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FACULTÉ DES ÉTUDES SUPÉRIEURES ET POSTDOCTORALES

FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

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M. Sc. (Biology)

GRADE - DEGREE

Department of Biology

FACULTÉ, ÉCOLE, DÉPARTEMENT - FACULTY, SCHOOL, DEPARTMENT

TITRE DE LA THÈSE - TITLE OF THE THESIS

Floating Algal Mats in the Rideau River and their Relationship to Nutrient Concentrations and Sources

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DEAN OF THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

FLOATING ALGAL MATS IN THE RIDEAU RIVER AND THEIR RELATIONSHIP TO NUTRIENT CONCENTRATIONS AND SOURCES

by

Maria Veronica Soledad Diaz Arce

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
University of Ottawa
In partial fulfilment of the requirements for the
M.Sc. degree in the

Ottawa-Carleton Institute of Biology

Thèse soumise à
Faculté des études supérieures et postdoctorales
Université d'Ottawa
En vue de l'obtention de la maîtrise ès sciences à

L'Institut de Biologie d'Ottawa-Carleton

Your file Votre référence
ISBN: 0-612-90059-2
Our file Notre référence
ISBN: 0-612-90059-2

To my mother, Soledad Arce Guzman, who has always been there for me

Acknowledgements

I am grateful to many people who gave me their support, trust and help to accomplish this project and personal goal. The following names are mentioned in no particular order. Each of them has a special place in my heart and memories.

I gratefully acknowledge the financial support I received from CONACyT-Mexico (National Council of Science and Technology). Scholarship: 133904.

I am also very thankful for the financial support provided by Dr. Frances Pick, the University of Ottawa and SCFP-CUPE 2626.

I am greatly indebted to my supervisor Dr. Frances Pick, whose support, advice and encouragement went beyond her supervising role, muchas gracias Frances.

Thanks to my committee Jules Blais, Ian Clark, Christiane Charest, and David Lean for their time and valuable comments. Additional thanks to Christiane who kindly edited the final version of my French abstract. I would also like to thank Paul Hamilton (Canadian Museum of Nature) for valuable comments and Scott Findlay for his statistical advice.

For additional statistical comments, thank you very much to Dr. Luis Capurro (CINVESTAV-IPN, Merida) and Dr. Luis Rodriguez Carvajal (Faculty of Mathematics, UADY).

Special thanks to Craig Reid (City of Ottawa), Patrick Larson (Rideau Valley Conservation Authority) and Michel McCartin (Statistic Canada, Agriculture Division)

for providing me with very useful information on storm sewer outfalls, land use and agriculture data, respectively.

Thanks to Paul Hamilton, David Lean and John Arnason for lending me their freeze dryers. Special thanks to Linda Kimpe and Virginie Treyvaud Amiguet for their very much appreciated help.

Thanks to my field and lab assistants Marc Demers and Rob Hurd, their help was much appreciated. Special thanks to Brigitte Lavallée for sampling support.

Thanks to Émilie Larivière, who provided me with valuable background information in the stable isotope field. I would also like to thank Hervé Beaudoin who patiently made the metaphyton sampler (known also as the shark-cage) and Paul Middlestead and Wendy Abdi for invaluable help at the G.G. Hatch Isotope Laboratories, University of Ottawa.

Special thanks to Irene Gregory-Eaves for her help and patience to answer some "power" questions.

I would like to thank past and present Pick/Blais/Currie labs whose sense of humor and support was invaluable.

I am very grateful for the emotional support from my family, friends in Canada and in Mexico who always made the effort to keep in touch with me. All of them unconditionally cheered me up.

Abstract

Metaphyton is a poorly studied algal community that can develop into large floating mats in rivers, wetlands and lakes. In this thesis, I examined the role of nutrients in determining differences in metaphyton biomass both seasonally and spatially within a lowland temperate river, the Rideau River, Ontario. The source of nutrients was also examined by analyzing the stable isotope signature of the mats in relation to adjacent land-use.

Metaphyton in the river was restricted to slow-flowing areas of the littoral zone and was mainly comprised of filamentous green algae (*Spirogyra* and *Cladophora*). Areal metaphyton biomass exceeded by several orders of magnitude the areal planktonic biomass in the littoral zone and, at times, exceeded the biomass of attached macrophytes. Metaphyton likely interact with both phytoplankton and macrophytes and compete for some of the same resources. The biomass of metaphyton was negatively correlated with planktonic biomass. While significant correlations were observed between planktonic biomass and water column nutrients (e.g. total phosphorus, total nitrogen), there were fewer and less significant correlations with the metaphyton in the littoral zones along the river. Total phosphorus did explain some of the seasonal variation in biomass (but not chlorophyll-*a*) at a site (Manotick) sampled from May until September 2001. In addition, both seasonally and spatially, the biomass of the metaphyton was significantly correlated with the ratio of NO_3+NO_2 to NH_3 in the water column. This ratio has been proposed as an indicator of natural versus anthropogenic sources of nitrogen in lakes. However, some river sites that were clearly impacted had ratios that would suggest that they were not influenced by anthropogenic activities.

With respect to stable isotope signals, there was a significant difference seasonally in $\delta^{15}N$ of metaphyton at Manotick, with high values in the spring (~9 ‰) which then declined through the summer. Nitrate concentrations were positively correlated with the $\delta^{15}N$ signals seasonally. With respect to land-use, contrary to what was expected, the isotopic signals were high and of similar value at the agricultural sites and urban sites in the city of Ottawa (7.95 *vs.*7.25 ‰, respectively). Lower values were found at sites grouped as light residential. However, $\delta^{15}N$ values of surficial sediments were low at agricultural sites (5.11 ‰) and high at urban sites (7.07 ‰).

There are several possible explanations for the high $\delta^{15}N$ signal of the metaphyton at the agricultural sites. The metaphyton community may have been taking up nutrients from an already heavy isotope source of inorganic nitrogen (e.g. manure and animal excretion). The light isotopic composition of fertilizers may have changed following application to the soils. Finally, the observed signal could be more a reflection of the physiological state of the metaphyton than that of the source signal. Based on the metaphyton C/N ratios, the agricultural sites were on average nitrogen limited, while the urban sites showed less nitrogen limitation. Clearly, additional controlled experiments in the field are necessary for interpretation of stable isotope signals in natural systems.

From the results of this study, conditions for the presence of large metaphyton communities in rivers include: 1) shallow littoral zones with minimal current, 2) the presence of macrophytes (as a substratum), and 3) moderate to high nutrient concentrations (particularly dissolved inorganic nitrogen). To control metaphyton in the Rideau River, the nitrogen loading to the system must be considered as well as phosphorus.

Résumé

Le métaphyton, qui constitue une communauté d'algues peu étudiée, peut former de grands tapis flottants dans les rivières, les milieux humides et les lacs. Dans cette thèse, j'ai analysé le rôle de substances nutritives dans le développement du métaphyton de façon saisonnière et spatiale, le long d'une rivière tempérée à faible gradient, la Rivière Rideau, Ontario. L'origine des substances nutritives a aussi été examinée en analysant la signature d'isotopes stables du métaphyton, et ce en fonction de l'usage des terres adjacentes.

Le métaphyton dans la rivière n'était présent que dans les zones du littoral à faible courant et principalement composé d'algues vertes filamenteuses (*Spirogyra* et *Cladophora*). La biomasse du métaphyton par unité de surface dépassait de plusieurs ordres de grandeur la biomasse planctonique dans la zone littorale et, de temps en temps, dépassait aussi la biomasse des macrophytes. Le métaphyton interagit vraisemblablement avec le phytoplancton et les macrophytes, et compétitionne pour certaines des mêmes ressources. La biomasse du métaphyton était négativement correlée à la biomasse planctonique. Alors que des corrélations significatives ont été observées entre la biomasse planctonique et des substances nutritives de la colonne d'eau (p. ex. phosphore total, azote total), il y avait moins de corrélations significatives avec le métaphyton dans les zones du littoral le long de la rivière. Le phosphore total a expliqué en partie la variation saisonnière de la biomasse (mais non pas celle de la chlorophylle-*a*) à un site (Manotick) échantillonné de mai jusqu'à septembre 2001. De plus, à la fois de façon saisonnière et spatiale, la biomasse du métaphyton était significativement correlée au

rapport de NO_3+NO_2 à NH_3 dans la colonne d'eau. Ce rapport a été proposé comme un indicateur de sources naturelles par rapport aux sources anthropogéniques d'azote dans les lacs. Cependant, quelques sites de la rivière, qui étaient visiblement affectés, avaient des rapports qui suggéraient qu'ils n'étaient pas influencés par les activités anthropogéniques.

Par rapport aux signaux d'isotopes stables, il y avait une différence significative de façon saisonnière dans le signal δN^{15} du métaphyton à Manotick, avec de hautes valeurs au printemps (~9 ‰), qui par la suite ont diminué . Les concentrations de nitrate étaient correlées de façon positive aux signaux δN^{15}. En fonction de l'usage des terres adjacentes et contrairement à ce qui était prévu, les signaux isotopiques étaient élevés et similaires aux sites agricoles et aux sites urbains de la ville d'Ottawa (7.95 vs 7.25 ‰, respectivement). Des valeurs plus basses ont été trouvées aux sites plutôt résidentiels, à faible développement. Cependant, les valeurs de δN^{15} dans les sédiments superficiels étaient basses aux sites agricoles (5.11 ‰) et élevées aux sites urbains (7.07 ‰).

Il y a plusieurs explications possibles pour un signal δN^{15} élevé du métaphyton aux sites agricoles. Le métaphyton aurait déjà pu être exposé à une source d'azote inorganique (p. ex. le fumier et l'excrétion animale). La composition isotopique d'engrais initialement légère a pu changer suivant son application dans les sols. Finalement, le signal observé pourrait plus être un reflet de l'état physiologique du métaphyton qu'un signal de source. D'après les rapports C/N, le métaphyton aux sites agricoles était limité par l'azote, alors qu'aux sites urbains, cette limitation semblait moindre. De toute évidence, d'autres expériences contrôlées sur le terrain sont nécessaires pour l'interprétation des signaux d'isotopes stables dans les systèmes naturels.

À partir des résultats de cette étude, les conditions pour une présence abondante de métaphyton dans les rivières incluent : 1) des zones du littoral peu profondes avec un courant minime, 2) la présence de macrophytes (comme support) et 3) des concentrations nutritives moyennes à élevées (particulièrement en azote inorganique dissous). Pour contrôler le métaphyton dans la Rivière Rideau, les intrants d'azote dans le système doivent être pris en considération tout autant que le phosphore.

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Chapter 1.0

Introduction

1.1 Nutrients in aquatic ecosystems

A major concern around the world is the contamination of aquatic ecosystems by excess nutrient loading. Many researchers agree that human activity has profoundly altered the global biogeochemical cycles of nitrogen and phosphorus (e.g. Vitousek et al. 1997, Carpenter et al. 1998, Smith et al. 1999). Anthropogenic inputs of nitrogen currently add at least as much fixed nitrogen to terrestrial ecosystems, as do all natural sources combined (Vitousek et al. 1997). Large quantities of phosphorus containing fertilizers are heavily applied worldwide even to soils with significant phosphorus reserves (Carpenter et al. 1998). When nitrogen and phosphorus are in surplus they can accumulate in soils, migrate from land to surface or ground waters, or in the case of nitrogen enter the atmosphere via ammonia volatilization and nitrous oxide production.

The nutrients that aquatic systems receive come from a variety of sources. Some of these sources are point sources (e.g. sewage or industrial outfalls) whereas others are non-point sources. Agricultural runoff and urbanization are diffuse sources of nutrients impacting water quality (e.g. Hall et al. 1999, Romeis et al. 1999, Behrendt & Opitz 2000). Stålnacke et al. (1999) found that nutrient losses from agricultural soils were responsible for the major input of nitrogen to some European rivers. Caraco and Cole

(1999) found that fertilizer use was on average responsible for 50 % of the nitrogen inputs to rivers. In addition, they found that nitrate was the form of nitrogen most sensitive to changes in human activities when compared to other forms of dissolved nitrogen.

In Canada, the majority of the wastewater is treated prior to its release to surface waters, but the level of treatment varies greatly. Environment Canada (1996) reported that approximately 6 % of Canadians (1.3 millions) are serviced by sewage collection structures not connected to wastewater treatment facilities. However, perhaps of greater concern, are agricultural and livestock areas located along rivers. These nutrient sources are not monitored or regulated as well as wastewater (Chambers et al. 2001).

Nitrogen and phosphorus exports from both point and non-point sources can affect the quality of receiving waters. Excess nutrient loading can result in significant environmental effects (e.g. loss of component species) as well as substantial economic effects (e.g. loss of amenities or services that these systems provide). The most common result of increases in the inputs of nitrogen and phosphorus is an increase in primary producers including photosynthetic algae and aquatic plants. This is the most commonly observed response to cultural eutrophication identified by the public in general (various authors cited in Smith et al. 1999). In addition to increases in primary production and biomass, increases in specific types of photosynthetic organisms are observed. Increased nutrient loading can give rise to blooms of pennate or centric diatoms, cyanobacteria,

dinoflagellates or filamentous green algal mats in lakes, rivers and estuaries (Allan 1995, Biggs 1996).

Filamentous green algae can form visible assemblages on rocks and other surfaces along littoral zones of lakes, rivers and wetlands. The presence of these algae in littoral zones is due to the low currents and wave shelter provided by aquatic macrophytes and surrounding vegetation. These conditions allow a continuous growth of the algae in the water column while the algae are still partly attached to the substrata yet forming large floating mats. This was the definition of metaphyton given by Behre in 1956 (as cited in Wetzel 2001). More recently, Stevenson (1996) defined metaphyton as the algae of the photic zone that are not directly attached to substrata, or freely suspended in the water column. Previous terms used to describe this community include tychoplankton, pseudoplankton and pseudoperiphyton (Wetzel 2001). Metaphyton may derive from epiphyton (algae growing on macrophytes), epipelon (algae growing on inorganic or organic sediments) or epilithon (algae growing on submerged rocks). *Spirogyra*, *Mougeotia*, *Hydrodictyon* and *Zygnema* are some common filamentous green algae that can form large macroscopic flocculent colonies. Filamentous cyanobacteria, diatoms, bacteria and fungi can also form macroscopic assemblages in the water column or water surface (Round 1981, Stokes 1986, Stevenson 1996, Pillsbury & Lowe 1999, Adrian & Lembi 2000).

Metaphyton is one of the most poorly understood of all algal communities. In the most recent edition of a major textbook in freshwater ecology, Wetzel (2001) indicated

that "information is sparse on their geographical distribution, seasonal population dynamics, utilization of microhabitats, responses to parameters of water movement or water and substratum chemistry or on their interactions with other organisms". Wetzel (2001) concluded "our poor understanding of the complex interactions between the sessile flora and their substrata and the contributions of the attached microorganisms to the total system productivity, represents a major void in contemporary limnology that warrants intensified study".

1.2 Metaphyton ecology

Lakes

In lakes, the development of metaphyton mats has been observed in the littoral zone of acidified lakes. Four mechanisms have been proposed to explain the proliferation of filamentous algae during lake acidification: 1) a physiological preference for low pH that helps maintain high rates of growth, 2) reduced microbial decomposition permitting more biomass to accumulate, 3) decreased competition, and 4) reduced grazing pressure. Some of these hypotheses have not been tested or properly documented (1, 3 & 4) or seem unlikely (2) (Stokes 1986, France et al. 1991). Because of both experimental and empirical evidence, there is little doubt that the dominance of metaphyton in lakes of low pH is related to acidification (Brezonik 1986, Howell et al. 1990).

The threshold pH for the development of filamentous green algae in the littoral zone has not been clearly established. The filamentous green alga *Mougeotia* was abundant in an experiment held at about pH 6.0 (Müller 1980). *Mougeotia* can utilize free CO_2, which predominates at low pH, thus providing it with a competitive advantage during acidification (Raven 1970 as cited in Turner et al. 1987). In contrast, filamentous cyanobacteria, such as members of the Oscillatoriaceae and Nostocaceae (*Lyngbya* (Agardh 1824), *Anabaena* (Bory 1822), *Oscillatoria* (Vaucher 1803)) tend to form reticulated clumps or mats (Gruendling 1971, Turner et al. 1987) in neutral or circumneutral lakes.

The proliferation of filamentous green algae (Chlorophyta) in acidic lakes may be a consequence of changes in grazing pressure or the elimination of specific types of grazing organisms. France et al. (1991) suggested that large fauna, particularly crayfish, are the most likely candidates whose absence or limited abundance may be related to metaphytic blooms.

