3	1044	2.78	130	11	12.4	2.7	9.7	341	7.8	0.08	25
51	15.2	20.1	421	2.76	168	11	5.1	0.4	4.7	182	8.1	0.05	9
52	17.6	18.8	781	2.09	39	27	43.2	20.7	22.5	386	8.2	0.05	139
53	17.6	19.9	421	2.80	115	21	28.8	15.6	13.2	165	7.6	0.05	19
54	20.0	21.6	289	2.22	96	14	14.3	5.8	8.5	182	8.6	0.05	17
55	22.3	21.6	314	1.69	68	16	25.2	10.9	14.3	134	7.2	0.07	86
56	14.1	18.6	574	2.99	79	12	4.0	0.0	4.0	308	7.6	0.12	76
57	18.2	20.0	568	1.83	100	12	5.4	0.0	5.4	288	8.2	0.05	6
58	18.4	19.5	1216	3.48	62	14	14.5	3.3	11.2	330	7.9	0.44	43
59	17.6	19.0	459	2.75	79	24	28.5	13.8	14.7	206	7.6	0.15	25
Min	**14.1**	**16.7**	**263**	**1.02**	**6**	**7**	**3.9**	**0.0**	**2.2**	**108**	**7.2**	**0.05**	**3**
Max	**25.9**	**26.3**	**2607**	**4.51**	**243**	**85**	**164.2**	**65.0**	**99.2**	**734**	**8.9**	**1.42**	**268**
Mean	**19.7**	**20.4**	**676**	**2.66**	**103**	**15**	**18.0**	**5.1**	**12.9**	**249**	**8.0**	**0.13**	**55**

Table A-3. Seasonal means of nutrient and ion analysis for farm ponds, 2005.

Site	TP (mg/L)	TRP (mg/L)	TN (mg/L)	Ammonia-N (mg/L)	NO_3 and NO_2-N (mg/L)	TN:TP molar	DOC (mg/L)	Chloride (mg/L)	Sulphate (mg/L)	Potassium (mg/L)	Sodium (mg/L)
1	0.04	0.01	4.34	0.01	0.18	190	13.4	244	201		
2	1.14	0.88	9.85	0.12	0.27	18	17.9	10	24		
3	3.18	1.81	9.45	1.05	0.47	7	41.8	331	125		
4	0.20	0.25	2.64	0.02	0.23	37	22.9	3	1		
5	0.13	0.03	1.94	0.01	0.42	46	21.4	22	11		
6	1.58	1.09	4.51	0.10	0.09	7	16.0	9	304	8	58
7	0.07	0.01	2.23	0.01	0.27	105	22.1	1	15	1	12
8	2.23	1.05	25.05	0.84	0.25	26	43.2	15	10		
9	0.06	0.01	2.80	0.01	0.20	160	26.9	2	22	2	5
10	0.14	0.04	2.69	0.02	0.23	46	26.4	9	38	4	10
11	0.50	0.35	3.50	0.01	0.21	29	19.0	18	23	13	5
12	1.91	1.25	6.50	0.49	0.33	8	32.8	25	16	17	9
13	3.72	3.32	24.83	2.30	0.84	15	43.1	152	36	100	28
14	0.08	0.02	2.48	0.02	0.20	94	25.8	32	55		
15	0.07	0.03	3.39	0.03	0.15	116	23.6	116	251		
16	0.36	0.20	3.27	0.06	0.16	26	11.7	4	24	1	2
17	0.26	0.12	2.11	0.01	0.13	23	11.2	8	6	1	3
18	0.10	0.01	2.16	0.01	0.17	59	14.4	3	4	0	1
19	0.69	0.37	4.27	0.12	0.23	17	15.8	4	9	5	1
20	0.82	0.69	3.45	0.81	0.23	10	21.5	17	7	13	4
21	0.80	0.71	2.24	0.07	0.21	6	21.7	6	6	6	4
22	0.18	0.08	1.99	0.01	0.12	26	11.7	19	41	4	4
23	0.45	0.35	3.29	0.10	0.17	56	13.2	9	199	6	5
24	0.10	0.02	3.73	0.33	0.18	124	15.8	72	40	4	10
25	0.04	0.01	1.14	0.01	0.18	107	8.2	2	32	1	14
26	0.49	0.43	3.55	0.06	0.15	18	14.9	3	2	4	1
27	2.13	1.39	6.24	0.65	0.62	6	19.3	9	17	14	4
28	0.30	0.25	1.85	0.01	0.21	15	13.9	4	5	1	1
29	2.55	1.45	10.42	0.67	0.63	9	29.2	440	387	25	85
30	0.10	0.03	4.29	0.03	0.29	123	29.1	7	22	3	6
31	0.24	0.08	3.31	0.01	0.19	54	18.2	5	5	2	2
32	0.53	0.31	3.35	0.05	0.20	36	18.7	5	20	4	3
33	0.39	0.20	3.01	0.20	0.20	22	15.5	11	328	2	29
34	0.36	0.17	4.94	0.01	0.15	30	16.6	155	35	3	18
35	0.22	0.05	3.05	0.02	0.10	35	12.0	44	47	2	8
36	0.18	0.06	3.70	0.07	0.20	55	26.2	12	3	18	4
37	0.14	0.05	3.27	0.02	0.14	45	23.6	4	4	4	1
38	2.13	1.27	3.72	0.11	0.16	4	17.3	8	151	6	26
39	0.09	0.02	4.13	0.01	0.19	102	25.2	3	45		
40	1.45	0.80	8.52	1.34	0.32	16	35.9	12	9	16	16
41	0.18	0.02	2.83	0.03	0.19	44	24.6	4	8	2	3
42	0.49	0.37	2.38	0.08	0.17	14	25.5	8	108		
43	0.84	0.51	4.39	0.67	0.37	11	23.4	7	77		
44	0.29	0.19	1.51	0.03	0.13	12	10.2	12	25	1	4
45	0.05	0.01	2.66	0.01	0.15	150	15.2	1	3	0	0
46	0.18	0.03	3.00	0.01	0.20	65	15.3	6	16		
47	0.64	0.28	4.20	0.03	0.19	16	22.7	14	7		
48	0.56	0.39	5.30	0.03	0.15	21	16.5	33	13	6	7
49	0.17	0.08	2.80	0.01	0.13	53	13.3	29	40	2	1
50	0.27	0.18	3.53	0.04	0.34	80	17.2	8	212	1	7
51	0.04	0.01	3.02	0.04	0.99	140	7.9	5	41	1	3
52	0.44	0.15	5.18	0.08	0.28	27	35.3	14	81		
53	0.96	0.95	3.77	0.39	0.54	14	14.2	4	20		
54	0.10	0.03	1.78	0.01	0.47	40	15.1	80	62	2	1
55	1.56	0.95	4.26	0.02	0.16	9	18.0	6	4	6	1
56	0.47	0.27	5.13	0.33	0.20	38	33.7	8	19		
57	0.06	0.01	2.97	0.01	0.22	210	23.1	3	37		
58	2.64	1.52	10.68	1.74	0.22	9	32.8	70	199		
59	0.39	0.16	2.72	0.05	0.32	20	16.3	16	15		
Min	**0.04**	**0.01**	**1.14**	**0.01**	**0.09**	**4**	**7.9**	**1**	**1**	**0**	**0**
Max	**3.72**	**3.32**	**25.05**	**2.30**	**0.99**	**210**	**43.2**	**440**	**387**	**100**	**85**
Mean	**0.69**	**0.43**	**4.63**	**0.23**	**0.26**	**49**	**21.0**	**37**	**60**	**8**	**10**

Table A-4. Seasonal mean of field and water chemistry variables for farm ponds, 2006.

Site	Air Temp (°C)	Water Temp (°C)	Conductivity (µS/cm)	Dissolved Oxygen (mg/L)	Max Depth (m)	Secchi (cm)	Turbidity (NTU)	TSS (mg/L)	ISS (mg/L)	OSS (mg/L)	Alkalinity (mg/L)	pH	Microcystin (µg/L)	Total Chlorophyll (µg/L)
1	25.2	23.0	1312	10.7	2.26	133	4	6	0	5	177	8.8	0.05	5
2	18.9	19.1	532	7.1	2.95	47	13	21	10	11	210	8.3	0.08	71
3	23.0	22.1	2800	9.3	1.66	108	2	9	1	8	711	8.6	0.28	13
4	24.1	21.1	511	3.9	2.43	109	3	10	2	9	298	7.4	0.06	13
5	24.3	21.4	445	3.3	2.78	93	5	13	2	11	240	7.2	0.05	27
6	23.2	21.3	863	10.7	2.34	70	15	21	6	15	228	8.6	0.05	97
7	23.8	21.3	614	8.1	1.83	115	16	22	12	11	379	8.4	0.05	21
8	23.5	18.8	720	0.9	2.52	22	104	72	28	44	378	7.0	0.10	58
9	23.5	22.5	848	6.3	1.46	65	9	16	3	13	344	8.0	0.12	71
10	24.3	22.1	592	6.4	1.46	52	14	39	3	36	290	7.9	0.05	73
11	25.1	21.4	414	8.8	2.31	120	5	12	3	9	205	9.1	0.05	33
12	24.6	21.4	1159	2.1	0.70	9	283	447	199	248	437	8.0	0.21	914
13	25.3	22.8	1621	3.3	2.11	8	115	53	13	40	591	8.0	0.30	84
14	19.0	19.9	446	8.0	1.46	88	5	8	1	7	230	8.3	0.05	13
15	20.3	20.9	1652	7.4	2.38	181	2	9	3	6	233	8.3	0.05	2
16	21.7	20.7	181	10.2	2.72	30	66	33	4	29	80	9.1	0.06	309
17	23.1	21.5	332	8.4	2.27	106	6	13	1	12	163	7.6	0.07	66
18	23.7	22.2	319	8.8	2.19	121	3	6	0	6	176	7.9	0.05	34
19	23.1	21.9	309	5.6	1.44	18	42	55	16	39	154	7.8	0.07	134
20	24.5	22.8	410	8.2	3.00	61	18	12	2	10	200	8.5	0.08	75
21	25.0	23.8	419	11.0	2.98	75	17	21	8	12	220	8.6	0.05	60
22	27.0	18.4	3155	2.4	3.03	63	23	10	2	7	186	7.3	0.05	77
23	21.5	19.8	1150	5.9	2.92	162	2	9	1	7	288	7.8	0.05	31
24	27.5	23.6	635	9.2	2.53	120	3	3	1	2	162	8.2	0.11	12
25	25.5	21.3	630	9.1	2.14	156	3	3	0	3	314	8.1	0.05	7
26	21.4	21.1	393	9.2	2.89	81	6	13	1	12	233	8.1	0.05	56
27	24.3	23.9	728	9.8	2.28	38	34	20	6	14	354	8.5	0.08	464
28	19.8	20.1	411	8.6	3.59	104	7	11	3	8	278	8.0	0.05	31
29	23.4	22.7	2900	10.1	0.69	19	29	98	23	75	414	8.0	0.13	387
30	20.3	19.9	672	3.4	2.44	29	30	26	11	15	378	7.5	0.13	21
31	22.4	21.5	396	9.3	1.83	55	15	22	5	16	195	8.0	0.06	86
32	21.3	20.9	411	8.6	0.75	40	24	27	7	20	186	8.8	0.42	121
33	24.1	21.6	869	9.4	1.05	54	23	26	4	22	277	8.4	0.09	113
34	23.7	21.9	930	7.6	3.10	87	12	25	2	23	187	7.8	0.10	124
35	23.0	21.6	428	8.8	4.14	94	9	10	2	8	125	8.5	0.18	17
36	20.1	20.5	569	7.3	2.43	140	4	9	2	7	362	7.7	0.05	30
37	20.5	20.3	512	5.4	2.48	130	3	3	0	3	287	7.6	0.12	17
38	23.5	21.6	1627	10.1	2.58	104	10	16	3	13	365	8.6	0.29	54
39	20.3	21.3	652	5.5	2.95	47	23	38	11	27	335	8.0	0.09	263
40	21.1	20.9	898	3.8	1.45	23	183	107	63	44	475	8.0	0.33	110
41	21.5	20.2	402	5.9	3.45	72	11	21	3	18	207	7.8	0.05	136
42	25.7	22.8	847	4.3	1.90	45	13	48	2	46	334	8.0	0.09	524
43	26.4	21.9	772	7.7	1.99	38	42	80	13	67	316	7.8	0.06	636
44	24.6	23.4	315	6.5	2.59	98	3	8	1	7	121	7.9	0.05	10
45	21.1	21.0	450	9.1	2.67	174	2	4	0	4	236	7.6	0.05	9
46	22.9	21.2	376	10.9	1.77	39	32	52	26	26	195	8.6	0.07	171
47	23.5	21.6	477	10.3	1.84	19	35	53	27	27	230	8.2	0.19	197
48	26.6	23.9	439	9.3	1.97	82	10	9	0	9	193	9.5	0.07	70
49	20.5	20.2	344	8.1	1.60	109	5	15	1	11	148	8.2	0.05	46
50	26.6	22.1	1452	5.2	2.38	172	2	4	2	3	331	7.8	0.06	16
51	22.6	23.2	407	8.6	2.54	200	2	4	1	3	180	8.3	0.05	23
52	21.9	20.1	1071	3.1	1.55	38	55	68	19	49	479	7.7	0.13	269
53	23.1	21.0	439	7.3	2.49	83	12	8	2	6	213	8.0	0.05	71
54	19.9	20.8	311	9.8	2.12	73	7	11	3	8	175	8.2	0.05	26
55	20.9	19.5	317	7.7	1.65	29	32	43	22	20	173	8.1	0.05	100
56	22.5	20.6	683	3.1	2.34	28	33	42	14	28	367	7.5	0.08	143
57	21.8	21.1	664	7.1	1.44	73	6	9	2	7	331	8.3	0.07	23
58	21.9	20.6	1208	8.1	2.87	110	4	9	3	6	330	8.2	0.55	10
59	23.0	21.4	546	9.9	1.67	49	19	18	1	16	237	8.0	0.07	158
Min	**18.9**	**18.4**	**181**	**1**	**0.69**	**8**	**2**	**3**	**0**	**2**	**80**	**7.0**	**0.05**	**2**
Max	**27.5**	**23.9**	**3155**	**11**	**4.14**	**200**	**283**	**447**	**199**	**248**	**711**	**9.5**	**0.55**	**914**
Mean	**23.0**	**21.4**	**779**	**7**	**2.23**	**80**	**26**	**32**	**10**	**21**	**274**	**7.9**	**0.11**	**116**

Table A-5. Seasonal means of nutrient and ion analysis for farm ponds, 2006.

Site	TP (mg/L)	TRP (mg/L)	TN (mg/L)	Ammonia-N (mg/L)	NO_3 and NO_2-N (mg/L)	TN:TP molar	DOC (mg/L)	Chloride (mg/L)	Sulphate (mg/L)	Potassium (mg/L)	Sodium (mg/L)
1	0.02	0.01	1.94	0.01	0.005	475	13.3	295	171	5	117
2	0.66	0.48	2.40	0.26	0.010	8	25.0	13	72	5	7
3	1.58	0.99	10.07	0.01	0.005	20	48.1	508	143	32	342
4	0.23	0.12	2.05	0.07	0.007	24	25.4	5	1	10	5
5	0.08	0.01	1.68	0.07	0.007	61	21.7	4	0	3	2
6	0.46	0.29	2.04	0.02	0.017	10	19.3	12	211	12	85
7	0.10	0.02	2.80	0.34	0.008	73	25.5	4	21	2	29
8	2.10	1.06	9.32	1.49	0.006	9	39.5	17	3	28	8
9	0.09	0.01	1.46	0.02	0.006	42	28.5	9	24	5	9
10	0.30	0.03	2.48	0.19	0.006	25	23.4	13	17	14	9
11	0.59	0.02	2.18	0.01	0.006	39	18.3	22	8	12	7
12	2.49	0.93	48.46	3.71	0.005	41	41.7	71	60	62	15
13	4.22	3.17	23.90	1.90	0.006	13		189	18	120	41
14	0.06	0.01	0.98	0.01	0.005	33	21.5	18	19	6	9
15	0.04	0.01	6.15	0.01	0.005	728	20.2	214	372	1	66
16	0.21	0.03	2.83	0.02	0.006	31	11.5	3	20	1	3
17	0.12	0.02	0.72	0.01	0.006	12	11.1	7	3	1	5
18	0.08	0.01	1.90	0.01	0.006	55	13.7	4	12	0	2
19	0.41	0.11	6.46	1.21	0.007	37	18.0	9	1	15	2
20	0.59	0.36	4.13	0.21	0.007	26	25.7	10	14	14	6
21	0.62	0.10	3.16	0.01	0.005	43	25.1	20	9	4	8
22	0.57	0.47	7.82	0.48	0.006	49	10.9	875	364	7	267
23	0.55	0.46	1.54	0.01	0.005	6	19.9	21	349	10	19
24	0.04	0.01	1.44	0.03	0.005	72	13.0	76	43	6	16
25	0.06	0.01	0.49	0.01	0.007	28	7.6	4	52	1	40
26	0.44	0.29	2.16	0.34	0.013	11	17.3	3	2	10	1
27	2.06	1.14	9.83	1.65	0.012	11	31.8	30	28	27	13
28	0.18	0.10	0.76	0.01	0.007	15	13.5	6	19	2	2
29	2.74	1.52	12.71	0.26	0.102	12	39.1	549	366	47	208
30	0.30	0.12	8.02	1.87	0.009	58	40.0	18	23	18	19
31	0.14	0.02	3.58	0.01	0.007	70	16.5	8	4	3	4
32	0.32	0.11	2.33	0.02	0.005	20	24.4	14	33	6	7
33	0.21	0.03	2.54	0.02	0.006	29	17.9	18	209	2	55
34	0.19	0.08	2.97	0.05	0.005	36	15.6	174	23	3	34
35	0.12	0.05	1.30	0.01	0.005	23	11.0	49	48	1	13
36	0.09	0.03	1.92	0.07	0.025	54	27.4	7	1	8	3
37	0.12	0.01	3.96	0.01	0.024	73	29.1	5	5	7	2
38	1.16	0.86	3.51	0.25	0.043	8	28.2	20	557	13	130
39	0.16	0.02	2.52	0.03	0.005	49	28.3	7	50	4	12
40	1.91	1.14	11.50	2.30	0.064	17	54.2	28	19	41	44
41	0.22	0.01	2.74	0.18	0.006	30	23.3	8	41	4	4
42	0.83	0.63	3.67	0.03	0.006	11	37.5	15	147	13	16
43	1.36	0.56	11.09	2.57	0.034	17	26.2	17	84	22	8
44	0.32	0.21	0.84	0.01	0.013	6	10.2	12	19	1	6
45	0.05	0.01	0.86	0.01	0.021	62	14.6	1	11	0	1
46	0.22	0.03	2.82	0.03	0.007	31	15.7	11	13	4	5
47	0.35	0.14	3.39	0.14	0.006	22	22.2	21	11	8	6
48	0.32	0.13	2.86	0.01	0.006	20	20.6	30	12	8	10
49	0.08	0.01	1.62	0.01	0.006	59	14.7	11	31	3	3
50	0.13	0.06	1.08	0.02	0.005	16	16.6	31	482	1	23
51	0.04	0.01	1.28	0.02	0.361	431	8.6	7	45	1	4
52	0.96	0.11	12.75	1.88	0.012	29	44.9	42	123	25	19
53	0.60	0.41	1.36	0.09	0.148	5	14.8	8	40	5	8
54	0.12	0.01	0.85	0.01	0.006	17	14.9	21	10	3	3
55	0.65	0.45	0.87	0.05	0.006	3	18.8	6	3	7	2
56	0.37	0.05	9.07	1.96	0.006	49	35.8	18	6	16	9
57	0.05	0.01	1.57	0.01	0.005	68	22.8	7	38	2	10
58	2.25	1.35	6.63	0.89	0.671	6	30.7	79	198	61	19
59	0.17	0.04	1.97	0.01	0.006	26	16.5	30	36	4	17
Min	**0.02**	**0.01**	**0.49**	**0.01**	**0.005**	**3**	**7.6**	**1**	**0**	**0**	**1**
Max	**4.22**	**3.17**	**48.46**	**3.71**	**0.671**	**728**	**54.2**	**875**	**557**	**120**	**342**
Mean	**0.60**	**0.31**	**4.84**	**0.42**	**0.031**	**57**	**23.0**	**63**	**80**	**13**	**31**

Table A-6. Cattle variables for all farm ponds in 2005 and 2006.

	Cattle 2005					Cattle 2006				
Site	Time around Pond Rank	Cattle # Rank	Cattle Access Rank	Cattle Index	Trampling Rank	Time around Pond Rank	Cattle # Rank	Cattle Access Rank	Cattle Index	Trampling Rank
1	2	1	1	2	1	2	1	1	2	1
2	1	2	3	6	2	2	2	3	12	2
3	2	2	2	8	2	2	2	2	8	2
4	2	3	2	12	1	2	3	2	12	2
5	1	3	3	9	1	1	3	3	9	2
6	2	2	3	12	3	2	2	3	12	3
7	1	2	3	6	2	1	2	3	6	2
8	3	3	3	27	4	3	3	3	27	4
9	1	4	3	12	1	1	4	3	12	2
10	1	4	3	12	1	1	4	3	12	2
11	2	2	1	4	1	2	2	1	4	1
12	2	2	3	12	4	2	2	3	12	4
13	3	3	2	18	4	3	3	2	18	4
14	2	2	3	12	2	2	2	3	12	2
15	1	1	3	3	1	1	1	3	3	1
16	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0
19	2	2	3	12	3	2	2	3	12	3
20	2	2	2	8	2	2	2	2	8	2
21	2	2	3	12	1	2	2	3	12	2
22	2	2	2	8	3	2	2	2	8	3
23	0	0	0	0	0	0	0	0	0	0
24	3	3	1	9	1	3	3	1	9	1
25	2	2	1	4	1	2	2	1	4	1
26	1	1	3	3	2	1	1	3	3	1
27	3	1	3	9	4	3	1	3	9	4
28	1	2	1	2	2	1	2	1	2	2
29	2	2	2	8	3	2	2	2	8	3
30	1	1	3	3	1	2	2	3	12	3
31	2	3	3	18	1	2	3	3	18	3
32	2	2	3	12	2	2	2	3	12	3
33	2	2	3	12	2	2	2	3	12	3
34	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0
36	2	3	2	12	1	2	3	2	12	2
37	2	3	2	12	1	2	3	2	12	2
38	3	1	3	9	3	3	1	3	9	3
39	2	3	2	12	2	2	3	3	18	3
40	3	2	3	18	4	3	2	3	18	4
41	2	2	3	12	2	2	2	3	12	2
42	2	1	3	6	1	2	1	3	6	2
43	3	1	3	9	3	3	1	3	9	3
44	0	0	0	0	0	0	0	0	0	0
45	2	2	3	12	1	2	2	3	12	2
46	2	2	3	12	2	2	2	3	12	3
47	2	2	3	12	2	2	2	3	12	3
48	3	3	2	18	3	3	3	2	18	3
49	2	2	1	4	1	2	2	1	4	1
50	1	1	1	1	1	1	1	1	1	1
51	3	0	1	0	1	3	0	1	0	1
52	2	2	3	12	2	2	2	3	12	3
53	0	0	0	0	0	0	0	0	0	0
54	2	2	3	12	2	1	2	3	6	1
55	2	3	3	18	2	2	3	3	18	3
56	2	3	3	18	3	2	3	3	18	3
57	2	2	3	12	1	2	2	3	12	2
58	3	3	2	18	3	3	3	1	9	3
59	1	1	3	3	2	1	1	2	2	1
Min	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Max	**3**	**4**	**3**	**27**	**4**	**3**	**4**	**3**	**27**	**4**
Mean	**2**	**2**	**2**	**9**	**2**	**2**	**2**	**2**	**9**	**2**

Table A-7. Land use variables within a 250 m and 1000m radius of each farm pond.

Site	% Forested (250m)	% Crop (250m)	% Pasture (250m)	% Natural (250m)	% Wetland (250m)	% Forested (1000m)	% Wetland (1000m)	% Crop (1000m)	% Pasture (1000m)	% Natural (1000m)
1	35	0	90	5	5	30	0	15	80	5
2	10	30	65	0	0	0	0	55	40	5
3	0	5	85	10	10	5	20	20	30	45
4	10	30	50	20	20	20	10	25	45	25
5	70	0	60	40	10	55	5	15	50	30
6	5	10	80	5	5	5	0	30	65	5
7	5	10	80	5	0	15	0	69	20	10
8	60	0	70	30	0	25	0	25	60	10
9	40	0	80	20	15	20	5	0	90	5
10	0	0	95	0	0	5	0	5	95	0
11	15	40	55	0	0	10	0	80	10	5
12	15	40	55	0	0	10	0	80	10	5
13	5	25	70	0	0	5	0	80	10	5
14	5	5	80	10	10	20	2	20	70	5
15	20	10	75	15	0	20	0	20	70	5
16	0	95	0	0	0	0	0	95	0	1
17	5	80	5	10	0	0	0	90	2	1
18	15	35	5	55	0	20	0	60	17	20
19	20	20	65	10	0	15	0	50	35	15
20	5	20	70	10	5	15	1	65	15	20
21	0	20	70	10	10	15	1	65	15	20
22	0	20	65	0	0	0	0	70	25	0
23	0	80	0	15	15	5	5	89	0	5
24	35	25	40	30	0	20	0	60	10	25
25	15	25	70	5	0	15	0	60	20	15
26	10	60	35	5	0	20	0	40	50	5
27	5	55	35	5	0	0	0	90	5	0
28	25	20	60	20	0	15	0	65	15	15
29	0	70	25	5	0	0	5	50	10	40
30	0	25	65	5	0	5	0	55	35	5
31	20	0	100	0	0	10	0	10	85	0
32	10	0	95	5	0	15	0	15	80	5
33	0	20	70	5	0	5	0	60	30	6
34	5	60	0	25	0	0	0	95	0	5
35	5	80	0	10	0	0	0	95	0	5
36	40	5	70	30	10	70	0	0	60	40
37	50	0	70	30	5	70	0	0	60	40
38	5	30	70	5	0	5	0	70	25	5
39	40	0	80	20	10	40	0	0	85	10
40	15	0	85	5	0	5	0	20	75	0
41	15	5	85	5	0	10	0	20	65	10
42	5	20	70	5	0	0	0	75	15	0
43	5	55	40	5	0	5	0	65	30	0
44	5	90	0	5	0	0	0	75	15	5
45	55	0	70	20	5	55	0	0	60	35
46	5	0	95	5	5	5	0	15	80	0
47	0	0	100	0	0	5	0	20	85	0
48	5	55	35	5	0	5	0	72	20	2
49	5	0	95	5	5	50	0	0	80	18
50	20	70	10	15	5	5	5	70	10	15
51	5	15	75	5	0	20	0	16	55	25
52	30	0	90	10	0	25	5	5	75	10
53	5	75	10	10	5	0	0	90	5	0
54	30	25	65	5	5	20	0	50	45	0
55	0	25	70	5	5	0	0	60	35	0
56	20	20	70	10	10	10	0	60	30	5
57	40	0	80	20	10	25	0	0	90	5
58	5	10	75	5	0	5	0	80	10	0
59	0	30	45	20	20	0	5	70	20	5
Min	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Max	**70**	**95**	**100**	**55**	**20**	**70**	**20**	**95**	**95**	**45**
Mean	**15**	**26**	**60**	**11**	**3**	**14**	**1**	**47**	**39**	**10**

Table A-8. Physical geography and soils data within a 250 m radius of farm ponds.

Site	AG Capability Class	Slope Rank	Soil Texture	Soil Texture Class	Soil pH	Organic Matter (%)	Salts (µS/cm)	Soil Nitrogen (kg/ha)	Potassium (ppm)	Sulfur (kg/ha)	Chloride (kg/ha)	P-Olsen (ppm)
1	4	1	fine loamy	2	7.8	13	1300	35.8	1109	134	262	66
2	3	1	clayey	1	7.7	9	1030	25.8	610	134	43	23
3	3	1	clayey	1	7.9	3	1150	7.8	207	134	612	19
4	4	2	sand	4	8	3	240	4.5	157	40	10	15
5	6	3	sand	4	7.3	2	150	5.6	95	29	3	12
6	5	1	fine loamy	2	8.4	2	260	15.7	109	54	31	20
7	5	2	fine loamy	2	7.5	5	1620	62.7	708	134	464	54
8	3	1	sand	4	8.3	5	220	16.8	219	81	19	21
9	4	1	fine loamy	2	8.1	11	800	13.4	391	134	196	12
10	4	1	fine loamy	2	7.8	11	1250	16.8	562	134	233	13
11	4	1	sand	4	8	5	2210	10.1	385	134	116	23
12	4	1	sand	4	7.7	2	200	11.2	174	36	12	19
13	3	1	sand	4	7.8	7	1200	24.6	856	134	93	86
14	4	1	fine loamy	2	8	5	460	10.1	282	125	80	12
15	5	1	fine loamy	2	8	8	680	13.4	284	134	143	10
16	3	1	clayey	1	8	3	1660	10.1	285	134	77	25
17	2	1	clayey	1	7.8	6	570	20.2	517	134	22	23
18	3	1	sand	4	8.1	3	130	7.8	66	47	11	10
19	3	2	sand	4	7.5	2	180	19.0	267	34	19	28
20	4	1	sand	4	8	3	280	12.3	136	125	59	36
21	4	1	sand	4	8	3	220	15.7	128	43	9	26
22	2	1	clayey	1	7.3	9	1300	43.7	1279	134	209	78
23	5	1	fine loamy	2	7.7	4	1050	29.1	475	134	11	19
24	3	1	sand	4	7.9	4	300	16.8	239	74	60	92
25	3	2	fine loamy	2	8.1	7	590	21.3	204	94	18	15
26	4	2	sand	4	8.4	3	330	26.9	162	78	37	18
27	3	1	sand	4	8.2	3	280	20.2	330	94	67	38
28	5	3	fine loamy	2	8	3	290	22.4	468	112	93	84
29	3	1	clayey	1	7.8	6	3320	9.0	472	134	1307	43
30	3	1	sand	4	8.1	7	580	13.4	223	134	50	19
31	2	1	clayey	1	7.8	9	1240	14.6	544	134	119	12
32	2	1	clayey	1	7.7	8	1050	11.2	407	134	72	9
33	2	3	fine loamy	2	7.3	7	870	34.7	770	81	159	64
34	2	1	clayey	1	8	9	1140	14.6	234	134	54	14
35	2	1	clayey	1	7.1	6	1200	84.0	704	128	340	52
36	6	2	sand	4	7.7	4	200	13.4	162	112	19	18
37	6	3	sand	4	8	4	240	10.1	58	54	11	10
38	2	2	fine loamy	2	8.2	3	430	47.0	737	132	119	132
39	4	1	fine loamy	2	8.2	7	940	9.0	316	134	36	11
40	4	1	sand	4	8.2	4	380	23.5	457	116	136	42
41	4	1	sand	4	7.7	2	80	10.1	88	38	9	12
42	3	1	coarse loamy	3	7.9	5	1270	24.6	161	134	67	16
43	3	1	sand	4	7.9	3	720	56.0	209	134	69	45
44	2	1	clayey	1	7.4	6	870	52.6	805	69	30	54
45	6	2	organic	6	8	3	260	7.8	115	87	21	12
46	5	1	clayey	1	7.8	8	910	7.8	534	134	85	13
47	2	1	clayey	1	7.8	10	770	6.7	595	83	83	11
48	3	1	sand	4	7.8	7	430	17.9	491	76	27	86
49	5	2	coarse loamy	3	7.6	4	220	13.4	257	49	37	43
50	5	3	fine loamy	2	7.5	6	850	43.7	385	134	22	38
51	4	1	sand	4	7.5	4	240	25.8	305	60	13	49
52	5	1	fine loamy	2	8	11	900	9.0	372	134	97	11
53	1	2	fine loamy	2	8	3	380	29.1	233	92	34	24
54	3	1	fine loamy	2	7.6	9	1980	12.3	512	134	110	17
55	2	1	clayey	1	7.4	8	880	15.7	668	134	35	18
56	3	2	sand	4	8.3	3	260	6.7	104	52	19	10
57	4	1	fine loamy	2	8.1	10	550	12.3	352	81	19	11
58	3	1	fine loamy	2	7.9	4	1150	29.1	870	134	515	92
59	3	1	fine loamy	2	8.2	3	650	9.0	317	134	116	17
Min	**1**	**1**		**1**	**7.1**	**2**	**80**	**4.5**	**58**	**29**	**3**	**9**
Max	**6**	**3**		**6**	**8.4**	**13**	**3320**	**84.0**	**1279**	**134**	**1307**	**132**
Mean	**4**	**1**		**3**	**7.8**	**6**	**761**	**20.6**	**393**	**104**	**116**	**32**

Appendix C. RDA input data and CANOCO RDA printouts

Table C-1. Response variables (water chemistry) for RDA, 2005.