Some authors suggest that the spatial distribution of metaphyton is dependent on the slope of the lake bottom. Areas of high slope had consistently lower biomass probably because of wave action: the degree of water movement decreases and the hydrostatic pressure increase over 2-m depth (Howell et al. 1990). In shallow protected areas, low hydrostatic pressure may also enhance the development of floating mats by facilitating oxygen bubble growth (Howell et al. 1990). Biomass clearly declines with depth in relation to the attenuation of light (Turner et al. 1987, Howell et al. 1990). It appears that

high light conditions are required for the development of large blooms of filamentous green algae (Pillsbury & Lowe 1999). Acidified lakes often become clearer because of a decrease in dissolved organic carbon that contributes to light attenuation.

Wetlands and Ponds

According to Goldsborough and Robinson (1996), metaphyton is present in wetlands when the nutrient loading is high and the water column is stable as a consequence of the shelter provided by macrophytes or by bordering vegetation. Experimental studies on nutrient addition to wetlands have confirmed this (McDougal et al. 1997, McCormick et al. 2001). Epiphytic algae may develop to the extent that they detach from macrophytes, forming dense mats that carpet the bottom or float to the surface. Mats may persist in the absence of physical disturbance (by wind or animals).

In ponds, metaphyton assemblages have not been investigated specifically. However, Adrian and Lembi (2000) recently examined the autoecology of *Spirogyra*, a filamentous green alga, which formed extensive metaphytic mats in a pond. They found that this particular taxon ranges from benthic to floating. As filaments aggregate and rapidly photosynthesize, oxygen bubbles become trapped in the mats, making them buoyant. At high temperatures and low light, *Spirogyra* cannot maintain optimal rates of photosynthesis. Mat cohesiveness also appears to play a role in the rapid decline of *Spirogyra* populations. The tendency of mats to fall apart increases with temperature and irradiance. These authors did not observe any grazers feeding on filaments and concluded

that herbivory did not play a major role in regulating filament form, abundance and senescence.

Rivers

Studies on the development of metaphyton in rivers are scarce. In a few studies, indirect reference is made to their presence. For example, Silva-Benavides (1998) examined the metaphyton community along with the benthic macroalgae of a tropical river in Costa Rica. Two previous works related to this thesis focused on the Rideau River but did not study the metaphyton directly (Preece 2001, Makkay 2002). An attempt to assess the Rideau River as a whole was made by a group of multidisciplinary researchers (Rideau River Round Table 2001); however, the metaphyton community was sampled only sparsely for qualitative taxonomic analyses.

In the Rideau River, Ontario, metaphytic growth is commonly observed in many reaches, particularly in stagnant littoral areas, that represent hydraulic "dead zones". Their presence has been noted from early spring to September (Preece 2001). These mats are particularly unsightly and are most likely related to excess nutrient loading or food web effects rather than symptomatic of acidification since the Rideau River has fairly high conductivity and is well buffered.

In summary, most studies in metaphyton ecology have focused on the interaction between the development of mats in experimentally acidified lakes and the abundance of

different grazers. However, there are no studies on the characteristics of rivers that might promote the growth of the metaphyton. The relationship between metaphytic algae and nutrient loading has not been specifically quantified, although McDougal et al. (1997) found that nutrient inputs from allochthonous or autochthonous sources triggered the metaphyton development in a wetland. With respect to the Rideau River, metaphyton mats likely arise in the littoral zone of the river perhaps due to nutrient loading from both point and non-point sources. Furthermore, it may be possible to determine the relative importance of some of these sources to mat development by examining the stable isotope composition of metaphyton.

1.3 Stable isotopes in aquatic ecology

Generally, when chemical exchange occurs between two molecules, heavy isotopes concentrate in the molecule where bond strengths are greatest, but most biological reactions involve kinetic isotope effects that can be simply illustrated by physical processes such as diffusion (Peterson & Fry 1987). The isotopic effects or discrimination values are positive in sign when light isotope species react faster than their heavy isotope counterparts, a process known as fractionation (O'Leary 1981).

Stable isotopes record two kinds of information. Where physical and chemical reactions fractionate stable isotopes, the resulting isotopic distributions reflect reaction conditions (process information). Stable isotope distributions also record information about the origin of samples (source information). A well-studied example is carbon

isotope fractionation in photosynthesis. Terrestrial C_3 plants (Calvin cycle) have an average $\delta^{13}C$ of -27.8 ‰. This is approximately 20 ‰ more negative than the source of carbon for plants since the CO_2 in air has a $\delta^{13}C$ of -7.4 ‰. Thus, the plant isotopic composition reflects both source (-7.4 ‰) and fractionation (-20.4 ‰) information (Peterson and Fry 1987). In C_4 plants (Hatch-Slack cycle), the isotopic composition is quite different from that of C_3 plants because of phosphoenolpyruvate (PEP) carboxylase, the initial carboxylating enzyme. Median $\delta^{13}C$ values for C_4 and CAM (Crassulacean acid metabolism) plants cluster closer to about –14 ‰ (Lajtha & Marshall 1994).

In general, the isotopic composition of primary producers is due to the isotopic composition of inorganic nutrients, isotopic fractionation during the uptake and metabolism of those nutrients and by fractionation during respiration (Lajtha & Marshall 1994). In aquatic systems, the $\delta^{13}C$ signal varies between planktonic and benthic algae as well as among macrophytes and there is considerable overlap in values (Table 1.1). This may reflect differences in the source of inorganic carbon (e.g. atmospheric CO_2 versus recycled CO_2 from respiration of organic matter) and or boundary layer diffusion effects (e.g. Hecky & Hesslein 1995).

In contrast to carbon fractionation in photosynthetic pathways, much less is known about the factors that influence variations in isotopic signal of nitrogen at the base of aquatic food webs (e.g. Goericke et al. 1994). Nevertheless, it has been reported that $\delta^{15}N$ signals varied from –4.9 ‰ (submersed macrophytes) up to 15 ‰ (phytoplankton) (Table 1.1). Some of this variation can be due to the source of inorganic nitrogen. For

example, cyanobacteria that fix atmospheric nitrogen have a $\delta^{15}N$ close to the atmospheric value.

Stable isotope ratios have been used in food web studies to provide information about feeding relationships and flow of N or C through communities (Peterson & Fry 1987). Nitrogen becomes isotopically heavier indicating that trophic levels increase in the same order. Minagawa and Wada (1984) found an average $\delta^{15}N$ enrichment of $+3.4 \pm 1.1$ ‰ per trophic level, independently of habitat (Table 1.1).

In contrast, the isotope signal of C changes very little as C flows through food webs (about 1 ‰), but is often used to distinguish between different sources of energy (phytoplankton, macrophyte, allochthonous material). Nitrogen isotopes also reflect the behavior of contaminants in the food web; species that occupy a lower trophic level tend to have the lowest contaminant concentrations (e.g. DDT, PCBs) (Spies et al. 1989, McClelland et al. 1997, Vander Zanden & Rasmussen 1999).

Stable isotopes can help distinguish between the various anthropogenic nitrogen sources entering aquatic ecosystems. Despite processes that fractionate nitrogen (nitrification, denitrification, microbial remineralization, and algal uptake), $\delta^{15}N$ signatures record changes in wastewater inputs to estuaries (McClelland et al. 1997). Differences in the isotope signal ($\delta^{15}N$ and $\delta^{34}S$) of primary producers (e.g. eelgrass, macroalgal species and plankton) can indicate distinct nutrient source entering estuaries (e.g. groundwater or water column) (Canuel et al. 1995, McClelland et al. 1997, Tucker et

al. 1999). In lakes, Cabana and Rasmussen (1996) found that human population densities in the watershed could explain much of the variation in the $\delta^{15}N$ signal of mussels with $\delta^{15}N$ values increasing as a function of human density.

The $\delta^{15}N$ signal of nitrate varies depending on its source. The nitrate from rain has a lighter signal than that in the groundwater (Table 1.1). Thus, if the nitrate is coming from synthetic fertilizers (derived from atmospheric nitrogen) the signal should be lighter than the one from human and animal wastes (urban). Therefore, depending on the environmental compartment, the same nutrient is carrying a different signal (Table 1.1).

1.4 Thesis objectives and hypotheses

The purpose of this research was to determine whether differences in nutrient concentration can explain the distribution and structure of metaphyton along the Rideau River and to identify, based on stable isotope information, the origin of nutrients contributing to metaphyton growth.

I addressed the following general questions:

1. Are nutrient concentrations determining the occurrence of metaphyton along the littoral zones of the Rideau River? In other words, is the presence of metaphyton indicative of eutrophic conditions?

2. Is the metaphyton biomass found along the lower reaches of the Rideau River related to known anthropogenic sources of nutrients (e.g. agricultural, residential (septic systems) and urban (stormwater, combined sewers))?
3. Does the metaphyton have an isotope signal that would allow the identification of the source of nutrients (non-point agricultural origin versus point sources such as combined sewers) causing its development?

I addressed the following three main hypotheses:

Hypothesis 1: The biomass of metaphyton is positively related to nutrient concentrations. I predicted that due to the requirement of primary producers for nitrogen and phosphorus as sources of nutrients, the biomass of metaphyton would be high in the littoral areas with high nutrient concentrations.

Hypothesis 2: The signal of $\delta^{15}N$ in metaphyton will be different depending on the adjacent or upstream nutrient source. I predicted that the metaphyton in agricultural areas would have a light isotope signal due to high nutrient concentration from fertilizers and likely discrimination against the heavier isotope. The metaphyton isotopic nitrogen signal in urban areas would be heavy due to uptake of nitrogen derived from human sources (combined stormwater) and therefore with a heavy isotopic signal (Table 1.1).

Hypothesis 3: While the metaphytic biomass is expected to be positively related with nitrogen and phosphorus concentrations, the nitrogen isotopic signal will be

negatively related to the dissolved inorganic nitrogen (ammonia and/or nitrate) concentrations. I predicted that if the dissolved inorganic forms are high, then the $\delta^{15}N$ signal in the metaphyton biomass should be light due to the discrimination against the heavier isotope.

Table 1.1 Some values of $\delta^{15}N$ and $\delta^{13}C$ for different environmental compartments in aquatic systems.

Environmental Compartments	*$\delta^{15}N$ (‰)*	*$\delta^{13}C$ (‰)*	*References*
Inorganic			
Synthetic fertilizers NO_3	–3 to +3		McClelland et al. 1997
Rain NO_3^- **NH_4^-**	–2 to –15 –6 to 5.2		Moore 1977
Groundwater NO_3^-	+2 to +8		McClelland et al. 1997
Lake water NO_2^-/NO_3^- (Lake Ontario)	–1.70 to 6.06		Cabana & Rasmussen 1994
Seawater (NO_3^-)*	1.1		Matson & Brinson 1990
Particulate inorganic material		–15 to –16	Spies et al. 1989
Dissolved Inorganic Carbon Marine* Freshwater		 –1.5 to –2.2 –12.7 to –12.9	Matson & Brinson 1990
Soil Total Nitrogen	 –1 to 17.0		 Moore 1974
Organic			
Increase value in consumers relatively to their food source	2 to 5 (Mean = 3.4)		Minagawa & Wada 1984, Peterson & Fry 1987
Primary producers	–4.9 to 13.6	–12.3 to –32	Neill & Cornwell 1992
Metaphyton *Enteromorpha intestinalis* & *Chaetophora* sp. *Cladophora vagabunda*	 –0.6 to 13.6 5 to 9	 –15 to –24.3	 Neill & Cornwell 1992 McClelland et al. 1997
Periphyton	3 to 6.2 –1.06 to 2.74	–24 to –27.5 –8.1 to –30.1	Neill & Cornwell 1992 Hecky & Hesslein 1995
Phytoplankton Marine* Freshwater	5 to 15	–21.4 to –35.7 –15.3 to –35.6 –21.0 to –24.8	Van Dover et al. 1992 Matson & Brinson 1990 Hecky & Hesslein 1995
Particulate organic carbon **Seston** (estuaries)		 –18.5 to –26	 Gearing et al. 1991
Macrophytes Emergent Submersed (*Potamogeton pectinatus*) Floating (*Lemna minor*)	 2 to 5 –4.9 to 1.6 –1.6 to 13.5	 –24.4 to –28.3 –12.3 to –20.2 –25.2 to –32.0	Neill & Cornwell 1992
Seaweed	8.1		Hoering 1955
Zooplankton (primary consumers)	–2 to 9	–19.5 to –46	Vander Zanden & Rasmussen 1999
Adult lake trout	7.5 to 17.5		Cabana & Rasmussen 1994

Table 1.1 Continued.

Particulate organic matter			
Marine water*	8 to 12	–19 to –21	Matson & Brinson 1990
Lake water		–19.8 to –30.8	Leggett et al. 2000
Surface sediments	3.7 to 7.3	–22 to –28	Gearing et al. 1991, Voβ & Struck 1997, Tucker et al. 1999
Sewage	–1.1 to 7.2	–16.5 to –26	Spies et al. 1989, Van Dover et al. 1992
Dissolved organic carbon			Matson & Brinson 1990
Marine*		–20.7	
Freshwater		–24.1 to –26.2	
Soil			
Organic Nitrogen	–5 to 25.4		Moore 1974

* Atlantic coastal water

Chapter 2.0

Materials and methods

2.1 Study site: the Rideau River

The Rideau River is a medium size temperate lowland river. It is primarily lake fed, flowing from Upper Rideau Lake in Eastern Ontario, for close to 100 km before discharging into the Ottawa River at Ottawa. The system as a whole is moderately enriched (average total phosphorus concentration 34.8 $\mu g\ L^{-1}$) and in general, there is an increase in both total nitrogen and total phosphorus with distance downstream in the main channel (Basu & Pick 1995, 1997). Along the Rideau River, several human activities are present: urban developments including point source discharges to the river, plant crops, and livestock farms (Census of Agriculture 2001). Unfortunately, a nutrient budget for the river or a source apportionment study has not been established and the relative importance of the various sources of nutrients to the river has not been quantified (Rideau River Roundtable 2001).

Metaphyton can be found in the littoral zone of the river (< 2 m) rather than in the main channel of the river, which is the area normally sampled in monitoring programs. This study focuses on the littoral zone of the river.

2.1.1 Sampling sites

A site located within the village of Manotick (Fig. 2.1, site 8 in Table 2.1) was chosen for sampling seasonally from May until September 2001 (May 1st, 15th, June 19th, August 15th & September 1st). This site was chosen due to the presence of metaphytic mats in early spring and ease of access from the launch next to the Manotick public library. A Magellan 2000 XL Satellite Navigator GPS was used to determine the site coordinates (45° 13.88' N, 75° 40.74' W).

Twelve sites were also chosen along the river, between Burrits Rapids and the city of Ottawa (Fig. 2.1). These were chosen depending on the adjacent land use (visual inspection, Table 2.1). Sites 1, 2, 3 and 4 were located mainly in agricultural areas, 5, 6, 7 and 8 (Manotick) near light residential areas, and 9, 10, 11 and 12 in the urban area of Ottawa (Table 2.1, Fig. 2.1).

There is no specific classification of the land use along the Rideau River watershed. However, Statistic Canada (Census of Agriculture 2001) reports data from those geographic areas through which the Rideau River flows: Ottawa Division, Leeds and Grenville United Counties, Edwardsburgh/Cardinal, Merrickville-Wolford, North Grenville, Lanark County and Montague. Alfalfa and alfalfa mixtures, hay and fodder crops, corn for grain, and soybeans are cultivated for more than 60 % of the farms in the Ottawa Division (Census of Agriculture 2001). Dairy and beef farming also represent a well-developed industry at this geographical division. The Canadian Land Inventory

determined that the major land use along the length of the Rideau River comprising Merrickville and the city of Ottawa are pastures (60 %), followed by urban and suburban areas (30 %) and other (10 % woodland, wetlands and recreation).

Thus, based on visual inspection from Burrits Rapids to the town of Kars, four sites were chosen adjacent to farms or field crops and were ascribed to the agricultural group (Table 2.1, Fig. 2.1).

Besides the urban area corresponding to downtown Ottawa, the section of the Rideau River from Kars to Manotick is the most densely inhabited sector with more than 50 % of the natural vegetation replaced by inert material (e.g. concrete, gabions, rocks), and almost 27 % of the natural vegetation replaced by lawns or modified in a certain way. Thus, sites 5, 6, 7 and 8 were ascribed to the light residential group (Table 2.1, Fig. 2.1).

Sites 9, 10, 11, and 12 are located within the downtown area of the City of Ottawa, which has several stormwater outfalls to the Rideau River. These were the sites corresponding to the urban group (Table 2.1, Fig. 2.1).

2.2 Field sampling and *in situ* measurements

2.2.1 Variables measured *in situ*

At each site and sampling date, basic physical and chemical information on water column conditions was collected using a Hydrolab Minisonde 4a water quality multiprobe (water temperature, conductivity, pH, and dissolved oxygen). Depth was also recorded. Irradiance was measured with a LiCor 4π photometer (model LI-185B) at depth intervals of 0.5 m respectively, in order to calculate light extinction coefficients (Wetzel & Likens 1991).

2.2.2 Water sampling

At each sampling event, water samples were taken with a 1 L Nalgene bottle attached to a pole, which was raised and lowered at a constant rate through the water column. Care was taken to avoid disturbing macrophytes, metaphyton or sediments when positioning the boat. Two replicates of integrated water samples were taken for nutrient analyses and estimates of plankton biomass (ash free dry mass) and chlorophyll-*a*.

2.2.3 Metaphyton sampling

Metaphyton, because of varying growth habits (attached and spreading), is difficult to sample. An entire water column of 0.25 m^3 was strained through a fine mesh sieve. The water column was isolated using an aluminum cage (0.5 m x 0.5m x 1.0 m) wrapped with mosquito netting and open at both ends. At each site, three such columns were randomly chosen and separated by at least 5 or 10 m, taking care to avoid disturbing the metaphyton mats and sediments.

2.2.4 Sediment sampling

Two sediment samples were collected at each site during the 2001 sampling season. The first centimetres of surficial sediment were sampled manually with a large Petri dish as a core, collecting each time approximately 74 cm^3. The sediment was kept frozen until analysed.

2.3 Laboratory analyses

2.3.1 Water samples

Water samples were stored in 300 ml clear polyethylene terephtalate glycol (PETG) bottles for nutrient analyses including total phosphorus (TP), total nitrogen (TN) and the soluble forms of nitrogen (NH_3, NO_2+ NO_3) and phosphorus (reactive phosphate, RP). Nutrient analyses were performed within 24 hours of collection at the Regional Municipality of Ottawa-Carleton (now City of Ottawa) Robert O. Pickard Environmental Center Laboratory using the protocols of the Ontario Ministry of Environment and Energy. These analytical protocols are detailed in Chételat et al. (1999). The detection limits were 0.005 mg L^{-1} for TP, 0.010 mg L^{-1} for TN, 0.003 mg L^{-1} for both NH_3 and NO_2+NO_3, and 0.002 mg L^{-1} for RP.

For plankton chlorophyll-*a* analyses, 500 ml of water sample were filtered through Whatman GF/C glass fiber filters (pore size ~ 1.2 μm). Pigments were extracted

with dimethyl sulfoxide (DMSO) and acetone heated at 65 °C for 10 min (Burnison 1980). Chlorophyll-*a* concentrations were calculated using the equation of Jeffrey and Humphrey (1975).

For estimates of ash free dry mass (AFDM) 500 ml of water were filtered through pre-ashed and pre-weighed Whatman GF/C filters (~ 1.2 μm). Filters were then dried at 80 °C for 24 hrs, weighed to estimate dry mass, ashed at 500 °C for four hours, and re-weighed to estimate the organic material lost upon combustion.

2.3.2 Metaphyton samples

The mat samples were cleaned of debris and higher plants to estimate dry weight, and chlorophyll-*a*. The non-metaphyton and the proportion of metaphyton were recorded and when possible, the plant species were identified.

On average, 5 g or less (depending on the sample biomass) of the mat was cleaned as much as possible trying to get a "pure" metaphyton sample. This subsample was blended with 0.3 L or less of river water, but always trying to get the same volume proportion (e.g. 5 g of sample for 0.3 L of water, 2.5 g of sample 0.15 L of water). From this blending four subsamples of 2 ml were taken: two subsamples for chlorophyll analyses and two more for dry weight measurements. They were preserved frozen at –20 °C.

The metaphytic chlorophyll results (g m^{-2}) were calculated as follow:

[ ] Chl-*a* MS * VB = Chl-*a* VB

(Chl-*a* VB * MADW)/ SSDW = [ ] MChl-*a*

[ ] = Concentration

MS = Metaphyton subsample (wet weight) (g L^{-1})

VB = Volume blended (L)

MADW = Metaphyton areal dry weight (g m^{-2})

SSDW = Subsample dry weight (g)

MChl-*a* = Metaphyton chlorophyll-*a* (g m^{-2})

2.3.3 Sediment analysis

Sediment organic matter was estimated by loss-on-ignition (LOI) as described by Ben-Dor and Banin (1989 in Soil and plant analysis council, Inc. 2000). Samples were dried for four hours at 105 °C, to obtain the sediment dry weight (W_{105}). Afterwards, samples were ashed in a muffle furnace at 400 °C for 4 hours, left to cool to room temperature in a dry atmosphere, and then reweighed (W_{400}). The percent of organic matter (OM) content was calculated as:

$$\% \text{ OM} = \left[(W_{105} - W_{400}) * 100 \right] / W_{105}$$

2.3.4 Sample preparation for stable isotope analysis

Metaphyton material

A 10 g-wet weight of the metaphyton sample was cleaned from debris, frozen, freeze-dried and ground. $\delta^{15}N$ and $\delta^{13}C$ analyses were carried out on each of the three-metaphyton samples taken at each sampling time and location. For each sample, two subsamples were analyzed to estimate the measurement error.

The algal material was freeze-dried at -16 °C to -20 °C for 3 to 4 days, ground and stored in glass vials. Then, 0.8 mg of metaphyton was weighed in order to obtain the $\delta^{13}C$ and $\delta^{15}N$ signals.

Sediment material

Sediment samples were freeze-dried at -16 °C to -20 °C for 3 days. Subsequently, the samples were ground and stored in glass vials. Then, 2.5 mg of each sample was weighed for the $\delta^{13}C$ and $\delta^{15}N$ analyses.

$\delta^{13}C$ and $\delta^{15}N$ analyses

Metaphyton and sediment analyses were all carried out at the G.G. Hatch Isotope Laboratories, University of Ottawa. Samples were analysed by continuous flow isotope

mass spectrometry. An automated CE Instrument EA-110 (elemental C and N analyzer) was coupled to a Finnighan Mat Delta^{plus} IRMS with a Conflow II Interface. The metaphyton and sediment samples were flash combusted at 1800 °C under a continuous stream of O_2. Both isotopes were measured by separating N_2 and CO_2 gases with a chromatographic column. Helium gas was used to carry both gases to the mass spectrometer. The precision for the samples was ±0.2 ‰ on the isotopes and 1 % on the percentages.

Conventionally, the δ notation in the stable isotope ratios is reported relative to international standards (air for nitrogen, and Vienna Peedee belemnite for carbon) and defined by the following expression:

$$\delta^{13}C \text{ or } \delta^{15}N\ (‰) = [(R_{sample}/ R_{standard}) - 1] \times 1000$$

Where,

$R = {}^{15}N/{}^{14}N$ or ${}^{13}C/{}^{12}C$

The percent C and percent N data were used to calculate C/N atomic ratios.

2.4 Statistical analyses

2.4.1 Temporal variation at one river site (Manotick)

In order to test whether there were temporal variations in metaphyton biomass at the Manotick site, univariate repeated measures ANOVA were performed. For the results to be valid, the standard assumptions of the ANOVA must hold, and additionally, the data must be compound symmetric (variances among the fixed factor (dates, in this case) should be the same). When compound symmetry failed, then the G-G (Greenhouse-Geisser Epsilon) and H-F (Huynh-Feldt Epsilon) test statistics were used (Sokal & Rohlf 1981, Zar 1999). When the repeated measures ANOVA did not show any significant differences among dates, then a one-way ANOVA was used.

Linear regression or Pearson product-moment correlations along with Bonferroni adjusted probabilities were conducted to test the strength of the linear relationships among the different variables at the site.

The biological variables of interest were metaphyton biomass ($biomass_{meta}$), metaphytic chlorophyll-*a* ($Chl\text{-}a_{meta}$), planktonic chlorophyll-*a* ($Chl\text{-}a_{plank}$), and planktonic biomass ($biomass_{plank}$). Other biological variables of interest were $\delta^{15}N_{metaphyton}$, $\delta^{13}C_{metaphyton}$, $\%N_{metaphyton}$, $\%C_{metaphyton}$, $C/N_{metaphyton}$ ratio, $\delta^{15}N_{sediment}$, $\delta^{13}C_{sediment}$, $\%N_{sediment}$, $\%C_{sediment}$, $C/N_{sediment}$ ratio. Physical and chemical variables included the light extinction coefficient (m^{-1}), temperature (T °C), dissolved oxygen (DO), percentage dissolved oxygen (%DO), pH, TN, TP, RP, %RP, NO_3+NO_2, NH_3, NO_3+NO_2/NH_3, and TN/TP.

2.4.2 Spatial variation within the Rideau River

First, in this study, it was hypothesized that the metaphyton biomass in the littoral zones was a positive linear function of nutrient concentration. Thus, linear regression analyses were conducted with the metaphyton biomass and metaphytic chlorophyll-*a* as the dependent variables and nutrients (i.e. TP, TN, NH_3, NO_3+NO_2, %RP, RP, TN/TP ratio and NO_3+NO_2/NH_3 ratio) as the independent variables. Prior to these analyses, a visual inspection of the relationships was conducted to confirm that linear regression was the appropriate test. Additionally, metaphytic and planktonic chlorophyll-*a* and biomass were also linearly associated with nutrients and isotopic signals and percent nitrogen and carbon of the metaphyton and sediments using Pearson product-moment correlation or Spearman correlation. Furthermore, variables such as temperature, extinction coefficient, dissolved oxygen, and percent dissolved oxygen were related with the prior dependent variables. The relationships between various independent variables with the metaphyton were compared with the plankton as both communities could compete for the same resources.

Second, it was expected that depending on the land use the $\delta^{15}N$ isotope signal in the metaphyton biomass would be lower at agricultural areas than the urban areas. As explained above (Section 2.1.1), the 12 sampled sites were classified into three main groups, depending on the adjacent land use: 1) agricultural group (AG), 2) light-residential group (RG) and 3) urban group (UG).

To test for differences in isotope composition among the agricultural, light residential and urban groups, a parametric Nested ANOVA was carried on the $\delta^{15}N$ of the metaphyton along with Bonferroni adjusted probabilities for *post-hoc* comparison among groups. Similar tests were conducted for the metaphyton chlorophyll-*a*, $\delta^{13}C$, percent N, percent C, C/N ratio, TN, NH_3, NO_3+NO_2, TP, RP, percent RP, TN/TP ratio and NO_3+NO_2/NH_3 ratio. Afterwards, Pearson product moment correlations among linearly related variables were carried on. In addition, since the metaphyton could be taking up nutrients from the sediments, the association of the isotope signal with sediment variables was similarly analyzed. The nested-ANOVA was carried out on the biomass, chlorophyll-*a*, and isotopic composition of the metaphyton estimated in triplicate.

Pooled variance t-tests with Dunn-Sidak adjusted probabilities were used to test *a priori* differences in concentrations of the variables between the littoral zone and the main channel. When the parametric assumptions failed, Mann-Whitney test was performed (Sokal & Rohlf 1981, Zar 1999).

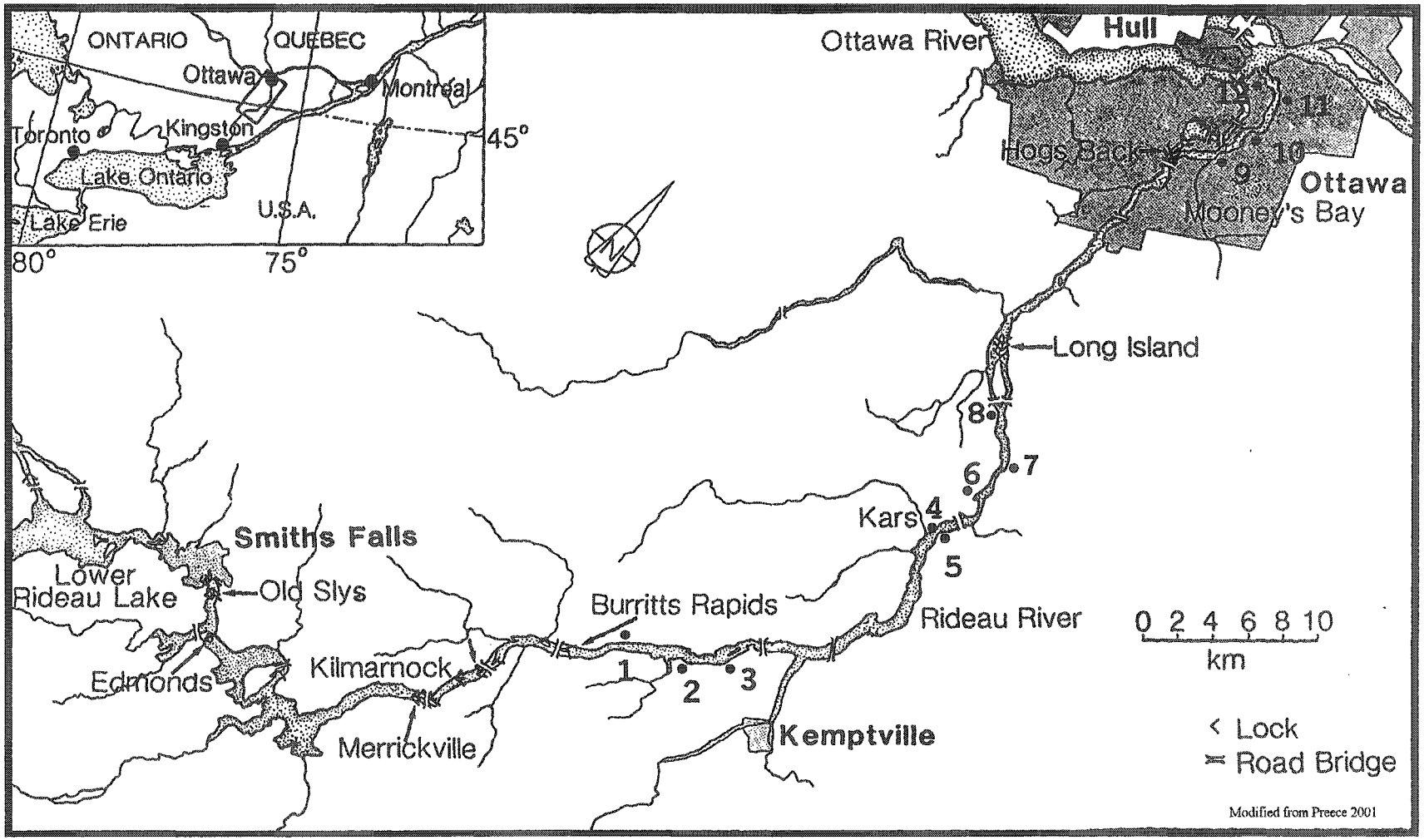
To determine whether linear regression and correlations were appropriate for the data, a scatterplot of the different dependent variables versus the independent variables was produced. Logarithmic transformation and/or square root transformations of the variables were used in order to meet the assumptions of normality, homoscedasticity and independence of residuals. When those assumptions were not met, non-parametric analyses were performed (Sokal & Rohlf 1981, Zar 1999).

All the statistical analyses were conducted with Systat 10 (SPSS Inc. 2000). Results were considered significant when $p \leq 0.05$.

Table 2.1 Name and geographic location of the 12 sites sampled along the lower section of the Rideau River. Some site names are assigned according to the nearest landmark. Groupings are assigned as Agricultural Group (AG), Residential Group (RG) and Urban Group (UG). Kilometer zero corresponds to where the Rideau flows into the Ottawa River.