SITE	COND	TCHLa	TP	TN	TURB	DOC	ORG	CARB	SAND
1	3.263	0.996	1.618	3.637	1.126	1.128	0.506	1.258	1.789
2	2.706	1.483	3.057	3.994	1.073	1.253	0.699	0.974	1.687
4	2.647	0.818	2.297	3.422	0.954	1.360	0.558	0.048	1.880
5	2.617	1.455	2.100	3.287	1.047	1.331	0.944	0.550	1.832
6	2.966	1.788	3.200	3.654	0.936	1.203	0.790	0.000	1.512
7	2.817	0.724	1.824	3.348	0.981	1.343	0.837	1.136	1.657
8	2.900	1.785	3.347	4.399	1.372	1.635	0.702	0.477	1.789
9	2.710	1.024	1.769	3.446	0.979	1.429	0.844	1.166	1.765
10	2.748	1.687	2.148	3.430	0.984	1.421	0.822	1.164	1.789
11	2.681	1.723	2.696	3.544	1.003	1.278	0.443	0.728	1.687
12	2.831	1.888	3.282	3.813	1.387	1.516	0.897	0.792	1.741
13	3.245	2.067	3.570	4.395	1.477	1.634	1.359	1.033	1.625
14	2.785	0.794	1.928	3.394	1.002	1.412	0.402	1.292	1.687
15	3.152	0.405	1.851	3.530	0.988	1.372	0.574	1.161	1.714
16	2.420	1.527	2.553	3.515	1.338	1.070	0.848	0.509	1.832
17	2.504	1.835	2.420	3.325	0.975	1.049	0.990	0.538	1.811
18	2.594	1.110	1.983	3.335	0.870	1.160	0.370	0.482	1.852
19	2.615	2.275	2.836	3.631	1.201	1.198	0.149	0.392	1.889
20	2.703	1.746	2.911	3.538	1.029	1.332	0.345	0.487	1.832
21	2.660	0.765	2.906	3.350	0.996	1.336	0.409	1.039	1.657
22	2.655	1.886	2.250	3.298	0.918	1.069	0.901	0.562	1.765
23	2.829	0.668	2.655	3.517	1.041	1.121	0.565	0.235	1.591
24	2.832	1.700	1.988	3.572	1.000	1.199	0.569	0.340	1.932
25	2.691	0.939	1.607	3.057	1.021	0.914	0.341	1.181	1.687
26	2.483	1.578	2.691	3.551	0.987	1.173	0.351	0.067	1.907
27	2.672	1.641	3.328	3.795	1.217	1.286	0.852	0.632	1.714
28	2.800	1.137	2.470	3.267	0.964	1.143	0.979	0.989	1.591
29	3.416	1.634	3.406	4.018	1.329	1.465	1.072	0.715	1.811
30	2.758	1.212	2.001	3.632	1.061	1.464	0.697	0.658	1.741
31	2.556	2.087	2.385	3.520	0.965	1.260	0.819	1.048	1.765
32	2.620	1.937	2.727	3.525	1.190	1.273	0.978	1.151	1.765
33	3.072	1.707	2.587	3.479	1.167	1.190	1.094	0.732	1.741
34	2.968	2.172	2.552	3.694	1.005	1.220	1.057	0.393	1.832
35	2.639	2.221	2.333	3.484	1.371	1.079	0.943	0.362	1.832
36	2.785	1.830	2.267	3.569	1.201	1.419	1.063	1.208	1.714
37	2.622	1.375	2.132	3.515	1.059	1.374	1.121	1.312	1.553
38	2.790	1.717	3.328	3.570	1.081	1.237	0.850	0.792	1.741
39	2.751	1.395	1.953	3.616	0.884	1.401	0.816	1.209	1.765
40	2.836	2.428	3.162	3.930	1.572	1.555	0.635	0.717	1.811
41	2.670	1.621	2.253	3.452	1.053	1.391	0.872	0.599	1.832
42	2.838	0.933	2.694	3.376	0.897	1.407	0.770	0.792	1.625
43	2.874	2.313	2.924	3.642	1.149	1.370	0.679	0.677	1.789
44	2.534	1.696	2.465	3.178	1.089	1.010	1.060	0.482	1.811
45	2.601	1.052	1.736	3.424	0.868	1.182	0.582	0.205	1.924
46	2.592	1.807	2.265	3.477	1.120	1.184	0.800	1.193	1.811
47	2.689	2.202	2.809	3.623	1.267	1.356	0.778	1.218	1.789
48	2.664	1.766	2.752	3.724	0.996	1.218	0.148	0.537	1.880
49	2.644	1.313	2.225	3.446	0.869	1.125	0.000	0.161	1.940
50	3.019	1.402	2.432	3.547	1.042	1.235	0.892	0.796	1.512
51	2.624	0.959	1.602	3.480	1.045	0.895	0.000	0.606	1.916
52	2.893	2.142	2.648	3.714	1.431	1.548	0.853	1.254	1.765
53	2.625	1.278	2.984	3.576	1.322	1.153	0.580	0.770	1.741
54	2.461	1.235	1.997	3.252	1.146	1.178	0.814	1.063	1.741
55	2.497	1.936	3.192	3.629	1.194	1.256	0.870	0.694	1.714
56	2.759	1.880	2.670	3.710	1.069	1.528	0.826	0.822	1.765
57	2.755	0.788	1.758	3.473	1.093	1.363	0.126	1.421	1.687
58	3.085	1.633	3.422	4.028	1.145	1.516	0.305	0.306	1.789
59	2.662	1.392	2.587	3.434	1.376	1.211	0.614	0.846	1.687

Table C-2. Predictor variables (landscape/land use) for RDA, 2005.

SITE	UTME	UTMN	TRAMP	AREA	DEPTH	OM	SALT	SoilN	SoilP	SLOPE	TEXT	FOR1KM
1	56.254	55.513	1	3.158	304	1.117	3.114	1.505	1.820	1	2	1.49
2	53.411	55.539	2	3.356	333	0.949	3.013	1.362	1.362	1	1	0.48
4	50.161	55.175	1	3.217	275	0.447	2.380	0.602	1.176	2	4	1.32
5	49.975	55.157	1	3.102	306	0.301	2.176	0.699	1.079	3	4	1.75
6	50.128	54.910	3	3.121	277	0.322	2.415	1.146	1.301	1	2	0.78
7	51.464	54.884	2	3.351	214	0.681	3.210	1.748	1.732	2	2	1.20
8	51.223	55.417	4	3.038	303	0.672	2.342	1.176	1.322	1	4	1.41
9	56.411	55.549	1	3.183	144	1.037	2.903	1.079	1.079	1	2	1.32
10	56.297	55.545	1	3.100	169	1.021	3.097	1.176	1.114	1	2	0.78
11	56.213	54.946	1	2.903	281	0.732	3.344	0.954	1.362	1	4	1.04
12	56.216	54.946	4	2.875	152	0.322	2.301	1.000	1.279	1	4	1.04
13	56.393	54.938	4	3.389	239	0.863	3.079	1.342	1.934	1	4	0.60
14	56.921	55.651	2	2.916	181	0.653	2.663	0.954	1.079	1	2	1.32
15	56.799	55.651	1	3.078	227	0.903	2.833	1.079	1.000	1	2	1.32
16	62.430	55.105	0	2.978	285	0.531	3.220	0.954	1.398	1	1	0.30
17	62.636	54.921	0	3.079	267	0.806	2.756	1.255	1.362	1	1	0.30
18	56.172	55.044	0	2.812	277	0.447	2.114	0.845	1.000	1	4	1.32
19	55.219	54.853	3	3.015	167	0.204	2.255	1.230	1.447	2	4	1.20
20	54.939	55.100	2	3.322	401	0.505	2.447	1.041	1.556	1	4	1.20
21	54.939	55.102	1	3.415	402	0.431	2.342	1.146	1.415	1	4	1.20
22	60.111	55.070	3	2.945	366	0.954	3.114	1.591	1.892	1	1	0.48
23	51.740	54.993	0	3.740	357	0.591	3.021	1.415	1.279	1	2	0.60
24	54.195	55.120	1	3.304	293	0.568	2.477	1.176	1.964	1	4	1.32
25	52.071	54.894	1	2.573	258	0.863	2.771	1.279	1.176	2	2	1.20
26	50.780	55.140	2	3.255	353	0.398	2.519	1.380	1.255	2	4	1.32
27	55.892	54.852	4	3.067	349	0.477	2.447	1.255	1.580	1	4	0.48
28	52.505	55.100	2	3.350	369	0.505	2.462	1.301	1.924	3	2	1.20
29	54.782	55.564	3	2.699	153	0.748	3.521	0.903	1.633	1	1	0.48
30	54.090	55.033	1	3.017	319	0.857	2.763	1.079	1.279	1	4	0.78
31	56.142	55.513	1	3.083	204	0.964	3.093	1.114	1.079	1	1	1.04
32	55.875	55.493	2	3.498	102	0.881	3.021	1.000	0.954	1	1	1.20
33	50.955	54.875	2	3.122	142	0.813	2.940	1.491	1.806	3	2	0.78
34	62.618	54.902	0	3.097	341	0.944	3.057	1.114	1.146	1	1	0.48
35	62.607	54.901	0	3.796	451	0.778	3.079	1.875	1.716	1	1	0.48
36	50.780	55.140	1	3.255	251	0.623	2.301	1.079	1.255	2	4	1.85
37	50.792	55.128	1	3.000	233	0.556	2.380	0.954	1.000	3	4	1.85
38	50.037	54.878	3	3.147	323	0.531	2.633	1.623	2.121	2	2	0.78
39	56.967	55.535	2	3.357	318	0.863	2.973	0.903	1.041	1	2	1.61
40	54.279	54.998	4	3.176	218	0.580	2.580	1.322	1.623	1	4	0.78
41	55.647	55.114	2	3.253	384	0.342	1.903	0.954	1.079	1	4	1.04
42	51.032	55.340	1	3.079	252	0.653	3.104	1.342	1.204	1	3	0.48
43	50.962	55.332	3	3.176	188	0.431	2.857	1.699	1.653	1	4	0.78
44	60.530	55.007	0	3.000	327	0.785	2.940	1.672	1.732	1	1	0.30
45	50.276	55.112	1	3.097	274	0.519	2.415	0.845	1.079	2	4	1.75
46	56.304	55.490	2	3.289	194	0.908	2.959	0.845	1.114	1	1	0.78
47	56.150	55.489	2	3.531	244	1.004	2.886	0.778	1.041	1	1	0.60
48	56.348	54.950	3	3.097	278	0.813	2.633	1.204	1.934	1	4	0.78
49	54.564	55.242	1	3.272	223	0.556	2.342	1.079	1.633	2	3	1.71
50	52.775	55.018	1	2.951	278	0.799	2.929	1.591	1.580	3	2	0.78
51	54.369	54.896	1	2.903	276	0.568	2.380	1.362	1.690	1	4	1.32
52	56.701	55.623	2	2.699	209	1.045	2.954	0.903	1.041	1	2	1.41
53	55.109	55.442	0	3.528	280	0.505	2.580	1.415	1.380	2	2	0.48
54	55.944	55.512	2	3.041	222	0.940	3.297	1.041	1.230	1	2	1.32
55	55.833	55.486	2	3.447	169	0.903	2.944	1.146	1.255	1	1	0.30
56	51.402	55.438	3	2.678	238	0.505	2.415	0.778	1.000	2	4	1.04
57	56.861	55.598	1	3.204	183	1.000	2.740	1.041	1.041	1	2	1.41
58	53.004	55.361	3	3.380	348	0.623	3.061	1.415	1.964	1	2	0.60
59	55.452	55.377	2	3.295	275	0.505	2.813	0.903	1.230	1	2	0.30

Table C-3. CANOCO printout of 2005 RDA using Cattle Trampling as a predictor.

```
*** Type of analysis ***
 Model          Gradient analysis
              indirect    direct    hybrid
 linear        1=PCA      2= RDA      3
 unimodal   4= CA       5= CCA      6
   ,,            7=DCA      8=DCCA      9
               10=non-standard analysis
 Type analysis number
 Answer =  2

 *** Data files ***
 Species data       : C:\Documents and Settings\Scott Kolochuk\Desktop\CANOCO RDA\2005 RESP RDA
 Covariable data    :
 Environmental data : C:\Documents and Settings\Scott Kolochuk\Desktop\CANOCO RDA\2005 PRED
TRAMP LOG FOR OCT 12
 Initialization file:
 Forward selection of envi. variables =    0
 Scaling of ordination scores         =    2
 Diagnostics                          =    1
 File   : C:\Documents and Settings\Scott Kolochuk\Desktop\CANOCO RDA\2005 RESP RDA
 Title  : 2005 RESP RDA
 Format :  (I5,1X,5F13.9,1(/6X,(5F13.9)))
 No. of couplets of species number and abundance per line :    0
 No samples omitted
 Number of samples            58
 Number of species             9
 Number of occurrences       519
 File  : C:\Documents and Settings\Scott Kolochuk\Desktop\CANOCO RDA\2005 PRED TRAMP LOG
FOR OCT 12
 Title : 2005 PRED TRAMP LOG FOR OCT 12
 Format :  (I5,1X,9F8.3,1(/6X,(9F8.3)))
 No. of environmental variables :    12
 No interaction terms defined
 No transformation of species data
 No species-weights specified
 No  sample-weights specified
 Centering/standardization by species  =    1
 Centering/standardization by samples  =    0
 No. of active  samples:     58
 No. of passive samples:      0
 No. of active  species:      9
 Total sum of squares in species data =     51.2517
 Total standard deviation in species data TAU =    0.313342
```

1

**** Correlation matrix ****

	SPECAX1	SPECAX2	SPECAX3	SPECAX4	ENVIAX1	ENVIAX2	ENVIAX3	ENVIAX4
SPEC AX1	1.0000							
SPEC AX2	-0.0534	1.0000						
SPEC AX3	0.1304	-0.0911	1.0000					
SPEC AX4	0.1248	0.1685	0.3241	1.0000				
ENVI AX1	0.7985	0.0000	0.0000	0.0000	1.0000			
ENVI AX2	0.0000	0.7669	0.0000	0.0000	0.0000	1.0000		
ENVI AX3	0.0000	0.0000	0.6130	0.0000	0.0000	0.0000	1.0000	
ENVI AX4	0.0000	0.0000	0.0000	0.5246	0.0000	0.0000	0.0000	1.0000
UTME	0.0104	-0.1751	0.3533	0.2000	0.0130	-0.2284	0.5763	0.3812
UTMN	-0.1427	-0.4198	-0.2993	-0.0841	-0.1787	-0.5474	-0.4882	-0.1603
TRAMP	0.6089	-0.1868	-0.2029	0.0845	0.7626	-0.2435	-0.3310	0.1610
AREA	0.1264	0.0921	0.0019	-0.0725	0.1584	0.1202	0.0030	-0.1382
DEPTH	0.0068	0.4275	0.0505	-0.0131	0.0085	0.5575	0.0824	-0.0249
OM	-0.1815	-0.5637	0.0325	-0.0756	-0.2273	-0.7351	0.0530	-0.1441
SALT	0.0577	-0.3287	0.0379	-0.2325	0.0722	-0.4287	0.0618	-0.4431
SoilN	0.1238	0.0803	0.0896	-0.0780	0.1550	0.1047	0.1462	-0.1486
SoilP	0.2929	0.2072	-0.0123	0.0396	0.3669	0.2702	-0.0201	0.0754
SLOPE	-0.1639	0.0578	0.1084	-0.2067	-0.2052	0.0754	0.1769	-0.3939
TEXT	0.0353	0.2524	-0.2466	0.2543	0.0442	0.3291	-0.4023	0.4847
FOR1KM	-0.4941	-0.0873	-0.2102	0.1459	-0.6188	-0.1139	-0.3429	0.2780

	UTME	UTMN	TRAMP	AREA	DEPTH	OM	SALT	SoilN
UTME	1.0000							
UTMN	0.0440	1.0000						
TRAMP	-0.2775	-0.0091	1.0000					
AREA	0.0246	0.0403	-0.1269	1.0000				
DEPTH	0.0908	-0.3765	-0.1889	0.2927	1.0000			
OM	0.4211	0.4526	-0.1770	0.0065	-0.2315	1.0000		
SALT	0.3612	0.2840	-0.0999	0.0607	-0.1913	0.6945	1.0000	
SoilN	0.0468	-0.3624	0.0265	0.2536	0.2585	0.1006	0.2841	1.0000
SoilP	-0.0040	-0.4571	0.2825	0.1513	0.2982	-0.0834	0.1404	0.6821
SLOPE	-0.5444	-0.2687	-0.0912	-0.0849	-0.0293	-0.3182	-0.3169	0.0444
TEXT	-0.4783	-0.3413	0.2631	-0.1788	0.1202	-0.6069	-0.6716	-0.2094
FOR1KM	-0.4105	0.1523	-0.0656	-0.1618	-0.1358	-0.1465	-0.4641	-0.3711

	SoilP	SLOPE	TEXT	FOR1KM
SoilP	1.0000			
SLOPE	0.0784	1.0000		
TEXT	0.0244	0.1858	1.0000	
FOR1KM	-0.2976	0.3618	0.4773	1.0000

N	name	(weighted) mean	stand. dev.	inflation factor
1	SPEC AX1	0.0000	1.2524	
2	SPEC AX2	0.0000	1.3040	
3	SPEC AX3	0.0000	1.6312	
4	SPEC AX4	0.0000	1.9063	
5	ENVI AX1	0.0000	1.0000	
6	ENVI AX2	0.0000	1.0000	
7	ENVI AX3	0.0000	1.0000	
8	ENVI AX4	0.0000	1.0000	
1	UTME	54.8393	3.2789	2.5019
2	UTMN	55.2052	0.2581	2.4241
3	TRAMP	1.7069	1.1448	1.7208
4	AREA	3.1519	0.2402	1.2846
5	DEPTH	266.3103	74.5347	1.5646
6	OM	0.6869	0.2257	2.8820
7	SALT	2.7467	0.3500	3.1974
8	SoilN	1.1752	0.2757	2.4477
9	SoilP	1.3866	0.3167	2.6965
10	SLOPE	1.3621	0.6351	2.2629
11	TEXT	2.6034	1.2168	3.3671
12	FOR1KM	0.9872	0.4380	2.3904

**** Summary ****

Axes	1	2	3	4	Total variance
Eigenvalues:	0.320	0.100	0.046	0.025	1.000
Species-environment correlations :	0.798	0.767	0.613	0.525	
Cumulative % variance					
of species data :	32.0	42.0	46.6	49.1	
of species-environment relation:	62.9	82.5	91.6	96.5	

Sum of all eigenvalues 1.000
Sum of all canonical eigenvalues 0.508

1

*** Unrestricted permutation ***

Seeds: 23239 945

**** Summary of Monte Carlo test ****

Test of significance of first canonical axis: eigenvalue = 0.320
F-ratio = 21.137
P-value = 0.0020

Test of significance of all canonical axes : Trace = 0.508
F-ratio = 3.879
P-value = 0.0020

(499 permutations under reduced model)

Table C-4. Response variables (water chemistry) for RDA in 2006.

SITE	COND	TCHLa	TP	TN	TURB	DOC	ORG	CARB	SAND
1	3.118	0.723	1.371	3.287	1.123	0.574	0.506	1.258	1.789
2	2.726	1.850	2.821	3.381	1.397	1.104	0.699	0.974	1.687
4	2.709	1.099	2.352	3.312	1.405	0.500	0.558	0.048	1.880
5	2.649	1.435	1.922	3.226	1.336	0.701	0.944	0.550	1.832
6	2.936	1.985	2.660	3.309	1.285	1.181	0.790	0.000	1.512
7	2.788	1.328	2.006	3.446	1.406	1.211	0.837	1.136	1.657
8	2.857	1.762	3.322	3.970	1.597	2.015	0.702	0.477	1.789
9	2.929	1.853	1.966	3.163	1.454	0.946	0.844	1.166	1.765
10	2.773	1.864	2.477	3.394	1.368	1.148	0.822	1.164	1.789
11	2.617	1.512	2.772	3.338	1.262	0.707	0.443	0.728	1.687
12	3.064	2.961	3.396	4.685	1.620	2.452	0.897	0.792	1.741
13	3.210	1.924	3.625	4.378	1.699	2.061	1.359	1.033	1.625
14	2.650	1.128	1.799	2.989	1.331	0.686	0.402	1.292	1.687
15	3.218	0.370	1.544	3.789	1.305	0.369	0.574	1.161	1.714
16	2.258	2.489	2.316	3.452	1.060	1.818	0.848	0.509	1.832
17	2.521	1.822	2.061	2.859	1.044	0.771	0.990	0.538	1.811
18	2.504	1.533	1.914	3.278	1.137	0.519	0.370	0.482	1.852
19	2.489	2.128	2.615	3.810	1.254	1.624	0.149	0.392	1.889
20	2.613	1.875	2.770	3.616	1.410	1.256	0.345	0.487	1.832
21	2.622	1.777	2.793	3.500	1.399	1.230	0.409	1.039	1.657
22	3.499	1.884	2.754	3.893	1.039	1.364	0.901	0.562	1.765
23	3.061	1.497	2.738	3.189	1.300	0.312	0.565	0.235	1.591
24	2.803	1.072	1.580	3.158	1.112	0.468	0.569	0.340	1.932
25	2.799	0.870	1.756	2.695	0.881	0.516	0.341	1.181	1.687
26	2.594	1.746	2.643	3.335	1.237	0.777	0.351	0.067	1.907
27	2.862	2.667	3.313	3.993	1.503	1.531	0.852	0.632	1.714
28	2.614	1.487	2.260	2.881	1.130	0.848	0.979	0.989	1.591
29	3.462	2.588	3.438	4.104	1.593	1.465	1.072	0.715	1.811
30	2.827	1.324	2.483	3.904	1.602	1.475	0.697	0.658	1.741
31	2.598	1.936	2.143	3.554	1.218	1.188	0.819	1.048	1.765
32	2.614	2.083	2.510	3.367	1.387	1.378	0.978	1.151	1.765
33	2.939	2.051	2.325	3.405	1.254	1.354	1.094	0.732	1.741
34	2.969	2.095	2.276	3.473	1.192	1.074	1.057	0.393	1.832
35	2.631	1.227	2.076	3.115	1.041	0.976	0.943	0.362	1.832
36	2.755	1.470	1.942	3.284	1.438	0.599	1.063	1.208	1.714
37	2.709	1.240	2.092	3.597	1.465	0.412	1.121	1.312	1.553
38	3.211	1.732	3.064	3.546	1.451	0.989	0.850	0.792	1.741
39	2.814	2.419	2.205	3.401	1.451	1.370	0.816	1.209	1.765
40	2.953	2.043	3.282	4.061	1.734	2.264	0.635	0.717	1.811
41	2.604	2.132	2.333	3.438	1.368	1.026	0.872	0.599	1.832
42	2.928	2.719	2.921	3.564	1.574	1.097	0.770	0.792	1.625
43	2.888	2.803	3.132	4.045	1.418	1.620	0.679	0.677	1.789
44	2.499	1.009	2.504	2.922	1.007	0.454	1.060	0.482	1.811
45	2.653	0.957	1.724	2.936	1.165	0.210	0.582	0.205	1.924
46	2.575	2.234	2.349	3.450	1.195	1.508	0.800	1.193	1.811
47	2.678	2.295	2.540	3.530	1.346	1.548	0.778	1.218	1.789
48	2.642	1.848	2.509	3.456	1.315	1.010	0.148	0.537	1.880
49	2.536	1.663	1.900	3.210	1.166	0.705	0.000	0.161	1.940
50	3.162	1.211	2.122	3.032	1.221	0.288	0.892	0.796	1.512
51	2.609	1.366	1.550	3.107	0.936	0.299	0.000	0.606	1.916
52	3.030	2.430	2.984	4.105	1.652	1.741	0.853	1.254	1.765
53	2.643	1.852	2.778	3.132	1.169	1.078	0.580	0.770	1.741
54	2.493	1.420	2.074	2.930	1.174	0.855	0.814	1.063	1.741
55	2.501	1.999	2.813	2.942	1.274	1.500	0.870	0.694	1.714
56	2.834	2.155	2.563	3.958	1.554	1.513	0.826	0.822	1.765
57	2.822	1.359	1.732	3.196	1.358	0.748	0.126	1.421	1.687
58	3.082	0.995	3.353	3.822	1.487	0.650	0.305	0.306	1.789
59	2.737	2.199	2.224	3.295	1.218	1.287	0.614	0.846	1.687

Table C-5. Predictor variables (landscape/land use) for Trampling RDA, 2006.

SITE	UTME	UTMN	TRAMP	AREA	DEPTH	OM	SALT	SoilN	SoilP	SLOPE	TEXT	FOR1KM
1	56.254	55.513	1	3.158	226	1.117	3.114	1.505	1.820	1	2	1.49
2	53.411	55.539	2	3.356	295	0.949	3.013	1.362	1.362	1	1	0.48
4	50.161	55.175	2	3.217	243	0.447	2.380	0.602	1.176	2	4	1.32
5	49.975	55.157	2	3.102	278	0.301	2.176	0.699	1.079	3	4	1.75
6	50.128	54.910	3	3.121	234	0.322	2.415	1.146	1.301	1	2	0.78
7	51.464	54.884	2	3.351	183	0.681	3.210	1.748	1.732	2	2	1.20
8	51.223	55.417	4	3.038	252	0.672	2.342	1.176	1.322	1	4	1.41
9	56.411	55.549	2	3.183	146	1.037	2.903	1.079	1.079	1	2	1.32
10	56.297	55.545	2	3.100	146	1.021	3.097	1.176	1.114	1	2	0.78
11	56.213	54.946	1	2.903	231	0.732	3.344	0.954	1.362	1	4	1.04
12	56.216	54.946	4	2.875	70	0.322	2.301	1.000	1.279	1	4	1.04
13	56.393	54.938	4	3.389	211	0.863	3.079	1.342	1.934	1	4	0.60
14	56.921	55.651	2	2.916	146	0.653	2.663	0.954	1.079	1	2	1.32
15	56.799	55.651	1	3.078	238	0.903	2.833	1.079	1.000	1	2	1.32
16	62.430	55.105	0	2.978	272	0.531	3.220	0.954	1.398	1	1	0.30
17	62.636	54.921	0	3.079	227	0.806	2.756	1.255	1.362	1	1	0.30
18	56.172	55.044	0	2.812	219	0.447	2.114	0.845	1.000	1	4	1.32
19	55.219	54.853	3	3.015	144	0.204	2.255	1.230	1.447	2	4	1.20
20	54.939	55.100	2	3.322	300	0.505	2.447	1.041	1.556	1	4	1.20
21	54.939	55.102	2	3.415	298	0.431	2.342	1.146	1.415	1	4	1.20
22	60.111	55.070	3	2.945	303	0.954	3.114	1.591	1.892	1	1	0.48
23	51.740	54.993	0	3.740	292	0.591	3.021	1.415	1.279	1	2	0.60
24	54.195	55.120	1	3.304	253	0.568	2.477	1.176	1.964	1	4	1.32
25	52.071	54.894	1	2.573	214	0.863	2.771	1.279	1.176	2	2	1.20
26	50.780	55.140	1	3.255	289	0.398	2.519	1.380	1.255	2	4	1.32
27	55.892	54.852	4	3.067	228	0.477	2.447	1.255	1.580	1	4	0.48
28	52.505	55.100	2	3.350	359	0.505	2.462	1.301	1.924	3	2	1.20
29	54.782	55.564	3	2.699	69	0.748	3.521	0.903	1.633	1	1	0.48
30	54.090	55.033	3	3.017	244	0.857	2.763	1.079	1.279	1	4	0.78
31	56.142	55.513	3	3.083	183	0.964	3.093	1.114	1.079	1	1	1.04
32	55.875	55.493	3	3.498	75	0.881	3.021	1.000	0.954	1	1	1.20
33	50.955	54.875	3	3.122	105	0.813	2.940	1.491	1.806	3	2	0.78
34	62.618	54.902	0	3.097	310	0.944	3.057	1.114	1.146	1	1	0.48
35	62.607	54.901	0	3.796	414	0.778	3.079	1.875	1.716	1	1	0.48
36	50.780	55.140	2	3.255	243	0.623	2.301	1.079	1.255	2	4	1.85
37	50.792	55.128	2	3.000	248	0.556	2.380	0.954	1.000	3	4	1.85
38	50.037	54.878	3	3.147	258	0.531	2.633	1.623	2.121	2	2	0.78
39	56.967	55.535	3	3.357	295	0.863	2.973	0.903	1.041	1	2	1.61
40	54.279	54.998	4	3.176	145	0.580	2.580	1.322	1.623	1	4	0.78
41	55.647	55.114	2	3.253	345	0.342	1.903	0.954	1.079	1	4	1.04
42	51.032	55.340	2	3.079	190	0.653	3.104	1.342	1.204	1	3	0.48
43	50.962	55.332	3	3.176	199	0.431	2.857	1.699	1.653	1	4	0.78
44	60.530	55.007	0	3.000	259	0.785	2.940	1.672	1.732	1	1	0.30
45	50.276	55.112	2	3.097	267	0.519	2.415	0.845	1.079	2	4	1.75
46	56.304	55.490	3	3.289	177	0.908	2.959	0.845	1.114	1	1	0.78
47	56.150	55.489	3	3.531	184	1.004	2.886	0.778	1.041	1	1	0.60
48	56.348	54.950	3	3.097	197	0.813	2.633	1.204	1.934	1	4	0.78
49	54.564	55.242	1	3.272	160	0.556	2.342	1.079	1.633	2	3	1.71
50	52.775	55.018	1	2.951	238	0.799	2.929	1.591	1.580	3	2	0.78
51	54.369	54.896	1	2.903	254	0.568	2.380	1.362	1.690	1	4	1.32
52	56.701	55.623	3	2.699	155	1.045	2.954	0.903	1.041	1	2	1.41
53	55.109	55.442	0	3.528	249	0.505	2.580	1.415	1.380	2	2	0.48
54	55.944	55.512	1	3.041	212	0.940	3.297	1.041	1.230	1	2	1.32
55	55.833	55.486	3	3.447	165	0.903	2.944	1.146	1.255	1	1	0.30
56	51.402	55.438	3	2.678	234	0.505	2.415	0.778	1.000	2	4	1.04
57	56.861	55.598	2	3.204	144	1.000	2.740	1.041	1.041	1	2	1.41
58	53.004	55.361	3	3.380	287	0.623	3.061	1.415	1.964	1	2	0.60
59	55.452	55.377	1	3.295	167	0.505	2.813	0.903	1.230	1	2	0.30

Table C-6. CANOCO printout of 2006 RDA using Cattle Trampling as a predictor.

```
*** Type of analysis ***
 Model           Gradient analysis
              indirect    direct    hybrid
 linear        1=PCA      2= RDA      3
 unimodal    4= CA       5= CCA       6
    ,,          7=DCA      8=DCCA     9
             10=non-standard analysis
 Type analysis number
 Answer =  2

 *** Data files ***
 Species data      : C:\Documents and Settings\Scott Kolochuk\Desktop\CANOCO RDA\2006 RESP
 Covariable data    :
 Environmental data : C:\Documents and Settings\Scott Kolochuk\Desktop\CANOCO RDA\2006 PRED
TRAMP LOG FOR OCT 12
 Initialization file:

 Forward selection of envi. variables =    0
 Scaling of ordination scores        =    2
 Diagnostics                        =    1
 File   : C:\Documents and Settings\Scott Kolochuk\Desktop\CANOCO RDA\2006 RESP
 Title  : 2006 RESP
 Format :  (I5,1X,9F8.4)
 No. of couplets of species number and abundance per line :    0
 No samples omitted
 Number of samples           58
 Number of species            9
 Number of occurrences       519

 File  : C:\Documents and Settings\Scott Kolochuk\Desktop\CANOCO RDA\2006 PRED TRAMP LOG
FOR OCT 12
 Title : 2006 PRED TRAMP LOG FOR OCT 12
 Format :  (I5,1X,9F8.3,1(/6X,(9F8.3)))
 No. of environmental variables :    12
 No interaction terms defined
 No transformation of species data
 No species-weights specified
 No  sample-weights specified
 Centering/standardization by species  =    1
 Centering/standardization by samples  =    0
 No. of active  samples:     58
 No. of passive samples:      0
 No. of active  species:      9
 Total sum of squares in species data =     77.4723
 Total standard deviation in species data TAU =    0.385246
```