Sites (km)	Sites Name and Grouping	Geographic Coordinates	
1 (72.0)	Burrits Rapids (AG)	45° 01.31'	75° 43.48'
2 (68.0)	Murphy Drain (AG)	45° 01.34'	75° 42.73'
3 (64.5)	Libby Island (AG)	45° 01.86'	75° 41.82'
4 (49.3)	Kars (AG)	45° 09.07'	75° 38.64'
5 (48.0)	Sanders Island (RG)	45° 09.40'	75° 38.16'
6 (46.5)	Golf Course (RG)	45° 10.84'	75° 38.19'
7 (35)	Beach Mark 285 (RG)	45° 12.21'	75° 38.63'
8 (27.5)	Manotick (RG)	45° 13.88'	75° 40.74'
9 (7.0)	Bank Street (UG)	45° 23.46'	75° 40.56'
10 (4.5)	St. Paul University (UG)	45° 24.88'	75° 40.14'
11 (1.0)	St Patrick Street (UG)	45° 26.31'	75° 40.84'
12 (0.0)	Maple Park (UG)	45° 26.18'	75° 41.22'

Figure 2.1 Sampling sites located along the lower part of the Rideau River. Site number eight corresponds to Manotick. Sites 1 to 4 were ascribed to the agricultural group, sites 5 to 8 to the light residential group and 9 to 12 to the urban group.


ONTARIO
QUEBEC
Ottawa
Montreal
Toronto
Kingston
Lake Ontario
Lake Erie
U.S.A.
45°
80°
75°
Ottawa River
Hull
Hogs Back
Ottawa
Mooney's Bay
Long Island
Kars
Smiths Falls
Lower
Rideau Lake
Old Slys
Burritts Rapids
Rideau River
Edmonds
Kilmarnock
Merrickville
Kemptville
1
2
3
4
5
6
7
8
9
10
11
0 2 4 6 8 10
km
Lock
Road Bridge
Modified from Preece 2001

Chapter 3.0

Results

3.1 Seasonal changes at Manotick site

3.1.1 Comparison between the main channel and the littoral zone

Over the sampling period the nutrient concentrations (TN, TP, NO_3+NO_2, DIN (NH_3 + NO_3+NO_2), and other variables such as temperature and conductivity were not significantly different between the Manotick littoral zone and the main channel (Tables 3.1.1 & 3.1.2). The temperature was slightly higher in the littoral zone than in the main channel but not statistically different ($p > 0.05$). However, the pH on average was higher in the littoral zone than in the main channel ($p = 0.034$). Also, the dissolved oxygen, and percent dissolved oxygen were on average higher in the littoral zone. The planktonic biomass (ash free dry weight) and chlorophyll-*a* were lower in the littoral zone than in the main channel where macrophytes and metaphyton were more abundant (Tables 3.1.1 & 3.1.2).

Overall, planktonic biomass values were too low given established biomass:chlorophyll-*a* or carbon:chlorophyll-*a* ratios (Descy & Gosselain 1994). This may have been due to the fact that the filters were not pre-washed prior to use. Loss of

glass fibers during filtration can lead to underestimation of seston weight (D. Lean, University of Ottawa, pers. comm.).

3.1.2 Comparison among dates and seasonal trends

Temperature, pH and percent dissolved oxygen

As the summer progressed, the water temperature increased (Fig. 3.1.1) and the differences among the dates were statistically significant (Bonferroni adjustment $p < 0.0001$). The dissolved oxygen decreased, this decline being significant between the May 15th (Julian day 133) and August 15th (Julian day 227) sampling dates (Bonferroni adjustment $p = 0.035$) (Fig. 3.1.1). However, the percent dissolved oxygen remained above saturation whereas in the main channel it dropped below saturation in late summer. The pH values peaked in mid-summer and decreased by August 15th as did the dissolved oxygen, but there were no significant pH differences among the dates (One-way ANOVA, $R^2 = 0.644$, F-ratio = 3.018, $p = 0.133$).

Seasonal trends of nutrients

Both dissolved forms of inorganic nitrogen were highest during the spring (May 1st; Julian day 121). Ammonia declined, but then increased as the summer progressed, while nitrate continued to decline and reached detection levels (0.003 mg L^{-1}) by late summer (Fig. 3.1.2). There were no differences among the dates in terms of the nitrate,

but ammonia decreased significantly between the first sampling date (121 Julian day) and the second one (133 Julian day). The increase of ammonia between the first and third (170 Julian day) dates was significant (Bonferroni adjustment $p \leq 0.020$) (Fig. 3.1.2).

The total phosphorus (TP) and reactive phosphorus (RP) increased as the summer progressed. At the last date, in early September, TP decreased while the RP increased (Fig. 3.1.2). The increase of TP was significant between Julian days 121 and 170 (Bonferroni adjustment $p = 0.076$) and between 133 and 227 (Bonferroni adjustment $p \leq 0.05$). The RP varied significantly among dates (One-way ANOVA, $R^2 = 0.974$, F-ratio = 56.864, $p < 0.0001$). This variable decreased significantly after the Julian day 133, but increased afterwards (Bonferroni adjustment $p \leq 0.043$).

Seasonal trends in biomass, chlorophyll-*a* and the metaphyton isotopic signal

The biomass and chlorophyll-*a* of the metaphyton increased as the summer progressed to decline on the last sampling (September 1st) (Fig. 3.1.3). The increase of metaphytic biomass and chlorophyll-*a* concentration was statistically significant mainly between Julian days 170 and 227 (Bonferroni adjustment $p \leq 0.009$), and for the biomass, between the dates 133 and 227 as well (Bonferroni adjustment $p \leq 0.029$). The planktonic biomass showed similar values for first three sampling dates, while the planktonic chlorophyll-*a* increased over the same time period (Fig. 3.1.3).

The $\delta^{15}N$ signal of the metaphyton was highest in the spring and decreased towards the end of the summer (Fig. 3.1.4). There were differences among dates (One-way ANOVA, $R^2 = 0.729$, F-value = 8.074, $p = 0.002$), but only between Julian days 121 and 242 and between 133 and 242 were significantly different (Bonferroni adjustment $p \leq 0.050$).

The $\delta^{13}C$ signal in the metaphyton fluctuated during the sampling season (One-way ANOVA, $R^2 = 0.532$, F-value = 3.415, $p = 0.044$). Except for a significant increase between Julian days 133 and 170 (May 15th and June 19th, respectively) (Bonferroni adjustment $p = 0.056$). However, there were no other differences among the dates (Fig. 3.1.4).

Metaphyton biomass and chlorophyll-*a*: linear relationships

The metaphytic biomass and chlorophyll-*a* concentration varied among the samples on a given date. Thus, it was decided to conduct the linear regressions and correlations not by averaging the values, but by using the individual paired samples of metaphyton and water column nutrients from each date in the case of Manotick and from each site for the longitudinal study.

Some nutrients were significantly related with the metaphytic biomass and chlorophyll-*a* over the whole sampling season. Results of the linear regression analyses showed that the metaphyton biomass increased with total phosphorus (Table 3.1.3).

However, the metaphyton chlorophyll-*a* was not related to water column TP, NH_3 or NO_3+NO_2. However, the ratio of NO_3+NO_2/NH_3 was significantly negatively related with both metaphyton measures (Table 3.1.3, Figs. 3.1.5 & 3.1.6).

It should be noted that the relationships with RP, percent RP and the ratio TN/TP, were significant when a single point with high metaphytic chlorophyll-*a* and biomass values was excluded from the analysis (Table 3.1.3).

$\delta^{15}N$ signal from the metaphyton biomass, linear relationships and associations among variables

The $\delta^{15}N$ signal of the metaphyton was negatively related to the temperature, light extinction coefficient, RP and TP ($p < 0.05$) (Table 3.1.4). In addition, there was a positive relationship of the $\delta^{15}N$ with NO_3+NO_2, DIN, NO_3+NO_2/NH_3, and TN/TP.

The relationships between the $\delta^{15}N$ signal and most biological variables (planktonic biomass and chlorophyll-*a* and metaphyton chlorophyll-*a*) tended to be negative but were not significant ($p > 0.05$). However, the relationship between the $\delta^{15}N$ and the metaphyton biomass was negative and significant ($n = 16$, $R^2 = 0.364$, Coefficient = -0.583, F-value = 7.999, $p = 0.013$). In contrast, there were no significant relations between the $\delta^{13}C$ signals of the metaphyton and any nutrient or physical variable (temperature and light extinction coefficient).

Some variables were significantly associated among one another. For example, TN and TP were positively correlated ($n = 11$, $R_{Correlation\ Coefficient(CC)} = 0.776$, $p = 0.005$); TN and DIN ($NO_3 + NO_2 + NH_3$) were negatively associated ($n = 11$, $R_{CC} = -0.620$, $p = 0.041$). Interestingly, the $\delta^{15}N$ in the metaphyton was negatively associated with the $\delta^{15}N$ signal of the sediments ($n = 8$, $R_{CC} = -0.845$, $p = 0.017$). Also, the $\delta^{13}C$ of the metaphyton was negatively associated with the $\delta^{13}C$ in sediments, but this correlation was not statistically significant ($p = 0.142$). Also of note are the strong associations of the $\delta^{15}N$ in sediments with both TP and TN/TP ratio ($n = 7$, $R_{CC} = 0.837$, $p = 0.019$ and $n = 7$, $R_{CC} = -0.852$, $p = 0.015$, respectively). Finally, the RP was negatively correlated with the conductivity ($n = 9$, $R_{CC} = -0.960$, $p < 0.001$).

The raw data for the various measurements and analyses related to the Manotick site can be found in Appendix 1.

3.1.4 Metaphyton community composition

The metaphyton community changed through the season at the Manotick site. Three genera largely comprised this community: *Spirogyra* Link 1820 (Chlorophyte), *Cladophora* Kuetzing 1843 (Chlorophyte) and *Lyngbya* Agardh 1824 (Cyanobacterium). At least 98% of the total biomass was composed of *Spirogyra* spp. *Cladophora glomerata* (L.) Kuetzing 1845 was hardly evident at the beginning of spring, but became more abundant as the summer progressed. The cyanobacterium *Lyngbya* sp. only appeared at the end of the summer (Table 3.1.5).

The *Spirogyra* species encountered differed in cell size, particularly at the beginning of spring. *Spirogyra ellipsospora* Transeau 1914 cells are rectangular while *Spirogyra crassa* Kuetzing 1843 cells are quadrate; also the strands of *S. ellipsospora* are narrower than the strands of *Spirogyra crassa* (Table 3.1.6) and its spiral chloroplast is more compacted than the latter species. *S. ellipsospora* was persistent through out the whole sampling period and, as the summer progressed underwent morphological changes (length of cells) (Table 3.1.6) and several sexual reproduction cycles (zygospore production).

Based on visual inspection of the entire sample *in situ*, it was possible to locate *Cladophora glomerata* in the mat. This dark green-colored filamentous alga is rough to the touch and was usually located at the bottom of the metaphyton mats. At the beginning of the sampling, it may have been unnoticed *in situ*, but as the summer progressed, the abundance of this species increased and became more evident.

Table 3.1.1 Comparison of variables at the Manotick littoral zone (LZ) versus the main channel (MC) during four sampling dates. Date one was excluded for the comparison because the main channel was not sampled at the same time. Means statistically significant, according to the pooled variance t-test, are in bold ($p < 0.05$) and values in italics are means slightly rejected.

Variable	n of Cases	Mean	Std. Error	Minimum	Maximum
Biomass	$LZ_{metaphy}$ (14)	**89.42**	38.63	3.02	435.36
(gdw m^{-2})	$LZ_{plankton*}$ (7)	0.001	0.0003	0.0004	0.002
	$MC_{plankton*}$(4)	0.003	0.001	0.001	0.005
Chl-*a* (g m^{-2})	$LZ_{metaphy}$ (14)	**0.784**	0.46	0.008	6.58
	$LZ_{plankton*}$ (9)	**0.006**	0.0006	0.004	0.010
	$MC_{plankton*}$(5)	**0.023**	0.007	0.010	0.041
TN (µg L^{-1})	LZ (9)	744.96	46.30	554.00	921.70
	MC (7)	658.90	46.46	568.00	928.60
NH_3 (µg L^{-1})	LZ (9)	15.56	3.90	3.00	30.00
	MC (7)	14.29	4.09	7.00	32.00
NO_3+NO_2	LZ (9)	4.74	1.90	2.50	20.00
(µg L^{-1})	MC (7)	10.19	3.47	2.60	20.00
NO_3+NO_2/ NH_3	LZ (9)	0.60	0.26	0.083	2.50
	MC (7)	1.21	0.47	0.087	2.85
TP (µg L^{-1})	LZ (9)	50.00	6.38	21.00	81.00
	MC (7)	34.87	5.06	24.00	53.00
RP (µg L^{-1})	LZ (9)	15.00	3.45	4.00	27.00
	MC (7)	12.28	4.09	3.00	28.00
Percent RP (%)	LZ (9)	*8.55*	2.56	1.68	19.44
	MC (7)	*5.17*	2.32	1.38	14.84
TN/TP	LZ (9)	16.54	1.77	10.48	26.38
	MC (7)	20.62	2.11	12.63	25.21
Temperature (°C)	LZ (18)	21.57	0.89	17.96	26.33
	MC (29)	21.36	0.61	16.87	26.10
Percent Oxygen	LZ (18)	**123.13**	7.08	76.90	200.00
(%)	MC (29)	**104.13**	7.74	1.90	189.90
Oxygen (mg L^{-1})	LZ (18)	**11.08**	0.75	6.30	20.00
	MC (29)	**9.37**	0.73	0.17	18.34
pH	LZ (18)	**8.30**	0.09	7.34	9.10
	MC (29)	**7.99**	0.10	6.92	9.03
Conductivity	LZ (30)	267.85	4.57	235.10	304.80
(µS cm^{-1})	MC (29)	268.11	2.95	242.70	305.00

* Planktonic weight refers to ash free dry weight.

Table 3.1.2 Basic statistics for all the variables analyzed in the littoral zone at Manotick. Mean, standard error (coefficient of variation), minimum and maximum values during five sampling dates.

Variable*	n of Cases	Mean	Std. Error	Minimum	Maximum
$Biomass_{metaphyton}$	17	74.14	32.66 (181.60)	0.69	435.36
Chl-$a_{metaphyton}$	17	0.648	0.38 (245.31)	0.002	6.58
$Biomass_{plankton}$	7	0.001	0.0003 (48.08)	0.0004	0.002
Chl-$a_{plankton}$	10	0.006	0.001 (38.16)	0.003	0.010
TN	11	705.79	45.87 (21.6)	506.00	921.70
NH_3	11	21.45	5.08 (78.5)	3.00	51.00
NO_3+NO_2	11	19.34	9.93 (170.4)	2.50	90.00
NO_3+NO_2/ NH_3	11	0.816	0.25 (103.8)	0.083	2.50
TP	11	44.54	6.33 (47.1)	20.00	81.00
RP	11	13.27	3.02 (75.5)	4.00	27.00
%RP	11	29.67	4.50 (50.3)	7.69	54.00
TN/TP	11	18.35	1.89 (34.1)	10.48	27.65
Temperature	21	20.68	0.90 (20.07)	15.14	26.33
Ext. Coefficient	11	1.93	0.33 (56.6)	0.475	3.43
Percent Oxygen	21	121.42	6.15 (23.21)	76.90	200.00
Oxygen	21	11.11	0.65 (26.76)	6.30	20.00
pH	21	8.28	0.08 (4.69)	7.34	9.10
Conductivity	21	267.83	3.91 (6.69)	235.1	304.80
$\%N_{metaphyton}$	17	3.05	0.18 (25.37)	1.91	4.38
$\delta^{15}N_{metaphyton}$	17	5.95	0.43 (30.08)	3.21	8.97
$\%C_{metaphyton}$	17	38.86	1.21 (12.88)	30.45	45.31
$\delta^{13}C_{metaphyton}$	17	-20.78	1.29 (25.67)	-36.24	-12.48
$C/N_{metaphyton}$	17	13.40	0.81 (25.00)	8.70	19.65

* Units: Biomass (gdw m^{-2}) and chlorophyll-*a* (g m^{-2}), TN, TP, NH_3, NO_3+NO_2, RP (µg L^{-1}), Temperature (°C), Oxygen (mg L^{-1}), extinction coefficient (m^{-1}), conductivity (µS cm^{-1}), $\delta^{15}N$, $\delta^{13}C$ (‰). Planktonic weight refers to ash free dry weight.

Table 3.1.3 Linear regressions of the metaphyton biomass and chlorophyll-*a* with nutrients at Manotick during five sampling dates spring-summer 2001.

		Metaphyton biomass			
Independent variables	**n of Cases**	**R^2**	**Coefficient**	**F-value**	**p-value**
RP	10	0.641	2.258	14.275	0.005
Percent RP	10	0.661	1.463	15.618	0.004
TP	11	0.416	2.908	6.425	0.032
TN/TP	10	0.544	-0.889	9.550	0.015
NO_3+NO_2/NH_3●	11	0.497	-1.519	8.883	0.015
		Metaphyton chlorophyll-*a*			
Independent variables	**n of Cases**	**R^2**	**Coefficient**	**F-value**	**p-value**
RP	10	0.563	2.366	10.325	0.012
Percent RP	10	0.459	0.529	6.793	0.031
TP	11	0.218	2.175	2.514	0.147
TN/TP	11	0.301	-0.781	3.882	*0.080*
NO_2+NO_3/NH_3●	11	0.374	-1.361	5.373	0.046

● Ranked variable.

Table 3.1.4 Correlations between the metaphyton biomass isotopic nitrogen signal, nutrients, temperature and light extinction coefficient at Manotick during five sampling dates.

	$\delta^{15}N$ metaphyton biomass signal		
Independent variables	**n of Cases**	**$R_{(coefficient\ of\ correlation)}$**	**p-value**
Temperature	9	-0.795	0.004
Light extinction coefficient	11	-0.827	0.002
NO_3+NO_2●	11	0.772	0.005
NH_3	11	0.287	0.393
DIN	11	0.647	0.031
TN	11	-0.447	0.168
RP	11	-0.728	0.008
%RP	11	-0.464	0.207
TP	11	-0.763	0.006
TN/TP	11	0.836	0.001
NO_3+NO_2/NH_3●	11	0.715	0.031

● Ranked variables.

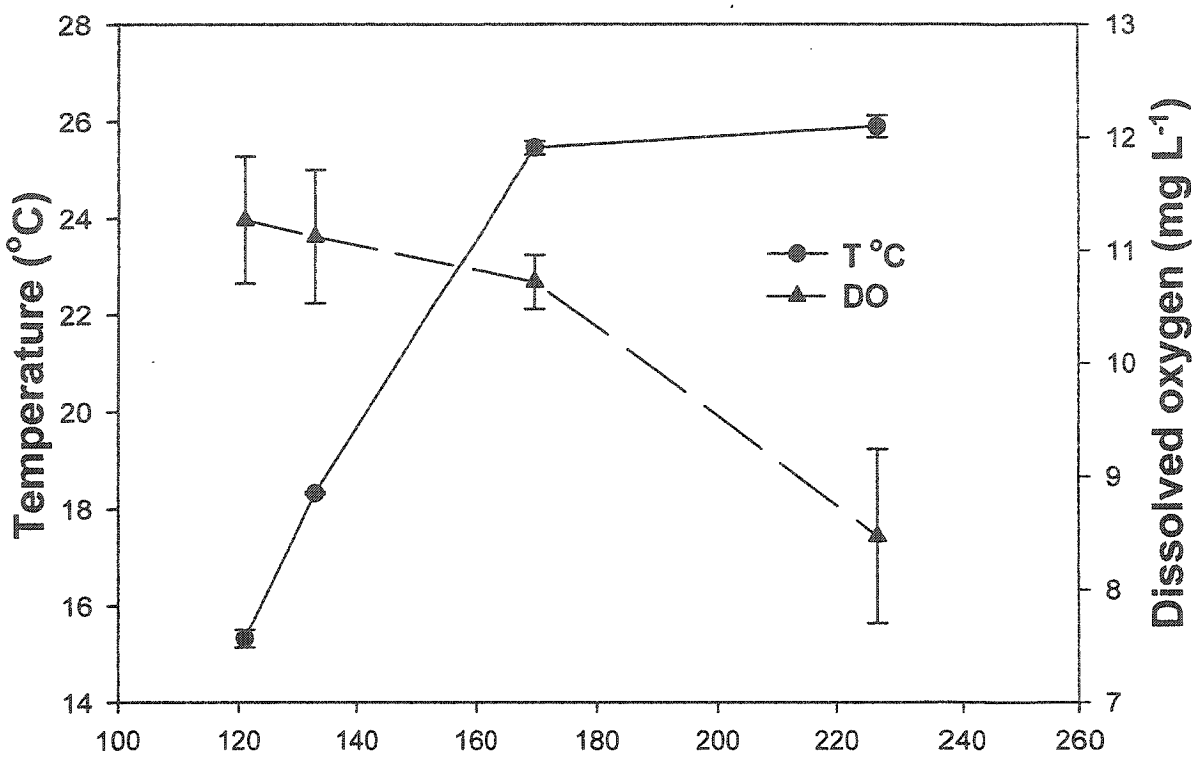
Table 3.1.5 The dominant taxa of the metaphytic algae at Manotick during five sampling dates.

Julian Day	***Spirogyra ellipsospora***	***Spirogyra crassa***	***Cladophora glomerata***	***Lyngbya*** spp.
121 (May 1st)	1	1	0	0
133 (May 15th)	1	1	1	0
170 (June 19th)	1	1	0	0
227 (August 15th)	1	0	1	0
244 (September 1st)	1	0	1	1

Table 3.1.6 Morphological measures of *Spirogyra* sp. at Manotick. Average (standard error) for length (*L*) and width (*W*) are indicated; i.e. *L*(ES) - *W*(ES). Underneath the length and width, the minimum and maximum values for each of them are specified (n = 5 cells per taxon).

Julian Day	***Spirogyra* sp. 1** ***S. ellipsospora* Transeau 1914**	***Spirogyra* sp. 2** ***S. crassa* Kuetzing 1843**
121	*122.36* (16.54) - *51.75* (8.62) 62.7 - 221.4 32.8 - 114.8	*128.09* (14.36) - *127.39* (9.42) 49.2 - 221.4 102.5 - 237.8
133	*267.21* (39.02) - *142.47* (19.94) 123.0 - 418.2 57.4 - 254.2	*166.05* (5.42) - *88.15* (1.18) 118.9 - 180.4 65.6 - 73.8
170	*192.37* (19.69) - *100.96* (3.91) 108.0 - 324.0 94.5 - 135.0	*90.0* (5.69) - *94.5* (0.00) 81.0 - 108.0
227	*226.32* (17.80) - *137.76* (4.81) 139.4 - 401.8 123.0 - 180.4	
244	*208.69* (21.14) - *121.36* (5.67) 98.4 - 323.9 86.1 - 147.6	

Figure 3.1.1 Patterns of temperature, dissolved oxygen and pH during four sampling dates during the summer 2001 at Manotick site. The standard error of two samples is shown for each sampling date.


Temperature (°C)
Dissolved oxygen (mg L-1)
T °C
DO
28
26
24
22
20
18
16
14
13
12
11
10
9
8
7
100
120
140
160
180
200
220
240
260

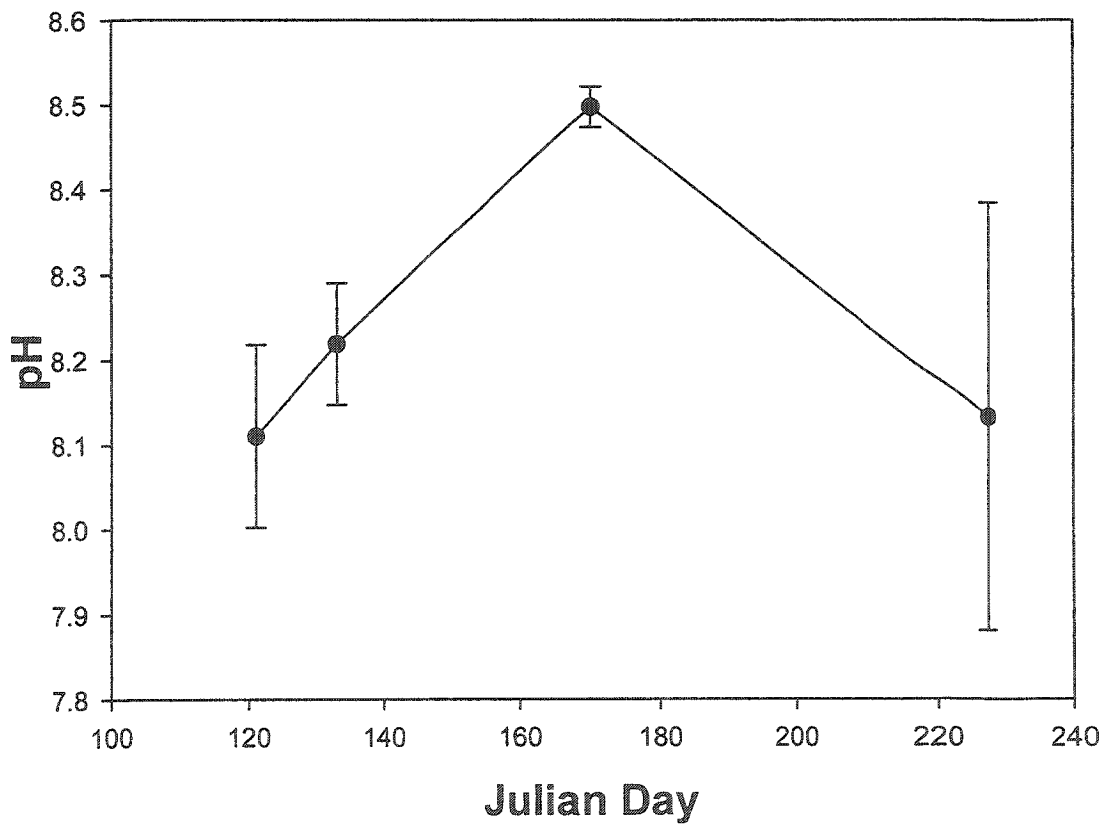
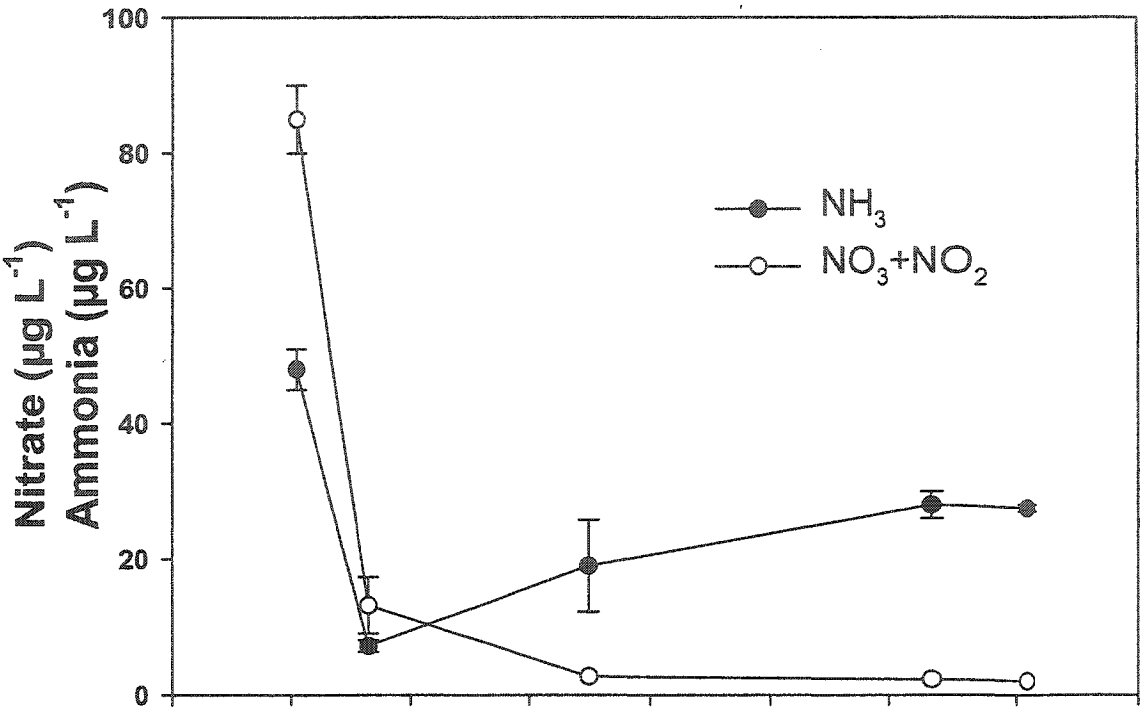

pH
Julian Day
8.6
8.5
8.4
8.3
8.2
8.1
8.0
7.9
7.8
100
120
140
160
180
200
220
240

Figure 3.1.2 Patterns of nitrate, ammonia and total phosphorus for the whole sampling season at Manotick site. The standard error of two samples is shown for each sampling date.


100
80
60
40
20
0
Nitrate (µg L-1)
Ammonia (µg L-1)
NH3
NO3+NO2

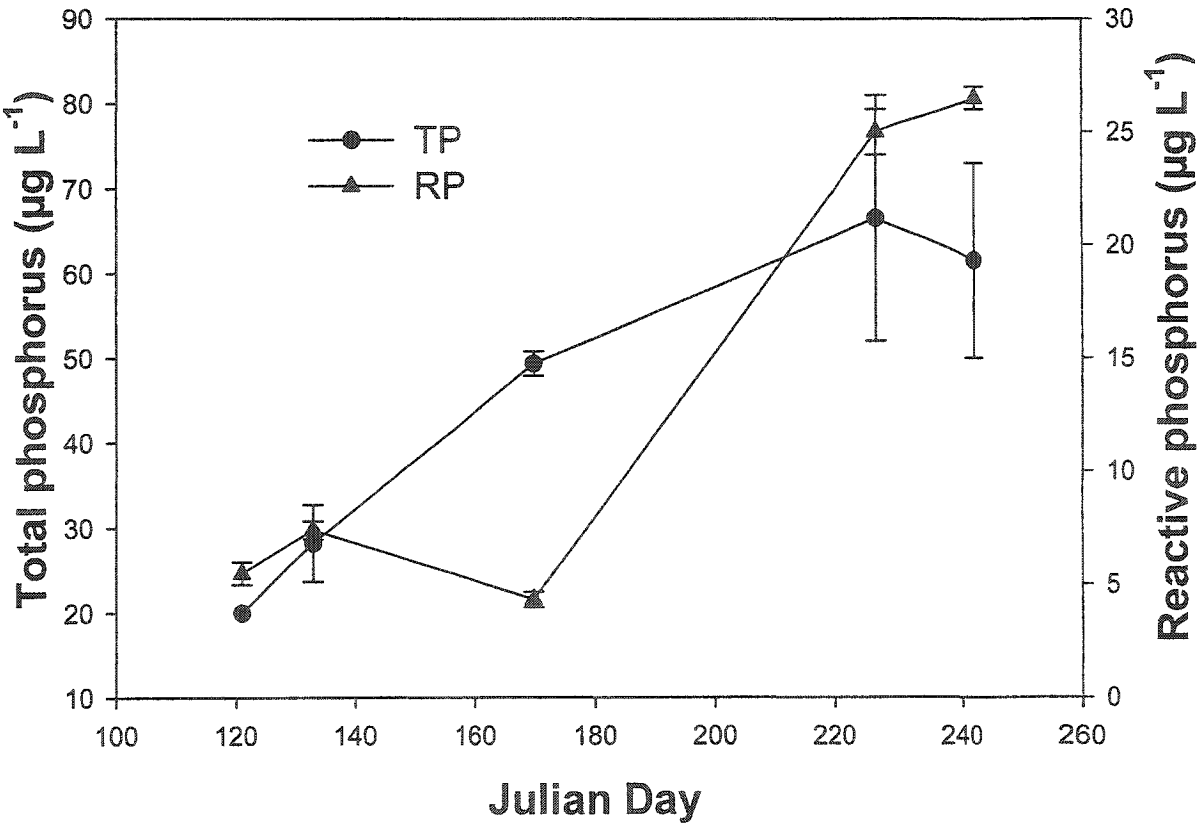

90
80
70
60
50
40
30
20
10
30
25
20
15
10
5
0
Total phosphorus (µg L-1)
Reactive phosphorus (µg L-1)
TP
RP
100
120
140
160
180
200
220
240
260
Julian Day

Figure 3.1.3 Metaphytic and planktonic biomass and chlorophyll-*a* patterns for five dates (Julian days) at Manotick site. The standard error of three samples is shown for each sampling date for the metaphyton, and two for the plankton.