**** Correlation matrix ****

	SPECAX1	SPECAX2	SPECAX3	SPECAX4	ENVIAX1	ENVIAX2	ENVIAX3	ENVIAX4
SPEC AX1	1.0000							
SPEC AX2	0.0177	1.0000						
SPEC AX3	0.0607	0.0615	1.0000					
SPEC AX4	0.0426	0.0618	-0.0666	1.0000				
ENVI AX1	0.8855	0.0000	0.0000	0.0000	1.0000			
ENVI AX2	0.0000	0.7534	0.0000	0.0000	0.0000	1.0000		
ENVI AX3	0.0000	0.0000	0.6073	0.0000	0.0000	0.0000	1.0000	
ENVI AX4	0.0000	0.0000	0.0000	0.7117	0.0000	0.0000	0.0000	1.0000
UTME	0.0356	0.1544	0.2898	0.0042	0.0402	0.2050	0.4772	0.0059
UTMN	0.0091	0.4583	-0.0067	-0.0669	0.0102	0.6084	-0.0110	-0.0941
TRAMP	0.6747	0.2055	-0.1970	-0.0658	0.7620	0.2728	-0.3244	-0.0925
AREA	-0.0385	-0.1190	0.0751	0.1550	-0.0435	-0.1580	0.1237	0.2178
DEPTH	-0.3143	-0.3481	-0.0859	0.1736	-0.3549	-0.4621	-0.1414	0.2439
OM	-0.1162	0.5335	-0.1019	0.2474	-0.1312	0.7082	-0.1678	0.3477
SALT	0.1083	0.2437	-0.0764	0.3850	0.1224	0.3235	-0.1258	0.5409
SoilN	-0.0270	-0.1588	-0.2285	0.2839	-0.0305	-0.2108	-0.3762	0.3989
SoilP	0.0818	-0.3095	-0.2924	0.1252	0.0924	-0.4109	-0.4814	0.1759
SLOPE	-0.2806	-0.0129	-0.0318	0.2001	-0.3168	-0.0171	-0.0523	0.2812
TEXT	0.0864	-0.2496	-0.2031	-0.4622	0.0975	-0.3313	-0.3344	-0.6494
FOR1KM	-0.4050	0.2436	-0.1319	-0.3919	-0.4574	0.3234	-0.2172	-0.5507

	UTME	UTMN	TRAMP	AREA	DEPTH	OM	SALT	SoilN
UTME	1.0000							
UTMN	0.0440	1.0000						
TRAMP	-0.3245	0.1159	1.0000					
AREA	0.0246	0.0403	-0.0944	1.0000				
DEPTH	0.0608	-0.2960	-0.3935	0.3133	1.0000			
OM	0.4211	0.4526	-0.0138	0.0065	-0.1899	1.0000		
SALT	0.3612	0.2840	-0.0902	0.0607	-0.1849	0.6945	1.0000	
SoilN	0.0468	-0.3624	-0.1363	0.2536	0.2354	0.1006	0.2841	1.0000
SoilP	-0.0040	-0.4571	0.0773	0.1513	0.1836	-0.0834	0.1404	0.6821
SLOPE	-0.5444	-0.2687	-0.0543	-0.0849	0.0957	-0.3182	-0.3169	0.0444
TEXT	-0.4783	-0.3413	0.2326	-0.1788	0.0766	-0.6069	-0.6716	-0.2094
FOR1KM	-0.4105	0.1523	0.0471	-0.1618	-0.0178	-0.1465	-0.4641	-0.3711

	SoilP	SLOPE	TEXT	FOR1KM
SoilP	1.0000			
SLOPE	0.0784	1.0000		
TEXT	0.0244	0.1858	1.0000	
FOR1KM	-0.2976	0.3618	0.4773	1.0000

N	name	(weighted) mean	stand. dev.	inflation factor
1	SPEC AX1	0.0000	1.1293	
2	SPEC AX2	0.0000	1.3274	
3	SPEC AX3	0.0000	1.6466	
4	SPEC AX4	0.0000	1.4051	
5	ENVI AX1	0.0000	1.0000	
6	ENVI AX2	0.0000	1.0000	
7	ENVI AX3	0.0000	1.0000	
8	ENVI AX4	0.0000	1.0000	
1	UTME	54.8393	3.2789	2.6483
2	UTMN	55.2052	0.2581	2.3492
3	TRAMP	2.0172	1.1816	1.6905
4	AREA	3.1519	0.2402	1.2888
5	DEPTH	223.6034	69.3338	1.5349
6	OM	0.6869	0.2257	3.0746
7	SALT	2.7467	0.3500	3.2116
8	SoilN	1.1752	0.2757	2.5504
9	SoilP	1.3866	0.3167	2.3892
10	SLOPE	1.3621	0.6351	2.1624
11	TEXT	2.6034	1.2168	3.3840
12	FOR1KM	0.9872	0.4380	2.3862

**** Summary ****

Axes	1	2	3	4	Total variance
Eigenvalues:	0.463	0.070	0.040	0.030	1.000
Species-environment correlations:	0.886	0.753	0.607	0.712	
Cumulative % variance					
of species data :	46.3	53.3	57.3	60.3	
of species-environment relation:	74.2	85.4	91.8	96.6	
Sum of all eigenvalues					1.000
Sum of all canonical eigenvalues					0.624

1

*** Unrestricted permutation ***

Seeds: 23239 945

**** Summary of Monte Carlo test ****

Test of significance of first canonical axis: eigenvalue = 0.463
F-ratio = 38.765
P-value = 0.0020

Test of significance of all canonical axes : Trace = 0.624
F-ratio = 6.220
P-value = 0.0020

(499 permutations under reduced model)

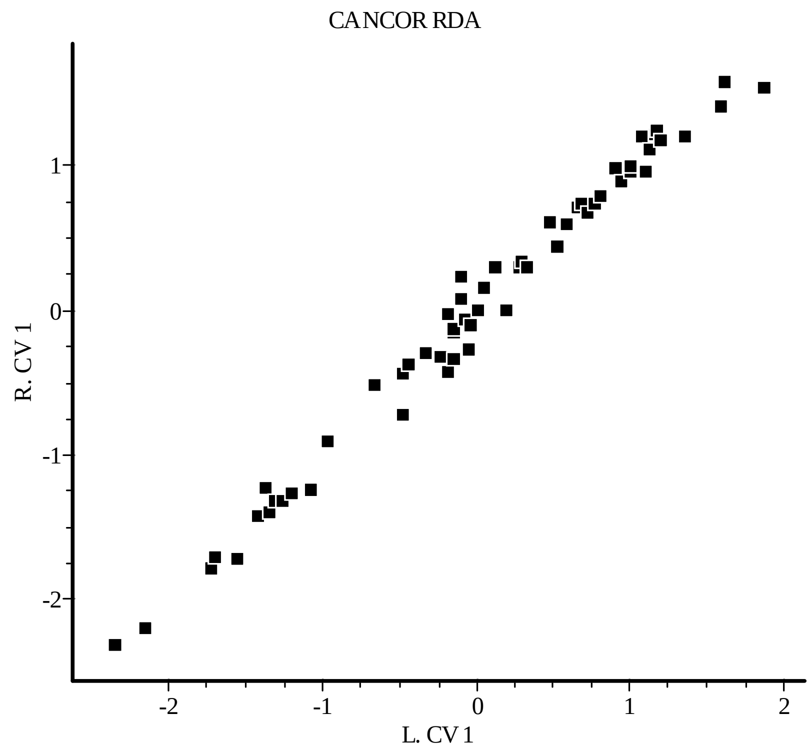

Figure C-1. Right and left set variable scores along the first canonical axis of the RDA using Cattle Trampling as the cattle disturbance variable plotted against one another in the canonical correlation (CANCOR) analysis.

Table C-7. From the RDA using Cattle Trampling the correlation matrix of the first 4 canonical axes in 2005 RDA (1-4) against first 4 canonical axes of 2006 RDA (1-4) as well as corresponding Chi-Square test.

Correlation Matrix

		2005			
		1st axis	2nd axis	3rd axis	4th axis
2006	1st axis	**0.80**	-0.31	-0.06	-0.30
	2nd axis	-0.25	**-0.90**	0.02	0.17
	3rd axis	0.03	-0.09	**0.54**	-0.35
	4th axis	0.03	0.29	-0.23	**-0.63**

Chi-Square Test with removal of eigenvalues successfully

Eigenvalues removed up to	Chi-Square	D.F.	Lambda
0	418	16	0.0003
1	194	9	0.0248
2	75	4	0.2397
3	12	1	0.7919

Table C-8. Predictor variables (landscape/land use) for Cattle Index RDA, 2005.

SITE	UTME	UTMN	CATIND	AREA	DEPTH	RIP	OM	SALT	SoilN	SoilP	SLOPE	TEXT	FOR1KM
1	56.254	55.513	0.477	3.158	304	70	1.117	3.114	1.505	1.820	1	2	1.49
2	53.411	55.539	0.845	3.356	333	70	0.949	3.013	1.362	1.362	1	1	0.48
4	50.161	55.175	1.114	3.217	275	95	0.447	2.380	0.602	1.176	2	4	1.32
5	49.975	55.157	1.000	3.102	306	95	0.301	2.176	0.699	1.079	3	4	1.75
6	50.128	54.910	1.114	3.121	277	73	0.322	2.415	1.146	1.301	1	2	0.78
7	51.464	54.884	0.845	3.351	214	65	0.681	3.210	1.748	1.732	2	2	1.20
8	51.223	55.417	1.447	3.038	303	40	0.672	2.342	1.176	1.322	1	4	1.41
9	56.411	55.549	1.114	3.183	144	80	1.037	2.903	1.079	1.079	1	2	1.32
10	56.297	55.545	1.114	3.100	169	70	1.021	3.097	1.176	1.114	1	2	0.78
11	56.213	54.946	0.699	2.903	281	90	0.732	3.344	0.954	1.362	1	4	1.04
12	56.216	54.946	1.114	2.875	152	80	0.322	2.301	1.000	1.279	1	4	1.04
13	56.393	54.938	1.279	3.389	239	60	0.863	3.079	1.342	1.934	1	4	0.60
14	56.921	55.651	1.114	2.916	181	70	0.653	2.663	0.954	1.079	1	2	1.32
15	56.799	55.651	0.602	3.078	227	50	0.903	2.833	1.079	1.000	1	2	1.32
16	62.430	55.105	0.000	2.978	285	1	0.531	3.220	0.954	1.398	1	1	0.30
17	62.636	54.921	0.000	3.079	267	100	0.806	2.756	1.255	1.362	1	1	0.30
18	56.172	55.044	0.000	2.812	277	100	0.447	2.114	0.845	1.000	1	4	1.32
19	55.219	54.853	1.114	3.015	167	80	0.204	2.255	1.230	1.447	2	4	1.20
20	54.939	55.100	0.954	3.322	401	90	0.505	2.447	1.041	1.556	1	4	1.20
21	54.939	55.102	1.114	3.415	402	75	0.431	2.342	1.146	1.415	1	4	1.20
22	60.111	55.070	0.954	2.945	366	45	0.954	3.114	1.591	1.892	1	1	0.48
23	51.740	54.993	0.000	3.740	357	95	0.591	3.021	1.415	1.279	1	2	0.60
24	54.195	55.120	1.000	3.304	293	90	0.568	2.477	1.176	1.964	1	4	1.32
25	52.071	54.894	0.699	2.573	258	80	0.863	2.771	1.279	1.176	2	2	1.20
26	50.780	55.140	0.602	3.255	353	95	0.398	2.519	1.380	1.255	2	4	1.32
27	55.892	54.852	1.000	3.067	349	80	0.477	2.447	1.255	1.580	1	4	0.48
28	52.505	55.100	0.477	3.350	369	96	0.505	2.462	1.301	1.924	3	2	1.20
29	54.782	55.564	0.954	2.699	153	65	0.748	3.521	0.903	1.633	1	1	0.48
30	54.090	55.033	0.602	3.017	319	65	0.857	2.763	1.079	1.279	1	4	0.78
31	56.142	55.513	1.279	3.083	204	90	0.964	3.093	1.114	1.079	1	1	1.04
32	55.875	55.493	1.114	3.498	102	90	0.881	3.021	1.000	0.954	1	1	1.20
33	50.955	54.875	1.114	3.122	142	48	0.813	2.940	1.491	1.806	3	2	0.78
34	62.618	54.902	0.000	3.097	341	90	0.944	3.057	1.114	1.146	1	1	0.48
35	62.607	54.901	0.000	3.796	451	80	0.778	3.079	1.875	1.716	1	1	0.48
36	50.780	55.140	1.114	3.255	251	98	0.623	2.301	1.079	1.255	2	4	1.85
37	50.792	55.128	1.114	3.000	233	98	0.556	2.380	0.954	1.000	3	4	1.85
38	50.037	54.878	1.000	3.147	323	63	0.531	2.633	1.623	2.121	2	2	0.78
39	56.967	55.535	1.114	3.357	318	99	0.863	2.973	0.903	1.041	1	2	1.61
40	54.279	54.998	1.279	3.176	218	60	0.580	2.580	1.322	1.623	1	4	0.78
41	55.647	55.114	1.114	3.253	384	90	0.342	1.903	0.954	1.079	1	4	1.04
42	51.032	55.340	0.845	3.079	252	95	0.653	3.104	1.342	1.204	1	3	0.48
43	50.962	55.332	1.000	3.176	188	75	0.431	2.857	1.699	1.653	1	4	0.78
44	60.530	55.007	0.000	3.000	327	60	0.785	2.940	1.672	1.732	1	1	0.30
45	50.276	55.112	1.114	3.097	274	85	0.519	2.415	0.845	1.079	2	4	1.75
46	56.304	55.490	1.114	3.289	194	80	0.908	2.959	0.845	1.114	1	1	0.78
47	56.150	55.489	1.114	3.531	244	80	1.004	2.886	0.778	1.041	1	1	0.60
48	56.348	54.950	1.279	3.097	278	30	0.813	2.633	1.204	1.934	1	4	0.78
49	54.564	55.242	0.699	3.272	223	98	0.556	2.342	1.079	1.633	2	3	1.71
50	52.775	55.018	0.301	2.951	278	97	0.799	2.929	1.591	1.580	3	2	0.78
51	54.369	54.896	0.000	2.903	276	60	0.568	2.380	1.362	1.690	1	4	1.32
52	56.701	55.623	1.114	2.699	209	60	1.045	2.954	0.903	1.041	1	2	1.41
53	55.109	55.442	0.000	3.528	280	100	0.505	2.580	1.415	1.380	2	2	0.48
54	55.944	55.512	1.114	3.041	222	90	0.940	3.297	1.041	1.230	1	2	1.32
55	55.833	55.486	1.279	3.447	169	95	0.903	2.944	1.146	1.255	1	1	0.30
56	51.402	55.438	1.279	2.678	238	40	0.505	2.415	0.778	1.000	2	4	1.04
57	56.861	55.598	1.114	3.204	183	30	1.000	2.740	1.041	1.041	1	2	1.41
58	53.004	55.361	1.279	3.380	348	65	0.623	3.061	1.415	1.964	1	2	0.60
59	55.452	55.377	0.602	3.295	275	50	0.505	2.813	0.903	1.230	1	2	0.30

Table C-9. CANOCO printout of 2005 RDA using Cattle Index as a predictor.

```
 *** Type of analysis ***
  Model            Gradient analysis
                indirect      direct       hybrid
 linear        1=PCA      2= RDA       3
 unimodal   4= CA       5= CCA       6
    ,,            7=DCA      8=DCCA     9
              10=non-standard analysis
 Type analysis number
 Answer =  2

 *** Data files ***
 Species data       : C:\Documents and Settings\Scott Kolochuk\Desktop\Canoco Nov 5 RDA
CATTLE\2005 Response
 Covariable data    :
 Environmental data : C:\Documents and Settings\Scott Kolochuk\Desktop\Canoco Nov 5 RDA
CATTLE\2005 Predictor Cattle Index Nov
 Initialization file:
 Forward selection of envi. variables =    0
 Scaling of ordination scores         =    2
 Diagnostics                          =    1
 File   : C:\Documents and Settings\Scott Kolochuk\Desktop\Canoco Nov 5 RDA CATTLE\2005 Response
 Title  : 2005 Response
 Format :  (I5,1X,9F7.3)
 No. of couplets of species number and abundance per line :    0
 No samples omitted
 Number of samples           58
 Number of species            9
 Number of occurrences       519
 File  : C:\Documents and Settings\Scott Kolochuk\Desktop\Canoco Nov 5 RDA CATTLE\2005 Predictor
Cattle Index Nov
 Title : 2005 Predictor Cattle Index Nov
 Format :  (I5,1X,7F10.5,1(/6X,(7F10.5)))
 No. of environmental variables :    13
 No interaction terms defined
 No transformation of species data
 No species-weights specified
 No  sample-weights specified
 Centering/standardization by species  =    1
 Centering/standardization by samples  =    0
 No. of active  samples:     58
 No. of passive samples:      0
 No. of active  species:      9

 Total sum of squares in species data =     51.2568
 Total standard deviation in species data TAU =    0.313358

 ****** Check on influence in covariable/environment data ******
 The following sample(s) have extreme values
 Sample Environmental       Covariable  + Environment space
        variable Influence   influence     influence
               15                    6             8.1x
 ****** End of check ******
1
```

*** Correlation matrix ****

	SPECAX1	SPECAX2	SPECAX3	SPECAX4	ENVIAX1	ENVIAX2	ENVIAX3	ENVIAX4
SPEC AX1	1.0000							
SPEC AX2	0.1333	1.0000						
SPEC AX3	0.0218	-0.0119	1.0000					
SPEC AX4	0.1263	-0.1150	-0.3401	1.0000				
ENVI AX1	0.7606	0.0000	0.0000	0.0000	1.0000			
ENVI AX2	0.0000	0.7360	0.0000	0.0000	0.0000	1.0000		
ENVI AX3	0.0000	0.0000	0.6707	0.0000	0.0000	0.0000	1.0000	
ENVI AX4	0.0000	0.0000	0.0000	0.5300	0.0000	0.0000	0.0000	1.0000
UTME	-0.0152	-0.2235	0.3007	-0.1875	-0.0199	-0.3037	0.4483	-0.3538
UTMN	0.1713	-0.3465	-0.3613	0.0829	0.2252	-0.4707	-0.5388	0.1565
CATIND	-0.2568	-0.3415	-0.3011	-0.0731	-0.3376	-0.4640	-0.4490	-0.1380
AREA	-0.1291	0.0785	-0.0074	0.0720	-0.1698	0.1067	-0.0110	0.1358
DEPTH	-0.0268	0.4053	0.1435	0.0051	-0.0353	0.5507	0.2140	0.0096
RIP	0.0925	0.0844	0.2534	0.0726	0.1216	0.1146	0.3778	0.1370
OM	0.2061	-0.5248	-0.0634	0.0904	0.2710	-0.7130	-0.0945	0.1706
SALT	-0.0417	-0.3182	-0.0566	0.2477	-0.0548	-0.4323	-0.0844	0.4674
SoilN	-0.1277	0.0603	0.0738	0.0873	-0.1680	0.0820	0.1101	0.1647
SoilP	-0.2979	0.1824	-0.0281	-0.0310	-0.3916	0.2478	-0.0419	-0.0586
SLOPE	0.1565	0.0556	0.1515	0.2051	0.2058	0.0756	0.2258	0.3871
TEXT	-0.0387	0.2713	-0.1833	-0.2691	-0.0509	0.3685	-0.2733	-0.5078
FOR1KM	0.5019	-0.0102	-0.1238	-0.1600	0.6599	-0.0139	-0.1845	-0.3020

	UTME	UTMN	CATIND	AREA	DEPTH	RIP	OM	SALT
UTME	1.0000							
UTMN	0.0443	1.0000						
CATIND	-0.4042	0.3132	1.0000					
AREA	0.0245	0.0404	-0.0579	1.0000				
DEPTH	0.0908	-0.3766	-0.3825	0.2927	1.0000			
RIP	-0.1949	-0.0611	-0.1160	0.2645	0.0954	1.0000		
OM	0.4213	0.4528	0.0219	0.0064	-0.2313	-0.1726	1.0000	
SALT	0.3612	0.2843	-0.1235	0.0607	-0.1913	-0.2119	0.6946	1.0000
SoilN	0.0468	-0.3623	-0.3204	0.2536	0.2584	-0.0929	0.1006	0.2839
SoilP	-0.0040	-0.4572	-0.1048	0.1515	0.2981	-0.2307	-0.0833	0.1404
SLOPE	-0.5444	-0.2689	-0.0057	-0.0849	-0.0293	0.2407	-0.3183	-0.3169
TEXT	-0.4783	-0.3416	0.2683	-0.1786	0.1202	0.1051	-0.6070	-0.6716
FOR1KM	-0.4105	0.1522	0.3018	-0.1616	-0.1358	0.2498	-0.1467	-0.4640

	SoilN	SoilP	SLOPE	TEXT	FOR1KM
SoilN	1.0000				
SoilP	0.6821	1.0000			
SLOPE	0.0445	0.0784	1.0000		
TEXT	-0.2093	0.0244	0.1858	1.0000	
FOR1KM	-0.3711	-0.2975	0.3618	0.4773	1.0000

N	name	(weighted) mean	stand. dev.	inflation factor
1	SPEC AX1	0.0000	1.3147	
2	SPEC AX2	0.0000	1.3586	
3	SPEC AX3	0.0000	1.4910	
4	SPEC AX4	0.0000	1.8869	
5	ENVI AX1	0.0000	1.0000	
6	ENVI AX2	0.0000	1.0000	
7	ENVI AX3	0.0000	1.0000	
8	ENVI AX4	0.0000	1.0000	
1	UTME	54.8393	3.2790	2.7333
2	UTMN	55.2052	0.2581	2.4767
3	CATIND	0.8420	0.4270	2.0771
4	AREA	3.1519	0.2403	1.4627
5	DEPTH	266.3103	74.5347	1.6265
6	RIP	75.1897	21.2087	1.4364
7	OM	0.6871	0.2257	3.0647
8	SALT	2.7468	0.3500	3.1893
9	SoilN	1.1753	0.2757	2.6705
10	SoilP	1.3867	0.3167	2.6079
11	SLOPE	1.3621	0.6351	2.2138
12	TEXT	2.6034	1.2168	3.3985
13	FOR1KM	0.9872	0.4380	2.3479

**** Summary ****

Axes	1	2	3	4	Total variance
Eigenvalues:	0.289	0.095	0.054	0.026	1.000
Species-environment correlations:	0.761	0.736	0.671	0.530	
Cumulative % variance					
of species data:	28.9	38.3	43.8	46.3	
of species-environment relation:	59.4	78.9	90.1	95.3	
Sum of all eigenvalues					1.000
Sum of all canonical eigenvalues					0.486

1
*** Unrestricted permutation ***
Seeds: 23239 945
**** Summary of Monte Carlo test ****

Test of significance of first canonical axis: eigenvalue = 0.289
F-ratio = 17.843
P-value = 0.0020

Test of significance of all canonical axes : Trace = 0.486
F-ratio = 3.201
P-value = 0.0020

(499 permutations under reduced model)

Table C-10. Predictor variables (landscape/land use) for Cattle Index RDA, 2006.

SITE	UTME	UTMN	CATIND	AREA	DEPTH	RIP	OM	SALT	SoilN	SoilP	SLOPE	TEXT	FOR1KM
1	56.254	55.513	0.477	3.158	226	70	1.117	3.114	1.505	1.820	1	2	1.49
2	53.411	55.539	1.114	3.356	295	70	0.949	3.013	1.362	1.362	1	1	0.48
4	50.161	55.175	1.114	3.217	243	95	0.447	2.380	0.602	1.176	2	4	1.32
5	49.975	55.157	1.000	3.102	278	95	0.301	2.176	0.699	1.079	3	4	1.75
6	50.128	54.910	1.114	3.121	234	73	0.322	2.415	1.146	1.301	1	2	0.78
7	51.464	54.884	0.845	3.351	183	65	0.681	3.210	1.748	1.732	2	2	1.20
8	51.223	55.417	1.447	3.038	252	40	0.672	2.342	1.176	1.322	1	4	1.41
9	56.411	55.549	1.114	3.183	146	80	1.037	2.903	1.079	1.079	1	2	1.32
10	56.297	55.545	1.114	3.100	146	70	1.021	3.097	1.176	1.114	1	2	0.78
11	56.213	54.946	0.699	2.903	231	90	0.732	3.344	0.954	1.362	1	4	1.04
12	56.216	54.946	1.114	2.875	70	60	0.322	2.301	1.000	1.279	1	4	1.04
13	56.393	54.938	1.279	3.389	211	50	0.863	3.079	1.342	1.934	1	4	0.60
14	56.921	55.651	1.114	2.916	146	70	0.653	2.663	0.954	1.079	1	2	1.32
15	56.799	55.651	0.602	3.078	238	50	0.903	2.833	1.079	1.000	1	2	1.32
16	62.430	55.105	0.000	2.978	272	1	0.531	3.220	0.954	1.398	1	1	0.30
17	62.636	54.921	0.000	3.079	227	100	0.806	2.756	1.255	1.362	1	1	0.30
18	56.172	55.044	0.000	2.812	219	100	0.447	2.114	0.845	1.000	1	4	1.32
19	55.219	54.853	1.114	3.015	144	80	0.204	2.255	1.230	1.447	2	4	1.20
20	54.939	55.100	0.954	3.322	300	90	0.505	2.447	1.041	1.556	1	4	1.20
21	54.939	55.102	1.114	3.415	298	75	0.431	2.342	1.146	1.415	1	4	1.20
22	60.111	55.070	0.954	2.945	303	20	0.954	3.114	1.591	1.892	1	1	0.48
23	51.740	54.993	0.000	3.740	292	95	0.591	3.021	1.415	1.279	1	2	0.60
24	54.195	55.120	1.000	3.304	253	90	0.568	2.477	1.176	1.964	1	4	1.32
25	52.071	54.894	0.699	2.573	214	80	0.863	2.771	1.279	1.176	2	2	1.20
26	50.780	55.140	0.602	3.255	289	95	0.398	2.519	1.380	1.255	2	4	1.32
27	55.892	54.852	1.000	3.067	228	70	0.477	2.447	1.255	1.580	1	4	0.48
28	52.505	55.100	0.477	3.350	359	96	0.505	2.462	1.301	1.924	3	2	1.20
29	54.782	55.564	0.954	2.699	69	55	0.748	3.521	0.903	1.633	1	1	0.48
30	54.090	55.033	1.114	3.017	244	45	0.857	2.763	1.079	1.279	1	4	0.78
31	56.142	55.513	1.279	3.083	183	70	0.964	3.093	1.114	1.079	1	1	1.04
32	55.875	55.493	1.114	3.498	75	80	0.881	3.021	1.000	0.954	1	1	1.20
33	50.955	54.875	1.114	3.122	105	48	0.813	2.940	1.491	1.806	3	2	0.78
34	62.618	54.902	0.000	3.097	310	90	0.944	3.057	1.114	1.146	1	1	0.48
35	62.607	54.901	0.000	3.796	414	80	0.778	3.079	1.875	1.716	1	1	0.48
36	50.780	55.140	1.114	3.255	243	88	0.623	2.301	1.079	1.255	2	4	1.85
37	50.792	55.128	1.114	3.000	248	88	0.556	2.380	0.954	1.000	3	4	1.85
38	50.037	54.878	1.000	3.147	258	73	0.531	2.633	1.623	2.121	2	2	0.78
39	56.967	55.535	1.279	3.357	295	89	0.863	2.973	0.903	1.041	1	2	1.61
40	54.279	54.998	1.279	3.176	145	50	0.580	2.580	1.322	1.623	1	4	0.78
41	55.647	55.114	1.114	3.253	345	70	0.342	1.903	0.954	1.079	1	4	1.04
42	51.032	55.340	0.845	3.079	190	95	0.653	3.104	1.342	1.204	1	3	0.48
43	50.962	55.332	1.000	3.176	199	75	0.431	2.857	1.699	1.653	1	4	0.78
44	60.530	55.007	0.000	3.000	259	60	0.785	2.940	1.672	1.732	1	1	0.30
45	50.276	55.112	1.114	3.097	267	75	0.519	2.415	0.845	1.079	2	4	1.75
46	56.304	55.490	1.114	3.289	177	60	0.908	2.959	0.845	1.114	1	1	0.78
47	56.150	55.489	1.114	3.531	184	60	1.004	2.886	0.778	1.041	1	1	0.60
48	56.348	54.950	1.279	3.097	197	30	0.813	2.633	1.204	1.934	1	4	0.78
49	54.564	55.242	0.699	3.272	160	98	0.556	2.342	1.079	1.633	2	3	1.71
50	52.775	55.018	0.301	2.951	238	97	0.799	2.929	1.591	1.580	3	2	0.78
51	54.369	54.896	0.000	2.903	254	60	0.568	2.380	1.362	1.690	1	4	1.32
52	56.701	55.623	1.114	2.699	155	50	1.045	2.954	0.903	1.041	1	2	1.41
53	55.109	55.442	0.000	3.528	249	100	0.505	2.580	1.415	1.380	2	2	0.48
54	55.944	55.512	0.845	3.041	212	90	0.940	3.297	1.041	1.230	1	2	1.32
55	55.833	55.486	1.279	3.447	165	85	0.903	2.944	1.146	1.255	1	1	0.30
56	51.402	55.438	1.279	2.678	234	40	0.505	2.415	0.778	1.000	2	4	1.04
57	56.861	55.598	1.114	3.204	144	30	1.000	2.740	1.041	1.041	1	2	1.41
58	53.004	55.361	1.000	3.380	287	65	0.623	3.061	1.415	1.964	1	2	0.60
59	55.452	55.377	0.477	3.295	167	50	0.505	2.813	0.903	1.230	1	2	0.30

Table C-11. CANOCO printout of 2006 RDA using Cattle Index as a predictor.

```
*** Type of analysis ***
 Model          Gradient analysis
            indirect    direct    hybrid
 linear        1=PCA      2= RDA      3
 unimodal      4= CA      5= CCA      6
   ,,          7=DCA      8=DCCA      9
            10=non-standard analysis
 Type analysis number
 Answer =  2
 *** Data files ***
 Species data      : C:\Documents and Settings\Scott Kolochuk\Desktop\Canoco Nov 5 RDA
CATTLE\2006 Response
 Covariable data   :
 Environmental data : C:\Documents and Settings\Scott Kolochuk\Desktop\Canoco Nov 5 RDA
CATTLE\2006 Predictor Cattle Index Nov
 Initialization file:
 Forward selection of envi. variables =    0
 Scaling of ordination scores  =    2
 Diagnostics  =    1
 File   : C:\Documents and Settings\Scott Kolochuk\Desktop\Canoco Nov 5 RDA CATTLE\2006 Response
 Title  : 2006 Response
 Format :  (I5,1X,9F7.3)
 No. of couplets of species number and abundance per line :    0
 No samples omitted
 Number of samples          58
 Number of species           9
 Number of occurrences      519
 File  : C:\Documents and Settings\Scott Kolochuk\Desktop\Canoco Nov 5 RDA CATTLE\2006 Predictor
Cattle Index Nov
 Title : 2006 Predictor Cattle Index Nov
 Format :  (I5,1X,7F10.5,1(/6X,(7F10.5)))
 No. of environmental variables :    13
 No interaction terms defined
 No transformation of species data
 No species-weights specified
 No  sample-weights specified
 Centering/standardization by species  =    1
 Centering/standardization by samples  =    0
 No. of active  samples:     58
 No. of passive samples:      0
 No. of active  species:      9

 Total sum of squares in species data =     77.4732
 Total standard deviation in species data TAU =    0.385248

 ****** Check on influence in covariable/environment data ******
 The following sample(s) have extreme values
 Sample Environmental       Covariable  + Environment space
       variable Influence      influence     influence
            15                    6            6.6x
 ****** End of check ******
```

1

**** Correlation matrix ****

SPEC AX1	1.0000							
SPEC AX2	-0.0795	1.0000						
SPEC AX3	-0.0431	0.1031	1.0000					
SPEC AX4	0.0832	-0.1206	0.1830	1.0000				
ENVI AX1	0.7939	0.0000	0.0000	0.0000	1.0000			
ENVI AX2	0.0000	0.7680	0.0000	0.0000	0.0000	1.0000		
ENVI AX3	0.0000	0.0000	0.6332	0.0000	0.0000	0.0000	1.0000	
ENVI AX4	0.0000	0.0000	0.0000	0.6951	0.0000	0.0000	0.0000	1.0000
UTME	-0.0352	0.1653	0.2784	0.1129	-0.0443	0.2153	0.4396	0.1624
UTMN	-0.0014	0.4542	0.0136	-0.0663	-0.0018	0.5915	0.0215	-0.0953
CATIND	-0.4009	0.3275	-0.1934	-0.0393	-0.5050	0.4264	-0.3054	-0.0565
AREA	0.0349	-0.1336	0.1078	-0.0887	0.0440	-0.1739	0.1702	-0.1275
DEPTH	0.3097	-0.3848	-0.0550	-0.0766	0.3901	-0.5011	-0.0868	-0.1102
RIP	0.3482	-0.3073	0.1772	-0.1115	0.4386	-0.4002	0.2798	-0.1604
OM	0.1283	0.5009	-0.0124	-0.3345	0.1616	0.6522	-0.0196	-0.4813
SALT	-0.1012	0.2161	0.0249	-0.4147	-0.1274	0.2814	0.0393	-0.5966
SoilN	0.0272	-0.1797	-0.1712	-0.2876	0.0343	-0.2340	-0.2704	-0.4137
SoilP	-0.0844	-0.3031	-0.2859	-0.1481	-0.1064	-0.3947	-0.4516	-0.2130
SLOPE	0.2825	-0.0563	0.0259	-0.1534	0.3558	-0.0734	0.0408	-0.2207
TEXT	-0.0912	-0.2006	-0.3202	0.3497	-0.1148	-0.2612	-0.5057	0.5030
FOR1KM	0.4094	0.2419	-0.1930	0.2714	0.5157	0.3150	-0.3048	0.3904
	SPECAX1	SPECAX2	SPECAX3	SPECAX4	ENVIAX1	ENVIAX2	ENVIAX3	ENVIAX4