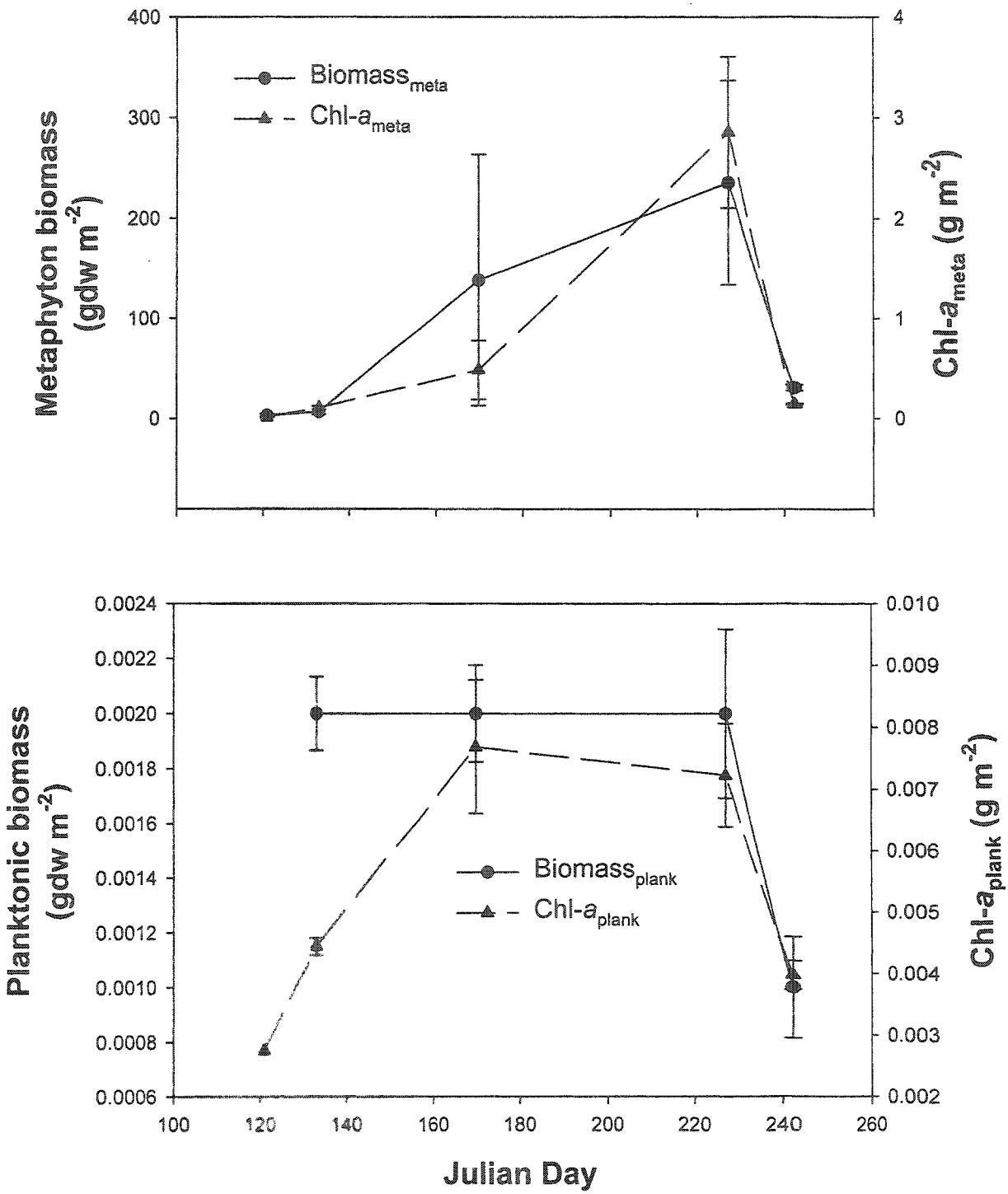

Metaphyton biomass (gdw m-2)
Chl-ameta (g m-2)
Biomassmeta
Chl-ameta
400
300
200
100
0
4
3
2
1
0
Planktonic biomass (gdw m-2)
Chl-aplank (g m-2)
Biomassplank
Chl-aplank
0.0024
0.0022
0.0020
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
0.0006
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
100
120
140
160
180
200
220
240
260
Julian Day

Figure 3.1.4 Comparison in $\delta^{15}N$ and $\delta^{13}C$ of the metaphyton biomass across the five sampling dates. Means with the same letter are not significantly different ($p > 0.05$).

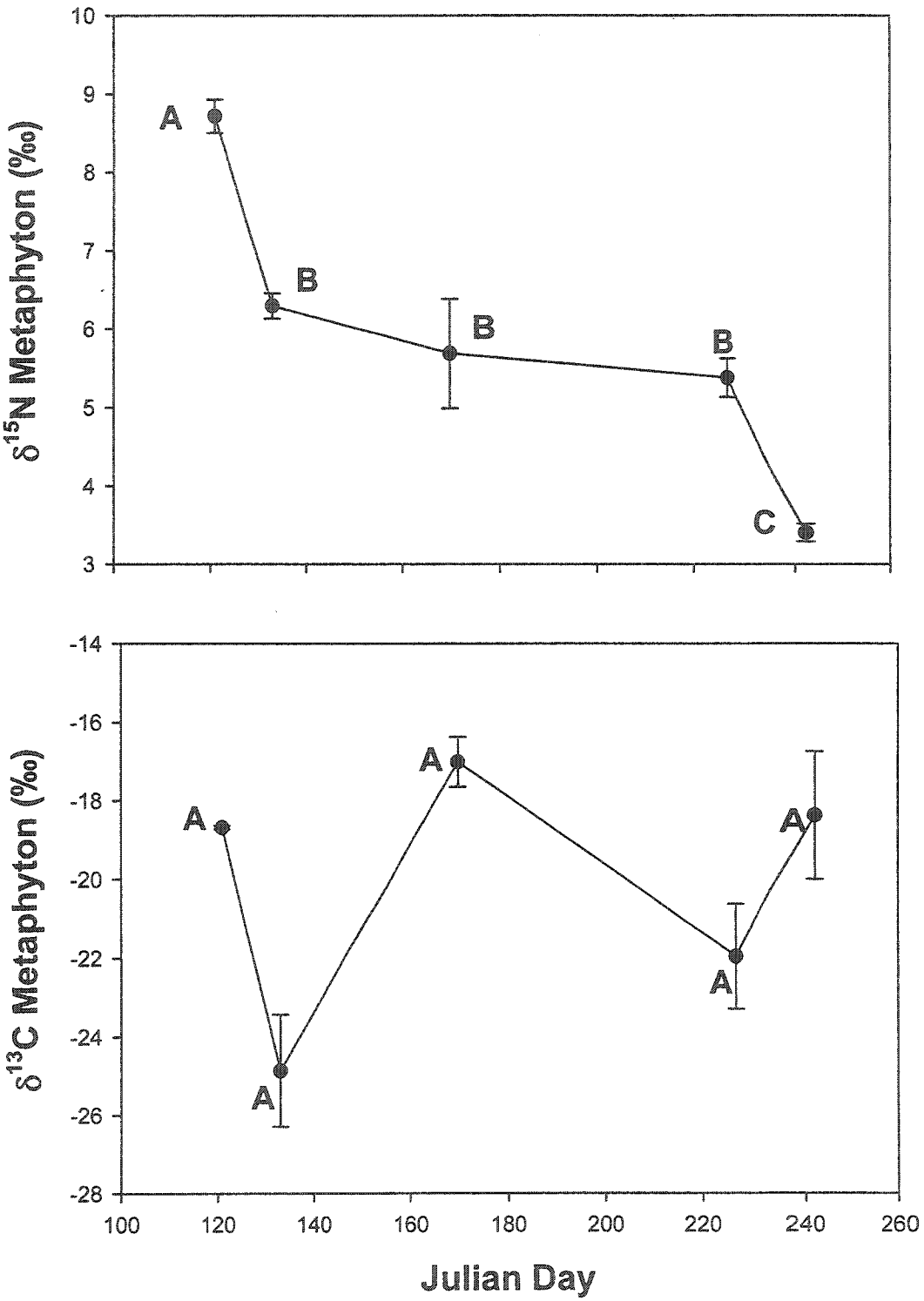
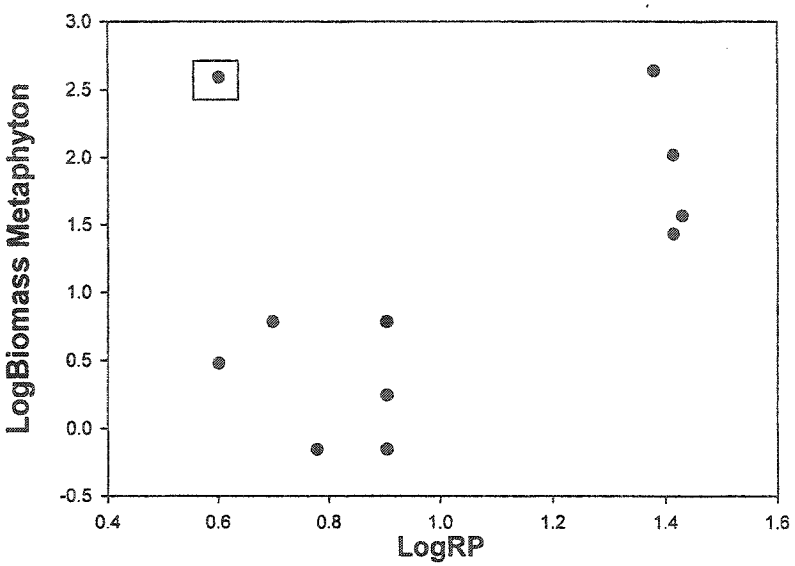
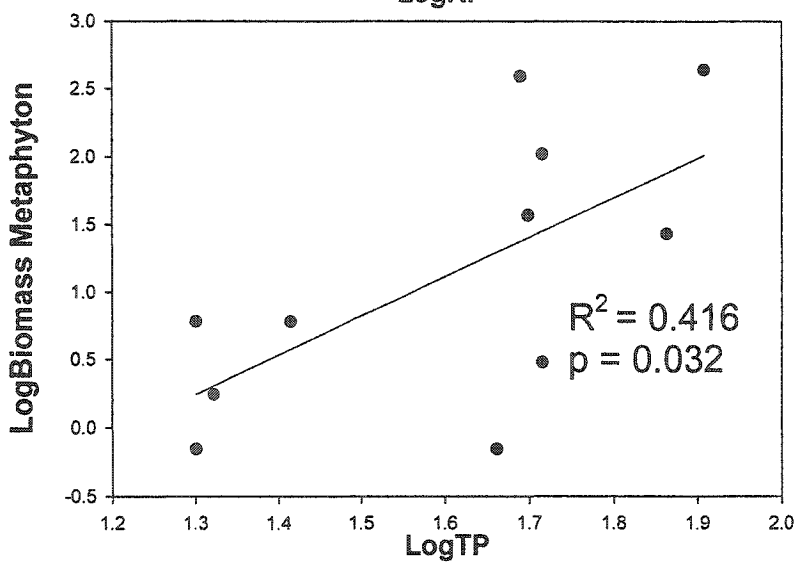

10
9
8
7
6
5
4
3
A
B
B
B
C
δ15N Metaphyton (‰)
-14
-16
-18
-20
-22
-24
-26
-28
A
A
A
A
A
δ13C Metaphyton (‰)
100
120
140
160
180
200
220
240
260
Julian Day

Figure 3.1.5 Linear regressions between the metaphyton biomass and reactive phosphorus, total phosphorus and the ratio nitrate + nitrite to ammonia. The regression of the metaphyton biomass and reactive phosphorus was significant with the exclusion of boxed point.


LogBiomass Metaphyton
LogRP
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
0.4
0.6
0.8
1.0
1.2
1.4
1.6


LogBiomass Metaphyton
LogTP
R2 = 0.416
p = 0.032
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0

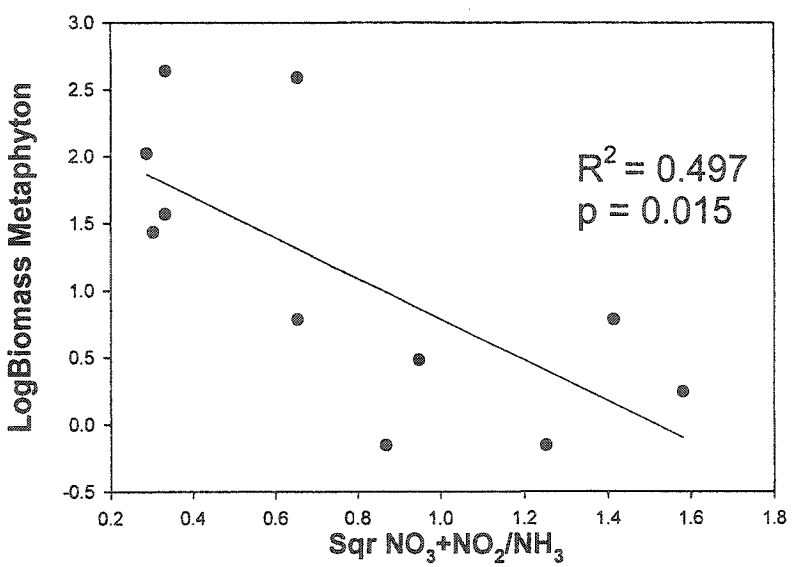
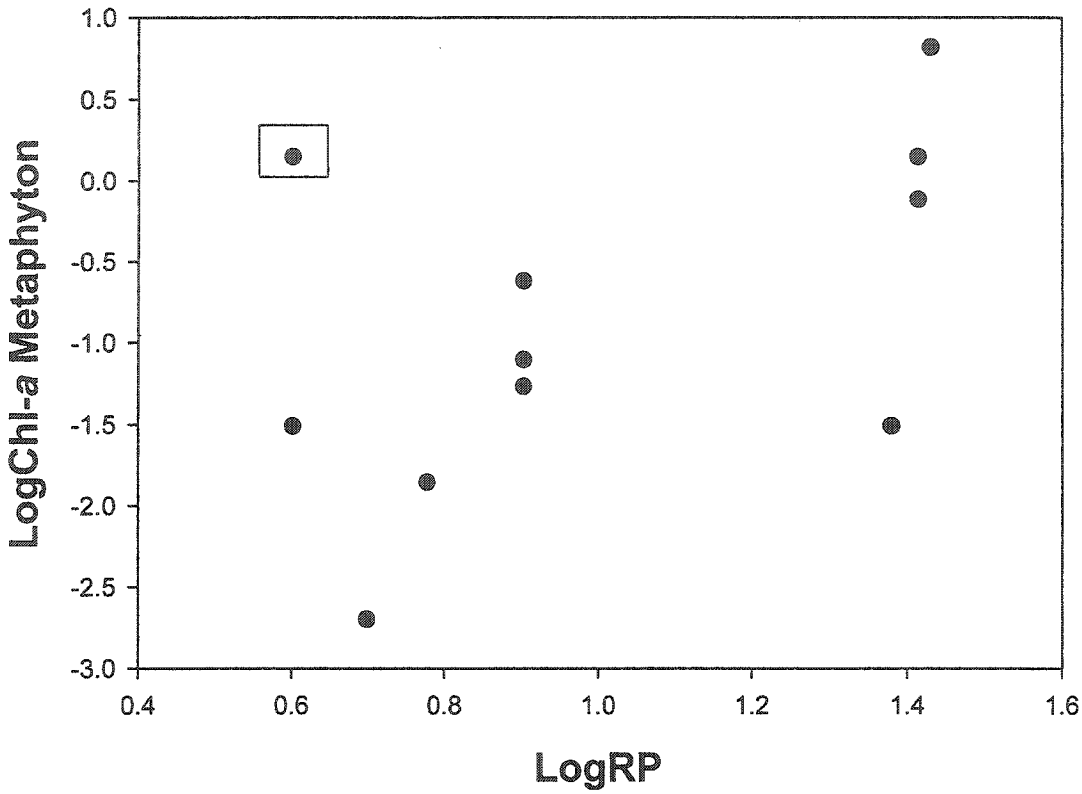
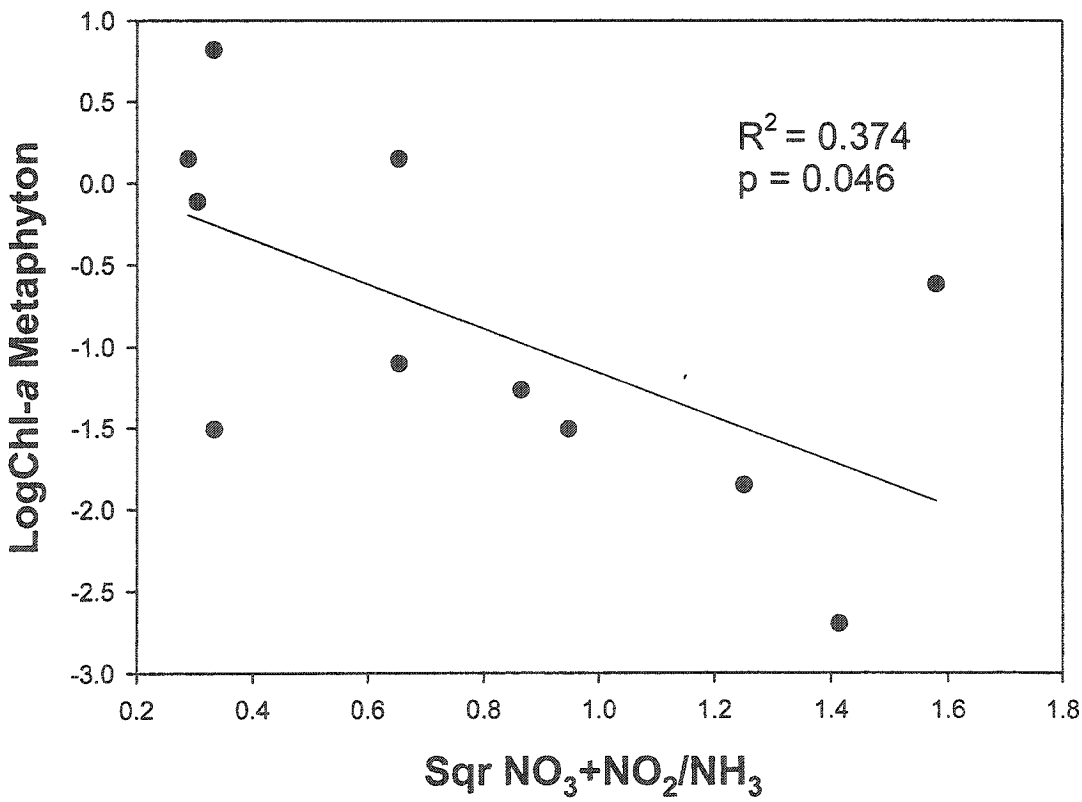

LogBiomass Metaphyton
Sqr NO3+NO2/NH3
R2 = 0.497
p = 0.015
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

Figure 3.1.6 Linear regressions between the metaphytic chlorophyll-*a* and reactive phosphorus and the ratio nitrate + nitrite to ammonia. The regression of the metaphyton biomass and reactive phosphorus was significant with the exclusion of boxed point.