UTME	1.0000							
UTMN	0.0443	1.0000						
CATIND	-0.4069	0.2983	1.0000					
AREA	0.0245	0.0404	-0.0631	1.0000				
DEPTH	0.0608	-0.2960	-0.3627	0.3132	1.0000			
RIP	-0.2467	-0.0990	-0.2413	0.2630	0.1976	1.0000		
OM	0.4213	0.4528	0.0503	0.0064	-0.1897	-0.2321	1.0000	
SALT	0.3612	0.2843	-0.1378	0.0607	-0.1849	-0.2112	0.6946	1.0000
SoilN	0.0468	-0.3623	-0.3258	0.2536	0.2353	0.0027	0.1006	0.2839
SoilP	-0.0040	-0.4572	-0.1324	0.1515	0.1834	-0.1430	-0.0833	0.1404
SLOPE	-0.5444	-0.2689	-0.0120	-0.0849	0.0957	0.3052	-0.3183	-0.3169
TEXT	-0.4783	-0.3416	0.2873	-0.1786	0.0766	0.1164	-0.6070	-0.6716
FOR1KM	-0.4105	0.1522	0.2980	-0.1616	-0.0178	0.2575	-0.1467	-0.4640
	UTME	UTMN	CATIND	AREA	DEPTH	RIP	OM	SALT

SoilN	1.0000				
SoilP	0.6821	1.0000			
SLOPE	0.0445	0.0784	1.0000		
TEXT	-0.2093	0.0244	0.1858	1.0000	
FOR1KM	-0.3711	-0.2975	0.3618	0.4773	1.0000
SoilN	SoilP	SLOPE		TEXT	FOR1KM

N	name	(weighted) mean	stand. dev.	inflation factor
1	SPEC AX1	0.0000	1.2596	
2	SPEC AX2	0.0000	1.3022	
3	SPEC AX3	0.0000	1.5792	
4	SPEC AX4	0.0000	1.4386	
5	ENVI AX1	0.0000	1.0000	
6	ENVI AX2	0.0000	1.0000	
7	ENVI AX3	0.0000	1.0000	
8	ENVI AX4	0.0000	1.0000	
1	UTME	54.8393	3.2790	2.8701
2	UTMN	55.2052	0.2581	2.3989
3	CATIND	0.8467	0.4278	2.2747
4	AREA	3.1519	0.2403	1.4918
5	DEPTH	223.6034	69.3338	1.4624
6	RIP	70.9655	21.9450	1.6158
7	OM	0.6871	0.2257	3.2459
8	SALT	2.7468	0.3500	3.1737
9	SoilN	1.1753	0.2757	2.6638
10	SoilP	1.3867	0.3167	2.4077
11	SLOPE	1.3621	0.6351	2.1736
12	TEXT	2.6034	1.2168	3.4465
13	FOR1KM	0.9872	0.4380	2.3971

**** Summary ****

Axes	1	2	3	4	Total variance
Eigenvalues:	0.371	0.071	0.041	0.033	1.000
Species-environment correlations:	0.794	0.768	0.633	0.695	
Cumulative % variance					
of species data:	37.1	44.2	48.3	51.7	
of species-environment relation:	68.4	81.6	89.2	95.3	

Sum of all eigenvalues 1.000
Sum of all canonical eigenvalues 0.542
1

*** Unrestricted permutation ***

Seeds: 23239 945

**** Summary of Monte Carlo test ****

Test of significance of first canonical axis: eigenvalue = 0.371
F-ratio = 25.929
P-value = 0.0020

Test of significance of all canonical axes : Trace = 0.542
F-ratio = 4.002
P-value = 0.0020

(499 permutations under reduced model)

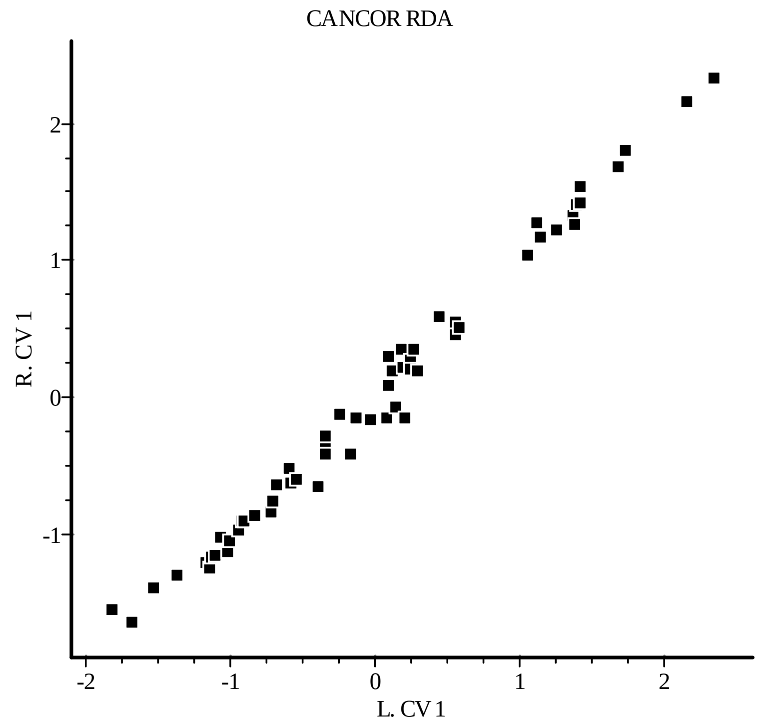

Figure C-2. Right and left set variable scores along the first canonical axis of the RDA using Cattle Index as the cattle disturbance variable plotted against one another in the canonical correlation (CANCOR) analysis

Table C-12. From the RDA using Cattle Index the correlation matrix of first 4 canonical axes in 2005 RDA (1-4) against first 4 canonical axes of 2006 RDA (1-4) as well as corresponding Chi-Square test.

Correlation Matrix

		2005			
		1st axis	2nd axis	3rd axis	4th axis
2006	1st axis	**0.79**	0.29	0.03	0.19
	2nd axis	0.30	**-0.82**	-0.18	0.38
	3rd axis	0.20	-0.24	**0.59**	0.16
	4th axis	0.00	0.20	-0.03	**-0.73**

Chi-Square test with removal of eigenvalues successfully

Eigenvalues removed up to	Chi-Square	D.F.	Lambda
0	403	16	0.0005
1	174	9	0.0365
2	68	4	0.2757
3	14	1	0.7629

Appendix D. Nutrient Diffusing Substrata

Table D-1. The 2005 NDS algal biomass, ANOVA statistics and corresponding limnological values.

	NDS	Mean algal biomass (µg/cm^2)				Anova p-value	Significant response	Limiting treatment	Nutrient treatment:Control			General limnological paramters						Molar nutrient ratios		
Site	#	Control	P	N	NP				P:C	N:C	NP:C	TURB	TCHL	TP	TN	TRP	DIN	TN:TP	DIN:TRP	DIN:TP
1	1	1.04	1.76	5.29	4.84	0.147			1.69	5.07	4.64	16	8	0.03	6.30	0.013	0.18	178	31	22
	2	1.84	3.14	2.34	13.67	<.0001	P**, NP***	NP	1.71	1.27	7.45	11	9	0.05	4.59	0.009	0.15	193	46	7
	3	1.29	1.59	1.05	8.18	0.0021	NP**	NP	1.23	0.81	6.32	11	9	0.04	2.35	0.014	0.19	115	43	10
	4	0.80	0.95	1.01	2.54	0.0729			1.18	1.26	3.18	13	11	0.05	4.28	0.019	0.22	186	26	9
12	1	15.74	10.86	6.51	9.52	0.3771			0.69	0.41	0.61	29	139	3.80	18.83	3.306	2.73	11	2	2
	2	2.25	2.08	4.03	2.34	0.1781			0.92	1.79	1.04	81	153	3.17	23.06	3.503	2.93	18	2	2
	3	0.25	0.27	0.22	0.49	0.0502			1.09	0.91	1.99	130	98	3.51	29.69	3.678	3.20	20	2	2
	4	0.15	0.11	0.11	0.27	0.0072	NP*	NP	0.73	0.72	1.85	120	64	4.22	28.59	3.147	3.33	15	2	2
16	1	4.89	3.00	16.73	12.80	0.0008	N**, NP*	N	0.61	3.42	2.62	9	10	0.16	2.89	0.121	0.10	41	2	2
	2	10.77	8.34	19.38	17.32	0.0248			0.77	1.80	1.61	6	48	0.29	2.95	0.154	0.10	26	1	1
	3	19.32	9.95	20.12	21.91	0.0179	P*inhib		0.51	1.04	1.13	7	105	0.36	1.94	0.147	0.14	12	2	1
	4	10.15	14.18	16.62	14.74	0.1495			1.40	1.64	1.45	12	117	0.31	1.28	0.093	0.18	9	5	1
17	1	2.26	3.13	3.31	6.82	0.2945			1.38	1.46	3.02	8	8	0.06	2.16	0.009	0.13	73	41	5
	2	2.82	1.94	2.86	10.36	0.0006	NP**	NP	0.69	1.01	3.68	6	11	0.08	3.21	0.007	0.15	87	48	4
	3	1.23	1.78	3.64	20.84	<.0001	N**, NP***	NP	1.44	2.95	16.90	7	16	0.14	2.54	0.007	0.17	54	58	3
	4	1.27	1.13	1.40	9.58	<.0001	NP***	NP	0.89	1.10	7.52	7	14	0.14	1.66	0.005	0.21	31	93	4
19	1	13.95	12.66	22.79	10.52	0.1896			0.91	1.63	0.75	12	6	0.50	2.89	0.469	0.65	13	3	3
	2	7.81	3.99	20.88	19.56	<.0001	N***, NP***	N	0.51	2.67	2.51	10	6	0.64	3.36	0.531	0.33	12	1	1
	3	10.54	7.64	10.48	14.06	0.0335			0.73	0.99	1.33	9	13	1.05	4.28	0.819	0.42	9	1	1
	4	6.27	11.84	21.97	13.46	0.0776			1.89	3.50	2.15	9	129	1.14	3.84	0.965	1.87	7	5	4
20	1	7.36	10.77	9.60	10.60	0.5133			1.46	1.30	1.44	9	7	0.73	1.78	0.648	0.32	5	1	1
	2	15.64	13.25	26.28	17.61	0.0334			0.85	1.68	1.13	12	4	0.78	1.94	0.657	0.27	6	1	1
	3	7.81	2.92	14.94	13.24	0.0128			0.37	1.91	1.70	10	4	0.84	2.67	0.724	0.16	7	0	0
	4	15.80	12.93	20.70	27.69	0.0181	NP*	NP	0.82	1.31	1.75	10	6	0.88	2.92	0.796	0.26	7	1	1
22	1	12.43	15.58	11.14	11.86	0.592			1.25	0.90	0.95	13	5	0.06	3.11	0.051	0.33	121	14	11
	2	15.27	6.97	9.03	17.57	0.0363			0.46	0.59	1.15	14	5	0.25	2.95	0.218	0.27	38	8	6
	3	4.83	1.97	9.84	9.06	0.0009	N*, P*inhib	N	0.41	2.04	1.88	11	4	0.54	4.18	0.480	0.11	18	1	1
	4	5.47	3.84	24.65	17.04	<.0001	N***, NP***	N	0.70	4.51	3.12	8	5	0.85	3.11	0.643	0.29	9	1	1
28	1	18.43	19.04	21.10	16.33	0.8531			1.03	1.15	0.89	12	10	2.50	14.10	1.498	0.41	12	1	0
	2	15.97	14.78	18.29	14.25	0.5809			0.93	1.15	0.89	11	4	2.35	10.56	1.481	0.58	9	1	1
	3	12.19	13.95	13.06	13.23	0.9489			1.15	1.07	1.09	22	17	2.51	7.37	1.426	1.40	6	2	1
	4	15.39	24.43	18.53	22.71	0.0019	P***, NP**	P	1.59	1.20	1.48	35	95	2.91	10.06	1.491	2.56	8	4	2

note: *, **, *** significant at $p < .05$, .01, and .001, respectively. Blank indicates no significant limitation. Inhib refers to treatment inhibition. Treatments are P= Phosphorus, N = Nitrogen, NP = Nitrogen and Phosphorus. All treatments log +1 transformed from µg/cm2. P:C, N:C, NP:C all represent nutrient treatment biomass:Control treatment biomass ratios. TURB = turbidity (NTU), TCHL = Total Chlorophyll a (µg/L) and TP, TN, TRP, DIN are in mg/L.

Table D-2. The 2005 NDS algal biomass, ANOVA statistics and corresponding limnological values (continued)

	NDS	Mean algal biomass (µg/cm^2)				Anova p-value	Significant response	Limiting treatment	Nutrient treatment:Control			General limnological paramters						Molar nutrient ratios		
Site	#	Control	P	N	NP				P:C	N:C	NP:C	TURB	TCHL	TP	TN	TRP	DIN	TN:TP	DIN:TRP	DIN:TP
30	1	4.61	2.40	5.62	16.37	0.0477			0.52	1.22	3.55	9	36	0.08	4.15	0.014	0.14	110	22	5
	2	7.95	5.10	19.28	15.92	0.0012	N**, NP*	N	0.64	2.42	2.00	8	76	0.22	3.87	0.085	0.15	69	11	2
	3	18.43	10.11	17.69	17.09	0.37			0.55	0.96	0.93	8	119	0.33	2.61	0.149	0.25	17	4	2
	4	12.33	13.93	14.04	19.05	0.0837	NP*	NP	1.13	1.14	1.55	11	207	0.36	3.39	0.116	0.15	21	2	1
32	1	11.03	14.04	17.98	11.04	0.1906			1.27	1.63	1.00	15	22	0.28	3.68	0.063	0.61	35	87	4
	2	10.81	9.00	9.73	9.57	0.7502			0.83	0.90	0.89	15	6	0.41	2.76	0.207	0.69	15	86	4
	3	9.53	4.52	14.34	6.73	0.002	P*inhib		0.47	1.50	0.71	14	33	0.42	2.57	0.317	0.25	14	2	1
	4	2.48	1.50	12.18	3.19	<.0001	N***	N	0.60	4.91	1.29	14	102	0.47	2.76	0.235	0.25	13	2	1
33	1	6.88	2.81	12.66	11.36	0.0015	P*inhib		0.41	1.84	1.65	8	17	0.28	4.72	0.108	0.12	36	5	1
	2	3.88	3.84	9.92	17.67	0.1434			0.99	2.56	4.56	6	68	0.42	7.85	0.188	0.12	43	5	1
	3	12.10	4.79	25.32	10.89	<.0001	N**	N	0.40	2.09	0.90	11	261	0.45	6.11	0.243	0.17	29	2	1
	4	9.37	4.05	15.64	13.48	<.0001	P**inhib, N*	N	0.43	1.67	1.44	14	295	0.35	3.21	0.133	0.21	20	3	1
34	1	6.97	2.96	7.79	14.92	0.0905			0.42	1.12	2.14	23	144	0.13	3.11	0.042	0.08	48	4	2
	2	6.60	4.72	11.18	8.96	0.0668			0.71	1.69	1.36	27	308	0.19	4.09	0.022	0.08	47	10	1
	3	7.89	3.58	6.45	4.31	0.2844			0.45	0.82	0.55	21	209	0.24	3.24	0.046	0.11	30	9	1
	4	4.60	3.12	14.78	9.63	0.0017	N***	N	0.68	3.21	2.09	24	102	0.31	2.92	0.086	0.18	22	4	1
35	1	8.01	7.28	5.79	15.80	0.0008	NP*	NP	0.91	0.72	1.97	19	22	0.16	4.66	0.055	0.35	63	16	5
	2	8.40	4.27	11.49	18.66	0.0002	NP*	NP	0.51	1.37	2.22	15	47	0.20	3.77	0.104	0.32	45	8	5
	3	1.75	1.17	10.48	11.16	0.0001	N***, NP***	N	0.67	6.00	6.39	13	97	0.16	2.89	0.087	0.16	61	5	5
	4	2.65	3.56	5.41	4.21	0.0327	N*	N	1.35	2.04	1.59	15	118	0.17	2.76	0.047	0.28	58	14	6
36	1	1.42	1.87	2.94	9.07	0.0075	NP**	NP	1.32	2.07	6.39	11	28	0.05	2.42	0.016	0.11	21	16	10
	2	2.16	2.20	6.45	14.77	0.0007	N*, NP***	NP	1.02	2.99	6.84	10	20	0.13	3.08	0.030	0.10	52	9	2
	3	3.08	1.32	13.50	13.76	<.0001	N***, NP***	N	0.43	4.38	4.46	10	24	0.19	3.84	0.063	0.12	46	4	1
	4	5.06	4.11	14.90	14.28	0.008	N*, NP*	N	0.81	2.95	2.82	14	19	0.21	3.52	0.090	0.26	38	6	3
38	1	3.31	2.73	10.25	10.89	0.0006	N**, NP**	N	0.83	3.10	3.29	6	15	0.08	6.52	0.019	0.18	168	20	5
	2	7.50	8.20	13.56	26.32	0.0008	N*, NP***	NP	1.09	1.81	3.51	7	19	0.09	6.39	0.016	0.15	154	22	4
	3	21.09	9.26	29.48	23.12	0.0008	P**inhib		0.44	1.40	1.10	8	16	0.09	2.07	0.014	0.17	51	27	4
	4	0.74	5.34	6.56	15.25	0.0048	NP**	NP	7.22	8.86	20.61	9	40	0.10	2.67	0.020	0.23	60	26	5
41	1	4.79	2.69	22.57	19.10	<.0001	N***, NP***	N	0.56	4.71	3.99	9	13	0.27	2.86	0.212	0.17	24	2	1
	2	12.17	7.50	22.16	17.61	0.0099			0.62	1.82	1.45	9	13	0.45	2.20	0.336	0.25	13	2	1
	3	5.59	4.60	18.03	10.88	0.0029	N**	N	0.82	3.23	1.95	8	5	0.65	1.85	0.483	0.32	6	1	1
	4	13.11	8.88	23.12	17.71	0.0041	N*	N	0.68	1.76	1.35	7	5	0.67	2.29	0.501	0.29	8	1	1

note: *, **, *** significant at $p < .05$, .01, and .001, respectively. Blank indicates no significant limitation. Inhib refers to treatment inhibition. Treatments are P= Phosphorus, N = Nitrogen, NP = Nitrogen and Phosphorus. All treatments log +1 transformed from µg/cm2. P:C, N:C, NP:C all represent nutrient treatment biomass:Control treatment biomass ratios. TURB = turbidity (NTU), TCHL = Total Chlorophyll a (µg/L) and TP, TN, TRP, DIN are in mg/L.

Table D-3. The 2005 NDS algal biomass, ANOVA statistics and corresponding limnological values (continued)

Site	NDS #	Mean algal biomass (µg/cm^2) Control	P	N	NP	Anova p-value	Significant response	Limiting treatment	Nutrient treatment:Control P:C	N:C	NP:C	TURB	General limnological paramters TCHL	TP	TN	TRP	DIN	Molar nutrient ratios TN:TP	DIN:TRP	DIN:TP
42	1	19.01	13.97	24.30	17.25	0.0366			0.74	1.28	0.91	11	17	0.60	2.67	0.399	0.63	12	5	3
	2	18.91	17.34	20.72	18.93	0.8861			0.92	1.10	1.00	9	15	0.56	1.63	0.466	0.48	9	4	3
	3	16.15	12.49	23.12	24.31	0.0197			0.77	1.43	1.51	18	63	0.98	4.75	0.661	1.44	9	5	3
	4	25.13	16.99	26.84	16.60	0.036			0.68	1.07	0.66	22	496	1.11	7.81	0.538	1.89	15	7	4
46	1	5.22	4.81	25.99	22.31	<.0001	N***, NP***	N	0.92	4.98	4.28	20	51	0.46	5.01	0.112	0.18	24	40	1
	2	8.75	7.07	21.10	24.21	0.0002	N**, NP***	N	0.81	2.41	2.77	16	32	0.70	4.06	0.317	0.17	14	40	1
	3	12.10	7.27	69.83	51.29	<.0001	*inhib, N***, NP*	N	0.60	5.77	4.24	13	248	0.75	3.24	0.377	0.19	10	2	1
	4	22.43	19.88	27.20	31.56	0.0279			0.89	1.21	1.41	23	343	0.75	4.72	0.271	0.29	14	3	1
47	1	6.06	1.89	9.86	9.77	0.0012	P**inhib		0.31	1.63	1.61	10	21	0.62	4.50	0.503	0.15	16	1	1
	2	6.08	3.11	10.06	10.37	0.0185			0.51	1.65	1.70	8	51	0.54	6.99	0.341	0.13	29	1	1
	3	10.91	10.46	21.04	14.72	0.0352	N*	N	0.96	1.93	1.35	10	63	0.50	5.95	0.320	0.16	25	1	1
	4	13.77	12.02	21.15	13.64	0.4835			0.87	1.54	0.99	12	92	0.53	4.03	0.306	0.21	16	2	1
50	1	1.12	3.35	1.87	2.26	0.153			2.99	1.67	2.02	12	7	0.03	4.82	0.017	1.85	108	237	221
	2	2.18	7.15	1.32	6.08	<.0001	P***, NP***	P	3.28	0.60	2.79	10	7	0.06	3.58	0.018	1.30	151	164	54
	3	2.65	7.97	3.29	9.56	0.0051	P**, NP*	P	3.01	1.24	3.60	10	7	0.04	2.26	0.012	0.64	153	124	34
	4	1.40	3.04	2.65	5.42	0.0977	NP*	NP	2.18	1.90	3.88	11	11	0.04	1.53	0.009	0.25	128	85	20
51	1	6.84	5.98	3.25	2.66	0.0056	N*& NP**inhib		0.87	0.47	0.39	25	216	0.50	7.09	0.163	0.32	31	4	1
	2	14.45	11.18	15.48	13.28	0.3033			0.77	1.07	0.92	24	184	0.52	5.57	0.278	0.30	24	3	1
	3	34.77	29.04	43.89	17.97	0.0049	P*inhib		0.84	1.26	0.52	32	74	0.49	4.18	0.204	0.36	21	17	2
	4	5.49	10.37	6.43	19.91	0.0002	P*, NP***	NP	1.89	1.17	3.63	37	129	0.35	5.29	0.017	0.43	33	118	3
52	1	18.43	11.43	19.56	13.54	0.0414			0.62	1.06	0.73	36	7	0.67	5.16	0.986	1.60	27	4	8
	2	8.55	8.89	19.72	13.76	0.0569			1.04	2.31	1.61	37	16	0.71	4.31	0.926	1.08	25	2	7
	3	14.34	12.97	16.58	18.91	0.4878			0.90	1.16	1.32	11	34	1.10	2.92	0.848	0.22	6	1	0
	4	18.04	18.89	24.62	21.82	0.2651			1.05	1.36	1.21	12	28	1.20	3.43	0.949	0.62	6	1	1
55	1	4.36	2.65	7.37	20.68	<.0001	NP***	NP	0.61	1.69	4.75	12	13	0.22	5.92	0.045	0.32	62	19	3
	2	13.07	9.02	25.19	26.77	0.0006	N*, NP**	N	0.69	1.93	2.05	11	10	0.55	3.90	0.441	0.25	38	5	2
	3	13.07	8.34	16.48	20.14	0.0013	NP*	NP	0.64	1.26	1.54	14	171	0.76	2.64	0.506	0.26	9	2	1
	4	20.92	15.17	13.66	10.52	0.1734			0.72	0.65	0.50	15	171	0.50	5.92	0.215	0.88	30	8	5
58	1	4.17	2.36	15.16	18.95	0.0009	N*, NP**	N	0.57	3.63	4.54	44	9	0.66	4.47	0.275	0.63	16	5	2
	2	7.15	6.10	11.84	4.15	0.034	N*	N	0.85	1.66	0.58	41	11	0.43	2.86	0.256	0.53	12	4	2
	3	4.16	3.54	42.79	24.60	<.0001	N***, NP***	N	0.85	10.28	5.91	10	23	0.26	1.09	0.110	0.18	10	7	2
	4	3.74	3.78	11.18	17.78	0.0004	N**, NP***	N	1.01	2.99	4.76	12	48	0.18	2.16	0.030	0.24	34	21	4

note: *, **, *** significant at $p < .05$, .01, and .001, respectively. Blank indicates no significant limitation. Inhib refers to treatment inhibition. Treatments are P= Phosphorus, N = Nitrogen, NP = Nitrogen and Phosphorus. All treatments log +1 transformed from µg/cm2. P:C, N:C, NP:C all represent nutrient treatment biomass:Control treatment biomass ratios. TURB = turbidity (NTU), TCHL = Total Chlorophyll a (µg/L) and TP, TN, TRP, DIN are in mg/L.

Table D-4. The 2006 NDS algal biomass, ANOVA statistics and corresponding limnological values.

	NDS	Mean algal biomass (µg/cm²)				Anova p-	Significant	Limiting	Nutrient treatment:Control			General limnological paramters						Molar nutrient ratios		
Site	#	Control	P	N	NP	value	response	treatment	P:C	N:C	NP:C	TURB	TCHL	TP	TN	TRP	DIN	TN:TP	DIN:TRP	DIN:TP
1	1	0.35	1.38	0.97	1.85	17.357	NP***	NP	0.70	1.34	12.61	5	6	0.04	2.32	0.01	0.01	140	3	1
	2	0.29	0.98	1.90	1.62	12.029	NP***	NP	1.94	1.65	12.28	3	4	0.03	2.54	0.01	0.01	270	3	1
	3	0.28	0.92	1.50	1.13	4.6946	P**, NP***	NP	1.63	1.22	5.08	3	4	0.02	2.51	0.01	0.01	327	3	1
	4	0.34	1.22	2.16	1.66	5.733	NP**	NP	1.77	1.36	4.69	3	5	0.02	1.50	0.01	0.01	147	3	1
12	1	1.17	14.32	12.91	9.55	10.336			0.90	0.67	0.72	73	72	3.99	26.13	2.99	3.08	15	2	2
	2	0.71	4.42	6.75	5.48	5.2563			1.53	1.24	1.19	92	50	4.24	26.38	3.02	2.79	14	2	2
	3	0.39	1.56	1.62	1.46	1.688			1.04	0.93	1.08	163	111	4.38	24.45	3.48	1.41	12	1	1
	4	0.53	2.43	1.53	2.39	1.9426			0.63	0.98	0.80	156	112	4.18	20.98	3.36	0.45	11	0	0
16	1	0.61	3.06	10.17	8.16	24.17	P**, N*, NP***	NP	3.32	2.66	7.89	2	18	0.09	0.36	0.01	0.01	9	3	0
	2	0.58	2.79	9.45	5.94	19.472	P***, N*, NP***	NP	3.38	2.13	6.97	3	51	0.12	0.62	0.02	0.01	11	3	0
	3	0.54	2.51	10.62	4.89	21.7	P***, N*, NP***	NP	4.24	1.95	8.66	9	74	0.11	0.49	0.02	0.01	8	1	0
	4	0.75	4.77	11.80	3.43	13.984	P**, NP**	P	2.47	0.72	2.93	11	113	0.13	0.96	0.02	0.01	13	1	0
17	1	0.60	2.98	5.61	1.69	19.132	NP**	NP	1.88	0.56	6.41	2	11	0.08	3.24	0.01	0.02	101	10	1
	2	0.41	1.58	2.30	2.65	12.879	NP***	NP	1.45	1.67	8.14	4	27	0.09	1.37	0.01	0.01	33	3	0
	3	0.39	1.52	4.07	2.12	11.302	P**, NP***	NP	2.68	1.39	7.43	5	54	0.08	0.49	0.01	0.01	14	2	0
	4	0.46	1.89	4.27	3.14	13.288	NP***	NP	2.26	1.66	7.03	4	54	0.09	1.31	0.01	0.01	32	4	0
19	1		0.00	22.93	33.37	30.886	N, NP	N				17	52	0.89	2.57	0.72	0.01	6	0	0
	2	0.57	2.75	1.53	28.19	16.106	N***, NP***	N	0.56	10.24	5.85	19	66	0.78	3.02	0.36	0.01	9	1	0
	3	1.29	18.62	11.64	27.15	20.061	N*	N	0.63	1.46	1.08	21	124	0.37	3.71	0.04	0.03	39	1	0
	4	1.31	19.36	13.83	19.28	23.13			0.71	1.00	1.19	24	121	0.29	6.39	0.17	0.52	55	5	3
20	1		0.00	8.01	24.25	31.115	N, NP	N				3	6	0.14	3.87	0.05	0.01	60	0	0
	2	0.54	2.55	1.85	9.68	16.412	N***,NP***	NP	0.73	3.80	6.44	20	59	0.15	3.49	0.20	0.02	54	0	0
	3	0.41	1.58	4.79	1.29	12.366	P***, NP***	NP	3.03	0.81	7.82	35	117	0.12	2.07	0.19	0.03	46	2	1
	4	1.14	13.19	17.80	13.67	27.509	NP*	NP	1.35	1.04	2.09	22	91	1.33	3.14	0.02	0.02	35	3	1
22	1	1.02	9.70	8.75	32.50	24.191	N***, NP**	N	0.90	3.35	2.49	2	4	0.58	1.63	0.51	0.01	7	0	0
	2	0.85	6.41	2.58	39.02	27.522	N***, NP**	N	0.40	6.09	4.30	1	2	0.59	1.15	0.52	0.01	4	0	0
	3	1.01	9.49	7.23	20.98	14.364	N**	N	0.76	2.21	1.51	1	49	0.49	1.09	0.39	0.01	5	0	0
	4	1.11	11.82	5.59	10.17	13.481	P*inhib		0.47	0.86	1.14	3	74	0.52	1.63	0.42	0.01	7	0	0
28	1	1.39	23.36	29.24	23.92	26.94			1.25	1.02	1.15	16	37	3.22	10.97	1.85	0.77	8	1	1
	2	0.96	8.12	7.99	33.70	24.669	N***, NP***	N	0.98	4.15	3.04	19	72	3.27	10.66	1.94	0.14	7	0	0
	3	0.62	3.19	4.54	11.92	15.401	N*, NP*	N	1.42	3.74	4.83	42	465	2.72	7.72	1.62	0.11	6	0	0
	4	0.88	6.70	8.23	13.09	9.314	N*	N	1.23	1.95	1.39	47	884	2.18	15.27	1.06	0.12	18	0	0

note: *, **, *** significant at $p < .05$, .01, and .001, respectively. Blank indicates no significant limitation. Inhib refers to treatment inhibition. Treatments are P= Phosphorus, N = Nitrogen, NP = Nitrogen and Phosphorus. All treatments log +1 transformed from µg/cm2. P:C, N:C, NP:C all represent nutrient treatment biomass:Control treatment biomass ratios. TURB = turbidity (NTU), TCHL = Total Chlorophyll a (µg/L) and TP, TN, TRP, DIN are in mg/L.

Table D-5. The 2006 NDS algal biomass, ANOVA statistics and corresponding limnological values (continued).

Site	NDS #	Mean algal biomass (μg/cm²) Control	P	N	NP	Anova p-value	Significant response	Limiting treatment	Nutrient treatment:Control P:C	N:C	NP:C	TURB	General limnological paramters TCHL	TP	TN	TRP	DIN	Molar nutrient ratios TN:TP	DIN:TRP	DIN:TP
30	1	1.90	6.25	2.85	17.84	<.0001	P***, N*, NP***	NP	3.28	1.50	9.37	8	34	0.11	7.25	0.01	0.01	142	4	0
	2	2.25	10.56	3.72	27.21	<.0001	P***, NP***	NP	4.70	1.65	12.10	4	57	0.12	6.14	0.01	0.01	118	4	0
	3	2.32	6.74	2.94	11.48	0.0003	P**, NP***	P	2.91	1.27	4.95	17	49	0.12	1.69	0.02	0.03	34	3	1
	4	5.90	8.86	7.36	16.05	0.0251	NP*	NP	1.50	1.25	2.72	29	148	0.17	1.47	0.02	0.03	30	3	1
32	1	4.81	2.05	16.46	10.32	<.0001	N***, NP**	N	0.43	3.42	2.15	9	17	0.09	1.72	0.04	0.01	38	1	0
	2	6.31	1.31	8.65	7.97	0.0248			0.21	1.37	1.26	10	38	0.18	2.01	0.04	0.01	35	1	0
	3	4.52	4.60	4.97	9.87	0.1572			1.02	1.10	2.18	14	122	0.30	1.53	0.03	0.02	11	5	0
	4	2.39	5.49	5.05	10.21	0.0061	NP**	NP	2.29	2.11	4.27	42	236	0.32	4.12	0.01	0.04	30	9	0
33	1	20.71	14.63	34.87	27.84	0.0004	N**	N	0.71	1.68	1.34	5	16	0.19	1.28	0.12	0.12	15	2	2
	2	5.55	3.86	18.19	9.49	0.0007	N**	N	0.70	3.28	1.71	4	68	0.18	1.60	0.13	0.12	19	2	2
	3	13.73	11.71	19.71	9.12	0.0019	N*	N	0.85	1.44	0.66	18	131	0.16	2.83	0.08	0.01	44	0	0
	4	16.60	15.19	16.09	14.22	0.947			0.91	0.97	0.86	23	234	0.19	5.23	0.04	0.01	64	1	0
34	1	2.10	0.77	9.33	8.38	<.0001	N***, NP***	N	0.37	4.45	4.00	8	12	0.12	1.72	0.03	0.01	29	1	0
	2	4.40	1.48	7.66	12.07	<.0001	N**, NP***	N	0.34	1.74	2.74	3	10	0.12	1.91	0.04	0.01	34	1	0
	3	3.10	2.71	8.28	5.62	0.0032	N**	N	0.87	2.67	1.81	13	14	0.11	0.36	0.05	0.01	8	0	0
	4	9.74	4.22	15.74	11.31	0.0011	P*inhib		0.43	1.62	1.16	14	25	0.13	1.18	0.07	0.01	19	0	0
35	1	1.46	2.16	10.99	20.61	<.0001	N***, NP***	N	1.48	7.54	14.13	4	53	0.07	2.04	0.03	0.04	64	3	1
	2	1.87	1.64	3.74	14.18	<.0001	N**, NP***	NP	0.88	2.00	7.57	4	15	0.09	2.07	0.04	0.04	54	2	1
	3	5.28	7.17	3.80	13.77	<.0001	NP***	NP	1.36	0.72	2.61	4	14	0.11	1.44	0.02	0.06	32	6	1
	4	6.97	9.29	5.06	13.47	0.0145	NP*	NP	1.33	0.73	1.93	3	10	0.10	1.63	0.03	0.18	44	15	5
36	1	6.84	8.26	6.06	28.19	0.0004	NP***	NP	1.21	0.89	4.12	2	28	0.10	6.05	0.02	0.03	111	6	1
	2	2.47	4.77	6.29	23.34	<.0001	P*, N**, NP***	NP	1.93	2.55	9.46	3	9	0.11	6.55	0.02	0.03	120	4	1
	3	6.95	8.71	8.86	13.62	0.0117	NP**	NP	1.25	1.28	1.96	3	10	0.14	2.26	0.01	0.03	45	6	1
	4	6.82	9.06	5.32	16.49	0.0481			1.33	0.78	2.42	3	9	0.16	2.51	0.01	0.04	38	7	1
38	1	6.60	6.60	12.70	16.54	0.0003	N**, NP***	N	1.00	1.93	2.51	4	19	0.06	1.85	0.02	0.03	79	3	1
	2	1.93	2.14	1.79	14.92	0.0002	NP***	NP	1.11	0.93	7.72	22	69	0.15	2.13	0.02	0.03	39	3	0
	3	5.55	5.16	6.23	13.01	0.028	NP*	NP	0.93	1.12	2.34	45	414	0.25	2.48	0.02	0.05	22	7	0
	4	4.52	3.24	4.14	16.18	<.0001	NP***	NP	0.72	0.92	3.58	36	585	0.23	3.14	0.03	0.05	32	7	0
41	1	10.75	6.17	28.96	21.33	0.0001	N**, NP*	N	0.57	2.69	1.98	5	27	0.73	2.10	0.37	0.01	7	0	0
	2	6.84	7.96	25.74	23.48	<.0001	N***, NP***	N	1.16	3.77	3.43	8	69	0.96	1.63	0.66	0.01	4	0	0
	3	6.55	8.80	8.80	7.92	0.391			1.34	1.34	1.21	24	525	1.14	4.75	0.64	0.07	9	0	0
	4	8.64	4.96	5.62	4.18	0.0263	P & NP*inhib		0.57	0.65	0.48	22	1238	0.86	6.43	0.88	0.07	19	0	0

note: *, **, *** significant at $p < .05$, .01, and .001, respectively. Blank indicates no significant limitation. Inhib refers to treatment inhibition. Treatments are P= Phosphorus, N = Nitrogen, NP = Nitrogen and Phosphorus. All treatments log +1 transformed from μg/cm2. P:C, N:C, NP:C all represent nutrient treatment biomass:Control treatment biomass ratios. TURB = turbidity (NTU), TCHL = Total Chlorophyll a (μg/L) and TP, TN, TRP, DIN are in mg/L.

Table D-6. The 2006 NDS algal biomass, ANOVA statistics and corresponding limnological values (continued).

Site	NDS #	Mean algal biomass (μg/cm^2) Control	P	N	NP	Anova p-value	Significant response	Limiting treatment	Nutrient treatment:Control P:C	N:C	NP:C	TURB	General limnological paramters TCHL	TP	TN	TRP	DIN	Molar nutrient ratios TN:TP	DIN:TRP	DIN:TP
42	1	32.80	24.13	30.31	20.73	0.057	NP*inhib		0.74	0.92	0.63	7	6	0.58	3.36	0.52	1.26	12	5	4
	2	10.23	11.87	16.33	16.36	0.0173	N*, NP*	N	1.16	1.60	1.60	55	266	0.87	7.53	0.45	2.15	19	12	6
	3	5.55	4.47	4.13	3.97	0.3297			0.81	0.74	0.72	80	1475	1.54	14.63	0.28	3.02	21	24	4
	4	8.00	5.71	8.84	6.82	0.511			0.71	1.10	0.85	48	1322	2.29	19.37	0.72	4.18	19	21	4
46	1	32.06	26.00	27.41	27.21	0.6644			0.81	0.86	0.85	24	36	0.28	1.63	0.18	0.32	13	4	2
	2	10.28	7.31	15.99	31.24	0.0003	N*, NP***	N	0.71	1.55	3.04	33	78	0.44	2.61	0.21	0.27	12	3	2
	3	11.90	7.77	19.40	14.14	0.0199			0.65	1.63	1.19	49	231	0.43	4.82	0.13	0.04	28	1	0
	4	19.81	16.99	9.35	12.71	0.0004	N***inhib		0.86	0.47	0.64	45	385	0.31	4.91	0.07	0.04	35	1	0
47	1	2.79	1.50	15.31	7.90	<.0001	N***, NP***	N	0.54	5.48	2.83	4	15	0.34	2.73	0.17	0.01	19	0	0
	2	4.50	1.49	19.48	12.43	<.0001	**inhib, N***, NP*	N	0.33	4.33	2.76	14	59	0.39	2.42	0.21	0.01	14	0	0
	3	6.54	8.09	11.45	18.02	<.0001	N***, NP***	NP	1.24	1.75	2.75	16	94	0.28	2.29	0.11	0.01	20	0	0
	4	6.98	10.21	15.78	16.97	0.0053	N**, NP**	N	1.46	2.26	2.43	9	111	0.28	3.08	0.05	0.01	25	1	0
50	1	0.00	6.72	2.10	5.67	0.0086	P, NP	P				2	34	0.03	2.20	0.01	0.91	232	401	143
	2	2.98	4.25	2.21	12.32	0.0041	NP**	NP	1.43	0.74	4.13	2	7	0.07	1.18	0.01	0.15	47	68	6
	3	1.43	1.42	1.36	7.91	0.0006	NP***	NP	1.00	0.95	5.55	2	18	0.05	0.27	0.01	0.03	30	15	1
	4	0.45	0.43	1.50	6.92	<.0001	NP***	NP	0.95	3.30	15.24	2	22	0.02	0.96	0.01	0.01	101	5	1
51	1	20.91	23.05	18.40	20.29	0.5418			1.10	0.88	0.97	48	39	0.54	7.44	0.20	2.49	30	30	11
	2	28.92	21.26	23.36	16.87	0.6484			0.74	0.81	0.58	68	101	0.81	9.80	0.15	1.89	27	42	5
	3	9.82	12.23	11.55	10.09	0.613			1.24	1.18	1.03	52	299	0.97	12.46	0.05	1.37	28	61	3
	4	19.81	16.99	12.00	10.06	0.2124			0.86	0.61	0.51	66	570	1.42	19.81	0.06	1.63	31	56	3
52	1	5.43	6.25	22.03	15.23	0.0001	N***, NP**	N	1.15	4.06	2.81	5	85	0.87	2.01	0.67	0.56	5	2	1
	2	6.47	10.09	11.18	9.92	0.245			1.56	1.73	1.53	19	121	0.67	1.47	0.39	0.07	5	0	0
	3	10.73	5.47	18.68	8.55	0.0209			0.51	1.74	0.80	20	64	0.38	0.49	0.19	0.03	2	0	0
	4	5.12	4.09	22.46	8.02	<.0001	N***, NP*	N	0.80	4.39	1.57	10	52	0.36	0.96	0.22	0.02	5	0	0
55	1	29.06	22.60	27.95	28.81	0.3723			0.78	0.96	0.99	11	9	0.21	2.45	0.05	0.92	25	37	9
	2	8.60	9.68	10.11	11.58	0.5415			1.13	1.18	1.35	41	71	0.25	5.86	0.06	1.86	51	66	16
	3	3.41	3.13	3.76	5.59	0.051			0.92	1.10	1.64	57	159	0.38	10.78	0.06	2.60	65	97	16
	4	3.63	3.25	3.12	5.59	0.1002			0.89	0.86	1.54	38	283	0.58	16.12	0.06	2.94	61	108	11
58	1	7.27	7.44	26.86	34.36	<.0001	N***, NP***	N	1.02	3.69	4.72	7	37	0.11	1.97	0.05	0.02	36	1	0
	2	7.36	6.78	12.05	15.08	0.1206			0.92	1.64	2.05	13	49	0.14	1.56	0.04	0.01	27	1	0
	3	8.59	9.02	35.06	26.38	0.5462			1.05	4.08	3.07	34	263	0.18	1.25	0.03	0.02	14	2	0
	4	8.96	9.40	6.84	17.93	0.0002	NP***	NP	1.05	0.76	2.00	33	334	0.23	2.95	0.03	0.02	29	2	0

note: *, **, *** significant at $p < .05$, .01, and .001, respectively. Blank indicates no significant limitation. Inhib refers to treatment inhibition. Treatments are P= Phosphorus, N = Nitrogen, NP = Nitrogen and Phosphorus. All treatments log +1 transformed from μg/cm2. P:C, N:C, NP:C all represent nutrient treatment biomass:Control treatment biomass ratios. TURB = turbidity (NTU), TCHL = Total Chlorophyll a (μg/L) and TP, TN, TRP, DIN are in mg/L.

Appendix E. CCA input data and CANOCO CCA printouts

Table E-1. 2005 CCA Response variables

Site	ns	P	N	NP	Site	ns	P	N	NP
1a	1	0	0	0	35a	0	0	0	1
1b	0	0	0	1	35b	0	0	0	1
1c	0	0	0	1	35c	0	0	1	0
1d	1	0	0	0	35d	0	0	1	0
12a	1	0	0	0	36a	0	0	0	1
12b	1	0	0	0	36b	0	0	0	1
12c	1	0	0	0	36c	0	0	1	0
12d	0	0	0	1	36d	0	0	1	0
16a	0	0	1	0	38a	0	0	1	0
16b	1	0	0	0	38b	0	0	0	1
16c	1	0	0	0	38c	1	0	0	0
16d	1	0	0	0	38d	0	0	0	1
17a	1	0	0	0	41a	0	0	1	0
17b	0	0	0	1	41b	1	0	0	0
17c	0	0	0	1	41c	0	0	1	0
17d	0	0	0	1	41d	0	0	1	0
19a	1	0	0	0	42a	1	0	0	0
19b	0	0	1	0	42b	1	0	0	0
19c	1	0	0	0	42c	1	0	0	0
19d	1	0	0	0	42d	1	0	0	0
20a	1	0	0	0	46a	0	0	1	0
20b	1	0	0	0	46b	0	0	1	0
20c	1	0	0	0	46c	0	0	1	0
20d	0	0	0	1	46d	1	0	0	0
22a	1	0	0	0	47a	1	0	0	0
22b	1	0	0	0	47b	1	0	0	0
22c	0	0	1	0	47c	0	0	1	0
22d	0	0	1	0	47d	1	0	0	0
28a	1	0	0	0	50a	1	0	0	0
28b	1	0	0	0	50b	0	1	0	0
28c	1	0	0	0	50c	0	1	0	0
28d	0	1	0	0	50d	0	0	0	1
30a	1	0	0	0	51a	1	0	0	0
30b	0	0	1	0	51b	1	0	0	0
30c	1	0	0	0	51c	1	0	0	0
30d	0	0	0	1	51d	0	0	0	1
32a	1	0	0	0	52a	1	0	0	0
32b	1	0	0	0	52b	1	0	0	0
32c	1	0	0	0	52c	1	0	0	0
32d	0	0	1	0	52d	1	0	0	0
33a	1	0	0	0	55a	0	0	0	1
33b	1	0	0	0	55b	0	0	1	0
33c	0	0	1	0	55c	0	0	0	1
33d	0	0	1	0	55d	1	0	0	0
34a	1	0	0	0	58a	0	0	1	0
34b	1	0	0	0	58b	0	0	1	0
34c	1	0	0	0	58c	0	0	1	0
34d	0	0	1	0	58d	0	0	1	0

Table E-2. 2005 CCA Predictor variables.

Site	TURB	TP	TN	DIN	Site	TURB	TP	TN	DIN
1a	1.2	1.52	3.80	2.27	35a	1.3	2.21	3.67	2.54
1b	1.1	1.67	3.66	2.19	35b	1.2	2.30	3.58	2.51
1c	1.1	1.63	3.37	2.27	35c	1.1	2.19	3.46	2.19
1d	1.1	1.71	3.63	2.33	35d	1.2	2.23	3.44	2.44
12a	1.5	3.58	4.20	3.44	36a	1.1	1.70	3.38	2.05
12b	1.6	3.50	4.20	3.47	36b	1.0	2.10	3.49	1.99
12c	1.6	3.54	4.20	3.50	36c	1.1	2.29	3.58	2.08
12d	1.6	3.62	4.20	3.52	36d	1.2	2.32	3.55	2.41
16a	1.0	2.20	3.46	1.99	38a	0.8	1.90	3.81	2.25
16b	0.9	2.47	3.47	1.99	38b	0.9	1.97	3.81	2.18
16c	0.9	2.55	3.29	2.14	38c	1.0	1.95	3.32	2.22
16d	1.1	2.49	3.11	2.27	38d	1.0	1.98	3.43	2.36
17a	1.0	1.79	3.34	2.13	41a	1.0	2.43	3.46	2.23
17b	0.8	1.91	3.51	2.17	41b	1.0	2.65	3.34	2.40
17c	0.9	2.15	3.41	2.23	41c	1.0	2.81	3.27	2.50
17d	0.9	2.14	3.22	2.32	41d	0.9	2.82	3.36	2.46
19a	1.1	2.70	3.46	2.81	42a	1.1	2.77	3.43	2.80
19b	1.1	2.81	3.53	2.52	42b	1.0	2.75	3.21	2.68
19c	1.0	3.02	3.63	2.63	42c	1.3	2.99	3.68	3.16
19d	1.0	3.06	3.58	3.27	42d	1.4	3.05	3.89	3.28
20a	1.0	2.86	3.25	2.50	46a	1.3	2.66	3.70	2.27
20b	1.1	2.89	3.29	2.44	46b	1.2	2.85	3.61	2.22
20c	1.0	2.92	3.43	2.20	46c	1.1	2.88	3.51	2.28
20d	1.1	2.95	3.47	2.42	46d	1.4	2.88	3.67	2.46
22a	1.1	1.80	3.49	2.52	47a	1.0	2.79	3.65	2.19
22b	1.2	2.40	3.47	2.43	47b	0.9	2.73	3.84	2.10
22c	1.1	2.73	3.62	2.05	47c	1.1	2.70	3.77	2.20
22d	1.0	2.93	3.49	2.46	47d	1.1	2.72	3.60	2.33
28a	1.1	3.40	4.15	2.61	50a	1.1	1.49	3.68	3.27
28b	1.1	3.37	4.02	2.76	50b	1.1	1.74	3.55	3.11
28c	1.4	3.40	3.87	3.15	50c	1.1	1.62	3.35	2.81
28d	1.6	3.46	4.00	3.41	50d	1.1	1.59	3.19	2.40
30a	1.0	1.90	3.62	2.14	51a	1.4	2.70	3.85	2.51
30b	1.0	2.34	3.59	2.18	51b	1.4	2.72	3.75	2.47
30c	1.0	2.52	3.42	2.39	51c	1.5	2.69	3.62	2.56
30d	1.1	2.56	3.53	2.18	51d	1.6	2.54	3.72	2.63
32a	1.2	2.44	3.57	2.78	52a	1.6	2.82	3.71	3.20
32b	1.2	2.61	3.44	2.84	52b	1.6	2.85	3.63	3.03
32c	1.2	2.62	3.41	2.41	52c	1.1	3.04	3.47	2.34
32d	1.2	2.67	3.44	2.39	52d	1.1	3.08	3.53	2.79
33a	1.0	2.44	3.67	2.09	55a	1.1	2.33	3.77	2.50
33b	0.8	2.62	3.89	2.09	55b	1.1	2.74	3.59	2.40
33c	1.1	2.65	3.79	2.23	55c	1.2	2.88	3.42	2.42
33d	1.2	2.55	3.51	2.32	55d	1.2	2.70	3.77	2.94
34a	1.4	2.11	3.49	1.93	58a	1.6	2.82	3.65	2.80
34b	1.4	2.29	3.61	1.90	58b	1.6	2.63	3.46	2.73
34c	1.3	2.38	3.51	2.02	58c	1.0	2.41	3.04	2.26
34d	1.4	2.49	3.47	2.25	58d	1.1	2.25	3.34	2.39

Note: Shaded values were reduced because they were extreme outliers

Table E-3. CANOCO printout of 2005 CCA of NDS response.

```
*** Type of analysis ***
 Model           Gradient analysis
           indirect    direct    hybrid
linear        1=PCA      2 = RDA      3
unimodal   4 = CA      5 = CCA      6
  ,,        7 = DCA      8 =DCCA      9
           10 = non-standard analysis
Type analysis number
Answer = 5

*** Data files ***
Species data      : H:\Flash Drive\NDS MVA\NDS 2005\2005 NDS RESPONSE
Covariable data   :
Environmental data : H:\Flash Drive\NDS MVA\NDS 2005\2005 NDS PREDICTOR no TRP
Initialization file:

Forward selection of envi. variables = 0
Scaling of ordination scores = 2
Diagnostics = 3

File   : H:\Flash Drive\NDS MVA\NDS 2005\2005 NDS RESPONSE
Title  : 2005 NDS RESPONSE
Format :  (I5,1X,4F3.0)
No. of couplets of species number and abundance per line :    0

No samples omitted
Number of samples          96
Number of species           4
Number of occurrences       96

File  : H:\Flash Drive\NDS MVA\NDS 2005\2005 NDS PREDICTOR no TRP
Title : 2005 NDS PREDICTOR no TRP
Format :  (I5,1X,4F6.2)
No. of environmental variables :     4
No interaction terms defined
No transformation of species data
No species-weights specified
No  sample-weights specified
No downweighting of rare species
No. of active  samples:     96
No. of passive samples:      0
No. of active  species:      4
Total inertia in species data =
Sum of all eigenvalues of CA =    3.00000

****** Check on influence in covariable/environment data ******
The following sample(s) have extreme values
Sample Environmental       Covariable  + Environment space
      variable Influence   influence     influence

    77                              4.0x
****** End of check ******
```

**** Weighted correlation matrix (weight = sample total) ****

SPEC AX1	1.0000							
SPEC AX2	0.0000	1.0000						
SPEC AX3	0.0000	0.0000	1.0000					
SPEC AX4	0.0000	0.0000	-0.9943	1.0000				
ENVI AX1	0.4816	0.0000	0.0000	0.0000	1.0000			
ENVI AX2	0.0000	0.3247	0.0000	0.0000	0.0000	1.0000		
ENVI AX3	0.0000	0.0000	0.1068	0.0000	0.0000	0.0000	1.0000	
ENVI AX4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TURB	0.0988	0.1200	-0.0226	0.0000	0.2051	0.3697	-0.2119	0.0000
TP	-0.1174	0.3112	0.0076	0.0000	-0.2439	0.9584	0.0707	0.0000
TN	0.1046	0.1339	0.0795	0.0000	0.2172	0.4123	0.7440	0.0000
DIN	0.3382	0.2229	-0.0060	0.0000	0.7022	0.6866	-0.0558	0.0000
	SPECAX1	SPECAX2	SPECAX3	SPECAX4	ENVIAX1	ENVIAX2	ENVIAX3	ENVIAX4

TURB	1.0000			
TP	0.4042	1.0000		
TN	0.4612	0.4572	1.0000	
DIN	0.5682	0.5063	0.4802	1.0000
	TURB	TP	TN	DIN

N	name	(weighted) mean	stand. dev.	inflation factor
1	SPEC AX1	0.0000	2.0764	
2	SPEC AX2	0.0000	3.0802	
3	SPEC AX3	0.0000	9.3621	
4	SPEC AX4	0.0000	1.0000	
5	ENVI AX1	0.0000	1.0000	
6	ENVI AX2	0.0000	1.0000	
7	ENVI AX3	0.0000	1.0000	
8	ENVI AX4	0.0000	0.0000	
1	TURB	1.1573	0.2045	1.5999
2	TP	2.5377	0.4927	1.4759
3	TN	3.5769	0.2343	1.4894
4	DIN	2.4884	0.3910	1.7792

**** Summary ****

Axes	1	2	3	4	Total inertia
Eigenvalues :	0.232	0.105	0.011	0.989	3.000
Species-environment correlations :	0.482	0.325	0.107	0.000	
Cumulative percentage variance					
of species data :	7.7	11.2	11.6	44.6	
of species-environment relation:	66.5	96.7	100.0	0.0	
Sum of all eigenvalues					3.000
Sum of all canonical eigenvalues					0.349

*** Unrestricted permutation ***
Seeds: 23239 945

**** Summary of Monte Carlo test ****
Test of significance of first canonical axis: eigenvalue = 0.232
F-ratio = 7.625
P-value = 0.0040
Test of significance of all canonical axes: Trace = 0.349
F-ratio = 2.992
P-value = 0.0020
(499 permutations under reduced model)

Table E-4. 2006 CCA Response variables.

Site	ns	P	N	NP	Site	ns	P	N	NP
1a	0	0	0	1	35a	0	0	1	0
1b	0	0	0	1	35b	0	0	0	1
1c	0	0	0	1	35c	0	0	0	1
1d	0	0	0	1	35d	0	0	0	1
12a	1	0	0	0	36a	0	0	0	1
12b	1	0	0	0	36b	0	0	0	1
12c	1	0	0	0	36c	0	0	0	1
12d	1	0	0	0	36d	1	0	0	0
16a	0	0	0	1	38a	0	0	1	0
16b	0	0	0	1	38b	0	0	0	1
16c	0	0	0	1	38c	0	0	0	1
16d	0	1	0	0	38d	0	0	0	1
17a	0	0	0	1	41a	0	0	1	0
17b	0	0	0	1	41b	0	0	1	0
17c	0	0	0	1	41c	1	0	0	0
17d	0	0	0	1	41d	1	0	0	0
19a	0	0	1	0	42a	1	0	0	0
19b	0	0	1	0	42b	0	0	1	0
19c	0	0	1	0	42c	1	0	0	0
19d	1	0	0	0	42d	1	0	0	0
20a	0	0	1	0	46a	1	0	0	0
20b	0	0	0	1	46b	0	0	1	0
20c	0	0	0	1	46c	1	0	0	0
20d	0	0	0	1	46d	1	0	0	0
22a	0	0	1	0	47a	0	0	1	0
22b	0	0	1	0	47b	0	0	1	0
22c	0	0	1	0	47c	0	0	0	1
22d	1	0	0	0	47d	0	0	1	0
28a	1	0	0	0	50a	0	1	0	0
28b	0	0	1	0	50b	0	0	0	1
28c	0	0	1	0	50c	0	0	0	1
28d	0	0	1	0	50d	0	0	0	1
30a	0	0	0	1	51a	1	0	0	0
30b	0	0	0	1	51b	1	0	0	0
30c	0	1	0	0	51c	1	0	0	0
30d	0	0	0	1	51d	1	0	0	0
32a	0	0	1	0	52a	0	0	1	0
32b	1	0	0	0	52b	1	0	0	0
32c	1	0	0	0	52c	1	0	0	0
32d	0	0	0	1	52d	0	0	1	0
33a	0	0	1	0	55a	1	0	0	0
33b	0	0	1	0	55b	1	0	0	0
33c	0	0	1	0	55c	1	0	0	0
33d	1	0	0	0	55d	1	0	0	0
34a	0	0	1	0	58a	0	0	1	0
34b	0	0	1	0	58b	1	0	0	0
34c	0	0	1	0	58c	1	0	0	0
34d	1	0	0	0	58d	0	0	0	1

Table E-5. 2006 CCA Predictor variables.

Site	TURB	TP	TN	DIN
1a	0.7	1.56	3.37	1.00
1b	0.5	1.40	3.41	1.00
1c	0.4	1.24	3.40	1.00
1d	0.5	1.33	3.18	1.00
12a	1.9	3.60	4.42	3.49
12b	2.0	3.63	4.42	3.45
12c	2.2	3.64	4.39	3.15
12d	2.2	3.62	4.32	2.65
16a	0.3	1.96	2.56	1.06
16b	0.5	2.07	2.79	1.06
16c	1.0	2.05	2.69	1.03
16d	1.0	2.10	2.98	1.03
17a	0.2	1.89	3.51	1.36
17b	0.5	1.95	3.14	1.06
17c	0.7	1.89	2.69	1.06
17d	0.6	1.93	3.12	1.06
19a	1.2	2.95	3.41	1.03
19b	1.3	2.89	3.48	1.06
19c	1.3	2.57	3.57	1.48
19d	1.4	2.46	3.81	2.72
20a	0.5	2.16	3.59	1.03
20b	1.3	2.17	3.54	1.23
20c	1.5	2.07	3.32	1.50
20d	1.3	3.12	3.50	1.39
22a	0.2	2.76	3.21	1.00
22b	0.0	2.77	3.06	1.00
22c	0.1	2.69	3.04	1.00
22d	0.5	2.72	3.21	1.00
28a	1.2	3.51	4.04	2.89
28b	1.3	3.52	4.03	2.16
28c	1.6	3.43	3.89	2.05
28d	1.7	3.34	4.18	2.09
30a	0.9	2.04	3.86	1.08
30b	0.6	2.09	3.79	1.08
30c	1.2	2.07	3.23	1.41
30d	1.5	2.24	3.17	1.49
32a	1.0	1.94	3.24	1.00
32b	1.0	2.25	3.30	1.00
32c	1.2	2.48	3.19	1.22
32d	1.6	2.51	3.62	1.59
33a	0.7	2.28	3.11	2.09
33b	0.5	2.26	3.20	2.09
33c	1.3	2.20	3.45	1.00
33d	1.4	2.27	3.72	1.00
34a	0.9	2.08	3.24	1.00
34b	0.5	2.06	3.28	1.00
34c	1.1	2.03	2.56	1.00
34d	1.1	2.11	3.07	1.00
35a	0.6	1.85	3.31	1.64
35b	0.6	1.93	3.32	1.60
35c	0.6	2.04	3.16	1.79
35d	0.5	2.01	3.21	2.25
36a	0.3	2.02	3.78	1.48
36b	0.4	2.04	3.82	1.53
36c	0.4	2.15	3.35	1.44
36d	0.5	2.21	3.40	1.56
38a	0.6	1.75	3.27	1.43
38b	1.3	2.17	3.33	1.46
38c	1.7	2.39	3.39	1.72
38d	1.6	2.36	3.50	1.69
41a	0.7	2.86	3.32	1.06
41b	0.9	2.98	3.21	1.06
41c	1.4	3.06	3.68	1.84
41d	1.3	2.93	3.81	1.83
42a	0.8	2.76	3.53	3.10
42b	1.7	2.94	3.88	3.33
42c	1.9	3.19	4.17	3.48
42d	1.7	3.36	4.29	3.62
46a	1.4	2.45	3.21	2.50
46b	1.5	2.64	3.42	2.44
46c	1.7	2.63	3.68	1.59
46d	1.7	2.49	3.69	1.59
47a	0.6	2.53	3.44	1.06
47b	1.2	2.59	3.38	1.00
47c	1.2	2.45	3.36	1.03
47d	0.9	2.44	3.49	1.03
50a	0.3	1.53	3.34	2.96
50b	0.2	1.83	3.07	2.19
50c	0.3	1.69	2.43	1.52
50d	0.4	1.30	2.98	1.03
51a	1.7	2.73	3.87	3.40
51b	1.8	2.91	3.99	3.28
51c	1.7	2.99	4.10	3.14
51d	1.8	3.15	4.30	3.21
52a	0.7	2.94	3.30	2.75
52b	1.3	2.82	3.17	1.84
52c	1.3	2.58	2.69	1.40
52d	1.0	2.55	2.98	1.20
55a	1.1	2.31	3.39	2.96
55b	1.6	2.40	3.77	3.27
55c	1.8	2.58	4.03	3.41
55d	1.6	2.77	4.21	3.47
58a	0.9	2.06	3.30	1.20
58b	1.1	2.15	3.19	1.13
58c	1.5	2.26	3.10	1.30
58d	1.5	2.35	3.47	1.33

Table E-6. CANOCO printout of 2006 CCA of NDS response.

```
*** Type of analysis ***
 Model          Gradient analysis
           indirect    direct    hybrid
linear       1=PCA      2= RDA      3
unimodal   4= CA      5= CCA      6
   ,,          7=DCA      8=DCCA      9
             10=non-standard analysis
Type analysis number
Answer =  5

*** Data files ***
Species data      : H:\Flash Drive\NDS MVA\NDS 2006\2006 NDS RESPONSE
Covariable data   :
Environmental data : H:\Flash Drive\NDS MVA\NDS 2005\2006 NDS PREDICTOR no TRP
Initialization file:
Forward selection of envi. variables =    0
Scaling of ordination scores        =    2
Diagnostics                         =    3
File   : H:\Flash Drive\NDS MVA\NDS 2006\2006 NDS RESPONSE
Title  : 2006 NDS RESPONSE
Format :  (I5,1X,4F3.0)
No. of couplets of species number and abundance per line :    0
No samples omitted
Number of samples          96
Number of species           4
Number of occurrences       96
File  : H:\Flash Drive\NDS MVA\NDS 2005\2006 NDS PREDICTOR no TRP
Title : 2006 NDS PREDICTOR no TRP
Format :  (I5,1X,4F6.2)
No. of environmental variables :     4
No interaction terms defined
No transformation of species data
No species-weights specified
No  sample-weights specified
No downweighting of rare species
No. of active  samples:     96
No. of passive samples:      0
No. of active  species:      4
Total inertia in species data=
Sum of all eigenvalues of CA =    3.00000
```

**** Weighted correlation matrix (weight = sample total) ****

SPEC AX1	1.0000							
SPEC AX2	0.0000	1.0000						
SPEC AX3	0.0000	0.0000	1.0000					
SPEC AX4	0.0000	0.0000	0.9916	1.0000				
ENVI AX1	0.6470	0.0000	0.0000	0.0000	1.0000			
ENVI AX2	0.0000	0.4851	0.0000	0.0000	0.0000	1.0000		
ENVI AX3	0.0000	0.0000	0.1294	0.0000	0.0000	0.0000	1.0000	
ENVI AX4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TURB	0.5302	-0.1250	-0.0430	0.0000	0.8195	-0.2576	-0.3324	0.0000
TP	0.5782	0.2101	-0.0143	0.0000	0.8938	0.4331	-0.1103	0.0000
TN	0.4458	-0.0645	-0.0738	0.0000	0.6891	-0.1329	-0.5704	0.0000
DIN	0.5244	-0.1916	0.0257	0.0000	0.8106	-0.3949	0.1983	0.0000
	SPECAX1	SPECAX2	SPECAX3	SPECAX4	ENVIAX1	ENVIAX2	ENVIAX3	ENVIAX4

TURB	1.0000			
TP	0.6426	1.0000		
TN	0.6224	0.6376	1.0000	
DIN	0.5505	0.5462	0.6619	1.0000
	TURB	TP	TN	DIN

N	name	(weighted) mean	stand. dev.	inflation factor
1	SPEC AX1	0.0000	1.5456	
2	SPEC AX2	0.0000	2.0614	
3	SPEC AX3	0.0000	7.7268	
4	SPEC AX4	0.0000	1.0000	
5	ENVI AX1	0.0000	1.0000	
6	ENVI AX2	0.0000	1.0000	
7	ENVI AX3	0.0000	1.0000	
8	ENVI AX4	0.0000	0.0000	
1	TURB	1.0563	0.5323	2.0133
2	TP	2.4273	0.5491	2.0576
3	TN	3.4496	0.4260	2.3556
4	DIN	1.7425	0.8326	1.9192

**** Summary ****

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.419	0.235	0.017	0.983	3.000
Species-environment correlations :	0.647	0.485	0.129	0.000	
Cumulative percentage variance					
of species data:	14.0	21.8	22.4	55.1	
of species-environment relation:	62.4	97.5	100.0	0.0	
Sum of all eigenvalues					3.000
Sum of all canonical eigenvalues					0.671

*** Unrestricted permutation ***
Seeds: 23239 945

**** Summary of Monte Carlo test ****
Test of significance of first canonical axis: eigenvalue = 0.419
F-ratio = 14.756
P-value = 0.0020
Test of significance of all canonical axes : Trace = 0.671
F-ratio = 6.550
P-value = 0.0020
(499 permutations under reduced model)

Appendix F. Crescent Lake Report

Crescent Lake
Water Quality Report
2006

Scott Kolochuk
University of Manitoba
Feb 2007

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Objective:

To characterize the water quality in Crescent Lake, MB in 2006 and compare it to other small shallow water bodies in the nearby region.