LogChl-a Metaphyton
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
LogRP


LogChl-a Metaphyton
R2 = 0.374
p = 0.046
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Sqr NO3+NO2/NH3

3.2 Environmental and metaphyton characteristics of Rideau River sites

3.2.1 Comparison between littoral zones and main channel sites

Seven sites were sampled in both the littoral zone, where metaphyton is present, and the adjacent main channel to determine whether there were differences between these areas along the lower part of the Rideau River (Table 3.2.1). On average, the temperature, pH, dissolved oxygen, and percent dissolved oxygen showed higher values in the littoral zones than those in the main channel ($p < 0.005$). Planktonic ash free dry weight (hereafter, planktonic biomass) and chlorophyll-*a* concentrations were lower on average in the littoral zone than in the main channel (Table 3.2.1).

Nutrient concentrations were similar between the littoral zones and main channel; however, the total nitrogen (TN) was marginally higher within the littoral zones ($p = 0.076$) and the NO_3+NO_2 was lower ($p = 0.070$).

3.2.2 Longitudinal patterns along the river

The general trends along the River are shown in the Figures 3.2.1 to 3.2.8. The chlorophyll-*a* areal concentration of the metaphyton tended to increase downstream, whereas the planktonic chlorophyll-*a*, expressed on an areal basis, decreased towards the urban sites in the downtown of Ottawa (Fig. 3.2.1). The metaphyton biomass showed a similar trend as the metaphytic chlorophyll-*a* with the exception of site 1, where the

biomass was high in comparison with the chlorophyll-*a* (Fig. 3.2.2). There was always higher metaphytic chlorophyll-*a* concentration than planktonic in the littoral zones, and there appears to be an inverse relationship between these two variables (Figs. 3.2.1 & 3.2.2).

Some nutrients and sediment variables showed a similar longitudinal trend as the chlorophyll-*a* in the metaphyton. The variables NO_3+NO_2 and NO_3+NO_2/NH_3 (Fig.3.2.3), conductivity (Fig. 3.2.4), sediment $\delta^{15}N$, sediment $\delta^{13}C$, and C/N ratio of the sediments (Fig. 3.2.5) increased downstream. Other variables tended to decrease downstream, as did the planktonic chlorophyll-*a*: percent organic matter in sediments (Fig. 3.2.6), NH_3, TN and TP (Fig. 3.2.7), and C/N of the metaphyton (Fig. 3.2.8). The $\delta^{15}N$ in the metaphyton (Fig. 3.2.8), DIN and RP decreased from upstream to the Manotick site, and increased at the city of Ottawa: sites 9 to 12.

3.2.3 Trends among variables by land-use grouping

In terms of nutrients, some urban sites had the lowest individual levels of TN and TP (10 and 11) (Table 3.2.2). Other urban sites had among the highest concentrations of NO_3+NO_2 and NO_3+NO_2/NH_3 (9 & 10). NO_3+NO_2/NH_3 showed the lowest values at both some agricultural sites (2 & 3) and at an urban site (12). The highest levels of TN and NH_3 corresponded to the agricultural sites (2, 3 & 4) (Table 3.2.2).

The lowest value of metaphyton biomass was sampled from a residential site (8) while the highest value was found in two sites corresponding to an urban and agricultural site, respectively (1 & 11, Table 3.2.2). However, the lowest concentration of metaphyton chlorophyll-*a* corresponded to some agricultural and residential sites (3 & 8) and the maximum to one urban site (11) (Table 3.2.2). The $\delta^{15}N_{sed}$ and $\delta^{15}N_{meta}$ values were lowest at a residential site (5). The highest values for these two variables were at agricultural sites (2 & 4, respectively) (Table 3.2.2). $\delta^{13}C_{sed}$ and $\delta^{13}C_{meta}$ had the lowest values in sites one (agricultural) and nine (urban), respectively; and the highest concentrations in sites eleven (urban) and six (residential), respectively (Table 3.2.2). The C/N_{sed} and C/N_{meta} were lowest at sites one and nine, respectively; and highest in sites eleven and one, respectively (Table 3.2.2).

After finding a significant variation among the sites in terms of nutrients (One-way ANOVA, $p < 0.05$), the sites were grouped according to dominant land-use to determine if differences might be reflecting land-use type as described in Chapter 2.

A nested ANOVA was performed to examine differences among sites within a land-use group as well as differences among the groups (Table 3.2.3). With respect to metaphyton variables (Biomass, Chl-*a*, $\delta^{15}N$, $\delta^{13}C$, percent C, and C/N ratio), there were no significant differences between sites within a group ($p > 0.05$), excepting the percent N ($p = 0.042$). Similarly, with respect to TP, NH_3 and TN/TP, there were no differences among sites within groups. However, with respect to nutrients such as NO_3+NO_2,

NO_3+NO_2/NH_3 ratio, TN, RP, and percent RP, significant differences between sites within groups were found (Table 3.2.3).

In general, there were significant differences among the three land-use groups (hereafter AG (agricultural grouping), RG (residential grouping), and UG (urban grouping)) in the majority of the variables, except NO_3+NO_2 (Table 3.2.3).

There appeared to be four main patterns with respect to land-use. For some variables, the highest concentrations were found in the agricultural sites and the lowest at the urban sites, with the residential sites intermediate (and significantly different) or overlapping (with no difference) with the other groupings (Table 3.2.4). This pattern was observed for water column TP and TN, along with the C/N ratio of the metaphyton, and percent N sediments (Fig. 3.2.9). The opposite pattern (almost the mirror image, with low values at agricultural sites and high values within the urban group) was observed with metaphyton chlorophyll-*a*, conductivity, the C/N ratio of the sediments, the percent N of metaphyton, and $\delta^{15}N$ sediments (Table 3.2.4, Fig. 3.2.10). Although NO_3+NO_2 showed the same pattern, it was not statistically significant because of considerable variation within sites of a grouping (Table 3.2.4).

Several variables were actually lowest within the residential group. This was the case for metaphyton biomass, reactive phosphorus (and percent RP), NH_3 and $\delta^{15}N$ metaphyton (Fig. 3.2.11). The only variable that was clearly highest in the residential

group relative to the other two groups was the $\delta^{13}C$ in the metaphyton (Table 3.2.4, Fig. 3.2.12).

Overall there were more differences between agricultural and urban sites than differences with the residential group (Table 3.2.4).

3.2.4 General trends among variables: linear relationships and associations

Metaphytic versus planktonic chlorophyll-*a* and biomass in the littoral zones

The metaphytic chlorophyll-*a* was negatively correlated with the planktonic chlorophyll-*a* across the river sites (R_{CC} = -0.390, p = 0.054) (Table 3.2.5, Fig. 3.2.13). A similar relationship was evident when comparing the metaphyton chlorophyll-*a* with the planktonic biomass (R_{CC} = -0.431, p = 0.040). The biomass of these two communities was positively related with their respective chlorophyll-*a* concentrations (metaphyton: R^2 = 0.586, p < 0.0001 and plankton: R^2 = 0.647, p < 0.0001) (Tables 3.2.5 & 3.2.6).

The light extinction coefficient, temperature, pH and percent oxygen were significantly and positively correlated with the plankton chlorophyll-*a*, but there was a lack of such relationships with the metaphytic chlorophyll-*a* (Table 3.2.5). However, conductivity of the water showed a linear relationship with chlorophyll-*a* in both communities; but while the relationship of the conductivity with the metaphyton

chlorophyll-*a* was positive, the relationship with plankton was negative and stronger (R^2 = 0.156 *vs.* R^2 = 0.466, respectively) (Table 3.2.5).

In both metaphyton and phytoplankton communities, chlorophyll-*a* was significantly related with total nitrogen (TN) in the water column, but these relationships were opposite in sign. The chlorophyll-*a* in the metaphyton was negatively related to TN, while the planktonic chlorophyll-*a* was positively related to TN. In addition, the coefficient of determination was higher for the planktonic than the metaphytic chlorophyll-*a* ($R^2_{plankton}$ = 0.543 *vs.* $R^2_{metaphyton}$ = 0.179 for TN) (Table 3.2.5, Fig. 3.2.14).

The relationships of the metaphytic biomass and metaphytic chlorophyll-*a* with nutrients were different (Tables 3.2.5 & 3.2.6). While the chlorophyll-*a* was significantly related to TN (Fig. 3.2.14), the only significant nutrient variable related to metaphyton biomass was the NO_3+NO_2/NH_3 ratio (R^2 = -0.172, p = 0.039, Fig. 3.2.15). In contrast, the relationships of the planktonic biomass with the different independent variables were similar to those found for planktonic chlorophyll-*a* (Tables 3.2.5 & 3.2.6).

The metaphyton chlorophyll-*a* and littoral planktonic chlorophyll-*a* were related to the percent N content of sediments. These relationships may simply reflect the correlations between TN and percent N in sediments (Table 3.2.7). However, for the metaphyton, the relationship with percent N in sediments was stronger than that with water column TN, but the reverse was the case for planktonic chlorophyll-*a*.

When considering all the sites, in contrast to planktonic chlorophyll-*a*, metaphytic chlorophyll-*a* showed no relationship with total phosphorus (TP). However, the relationship with TP was significant when a single point with high metaphytic chlorophyll-*a* value was excluded from the analysis ($n = 24$, $R^2 = -0.172$, $p = 0.044$).

Metaphytic community composition and comparison with other primary producers

The metaphyton biomass in the littoral zones was high in comparison to other primary producers (phytoplankton, periphyton, macrophytes) in the river (Table 3.2.8). The metaphyton biomass exceeded even the highest macrophyte biomass reported for the Rideau River by almost threefold. However, it should be noted that the metaphyton mats sampled were a composite of metaphytic algae, some macrophytes and/or debris. After cleaning, the sample was divided into metaphyton (Meta), which corresponded to the filamentous and/or branched algae. These included members of the families Zygnemataceae (*Spirogyra* spp. Link 1820); Cladophoraceae (*Cladophora glomerata* Kützing 1843), Oscillatoriaceae (*Lyngbya* spp. Link 1820) and Hydrodictyaceae (*Hydrodictyon* sp. Roth 1800) (systematic based on Prescott 1982) (Table 3.2.9). The non-metaphyton (Non-meta) section was comprised of some macrophytes and organic matter entangled with the metaphyton community. The macrophytes of the non-metaphytic portion of the sample were *Lemna trisulca*, *Ceratophyllum demersum*, *Elodea canadensis*, and *Potamogeton* spp. (Table 3.2.9). *Lemna trisulca*, *Ceratophyllum demersum*, *Elodea canadensis*, and *Potamogeton* spp. were present from Burrits Rapids

to Manotick and tended to disappear at the urban sites. The non-metaphyton portion at the urban sites comprised of organic debris. In some sites, the metaphyton community represented more than 90 % of the total sample, whereas in others was less than 30 %. Interestingly, the percent of the metaphyton in the whole mat tended to decrease at the urban sites (Fig. 3.2.16).

Nutrient composition of the metaphyton

In addition to changes in metaphyton biomass and chlorophyll-*a* along the river, changes in the nutrient composition of the metaphyton were observed (Fig. 3.2.9). The percent nitrogen content of the metaphyton was negatively correlated with the sediment nitrogen content and water column TN, yet positively correlated with the ratio of NO_3+NO_2/NH_3 (Table 3.2.10).

The percent carbon of the metaphyton showed a positive association with the temperature in the water column and with nutrients such as total nitrogen and total phosphorus ($p \leq 0.022$) (Table 3.2.10). As a result of the positive correlation with TN and TP, the percent carbon content of the metaphyton was negatively related to the ratio TN/TP.

The carbon to nitrogen ratio (C/N) of the metaphyton was positively related with physical variables such as temperature and percent oxygen in the water column (Table 3.2.10). The C/N ratio showed a negative correlation with conductivity and with the

NO_3+NO_2/NH_3 ratio. Perhaps as a reflection of the percent nitrogen of the metaphyton correlation with the TN, the C/N ratio was positively correlated with this nutrient (Table 3.2.10).

Interestingly, the percent nitrogen, percent carbon, and the C/N ratio of the metaphyton were significantly related to the sediment nutrient composition and the carbon and nitrogen isotopic signals of the sediments (Table 3.2.11).

Metaphyton stable isotopic signals

The $\delta^{15}N$ and $\delta^{13}C$ signals of the metaphyton were positively related to the percent reactive phosphorus (%RP) (Table 3.2.10). This was the only significant correlation with nutrient variables. It should be noted that there was a significant correlation between percent RP and nitrogen-based nutrients such as NH_3 and NO_3+NO_2 (Table 3.2.12). Additionally, the $\delta^{13}C$ signal of the metaphyton was positively correlated with the temperature of the water column (Table 3.2.10). Interestingly, the sediment isotopic signal and nutrient composition were not related to the isotopic signal of the metaphyton (Table 3.2.11).

The raw data for the various measurements and analyses related to the 12 sites can be found in Appendix 2.

Table 3.2.1 Comparison between values of variables in the littoral zone (LZ) versus the main channel (MC) at sites along the Rideau River. The mean values in bold are statistically different ($p \leq 0.05$). Values in italic correspond to only slightly different means.

Variable*	n of Cases	Mean	Std. Error	Minimum	Maximum
$Biomass_{metaphyton}$	LZ (22)	**105.25**	31.006	3.023	616.92
$Biomass_{plankton}$	LZ (14)	**0.002**	0.0003	0.001	0.006
	MC (7)	**0.007**	0.0003	0.004	0.006
Chl-$a_{metaphyton}$	LZ (22)	**0.37**	0.087	0.008	1.497
Chl-$a_{plankton}$	LZ (14)	**0.009**	0.0006	0.006	0.015
	MC (8)	**0.032**	0.003	0.019	0.043
TN	LZ (18)	***910.20***	27.30	735.00	1122.00
	MC (7)	***824.67***	20.11	779.90	932.80
NH_3	LZ (18)	17.67	3.27	3.00	49.00
	MC (7)	19.43	4.38	6.00	37.00
NO_3+NO_2	LZ (18)	***3.04***	0.42	1.80	10.00
	MC (7)	***6.33***	2.49	2.70	20.00
NO_3+NO_2/ NH_3	LZ (18)	0.29	0.05	0.06	0.90
	MC (7)	0.35	0.08	0.09	0.56
TP	LZ (18)	59.78	4.88	36.00	05.00
	MC (7)	47.57	1.98	42.00	58.00
RP	LZ (18)	10.50	1.26	4.00	20.00
	MC (7)	7.71	1.43	3.00	12.00
%RP	LZ (18)	17.46	1.67	7.69	34.78
	MC (7)	16.21	2.96	6.38	27.91
TN/TP	LZ (18)	16.26	0.85	10.21	25.67
	MC (7)	17.47	0.66	14.31	19.85
Temperature	LZ (22)	**25.19**	0.27	22.98	27.15
	MC (31)	**24.08**	0.25	20.90	25.80
%Oxygen	LZ (22)	**122.28**	4.31	91.47	170.80
	MC (31)	**91.90**	4.81	37.06	125.36
Oxygen	LZ (22)	**10.04**	0.31	7.70	13.61
	MC (31)	**7.74**	0.39	3.24	10.96
pH	LZ (22)	**8.61**	0.05	8.17	9.05
	MC (31)	**8.29**	0.04	7.77	8.69
Conductivity	LZ (22)	247.10	6.71	142.20	289.00
	MC (31)	256.58	3.62	232.00	305.00

* Units: Biomass (gdw m^{-2}) and chlorophyll-*a* (g m^{-2}), TN, TP, NH_3, NO_3+NO_2, RP (µg L^{-1}), Temperature (°C), Oxygen (mg L^{-1}), conductivity (µS cm^{-1}). Planktonic weight refers to ash free dry weight. n = number of cases.