Introduction:

This study was accomplished through collaboration with Dave Huck, manager of the La Salle-Redboine Conservation District and in conjunction with my Master's thesis research on farm ponds. I am including the results of this report in my appendix to help preserve unique, regional water quality data of southern Manitoba.

Crescent Lake is an important body of water that provides natural beauty, recreational enjoyment and economic enhancement to the surrounding city of Portage la Prairie, MB. In the distant past Crescent Lake was a segment of the Assiniboine River that was separated by natural processes of sedimentation and erosion. In more recent time Crescent Lake was a wetland where water levels ascended in early spring from surrounding snow melt and descended gradually over the summer and fall from evaporation and ground seepage. Presently the water levels in Crescent Lake are kept at a higher and more consistent level by pumping in water from the nearby Assiniboine River.

Water is abundant in many areas of Manitoba and is relied upon heavily for industrial, agricultural and recreational use. Much of Manitoba is subject to large pulses of water in the spring and then dry conditions throughout the summer and early fall. This cyclical, and somewhat unpredictable nature of Manitoba's water supply together with human and biological dependence make it an invaluable resource to protect.

Presently, the greatest water quality concern in Crescent Lake and much of southern Manitoba is an elevated level of nutrients in the water caused by agricultural runoff and sewage release. This increase of nutrients in the water is commonly referred to as eutrophication. Although essential for biological life, only a small addition of these nutrients can completely alter the biological conditions and cause the extinction of native plant and animal species.

Increased nutrient levels causes a proliferation of plant life including algae and aquatic macrophytes. Algae are simple plants that usually float in the water column or attach themselves to various surfaces under the water. Macrophytes refer to the more complex plants that are normally rooted and can be completely submerged (e.g., bladderwort), floating (e.g., duck weed) or emerging out from the water (e.g., cattails). Algae are particularly influenced by nutrient levels in the water because of their complete reliance on them for growth. Macrophytes, on the other hand, can often acquire much of their nutrients from their roots embedded in the sediment. An overall increase in plant life and diversity can significantly change the habitat physically and chemically.

Physically, the increased macrophyte cover may give some organisms food and protection while others have a harder time tracking down their prey. An accumulation of algae affects the level of light penetration and not only affects feeding habits of some organisms, but simultaneously inhibits submerged macrophytes from receiving sufficient sunlight.

Chemically, plants produce an abundance of oxygen in the water via photosynthesis but also deplete carbon dioxide, a valuable buffer against pH fluctuation, in the process. Dramatic changes in pH can alter numerous chemical reactions that in turn affect aquatic life. Significant decreases in oxygen occur when a large quantity of plant life dies off and microbial organisms use up oxygen to decompose them. Most aquatic organisms rely heavily on oxygen to survive and this fluctuation in oxygen can be difficult to tolerate. An additional concern is that specific algae which thrive in high nutrient conditions are known to release harmful toxins that affect the liver and nervous system as well as cause noxious odor and taste.

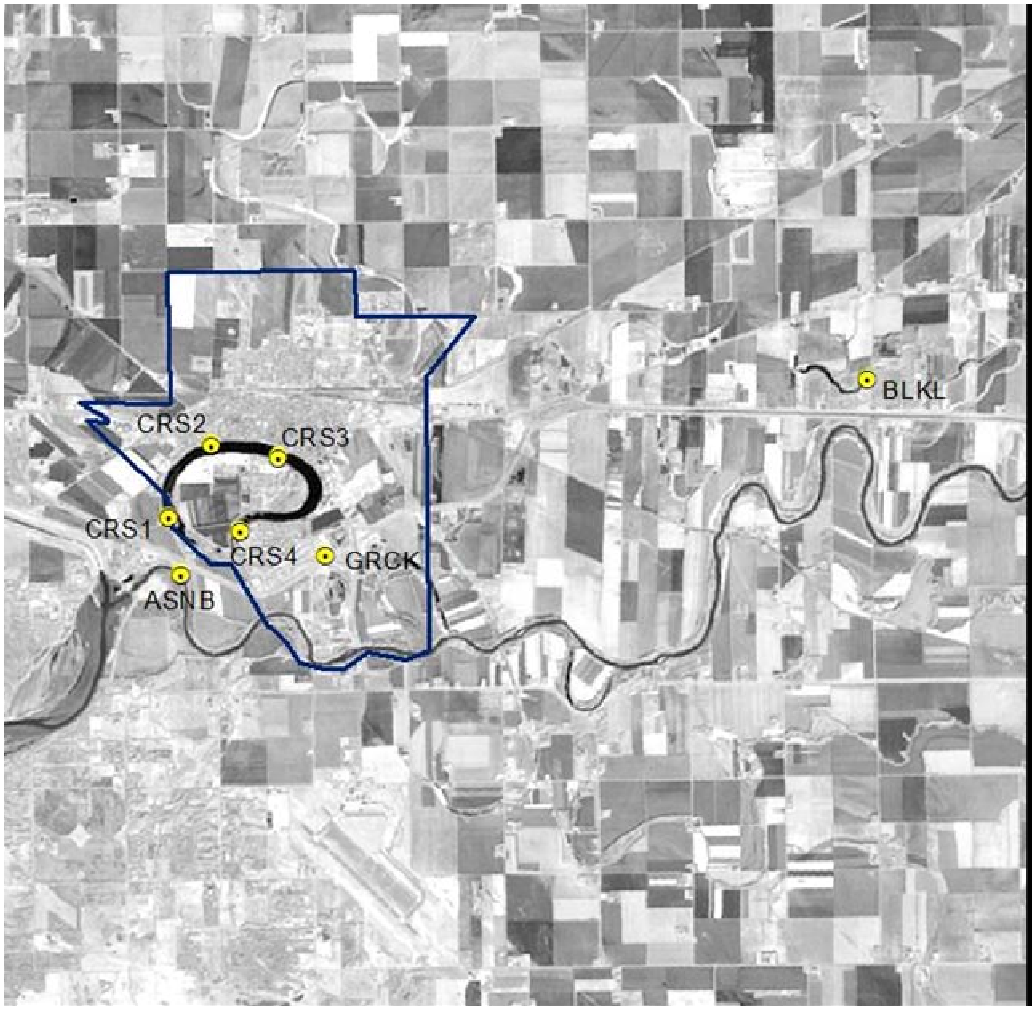
Biologists have developed a system to classify water bodies by trophic status which refers to the total amount of living biological material in a water body at a specific time and location (Carlson et al, 1996). This status is affected considerably by the amount of nutrients available in the water. Three common parameters used to estimate trophic status are Secchi depth and concentrations of total phosphorus and chlorophyll *a*. The trophic states are oligotrophic (i.e., low productivity), mesotrophic (i.e., moderate productivity), eutrophic (i.e., high productivity) and hypereutrophic (i.e., very high productivity).

Methods:

Water samples were taken on Crescent Lake at four staggered locations once during the winter and six times between early May and late August 2006. Additional samples were taken at the pumping station on Assiniboine River, the output stream of Garrioch's Creek and at Black Lake (used as a comparison/control). All samples were tested for nutrients, ions, water clarity, algal production (i.e., chlorophyll *a*), pH, alkalinity, conductivity and other common water quality parameters. As well, the sediment was characterized at each site and three rounds of bacterial sampling were accomplished throughout the spring and summer field season.

The study of Crescent Lake occurred simultaneously with another study of 59 farm ponds within the same geographical region of south-central Manitoba. The results of Crescent Lake are therefore comparative to this farm pond study for further indication of overall water quality in the region.

Study Area



Site Key:
ASNB - Assiniboine River (Crescent Lake input)
CRS1-4 - Crescent Lake sites 1-4
GRCK – Garrioch's Creek (Crescent Lake output)
BLKL – Black Lake (Control)

Figure 3: Crescent Lake water quality study area including the sample sites.

Table 7. Location and characterization of Crescent Lake sampling sites.

Site code	Site name	UTM E	UTM N	Latitude (deg/min'/sec")	Longitude (deg/min'/sec")	Characterization
ASNB	Assiniboine Input	549007	5533217	N 49º56'57.5"	W 098º19'0.8"	▪ Pumping station to Crescent Lake
CRS1	Crescent 1	548795	5534238	N 49º57'30.6"	W 098º19'11.0"	▪ Near the input from Assiniboine River ▪ Sparse residential development ▪ Natural riparian surrounding ▪ Dense submerged macrophytes throughout
CRS2	Crescent 2	549520	5535539	N 49º58'12.5"	W 098º18'34.0"	▪ Across from Golf Course ▪ Near storm water input pipe ▪ Near footpath and major residential development ▪ Dense submerged macrophytes in spring but more algae dominated as summer progresses.
CRS3	Crescent 3	550706	5535281	N 49º58'03.8"	W 098º17'34.6"	▪ Near the Crescent Lake bridge and boat launch ▪ Algae dominated
CRS4	Crescent 4	550027	5533974	N 49º57'21.7"	W 098º18'9.3"	▪ East end of Crescent Lake near output into Garrioch Creek ▪ Near large residential development, across from irrigation pumps ▪ Algae dominated.
GRCK	Garrioch Creek	551551	5533566	N 49º57'8.0"	W 098º16'53.0"	▪ Output from Crescent Lake ▪ Before Garrioch Creek travels under the #1 highway ▪ After it has gone through the last of the Portage residential area ▪ 3 m riparian area lines bank
BLKL	Blacks Lake	561028	5536643	N 49º58'44.4"	W 098º8'55.7"	▪ Chosen comparative body of water (control) ▪ Amongst agricultural land ▪ Large trees on either side ▪ Duckweed covers water throughout the summer
CRS	Crescent Lake					▪ Represents an average of all four sites (CRS1, CRS2, CRS3 and CRS4) on Crescent Lake.

Results and Discussion:

Unless specified, the average calculated values below relate to the spring and summer sampling time and do not include the winter values.

General Water Chemistry

5.1.1 Water Temperature

Temperature is a major driver in many biological and chemical activities and is important to monitor for the health of aquatic ecosystems. Crescent Lake is naturally subject to extremes in temperature common to southern Manitoba; even so, changes in timing and duration of temperature extremes can have lasting repercussions.

Little fluctuation is evident in water temperature in Crescent Lake from top to bottom due to its shallow depth. Therefore, the surface temperature of Crescent Lake is an accurate reflection of the temperature near the bottom. In deeper water bodies (i.e., >2 m) temperature differences can act as a barrier that prevents the ready flow of chemicals and organisms from one layer to the next. See Appendix Table 2 for more detail.

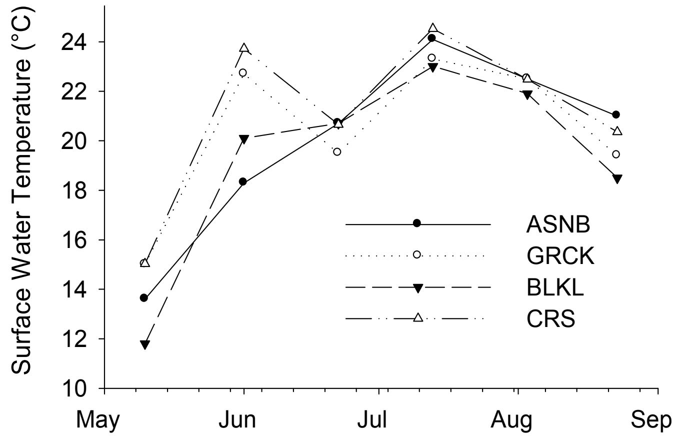


Figure 4. Surface water temperatures in ASNB, CRS, GRCK and BLKL over the spring and summer field season.

5.1.2 Alkalinity

Alkalinity refers to the concentration of dissolved chemicals (solutes) in water able to neutralize acids without the pH being changed. In other words, alkalinity measures the buffering capacity of the water. In natural environments the most common buffering solutes are bicarbonate and carbonate (Wetzel, 2001).

The mean alkalinity of Crescent Lake was 171 mg/L which appears consistent with regional values of Assiniboine River at 241 mg/L and Blacks Lake at 229 mg/L. The farm ponds had an average alkalinity of 274 mg/L and a range of 28 to 784 mg/L.

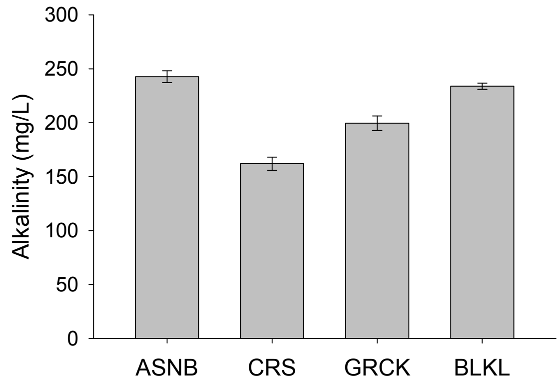


Figure 5. Average alkalinity in ASNB, CRS, GRCK and BLKL over the spring and summer field season (± 1 SE).

5.1.3 pH

The measure of pH is the number of hydrogen ions (H^+) found in solution and is very important in driving chemical reactions. Water with a pH of < 7 is considered acidic and has an excess of H^+ while water with a pH of > 7 is considered basic (has more chemicals able to accept H^+ than the concentration of H^+ itself). The suggested pH range for aquatic life is between 6.5 and 9.0 (Manitoba Conservation, 2002)

An example of the importance of pH is the chemical reactions involved with the waste product of ammonium (NH_4^+) that is given off by most aquatic organisms. The NH_4^+ is itself not a very toxic substance, but in an environment of pH > 7 (basic) the extra H^+ on NH_4^+ is quickly taken by a H^+ accepting basic chemical (i.e., OH^-, HCO_3^-) to transform NH_4^+ to ammonia (NH_3) which is highly toxic to aquatic organisms.

The pH in Crescent Lake was quite high overall with an average of 9.1, exceeding the water quality guideline. This consistent high pH value was probably a result of the abundant vegetation growth within the water body. Vegetation uses up carbon dioxide (CO_2) during photosynthesis faster than it can be replenished from the atmosphere which causes the pH to shift to a higher, more basic level (CO_2 accepts OH^- ions which then prevents those OH^- ions from accepting H^+ ions). Assiniboine River and Black Lake had average pH values of 8.2 and 8.9, respectively. The farm ponds had a mean pH of 7.9 and a range of 6.9 to 10.

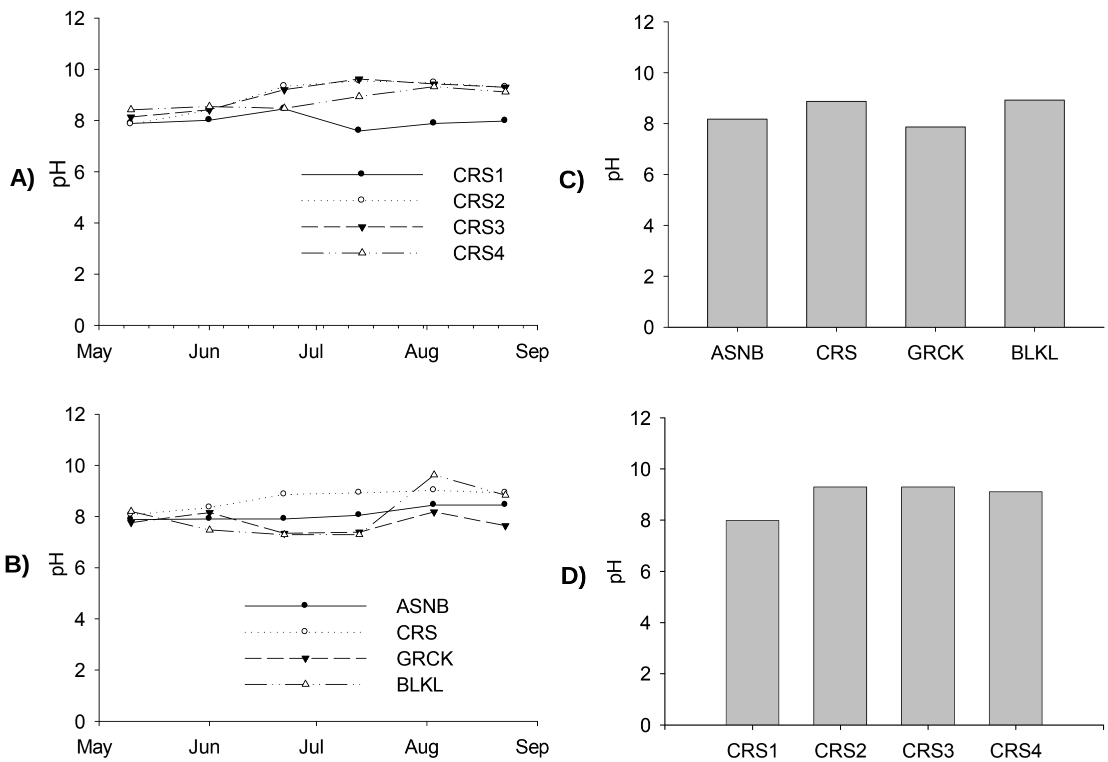


Figure 6. The pH in each sample round for A) ASNB, CRS, GRCK and BLKL and B) CRS1, CRS2, CRS3 and CRS4. Average pH of the spring and summer field season for C) ASNB, CRS, GRCK and BLKL and D) CRS1, CRS2, CRS3 and CRS4.

5.1.4 Dissolved Oxygen

Oxygen naturally dissolves in water from the atmosphere but is available in water at a much lower concentration. The capacity of water to hold oxygen is influenced by temperature and increases as temperatures decrease. Oxygen supplies can be elevated by plants throughout the day as they convert carbon dioxide to oxygen during photosynthesis. Dissolved oxygen (DO) is vital for aquatic organisms to use in the process of respiration. Organisms of larger size and activity tend to have a higher oxygen demand and are more sensitive to oxygen depletion. Rapid decreases in oxygen due to plant decomposition often leads to fish kills, especially in winter when the ice over the water prevents oxygen from being replenished. Indeed, winter oxygen levels of < 1.0 mg/L in Crescent Lake indicate that most fish species would not survive over the winter. The Manitoba standard for oxygen levels for cool water organisms depends on the life stage of the organism but is generally > 5.5 mg/L (MB Conservation 2002).

Percentage of DO represents the amount of oxygen available in the water in comparison with the carrying capacity of the water. If the percent of DO is 20% it shows that the water is able to hold at least 80% more oxygen but that other factors are affecting the concentration such as biological activity or gradients within the water body that prevent the flow of gases (i.e., temperature gradients).

The average surface water DO concentration for Crescent Lake and Assiniboine River was normal at 8.3 and 9.1 mg/L, respectively. Garrioch's Creek had an average value of 2.5 mg/L which is low and suggests there may be high biological oxygen demand (BOD) which is a measure of the amount of oxygen necessary for microorganisms to consume as they break down organic matter in the water. The source of the BOD was perhaps from sewage input from the nearby residential area. Black Lake had an average dissolved oxygen level of 1.3 mg/L which is also very low but probably due entirely to the duckweed covering the surface of the water. The farm ponds had an average surface DO concentration of 7.4 mg/L and a range of 0.1 to > 20.0 mg/L. To view corresponding percent DO values see the Appendix, Table 2.

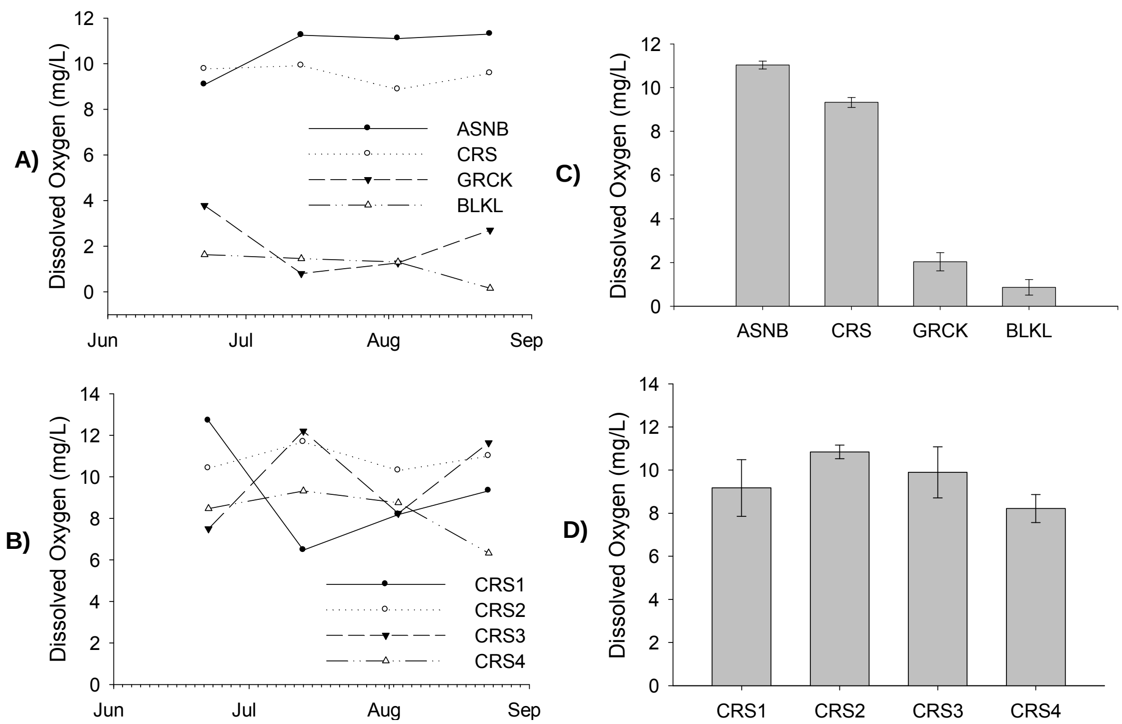


Figure 7. Surface water DO in each sample round for A) ASNB, CRS, GRCK and BLKL and B) CRS1, CRS2, CRS3 and CRS4. Average surface water DO of the spring and summer field season (± 1 SE) for C) ASNB, CRS, GRCK and BLKL and D) CRS1, CRS2, CRS3 and CRS4.

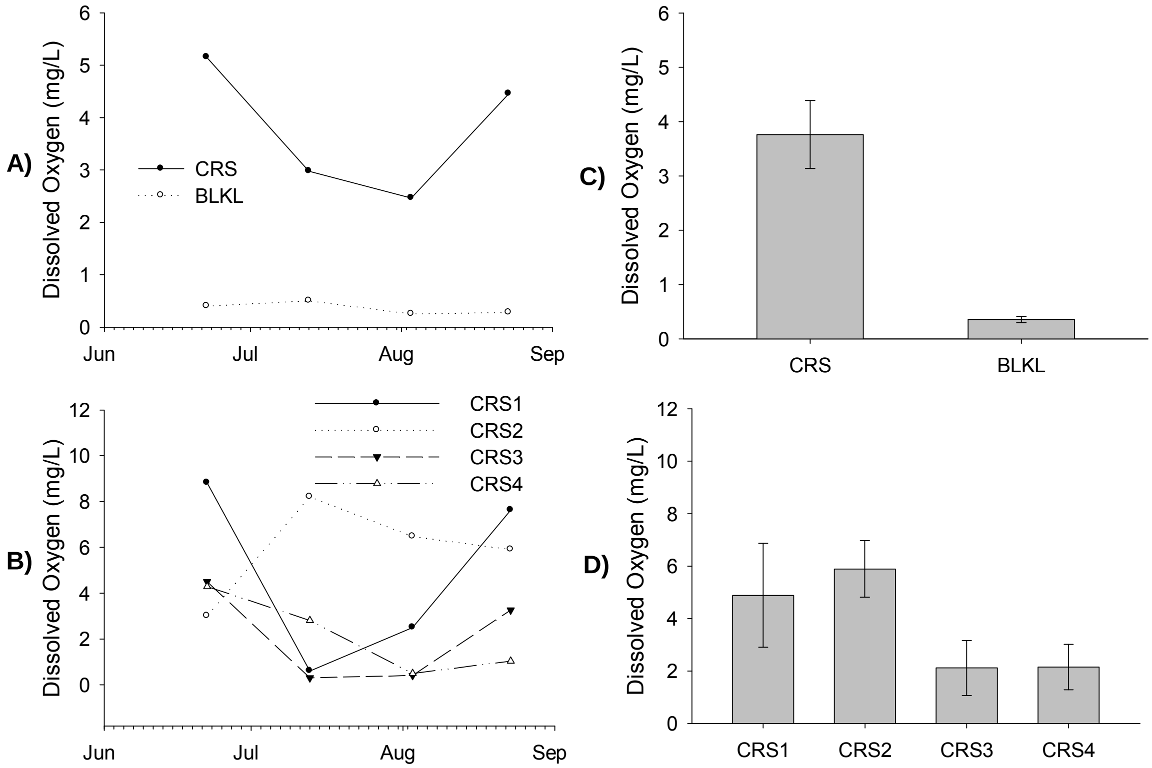


Figure 8. Bottom water DO in each sample round for A) CRS and BLKL and B) CRS1, CRS2, CRS3 and CRS4. Average bottom water DO of the spring and summer field season (± 1 SE) for C) CRS and BLKL and D) CRS1, CRS2, CRS3 and CRS4.

5.1.5 Depth

The depth at the sites we sampled was consistently around 1 m and no more than 2 m. No extensive transects of depth throughout Crescent Lake were carried out. Blacks Lake was on average 2 m at the sample location. The average maximum depth for farm ponds was 2.2 m and the overall range of maximum depth measurements was from 0.1 to 4.9 m.

Water Clarity

5.1.6 Secchi Depth

Secchi depth is the measure of how far down a Secchi disk can go in the water column before it disappears from sight when looking from above. A Secchi disk is a 20 cm disk with four quadrants alternating in black and white coloration. Secchi disk depth is a simple and common water clarity measure used internationally.

The Secchi depth was difficult to average because on many occasions the Secchi disk could be observed on the bottom of Crescent Lake and it was impossible to know what the actual limit of the Secchi visibility was. This is a common problem when measuring Secchi depth in shallow water bodies and was mostly an issue at the first site (CRS1) where the water clarity was the highest. Sites 2, 3 and 4 were much easier to measure because they had considerably less Secchi depth especially as the summer progressed and algae populations increased. Black Lake was especially complicated for Secchi depth because there was a layer of duckweed covering the water. The Secchi values from Black Lake were taken after pushing aside the duckweed and should not be used in deciding upon trophic status. As a whole, Secchi depth followed the same pattern as turbidity and total suspended solids showing decreasing clarity from CRS1 to CRS4 on Crescent Lake. The trophic status, according to Secchi depth was eutrophic to hypereutrophic. See Appendix, Table 2 for more details.

5.1.7 Turbidity

Turbidity measures the amount of light that passes through a water sample and higher turbidity values indicate more particles (e.g., soil, algae, etc.) in the water for bacteria to grow on. At the present the suggested drinking water limit is 1 NTU for consumption and less than or equal to 5 NTU for aesthetic purposes (MB Conservation, 2002). It is difficult to assess turbidity without knowing the natural pre-settlement conditions (MB Conservation, 2002).

Average turbidity levels in Crescent Lake, Assiniboine River and Black Lake were 11, 37 and 4 NTU, respectively. The turbidity in the farm ponds was on average 26 NTU and ranged from 1 to 487 NTU. The highest turbidity levels were in the Assiniboine River which was due to suspended soil particles such as silt and clay. Crescent Lake's turbidity levels consistently increased from CRS1 to CRS4 due to increased algal production. Black Lake had a low turbidity because it was covered in duck weed which inhibited any substantial algal growth.

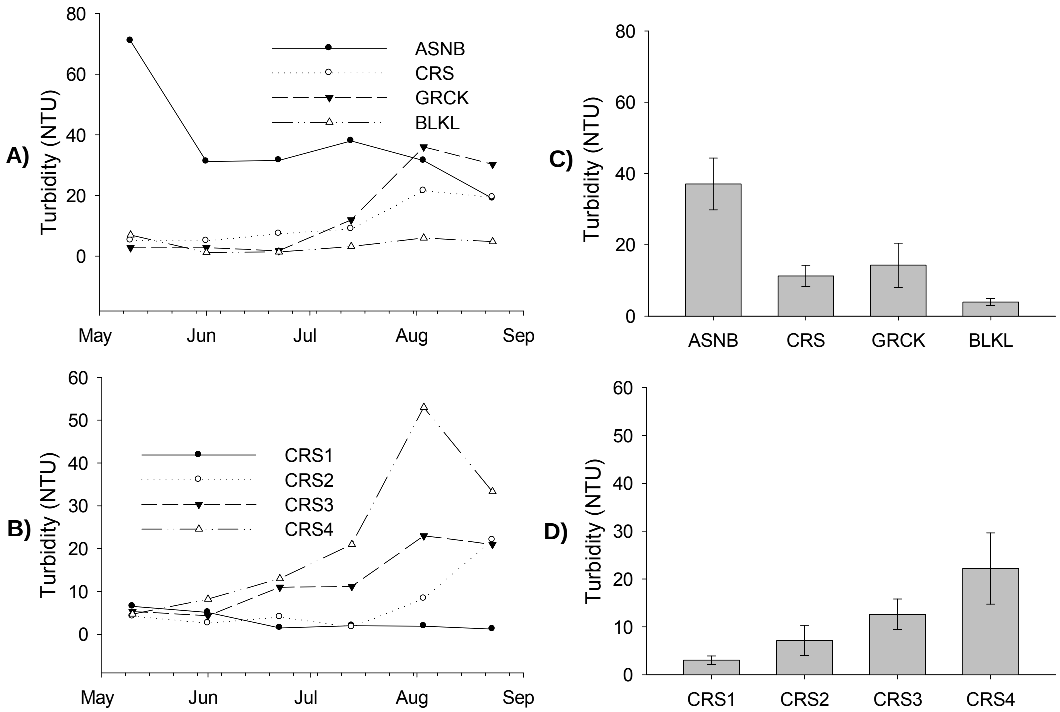


Figure 9. Turbidity in each sample round for A) ASNB, CRS, GRCK and BLKL and B) CRS1, CRS2, CRS3 and CRS4. Average turbidity of the spring and summer field season (± 1 SE) for C) ASNB, CRS, GRCK and BLKL and D) CRS1, CRS2, CRS3 and CRS4.

5.1.8 Total Suspended Solids

Total Suspended Solids (TSS) is the amount of suspended solids in solutions. Water clarity decreases with increasing suspended solids. The Manitoba suggested maximum is variable depending on the “normal” regional conditions. It is difficult to assess TSS without knowing pre-settlement conditions whereby you can compare the change (Manitoba Conservation, 2002).

The average TSS in Crescent Lake, Assiniboine River and Black Lake was 22, 86 and 11 mg/L, respectively. Assiniboine River is high in TSS because it is a flowing river carrying fine soil particles such as silt and clay. When the water from the Assiniboine pumped into Crescent Lake much of these particles settled out. The main source for suspended solids in Crescent Lake is organic matter such as algae and floating plant debris. Black Lake had a lower level of TSS because it was covered in duck weed and light was unable to penetrate and promote the growth of algae. On average the farm ponds had a TSS of 32 mg/L with a range between 1.0 to 487 mg/L

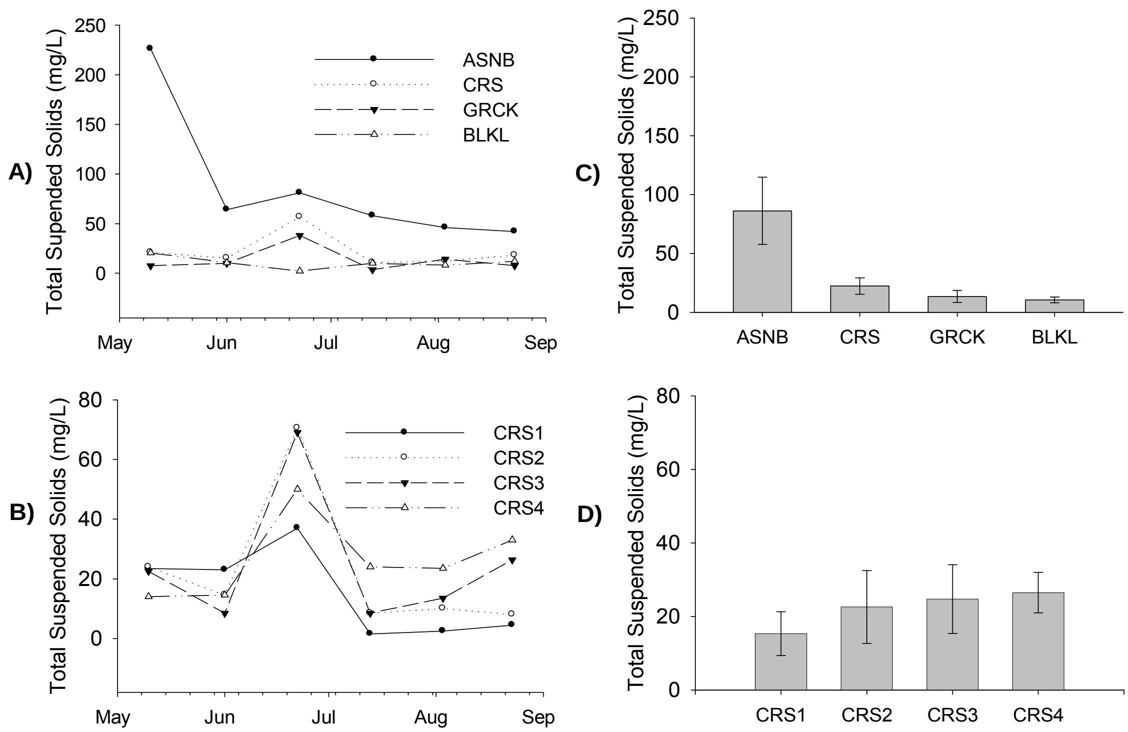


Figure 10. The TSS in each sample round for A) ASNB, CRS, GRCK and BLKL and B) CRS1, CRS2, CRS3 and CRS4. Average TSS of the spring and summer field season (± 1 SE) for C) ASNB, CRS, GRCK and BLKL and D) CRS1, CRS2, CRS3 and CRS4.

Biological Variables

5.1.9 Chlorophyll *a*

Chlorophyll *a* is a green pigment found in all plants and often used as a measure of algal production in the water. High amounts of algal production can be undesirable for obvious aesthetic reasons and because they can release toxins which may produce adverse taste, odor and health effects. Death of large amounts of algae also reduces oxygen concentrations in water which can lead to fish kills. The desirable limit of chlorophyll *a* is variable depending on the natural levels in a particular area. It is difficult to determine natural chlorophyll levels in southern Manitoba without knowing these values before human disturbance. Total chlorophyll includes chlorophyll *a* pigments from both living and dead plant cells and it is possible to distinguish between the two during the analysis.

Average total chlorophyll *a* values in Crescent Lake, Assiniboine River and Black Lake were 74, 73 and 68 µg/L, respectively. These concentrations are high but not uncommon for shallow water bodies in this region. Water bodies with chlorophyll *a* concentrations between 56 to155 µg/L are considered hypereutrophic (i.e., high in nutrients) and characterized by dense algae and macrophytic growth. On average, the total chlorophyll *a* concentration in the farm ponds were 116 µg/L and ranged between 0.2 to 3642 µg/L. Interestingly, total chlorophyll *a* concentrations rose dramatically from 28 µg/L at CRS1 to 139 µg/L at CRS4 due to a noticeable increase in algal growth.

The Assiniboine River chlorophyll average is exaggerated by a very high total chlorophyll *a* concentration of > 200 µg/L in July which is normally uncharacteristic of fast moving river systems. The high total chlorophyll *a* in the Assiniboine River was due entirely to chlorophyll pigments from plant cells that had already died off. It is possible that there was a large bloom of algae on the Assiniboine River retention reservoir upstream from the pumping site and the remnants of this bloom showed up in our results. This was the only sample that had such a high proportion of chlorophyll from dead plant cells.

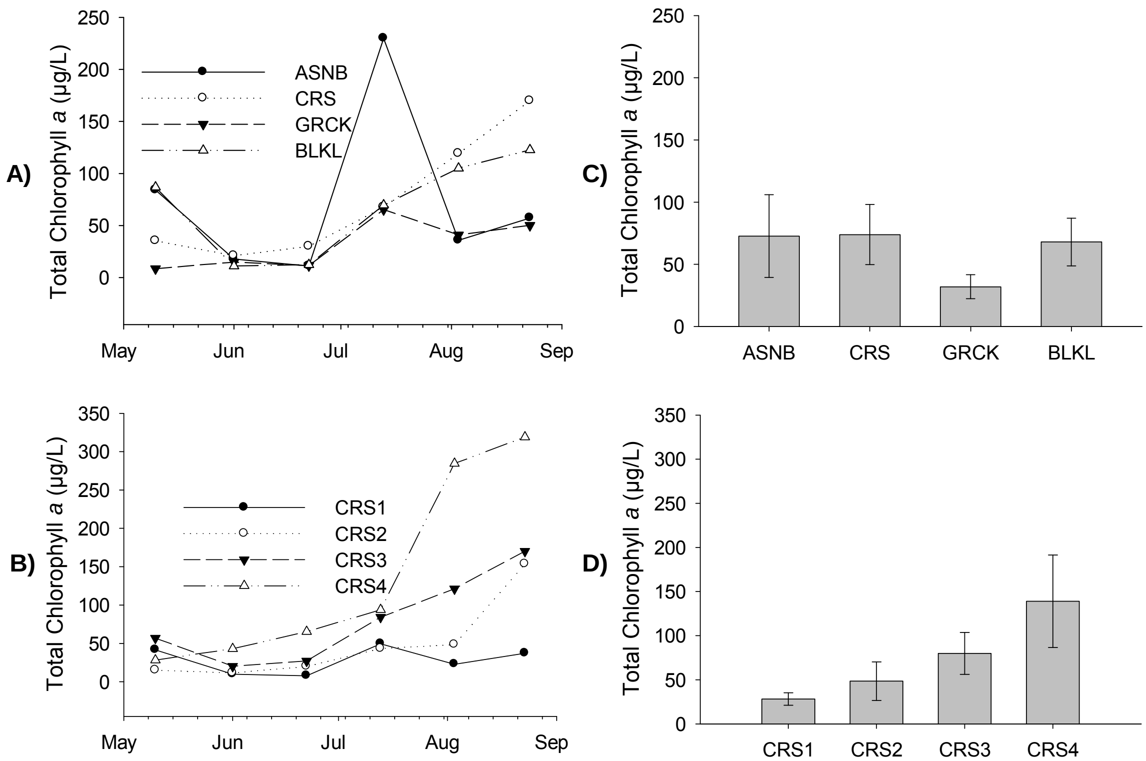


Figure 11. Total Chlorophyll *a* in each sample round for A) ASNB, CRS, GRCK and BLKL and B) CRS1, CRS2, CRS3 and CRS4. Average total chlorophyll *a* of the spring and summer field season (± 1 SE) for C) ASNB, CRS, GRCK and BLKL and D) CRS1, CRS2, CRS3 and CRS4.

5.1.10 Microcystin

Microcystin is an algal toxin that is produced by blue-green algae (also known as cyanobacteria) and is harmful to the liver. In high enough concentration this toxin can be lethal and in lower concentrations it may still cause liver dysfunction and induce cancerous tumors (Codd 2005). The algae that produce this toxin are associated with water that is high in nutrients. The Canadian drinking water standard for total microcystins is 1.5 µg/L (MB Conservation, 2002).

The CRS2 and CRS4 sites were sampled for all microcystin variants during the last three sampling times because this is when microcystin levels were expected to be the highest. Levels of microcystin generally increased and were highest in CRS4 where there was the most algal growth. The highest concentration of microcystin was > 2.0 µg/L which exceeds the suggested limit for human consumption. Overall, the levels of microcystin were not alarming; however, it is interesting that every sample taken in Crescent Lake contained a detectable amount. In comparison, most of the farm ponds tested did not contain a detectable amount of microcystin (0.10 µg/L) and the range was from < 0.10 to 2.30 µg/L.

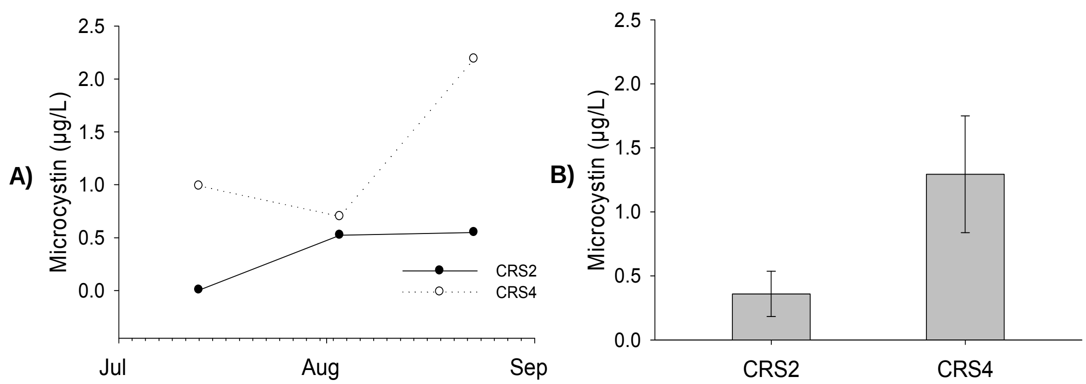


Figure 12. Total microcystins in CRS2 and CRS4 A) for each sample round and B) averaged across the spring and summer field season (± 1 SE).

5.1.11 Fecal Coliforms

Fecal coliforms are a diverse group of bacteria that originate primarily from within the animal digestive system and then are released into the surrounding environment via fecal matter. These coliforms can live for some time outside of the digestive system and the purpose of testing for them is to examine the potential threat of infection by harmful disease causing pathogens (e.g., some protozoa, bacteria and viruses) in the water. Most fecal coliforms are not harmful; however, they are easy to test for and closely associated with a multitude of other pathogens that also originate from fecal waste. The standard set for fecal coliforms in recreational waters is < 200 coliform units (CFU)/100 mL (MB Conservation, 2002). E. coli is the most common type of fecal coliform and, in 2005 studies on the farm ponds, accounted for 100% of the fecal coliforms found in this region.

Fecal coliform counts are highly variable and it is difficult to make conclusive claims without a rigorous and controlled sampling regime. The number of bacteria can be affected dramatically by many variables including temperature and precipitation. The source of these coliforms can be domesticated animals (e.g., cattle, dogs, cats, etc.), wildlife (e.g., deer, raccoons, geese) and humans. Our sampling of Crescent Lake was merely to get an indication of what levels of fecal coliforms exist and whether these levels are possible cause for concern and further follow-up sampling.

Only one of the samples on Crescent Lake had over 200 CFU/100 mL and that was near the bridge and boat launch area at the end of August. Generally speaking, the fecal coliform counts are more likely to be higher in Crescent Lake in late summer early fall due to less water dilution, higher temperatures and feces from migrating birds. Overall, for Crescent Lake's recreational purposes the samples did not cause any alarm.

The most interesting result from the fecal coliform tests was Garrioch's Creek because all three sample dates proved to have high fecal coliform counts. Two of these dates were over the recommended recreational limit of 200 CFU/100 mL. Unfortunately, the mid-July test was only able to give a value of > 200 CFU/100 mL. During the last test in late August we received a more specific value of 800 CFU/100 mL. Possible reasons for the high values are wildlife activity (e.g., waterfowl) or sewage seepage from the surrounding residential area.

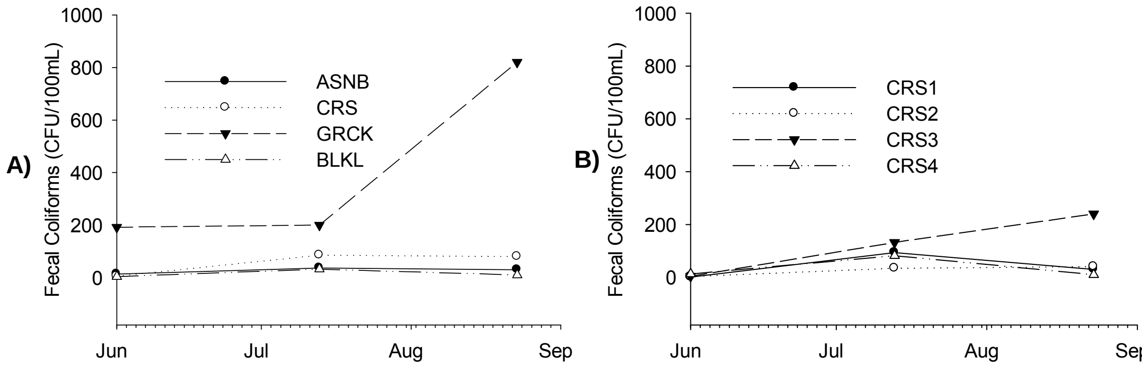


Figure 13. Fecal coliform counts in A) ASNB, CRS, GRCK and BLKL and B) CRS1, CRS2, CRS3 and CRS4 for each sample round.

Nutrients

The two greatest limiting factors for aquatic plant life are sunlight and nutrients. The nutrients that are normally in shortest supply are phosphorus (P) and nitrogen (N) and, in freshwater systems, P is expected to be the most limiting (Wetzel 2001).

Phosphorus is supplied naturally at a very slow rate through erosion of the soil and then recycled through the fecal waste and decay of living organisms such as plants and animals. In recent times, however, human activity has significantly increased the amount of P available by mining it from the ground and then applying it to the soil for fertilizer to grow crops. If even a small amount of this fertilizer ends up in the surrounding watershed it can greatly increase the concentration of P available for aquatic plant production. Much of the P consumed by animals is released again in their fecal matter. Thus, septic systems and large livestock operations can also elevate P concentrations in the water if it not properly contained.

The air we breathe contains 78% N; however, none of this N is in a form that is immediately available for plants. Instead, N available for plants comes mainly from recycled organic matter (e.g., decayed living organisms, fecal matter) and bacteria that “fix” the atmosphere’s N into a form plants can uptake. Like P, however, N can also be obtained easily from fertilizers and human and animal waste. Indeed, N fertilizer is the most commonly applied fertilizer in Manitoba.

Nutrients in water are essential to biological life, however, too much of them can have disastrous consequences. With an increase in nutrients there is a rapid increase in plant life in the water. Algae tends to be the aquatic plants that thrive in high nutrients because they float in the water and can therefore take full advantage of additional nutrient levels and shade out the rooted plants from receiving sunlight. As well, rooted aquatic plants can only grow to a certain depth in the water before there is not enough sunlight for them to utilize in photosynthesis. Many algae, however, are adapted to float so they can grow anywhere across the surface of a water body regardless of the depth. Rapid growth of algae can shade out native rooted plants and cause them to die off which subsequently eliminates further competition for nutrients. Algae often grow quickly in blooms and then die off suddenly for various reasons (e.g., it has used up most the nutrients or shaded itself out from light). The death of algae leads to a rapid decrease in oxygen levels in the water as microorganisms are busy decomposing the algae and using up oxygen in the process (i.e., respiration). This lack of oxygen can quickly lead to the death of fish and other aquatic organisms.

Another problem with algal growth is that some types of algae that grow in high nutrient conditions give off harmful toxins that can affect the liver and nervous system. As well, algae can release toxins that are foul smelling and reduce water palatability.

In much of southern Manitoba it is normal to have higher levels of nutrients in the water because the surrounding land is naturally rich in nutrients. The artificial addition of more nutrients into this aquatic system is harmful, but perhaps less severe than nutrients added to a system where nutrients are naturally low (e.g., The Whiteshell in the Canadian Shield). In deeper lakes nutrients tend to accumulate at the bottom and move throughout the water column infrequently. In southern Manitoba, however, many of the water bodies, including Crescent Lake, are shallow and nutrients are easily resuspended throughout the water column by wind and wave action.

It is common in the winter for nutrient levels to rise in northern water bodies because bacteria and other aquatic organisms are busy consuming dead plant matter and releasing much of the bound up nutrients as waste.

5.1.12 Total Phosphorus

Total phosphorus (TP) is the total amount of inorganic and organic P that is found in the water. The ideal for lakes and ponds according to Manitoba Water Quality Guidelines is 0.025 mg/L, however, the level of P in many water bodies of southern Manitoba would be expected to be higher due to naturally high nutrient levels in the surrounding soil.

Average TP concentration in Crescent Lake during the summer was 0.10 mg/L which is four times higher than the guideline of 0.025 mg/L. This value was, however, lower than the Assiniboine River and Black Lakes which were 0.22 and 0.47 mg/L, respectively. The trophic status of Crescent Lake would be considered hypereutrophic with TP values > 0.1 mg/L. The TP in the farm ponds was on average 0.60 mg/L and ranged from < 0.01 to 4.76 mg/L.

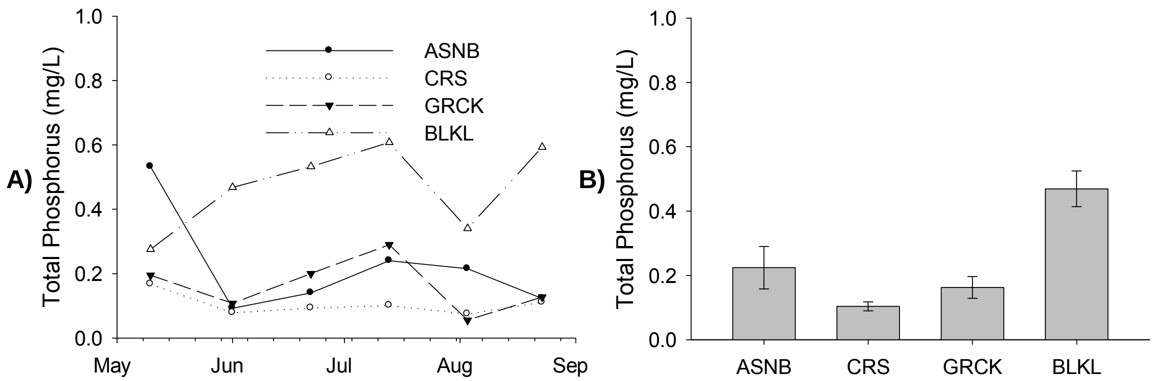


Figure 14. Total phosphorus in ASNB, CRS, GRCK and BLKL A) for each sample round and B) averaged across the spring and summer field season (± 1 SE).

5.1.13 Total Reactive Phosphorus

Total reactive phosphorus (TRP) is the amount of P in the water that is readily available for biological uptake. This value is important because it detects the P that can be immediately taken up by algae and plants.

Crescent Lake had low readings of TRP that were close to our detection limit of 0.01 mg/L. In comparison, Blacks Lake had on average 0.32 mg/L of TRP which was over 30 times more than Crescent Lake. Similarly, the farm ponds had on average 0.31 mg/L of TRP and ranged between less than 0.01 to 3.80 mg/L.

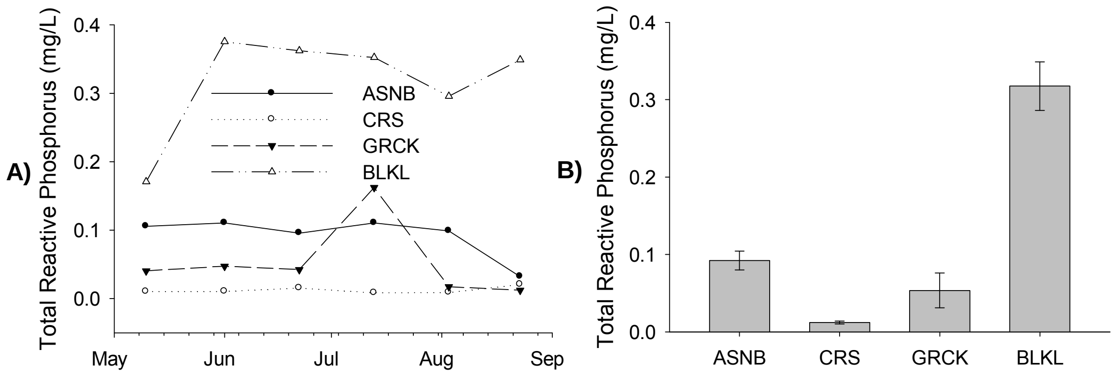


Figure 15. Total reactive phosphorus in ASNB, CRS, GRCK and BLKL A) for each sample round and B) averaged across the spring and summer field season (± 1 SE).

5.1.14 Total Nitrogen

Total nitrogen (TN) is the total amount of inorganic and organic N found in the water. There is no current guideline in Manitoba for the amount of TN to have in the water, although it is common to compare the ratio of TN to TP to try and predict which nutrient is limiting plant growth (see TN:TP ratio below).

The average amount of TN in Crescent Lake, Assiniboine River and Black Lake was 2.0, 0.8 and 2.1 mg/L, respectively. The TN in farm ponds was on average 4.9 mg/L and ranged between < 0.01 to 114 mg/L.

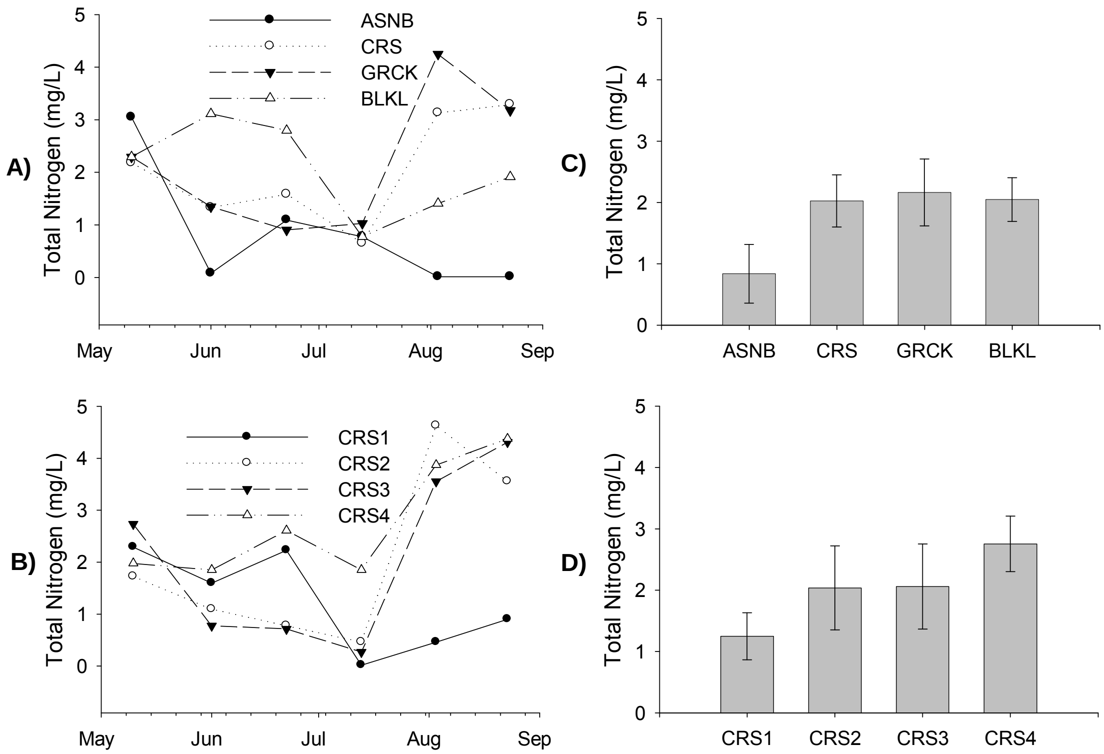


Figure 16. Total Nitrogen in each sample round for A) ASNB, CRS, GRCK and BLKL and B) CRS1, CRS2, CRS3 and CRS4. Average total nitrogen over the spring and summer field season (± 1 SE) for C) ASNB, CRS, GRCK and BLKL and D) CRS1, CRS2, CRS3 and CRS4.

5.1.15 Total Nitrogen : Total Phosphorus Ratio (TN:TP)

If the ratio of TN to TP is > 16 then P is considered the limiting nutrient. If the TN:TP ratio is < 16 then N is thought to become the limiting nutrient. In most freshwater systems P is naturally the limiting nutrient. Thus, a TN:TP ratio of < 16 is often a sign of human disturbance in elevating the amount of P and causing N to become the limiting nutrient. However, if N and P concentrations are very high in a water body they are no longer limiting to any degree and N:P ratios lose their significance.

In summer, the TN:TP ratio for Crescent Lake was much > 16 indicating that the limiting nutrient for Crescent Lake may be P which is normal for a freshwater system. The TN:TP ratio of Black Lake was < 16 indicating possible human disturbance and artificially elevated P conditions.

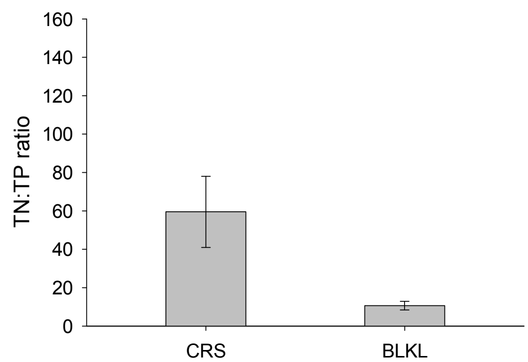


Figure 17. Mean TN:TP ratios for CRS and BLKL over the spring and summer sampling (± 1 SE).

5.1.16 Nutrient Diffusing Substrata

To test whether our water chemistry prediction of nutrient limitation (the TN:TP ratios) was an actual reflection of what was happening biologically in the water we set up an experiment with nutrient diffusing substrata (NDS). The NDS was designed to test which nutrient, N or P, was most limiting for algal growth. The NDS consisted of a floating frame with twelve different tubes (three tubes of four different agar treatments). The agar treatments within the tubes were: 1) Control (no nutrients) 2) 0.05 mol/L P added 3) 0.05 mol/L N added 4) 0.05 mol/L of both N and P added. Each tube had a porous disk on one end which algae could grow upon and any nutrients within the tube could diffuse out. After three weeks of floating in the water we took out the tubes and calculated the amount of algal growth on the disks by measuring chlorophyll *a* concentrations.

The sites monitored with NDS frames were CRS1 and CRS4 and Black Lake. Both Crescent Lake sites showed significant ($p < 0.05$) N and P co-limitation because the treatment with both nutrients added (N and P) had the greatest amount of algal growth; this result was also common for less disturbed water bodies in the farm pond study. In Black Lake, however, significant ($p < 0.05$) N limitation was evident because the nitrogen treatment had the most growth. This was not unexpected considering that Black Lake had a TN:TP ratio of < 16.

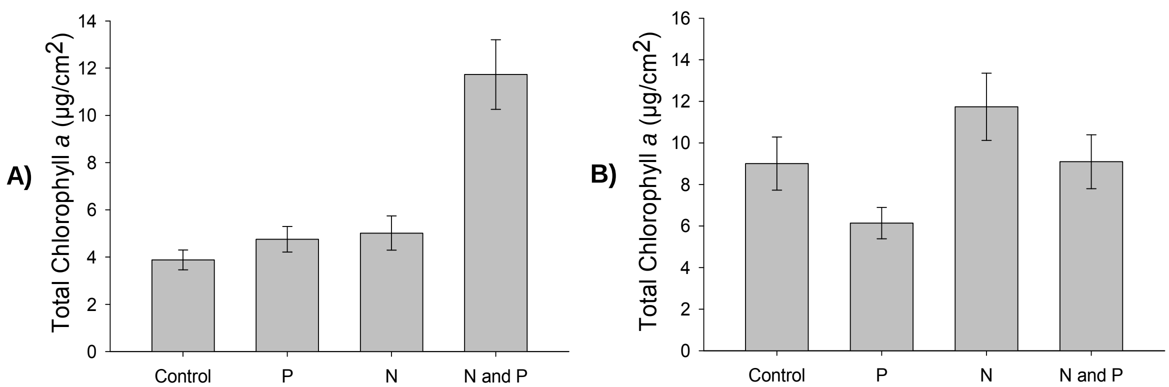


Figure 18. Average total chlorophyll *a* (± 1 SE) on NDS treatments in A) Crescent Lake and B) Blacks Lake (the control).

5.1.17 Nitrate and Nitrite-N

Nitrate and nitrite-N is the amount of N found in the water in a nitrate or nitrite form. High levels of nitrate and nitrite can be toxic to animals, especially the young. Greater than 10 and 100 mg/L of nitrate and nitrite-N is considered a health risk for human and livestock consumption, respectively. Nitrate and nitrite does not normally build up to such high levels in surface waters. However, nitrate and nitrite travel through the soil and often build up in groundwater and wells.

The nitrate and nitrite-N levels in Crescent Lake were 0.08 mg/L on average which is low and not of concern. The average farm pond concentration was 0.03 mg/L and ranged between < 0.01 to 1.54 mg/L

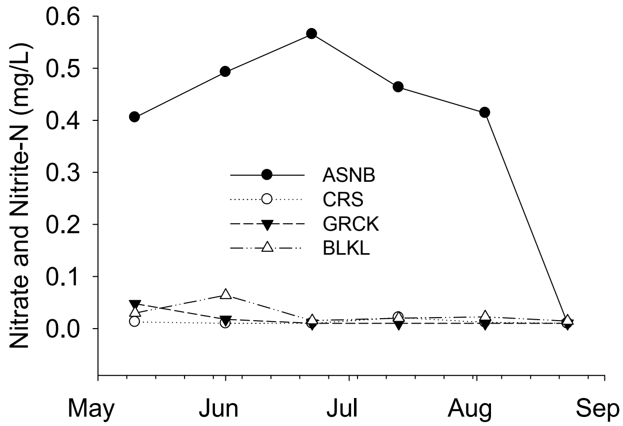


Figure 19. Nitrate and nitrite-N concentrations in ASNB, CRS, GRCK and BLKL over the spring and summer sampling.

5.1.18 Ammonia-N

Ammonia-N is the concentration of N that is found in the form of ammonia (NH_3) in the water. This form of N is a waste product of many organisms and is also toxic to aquatic organisms in high concentration. The toxicity of ammonia varies depending on the pH and temperature of the water. At a temperature of 20°C and pH of 9 a level of ammonia < 0.3 mg/L is desirable (MB Conservation, 2002).

The ammonia levels were undetectable for most of the summer in Crescent Lake at < 0.01 mg/L. Garrioch's Creek, however, had high ammonia levels > 0.6 mg/L later on in the summer which further suggest there was some waste input downstream from

Crescent Lake. During the last sample day the ammonia levels reached 1.2 mg/L in Garrioch Creek which was still a tolerable level at 20 °C and a pH of 7.6 (MB water quality guideline is < 2.6 mg/L of ammonia at pH 7.6 and 20 °C). In the winter, ammonia levels in Crescent Lake approached 1.0 mg/L but at 0 °C and a pH of 7.3 would need to have been > 5.0 mg/L to cause concern.

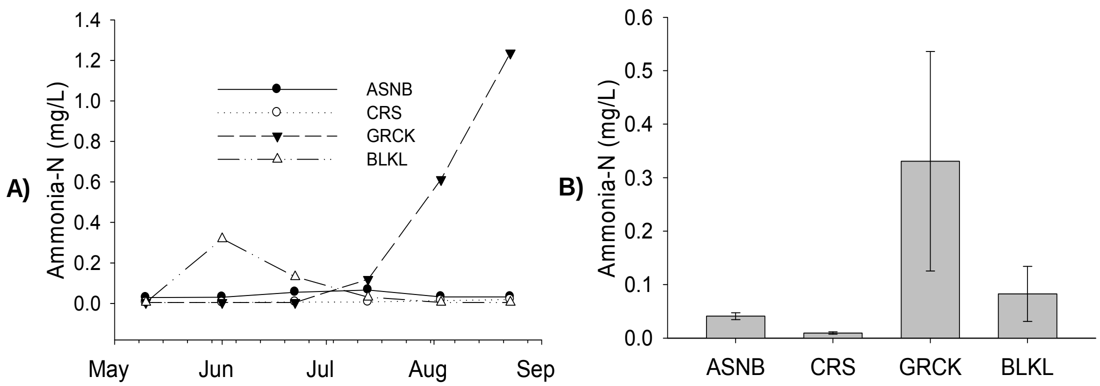


Figure 20. Ammonia-N in ASNB, CRS, GRCK and BLKL A) for each sample round and B) averaged across the spring and summer field season (± 1 SE).

5.1.19 Dissolved Organic Carbon

Dissolved Organic Carbon (DOC) is derived from plant and animal material that has been broken down to such an extent that it is able to dissolve in the water. DOC from animal waste and decomposition within a water body are in the form of carbohydrates, proteins and fats and do not affect the coloration of the water. DOC from plant material within the water would be expected to increase over the summer in Crescent Lake as plant production increased. Some DOC that is present in lakes and rivers are breakdown material from woody debris and leaves which has runoff into the water. This DOC from plant matter on land contains pigments that color the water column in much the same way tea colors hot water. Thus, water high in DOC is sometimes colored in appearance (i.e., normally yellow to black).

The DOC level for Crescent Lake was consistently between 13 and 16 mg/L throughout the summer with a general increasing trend as the summer progressed. The DOC levels in Crescent Lake were similar to that of Blacks Lake which ranged in value from 14 to 18 mg/L and also increased throughout the summer. These values are quite high and expected in a wetland environment where there is a lot of plant growth happening (Wetzel, 2001). The average farm pond DOC was 23 mg/L with a range of 7 to > 72 mg/L.

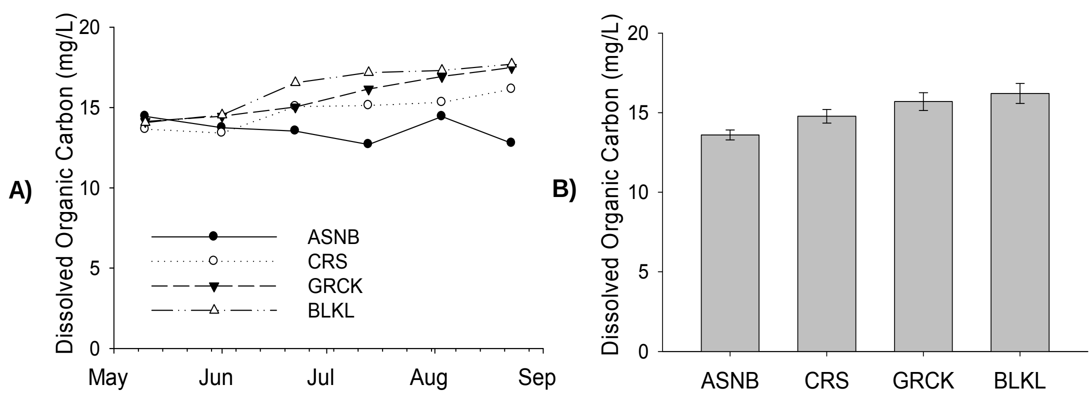


Figure 21. Dissolved organic carbon in ASNB, CRS, GRCK and BLKL A) for each sample round and B) averaged across the spring and summer field season (± 1 SE).

5.1.20 Soluble Reactive Silica

This is the amount of silica in the water that is readily available for chemical reaction or biologic uptake. Silica is an essential nutrient for many aquatic organisms and is especially important for an algal group called diatoms which use silica to produce their protective outer shell. Base silica values are often quite consistent in freshwater and what is of most interest is the change in concentration over time. In particular reduction in silica concentrations from the base level usually reflect changes in the diatom population. Sharp increases in silica from the base level are often a result of the sediment being resuspended in the water body (e.g., from heavy winds) and these values will stabilize again when the sediment settles out.

After the ice melt on Crescent Lake there is most likely a large bloom of diatoms that use up the initial abundance of nutrients in the water column. We starting sampling silica in June which was perhaps after the initial diatom bloom and why most of the silica values were initially quite low. The exception would be site 1 in Crescent Lake which still had high levels and reflected the constant input of silica from the Assiniboine River. Crescent Lake site 4 quickly regained a higher concentration of silica towards the middle of June which is an indication that by this time much of the diatoms had died off and released their silica in the process. Crescent Lake sites 2 and 3 also show this pattern beginning in early August. Blooms of diatoms and a subsequent decrease in silica concentration were synonymous with clear water conditions. The water clarity of Crescent Lake was consistently higher with low silica concentrations unless there was conditions where the suspended was resuspended (e.g., high winds). To get a full picture of diatom activity, silica concentrations would need to be monitored for the entire year.

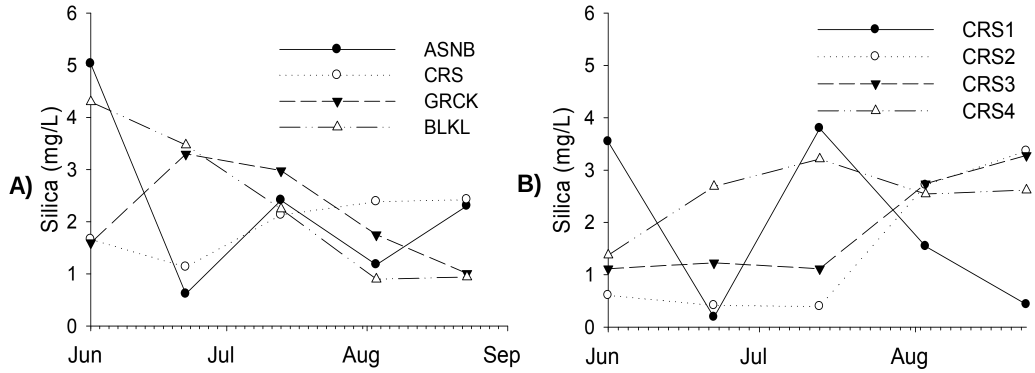


Figure 22. Soluble reactive silica in A) ASNB, CRS, GRCK and BLKL and B) CRS1, CRS2, CRS3 and CRS4 from each round of sampling in the spring and summer field season.

Ions

Ions are atoms (e.g., sodium, potassium, chloride) or molecules (e.g., sulphate) that have gained or lost an electric charge and as a result have become negative or positive. The measure of conductivity is actually a measure of the charge produced by ions in the water. Ions are essential for biological life and play important roles in the cell, particularly the cell membrane. Large fluctuations of ions in solution can cause problems for freshwater organisms because it affects their osmotic balance (i.e., capacity to take up and remove ions).

5.1.21 Conductivity

Conductivity is a measure of the ion concentration in water by examining the resistance of water to electrical flow (Wetzel, 2001). Ions are charged atoms and molecules in solution that, due to their charge, facilitate electrical flow. Thus waters that are high in ion concentration are high in conductivity. This is a similar measure to total dissolved solids within a water body and can be helpful in determining the source of the water, the type of aquatic organisms able to inhabit the water body and suitability of the water for activities such as irrigation or drinking water. The most common ions in solution are calcium (Ca^{2+}), magnesium (Mg^{2+}) sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}), sulphate (SO_4^{-}), carbonate (CO_3^{-}) and bicarbonate (HO_3^{-}) (Wetzel, 2001). Groundwater is normally much higher in conductivity than surface or rain water because it has picked up a high concentration of dissolved substances. The irrigation standard for conductivity in Manitoba is < 1000 µS/cm (MB conservation 2002).

During the summer the average conductivity values for Crescent Lake, Assiniboine River and Black Lake were 660, 818, and 490 µS/cm, respectively. The farm pond average was 779 µS/cm with a range between 153 to 4930 µS/cm. The conductivity in Crescent Lake appeared normal to the region and was fairly consistent throughout the summer with a general decreasing trend moving from CRS1 to CRS4.

There was no appreciable difference in conductivity levels in Crescent Lake from the surface to the bottom, again due to the shallow depth of the lake. Lakes or ponds that are deeper, such as Black Lake and many of the farm ponds, show more of a difference in conductivity values because of density gradients that occur (i.e., heavier water with more dissolved solids sink to the bottom). Bottom conductivity values are shown in the Appendix, Table 2.

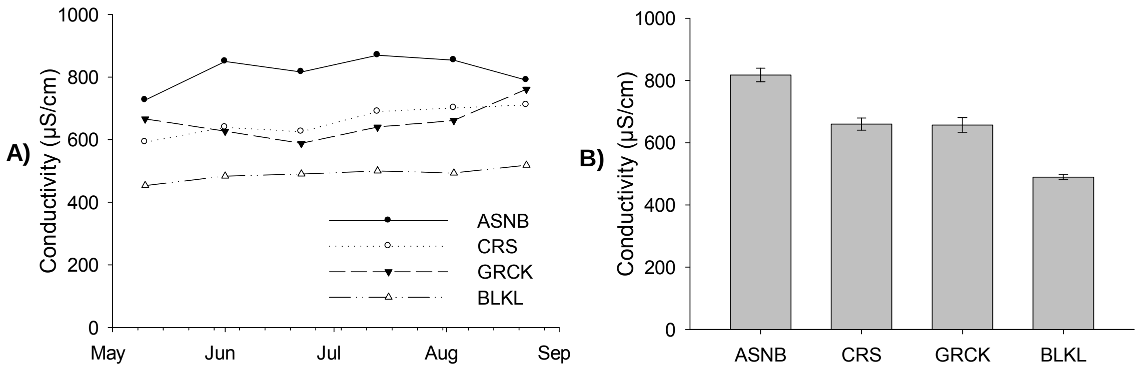


Figure 23. Surface conductivity of ASNB, CRS, GRCK and BLKL for A) each sample round and B) averaged across the entire field season (± 1 SE).

5.1.22 Chloride

Chloride is naturally found in surface water via rocks containing chlorides. Chloride can also enter surface water from agricultural runoff, sewage and industry wastewater, and road salts. The current standard for surface waters is < 250 mg/L for drinking water and < 100 mg/L for irrigating chloride sensitive crops (MB Conservation, 2002).

The average chloride concentrations for Crescent Lake, Assiniboine River and Black Lake were 31, 25 and 8.0 mg/L, respectively. The chloride concentration in farm ponds was on average 64 mg/L and ranged between 1 to 1247 mg/L.

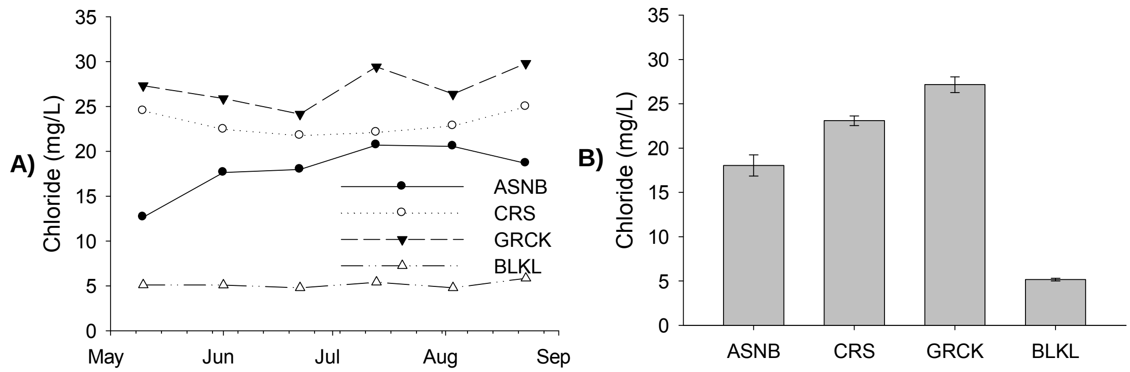


Figure 24. Chloride in ASNB, CRS, GRCK and BLKL A) for each sample round and B) averaged across the spring and summer field season (± 1 SE).

5.1.23 Sulphate

Sulphate is found naturally in surface water and via the breakdown of leaves and organic matter, through erosion of rocks, and atmospheric deposition. Also, sulphate concentrations can be increased by human sources such as sewage and industrial discharge and runoff from fertilized agricultural lands. Sulphate is a required nutrient for plant life but is rarely a limiting factor in surface waters of southern Manitoba. In low oxygen conditions sulfate can be transformed to hydrogen sulphide which is toxic to aquatic organisms at concentrated amounts. High sulphate concentrations have been known to cause diarrhea and indigestion in people and livestock with little long term effect. The current drinking water standard for sulphate in surface waters in Manitoba is < 500 mg/L (MB Conservation, 2002).

On average Crescent Lake has sulphate levels of 136 mg/L which is below the Assiniboine River input level of 179 mg/L and above Blacks Lake 37 mg/L. The sulphate concentration in farm ponds was on average 81 mg/L and ranged between 0.1 to 610 mg/L.

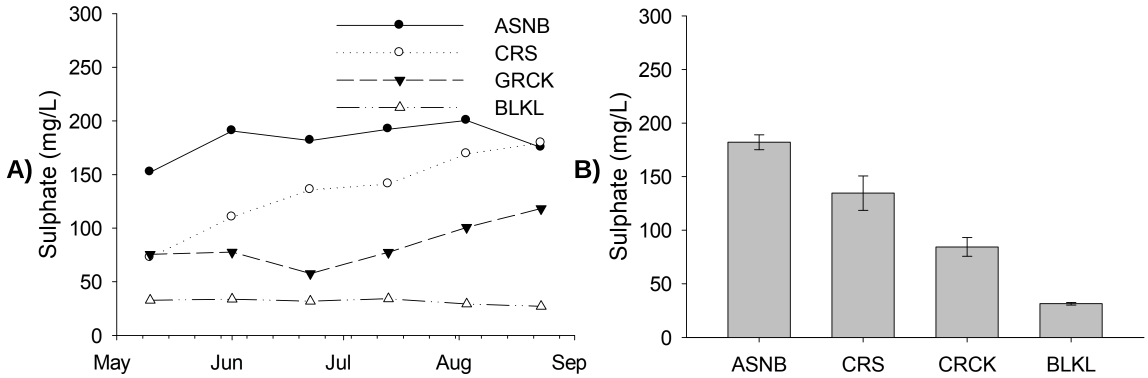


Figure 25. Sulphate in ASNB, CRS, GRCK and BLKL A) for each sample round and B) averaged across the spring and summer field season (± 1 SE).

5.1.24 Sodium

Sodium enters freshwater via natural causes (such as weathering of soil material) but can also be greatly increased by human influences such as road salts. The Manitoba water guidelines suggest having < 200 mg/L of sodium in water for human consumption (MB Conservation 2002).

The average sodium ion concentration in Crescent Lake, Assiniboine River and Blacks Lake was 48, 46 and 7 mg/L, respectively. The sodium concentration in the farm ponds was on average 31 mg/L and ranged between < 1 to 439 mg/L.

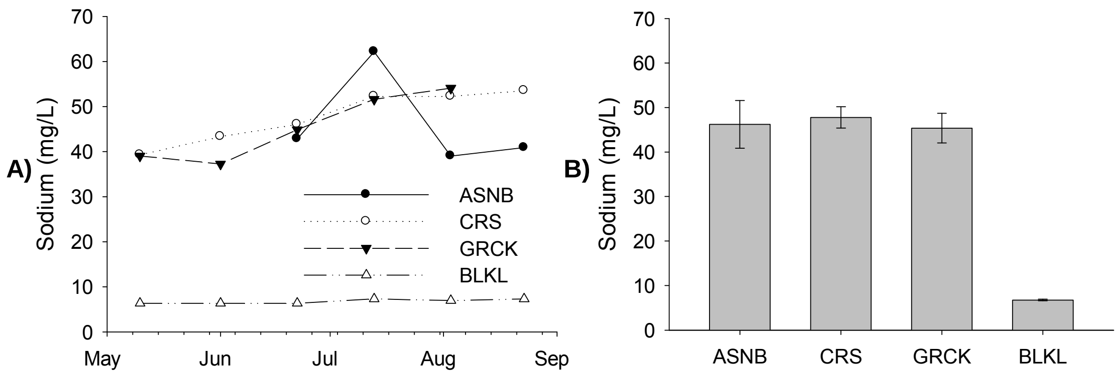


Figure 26. Sodium in ASNB, CRS, GRCK and BLKL A) for each sample round and B) averaged across the spring and summer field season (± 1 SE).

5.1.25 Potassium

Potassium is a common ion found in surface waters as a result of natural processes and from human application of fertilizers. Potassium levels were consistently around 4 mg/L in all Crescent Lake study sites. The potassium concentrations in the farm ponds were on average 13 mg/L and ranged between less than 1 to 164 mg/L.

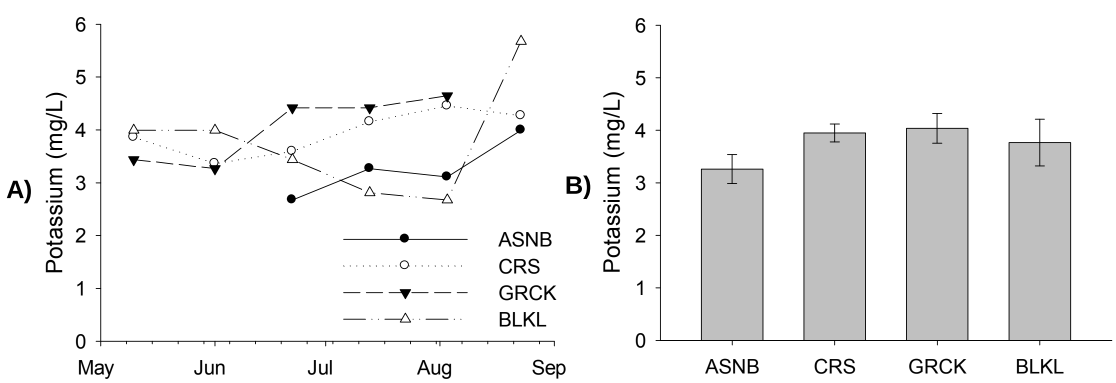


Figure 27. Potassium in ASNB, CRS, GRCK and BLKL A) for each sample round and B) averaged across the spring and summer field season (± 1 SE).

Sediment

5.1.26 Sediment Texture – Percent Sand/Silt/Clay

The percentage of sand, silt and clay helps to classify the sediment on the basin of a water body. Based on the results, Crescent Lake's sediment would be considered silt loam and Black Lake was considered loam. Generally, the higher percentage of clay, and to a lesser extent silt, the more potential there is for sediment to hold onto nutrients. Sediment high in sand content has low capability of holding onto nutrients.

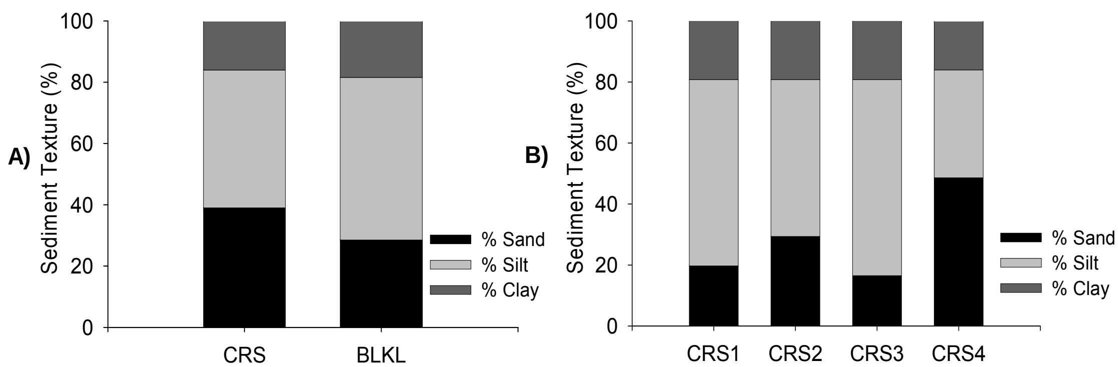


Figure 28. Sediment texture of A) CRS and BLKL and B) CRS1, CRS2, CRS3 and CRS4

Productive water bodies that have abundant vegetation would be expected to have sediment that is high in organic content. As well, leaves from trees surrounding the water bodies can also contribute considerable amounts of organic matter.

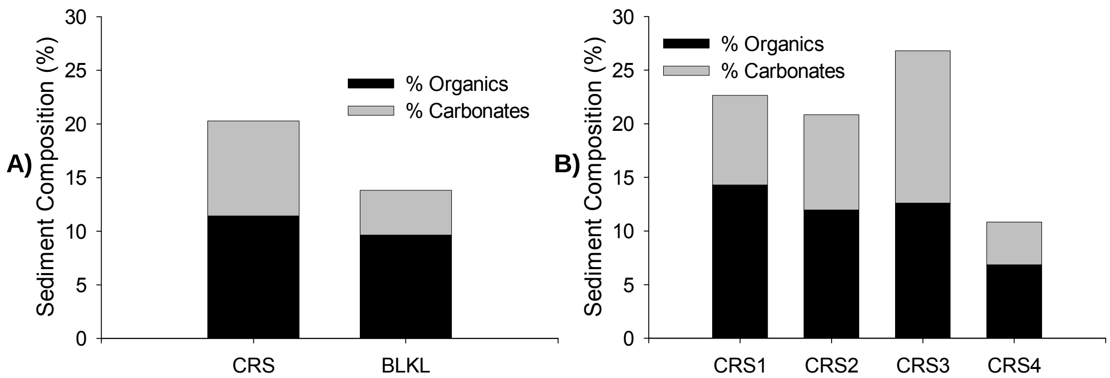


Figure 29. The percent organics and carbonates in sediment of A) CRS and BLKL and B) CRS1, CRS2, CRS3 and CRS4.

Conclusion:

There was a trend of increasing algal growth and turbidity when moving from CRS1 to CRS4 which corresponds to the level of human activity and disturbance on Crescent Lake. Along with this increase of algae was an increase in the algal toxin microcystin which originates from blue green algae. Low winter levels of dissolved oxygen indicate that few fish species could survive the winter in Crescent Lake. Later in the summer fecal coliform concentrations began to approach the suggested maximum of 200 CFU/100 mL for recreational swimming purposes. Garrioch's Creek had high fecal coliform counts and it would be interesting to investigate the cause.

It was difficult to find a suitable control (i.e., comparison site) for Crescent Lake because ideally we wanted a site with similar features that was relatively undisturbed by human activity. This is not easy to find in southern Manitoba and, interestingly our control had worse conditions than Crescent Lake itself. The watershed of Blacks Lake is not fully known but it probably encompasses a large amount of agricultural land and perhaps even some residential areas. As well, Blacks Lake does not have the benefit of having new water pumped through like Crescent Lake and it is perhaps more subject to the entrapment of nutrients.

According to trophic classification based on Secchi depth, TP and chlorophyll *a* concentrations Crescent Lake would be considered a eutrophic to hypereutrophic water body characterized by dense algae and macrophyte growth. Water quality is a relative term based on human value placed on water for a specific purpose. From this study Crescent Lake’s water quality seems characteristic of many shallow water bodies in this fertile, heavily cultivated region of southern Manitoba. It is doubtful that Crescent Lake had nutrient levels this high before human disturbance, but it is difficult to know without previous comparative data. Ultimately, the water quality of Crescent Lake is limited by its greatest source of surface water which is the Assiniboine River. Nutrient levels are artificially high in the Assiniboine River because of the extensive amount of agriculture within its watershed. For this reason, pumping water from the Assiniboine River should be limited to times when it is least turbid and has the lowest concentration of nutrients (after spring runoff). While it is difficult to control nutrient inputs from the Assiniboine River, it is much easier to control nutrient inputs from Portage itself. One suggestion would be to limit the use of fertilizer in close proximity to the lake. As well, consider the establishment of natural riparian areas around the water. The practice of clearing out submerged macrophytes from the lake bottom is often preferred for aesthetic and recreational use; however, it does make nuisance algal blooms more of a common occurrence (i.e., less competition for nutrients). Regular monitoring (i.e., at least annually) of Crescent Lake in multiple locations would be advisable for long-term trend analysis and a broader understanding of the lake water quality.

References:

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Appendix: Summary Data

Table A-1. Seasonal mean of field measurements.

Site Code	Wind (km/h)	Air Temp (°C)	Water Temp [surface] (°C)	Water Temp [bottom] (°C)	DO [surface] (mg/L)	% DO [surface]	DO [bottom] (mg/L)	% DO [bottom]	Conductivity [surface] (µS/cm)	Conductivity [bottom] (µS/cm)	Depth (m)	Secchi (m)	Ice Depth (m)	Snow Depth (m)
CRS1*	14	-11	0		0.9				425		0.8	0.44	0.58	0.18
CRS2*	9	-10	0		0.7				584		1.2	0.33	0.55	0.20
CRS3*	10	-12	0		0.9				434		1.1	0.37	0.64	0.16
CRS4*	5	-10	0		0.9				455		1.6	0.59	0.71	0.10
CRS*	9	-11	0		0.8				475		1.2	0.43	0.62	0.16
ASNB	6	18	20		9.1	105			818			0.23		
CRS1	6	19	21	21	7.9	77	4.6	49	741	766	0.8	0.84		
CRS2	6	19	21	21	9.2	103	5.1	58	646	672	1.0	0.72		
CRS3	8	20	21	21	8.4	96	2.3	26	632	654	1.1	0.56		
CRS4	5	20	22	21	7.5	87	2.7	30	619	622	0.9	0.33		
CRS	6	20	21	21	8.3	91	3.7	41	660	678	1.0	0.61		
GRCK	5	21	20		2.5	28			657		0.3			
BLKL	4	21	19	16	1.3	15	0.4	4.2	490	696	2.0	0.79		
Farm Ponds														
Mean	7	23	21	17	7.4	93	2.2	26	779	972	2.2	0.78		
Min	0	5	12	5	0.1	1	< 0.1	< 1	153	278	0.1	0.01		
Max	28	32	29	26	> 20.0	> 100	> 20.0	> 100	4970	5600	4.9	2.85		

* Winter sample

Table A-2. Seasonal means of routine water chemistry.

Site Code	Turbidity (NTU)	TSS (mg/L)	Alkalinity (mg/L)	pH	Total Chlorophyll (µg/L)	Fecal Coliforms (CFU/100mL)	Microcystin (µg/L)
CRS1*	89	10	480	7.3	164		
CRS2*	145	9	436	7.4	308		
CRS3*	80	9	344	7.4	108		
CRS4*	90	12	344	7.3	1795		
CRS*	101	10	401	7.3	594		
ASNB	37	86	241	8.2	73	27	
CRS1	3	15	197	8.0	28	42	
CRS2	7	23	145	9.3	49	26	0.5
CRS3	13	25	163	9.3	80	125	
CRS4	22	27	179	8.9	139	35	1.3
CRS	11	22	171	9.1	74	57	1.0
GRCK	14	13	202	7.9	32	506	
BLKL	4	11	229	8.9	68	15	
Farm Ponds							
Mean	26	32	274	7.9	116	350	0.1
Min	1	0	68	6.9	0.2	0	< 0.1
Max	487	1040	784	10.0	3642	1490	2.30

* Winter sample

Table A-3. Seasonal mean of routine water chemistry (Continued)

Site Code	TP (mg/L)	TRP (mg/L)	TN (mg/L)	Nitrate and Nitrite-N [NO_3/NO_2-N] (mg/L)	Ammonia-N [NH_3-N] (mg/L)	TN:TP ratio	DOC (mg/L)	Soluble Reactive Silica (mg/L)	Chloride [Cl^-] (mg/L)	Sulphate [SO_4^-] (mg/L)	Potassium [K+] (mg/L)	Sodium [Na+] (mg/L)
CRS1*	0.74	< 0.01	5.4	0.01	0.60	16	24		44	127		
CRS2*	0.42	< 0.01	4.6	0.01	0.79	24	22		42	119		
CRS3*	0.26	< 0.01	3.9	0.01	0.77	34	21		38	117		
CRS4*	0.44	< 0.01	4.4	0.01	0.71	22	20		35	90		
CRS*	0.46	< 0.01	4.6	0.01	0.71	24	22		40	113		
ASNB	0.22	0.09	0.8	2.35	0.04	7	14	2.3	18	182	3	46
CRS1	0.09	0.01	1.2	0.06	< 0.01	56	14	1.9	20	167	4	44
CRS2	0.10	0.01	2.0	0.08	< 0.01	89	15	1.5	22	139	4	48
CRS3	0.09	0.01	2.1	0.10	< 0.01	49	15	1.9	24	132	4	49
CRS4	0.14	0.01	2.8	0.06	0.02	44	15	2.5	27	101	4	50
CRS	0.10	0.01	2.0	0.08	< 0.01	59	15	1.9	23	135	4	48
GRCK	0.16	0.05	2.2	0.11	0.33	50	16	2.1	27	84	4	45
BLKL	0.47	0.32	2.0	.017	0.08	11	16	2.4	5	31	4	7
Farm Ponds												
Mean	0.60	0.31	4.8	0.03	0.42	57	23		64	81	13	31
Min	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 1	7		1	0.1	< 1	< 1
Max	4.76	3.80	114.0	1.54	5.60	> 100	72		1247	610	164	439

* Winter sample

Table A-4. Sediment analyses

Site Code	% Organics	% Carbonates	% Sand	% Clay	% Silt	Sediment Classification
CRS1*	14	8	20	19	61	Silt Loam
CRS2*	12	9	29	19	51	Silt Loam
CRS3*	13	14	16	19	64	Silt Loam
CRS4*	7	4	49	16	35	Loam
CRS *	11	9	29	18	53	Silt Loam
ASNB	3	7				
CRS1	14	8	20	19	61	Silt Loam
CRS2	12	9	29	19	51	Silt Loam
CRS3	13	14	16	19	64	Silt Loam
CRS4	7	4	49	16	35	Loam
CRS	11	9	29	18	53	Silt Loam
GRCK						
BLKL	10	4	39	16	45	Loam
Farm Ponds						
Mean	6	8				
Min	1	1				
Max	23	26				

* Winter sample

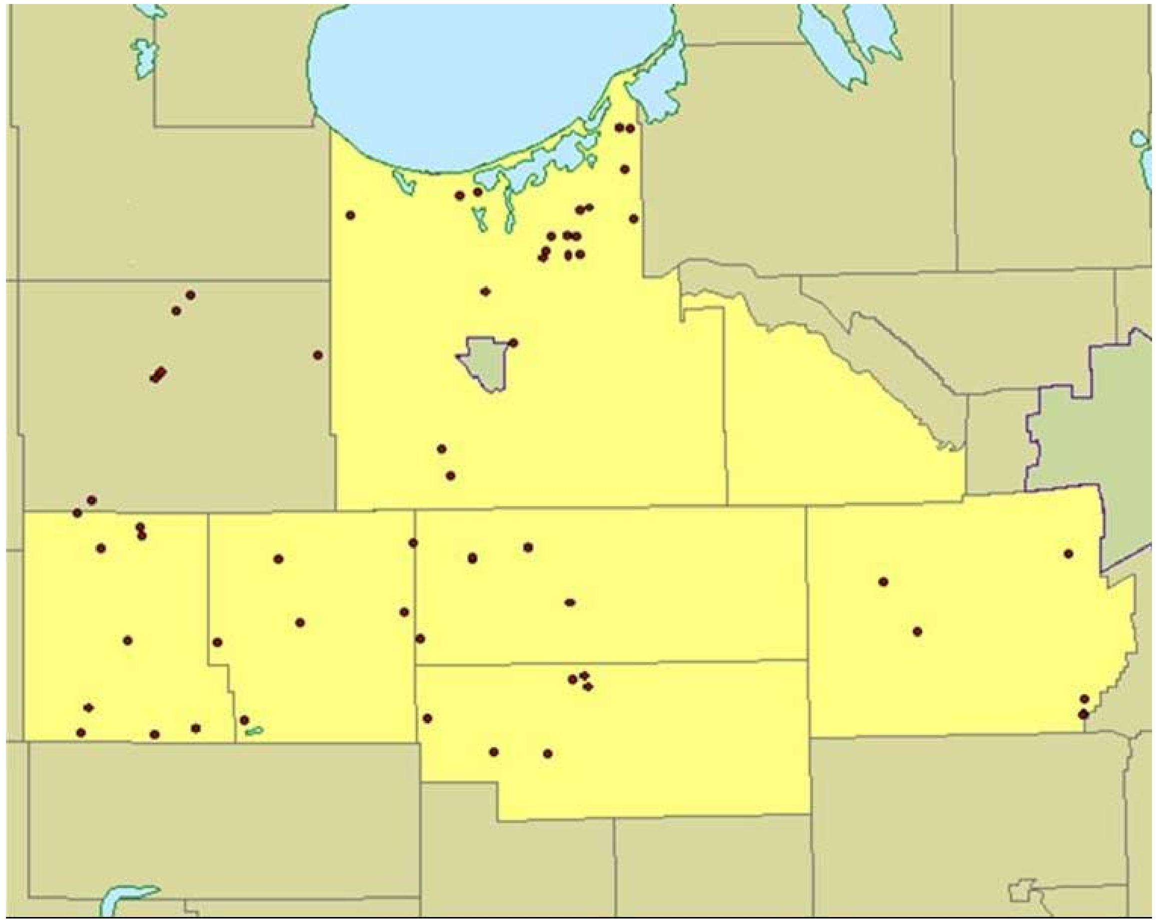

Figure A-1. Site locations for the 59 farm ponds sampled in 2006 in relation to the La Salle-Redboine Conservation District.

Appendix G. Thesis Raw Data and Photos