Table 3.2.2. Basic statistics for all the variables analyzed in this study. Mean, standard error, minimum and maximum values for 12 sites along the lower section of the Rideau River. The site numbers (Fig. 2.1) corresponding to the minimum and maximum values are specified in brackets.

Variable*	n of Cases	Mean	Std. Error	Minimum	Maximum
$Biomass_{metaphyton}$	37	112.81	26.05	3.02 (8)	616.92 (1,11)
Chl-$a_{metaphyton}$	37	0.632	0.156	0.008 (3,8)	4.89 (11)
$Biomass_{plankton}$	25	0.00185	0.00029	0.00028 (11)	0.00567 (6)
Chl-$a_{plankton}$	25	0.00657	0.00069	0.00158 (11)	0.01517 (4)
TN	25	837.76	30.62	616.00 (10)	1122.00 (3)
NH_3	25	17.60	2.46	3.00 (8)	49.00 (3)
NO_3+NO_2	25	4.99	1.17	1.80 (4,6)	20.00 (9,10)
NO_3+NO_2/ NH_3	25	0.38	0.07	0.06 (3)	1.43 (9)
TP	25	53.00	4.53	22.00 (11)	105.00 (4)
RP	25	10.76	1.52	3.00 (8)	35.00 (9)
%RP	25	20.07	2.13	7.69 (4)	56.45 (11)
TN/TP	25	17.65	1.03	10.21 (4)	28.31 (11)
Temperature	21	23.41	0.46	19.81 (9)	26.79 (4)
Ext. Coefficient	24	3.28	0.38	1.02 (10)	6.79 (5)
%Oxygen	21	115.43	3.76	85.10 (10)	146.11 (4)
Oxygen	21	9.80	0.28	7.30 (10)	11.90 (3)
pH	21	8.43	0.06	7.67 (10)	8.90 (4)
Conductivity	21	298.28	15.42	208.60 (6)	390.00 (10)
$\%N_{metaphyton}$	36	2.63	0.14	1.35 (1)	5.01 (9)
$\delta^{15}N_{metaphyton}$	36	7.12	0.25	3.87 (5)	10.36 (2)
$\%C_{metaphyton}$	36	37.03	0.62	29.44 (11)	45.81 (4)
$\delta^{13}C_{metaphyton}$	36	-22.47	0.74	-37.36 (9)	-15.35 (6)
$C/N_{metaphyton}$	36	15.55	0.84	7.96 (9)	27.73 (4)
$\%N_{sediment}$	24	0.63	0.09	0.08 (11)	1.79 (5)
$\delta^{15}N_{sediment}$	21	5.45	0.48	2.01 (5)	10.17 (4)
$\%C_{sediment}$	24	6.40	0.88	1.52 (12)	16.76 (5)
$\delta^{13}C_{sediment}$	24	-23.62	0.71	-26.62 (1)	-13.26 (11)
$C/N_{sediment}$	24	11.54	0.77	8.26 (2)	23.09 (11)

* Units: Biomass (gdw m^{-2}) and chlorophyll-*a* (g m^{-2}), TN, TP, NH_3, NO_3+NO_2, RP (µg L^{-1}), Temperature (°C), Oxygen (mg L^{-1}), extinction coefficient (m^{-1}), conductivity (µS cm^{-1}), $\delta^{15}N$, $\delta^{13}C$ (‰). Planktonic weight refers to ash free dry weight. n = number of cases.

Table 3.2.3 Summary of nested-ANOVA between groups (land use) and sites for the variables: metaphyton biomass, chlorophyll-*a*, nutrient and stable isotopes (n = 24, 25*, 36**, 37***). Variables were log transformed or squared root for parametric ANOVA or ranked for non-parametric ANOVA. Variables statistically different ($p \leq 0.05$) are in bold.

Variables	**Groups**		**Sites (Groups)**	
	F-ratio	*p-value*	*F-ratio*	*p-value*
Chl-a_{meta}***	9.819	**0.001**	1.427	0.230
$Biom_{meta}$***	3.393	**0.050**	1.759	0.127
$\delta^{15}N_{meta}$**	9.303	**0.001**	0.857	0.574
$\%N_{meta}$**	10.746	**<0.0001**	2.395	**0.042**
$\delta^{13}C_{meta}$**	5.394	**0.020**	2.577	*0.059*
$\%C_{meta}$**	5.372	**0.012**	1.700	0.144
C/N_{meta}**	18.165	**<0.0001**	1.744	0.133
NH_3*	11.924	**0.001**	2.626	*0.056*
NO_3+NO_2*●	2.924	*0.089*	4.354	**0.009**
NO_3+NO_2/NH_3*	25.426	**<0.0001**	9.075	**<0.0001**
TN*	59.578	**<0.0001**	5.896	**0.002**
RP*	19.409	**<0.0001**	4.002	**0.012**
%RP*	18.143	**<0.0001**	3.140	**0.030**
TP*	9.637	**0.003**	1.968	0.129
TN/TP*	7.594	**0.007**	2.001	0.124
$\delta^{15}N_{sed}$	20.546	**<0.0001**	8.300	**0.002**
$\%N_{sed}$	17.230	**<0.0001**	5.819	**0.003**
$\delta^{13}C_{sed}$●	8.893	**0.004**	3.590	**0.021**
$\%C_{sed}$	7.295	**0.008**	5.734	**0.003**
C/N_{sed}	43.045	**<0.0001**	1.611	0.217

● Non-parametric ANOVA.

Table 3.2.4 Matrix of Bonferroni pairwise comparison probabilities of the different groupings: 1 = Agricultural Group, 2 = Residential Group, 3 = Urban Group. Numbers in italic are for slightly significant comparisons. Variables statistically different ($p \leq 0.05$) are in bold.

Variables	**Groups** (*p-value*)		
	1-2	**1-3**	**2-3**
Chl-a_{meta}***	0.928	**0.035**	**0.003**
$Biom_{meta}$***	*0.069*	1.000	0.498
$\delta^{15}N_{meta}$**	**0.001**	0.550	**0.045**
$\%N_{meta}$**	**0.043**	**0.002**	0.509
$\delta^{13}C_{meta}$**●	**0.038**	0.804	**0.005**
$\%C_{meta}$**	1.000	**0.029**	**0.027**
C/N_{meta}**	**0.031**	**<0.0001**	**0.019**
NH_3*	**0.006**	1.000	**0.022**
NO_3+NO_2*●	1.000	0.439	1.000
NO_3+NO_2/NH_3*	**0.021**	**0.027**	1.000
TN*	0.219	**<0.0001**	**0.001**
RP*	**0.001**	**0.029**	0.484
%RP*	**0.007**	1.000	**0.002**
TP*	*0.069*	**0.002**	0.540
TN/TP*	**0.031**	**0.013**	1.000
$\delta^{15}N_{sed}$	1.000	**0.023**	**0.017**
$\%N_{sed}$	1.000	*0.058*	**0.006**
$\delta^{13}C_{sed}$●	1.000	**0.050**	**0.019**
$\%C_{sed}$	1.000	0.402	*0.082*
C/N_{sed}	0.659	**<0.0001**	**<0.0001**

● Non-parametric ANOVA.

Table 3.2.5 Comparison among the different relationships of the Chl-*a* concentrations in the metaphyton and in the plankton versus different independent variables. In italic are marginally significant regressions.

Independent Variables	Metaphyton Chlorophyll-*a*					Plankton Chlorophyll-*a*				
	n	R^2	Coefficient	F	p	n	R^2	Coefficient	F	p
$Biomass_{metaphyton}$	37	0.586	0.791	50.980	**0.00(*)**					
$Biomass_{plankton}$▣	23	-0.431♦			**0.040**					
Chl-$a_{plankton}$▣	25	-0.390♦			***0.054***					
TN	25	0.179	-3.221	5.005	**0.035**	25	0.543	2.711	27.356	**0.00(*)**
NH_3	25	*0.125*	0.704	3.289	*0.083*	24	0.012	-0.100	0.260	0.615
NO_3+NO_2●	25	0.058	-0.228	1.417	0.246	25	0.007	-0.077	0.159	0.694
NO_3+NO_2/NH_3	25	*0.120*	-0.778	3.135	*0.090*	25	0.029	-0.184	0.684	0.417
TP	25	*0.131*	-1.181	3.462	*0.076*	25	0.335	0.914	11.602	**0.002**
RP	25	0.001	-0.075	0.028	0.868	25	0.024	0.160	0.578	0.455
%RP	25	0.058	0.135	1.418	0.246	24	0.111	-0.090	2.875	0.103
TN/TP	25	0.089	0.299	2.234	0.149	24	0.194	-0.401	5.287	**0.031**●
Temperature	21	0.104	-5.472	2.202	0.154	21	0.668	6.488	38.227	**0.00(*)**
Ext. Coefficient	24	0.058	-0.232	1.350	0.258●	24	0.424	0.616	16.209	**0.001**●
%Oxygen	21	0.023	-0.123	0.438	0.516	21	0.208	0.535	4.984	**0.038**●
Oxygen	21	0.004	-0.769	0.085	0.774	21	0.097	0.377	1.924	0.182●
pH	21	0.042	-0.257	0.840	0.371●	21	0.254	0.596	6.641	**0.020**●
Conductivity	21	*0.156*	2.594	3.515	*0.076*	21	0.466	-2.094	16.551	**0.001**
$\%N_{metaphyton}$	36	0.004	0.145	0.126	0.725	25	-0.338▣♦			0.099
$\delta^{15}N_{metaphyton}$	36	0.186	0.904	7.788	**0.009**	25	-0.105▣♦			0.615
$\%C_{metaphyton}$	36	0.192	-0.882	8.083	**0.008**	25	0.591▣♦			**0.002**
$\delta^{13}C_{metaphyton}$●	36	0.017	0.131	0.571	0.455	25	0.419▣♦			**0.037**●
$C/N_{metaphyton}$	36	0.041	-0.198	1.465	0.235	25	0.423▣♦			**0.035**●
$\%N_{sediment}$▣	24	-0.503♦			**0.012**	24	0.559♦			**0.004**
$\delta^{15}N_{sediment}$▣	21	0.276♦			0.228	21	-0.232♦			0.310
$\%C_{sediment}$▣	24	-0.589♦			**0.002**	24	0.411♦			**0.046**
$\delta^{13}C_{sediment}$▣●	24	0.668♦			**0.00(*)**	24	-0.454♦			**0.026**●
$C/N_{sediment}$▣	24	0.260♦			0.217	24	-0.869♦			**0.00(*)**

* $p < 0.0001$
● Non-parametric regression
▣ Pearson product moment correlation
♦ Coefficient of correlation
Bolds are $p < 0.05$

Table 3.2.6 Metaphytic and planktonic biomass as a linear function of biological, physical and chemical variables. Significant regressions are in italic.

Independent Variables	Metaphyton Biomass					Plankton Biomass				
	n	R^2	Coefficient	F	p	n	R^2	Coefficient	F	p
$Biomass_{plankton}$	23	0.049	-0.397	1.089	0.309					
Chl-$a_{plankton}$	25	0.026	-0.363	0.609	0.443	22	0.804▣♦			**0.00**(*)
TN	25	0.006	-0.073	0.132	0.720	23	0.738	4.254	59.069	**0.00**(*)
NH_3	25	0.050	0.218	1.213	0.282	23	0.034	-0.182	0.741	0.399
NO_3+NO_2●	25	0.028	-0.349	0.660	0.425	23	0.079	-0.252	1.809	0.193
NO_3+NO_2/NH_3	25	0.172	-1.016	4.787	**0.039**	23	0.027	-0.163	0.580	0.455
TP	25	0.005	-0.066	0.112	0.741	23	0.608	0.734	32.610	**0.00**(*)
RP	25	0.001	0.027	0.019	0.892	23	0.123	0.324	2.950	0.101
%RP	25	0.030	0.168	0.709	0.408	23	0.049	-0.198	1.091	0.308
TN/TP	25	0.000	0.016	0.007	0.935	23	0.374	-0.571	12.530	**0.002**●
Temperature	21	0.074	-0.330	1.520	0.233	19	0.489	0.722	16.273	**0.001**
Ext. Coefficient	24	0.036	-0.187	0.811	0.378	22	0.332	0.540	9.961	**0.005**●
%Oxygen	21	0.001	0.042	0.023	0.881	19	0.282	0.565	6.662	**0.019**
Oxygen	21	0.021	0.176	0.415	0.527	19	0.147	0.458	2.940	0.105●
pH	21	0.013	-0.136	0.241	0.629	19	0.281	0.546	6.640	**0.020**
Conductivity	21	0.000	0.021	0.004	0.947	19	0.681	-3.050	36.232	**0.00**(*)
$\%N_{metaphyton}$	36	0.127	-0.862	4.962	**0.033**	23	-0.264▣♦			0.222
$\delta^{15}N_{metaphyton}$	36	0.187	0.919	7.838	**0.008**	23	0.095▣♦			0.661
$\%C_{metaphyton}$	36	0.164	-0.825	6.652	**0.014**	23	0.435▣♦			**0.038**
$\delta^{13}C_{metaphyton}$●	36	0.003	-0.059	0.111	0.741	23	0.138▣♦			0.526
$C/N_{metaphyton}$	36	0.049	0.220	1.763	0.193	23	0.431▣♦			**0.040**
$\%N_{sediment}$▣	24	-0.197♦			0.357	22	0.565♦			**0.006**●
$\delta^{15}N_{sediment}$▣	21	-0.000♦			0.996	19	-0.362♦			0.127
$\%C_{sediment}$▣	24	-0.181♦			0.398	22	0.450♦			**0.035**
$\delta^{13}C_{sediment}$▣●	24	*0.356*♦			*0.088*	22	-0.574♦			**0.005**
$C/N_{sediment}$▣	24	0.200♦			0.346	22	-0.722♦			**0.00**(*)

* $p < 0.0001$
● Non-parametric regression
▣ Pearson product moment correlation
♦ Coefficient of correlation
Bolds are $p < 0.05$

Table 3.2.7 Pearson product-moment correlation with Bonferroni probabilities. Linear associations among nutrients and isotopic signals in the sediments. Variables were log-transformed or square root transformed for parametric correlations or ranked for Spearman correlations (n = 21, 25). Slightly significant regressions are in italic.

	$\%N_{sediment}$ n = 24	$\delta^{15}N_{sediment}$ n = 21	$\%C_{sediment}$ n = 24	$\delta^{13}C_{sediment}$● n = 24	$C/N_{sediment}$ n = 24
TN	r=**0.693** p<**0.0001**	r=*-0.425* p=*0.055*	r=**0.599** p=**0.002**	r=**-0.509** p=**0.011**	r=**-0.657**● p<**0.0001**
NH_3	r=-0.054 p=0.802	r=0.075 p=0.747	r=-0.052 p=0.810	r=0.165 p=0.442	r=0.044 p=0.838
NO_3+NO_2●	r=0.240 p=0.258	r=-0.054 p=0.818	r=0.317 p=0.131	r=-0.200 p=0.348	r=0.190 p=0.374
NO_3+NO_2/NH_3 ●	r=0.001 p=0.995	r=0.310 p=0.171	r=0.040 p=0.852	r=-0.113 p=0.599	r=0.288 p=0.173
TP	r=**0.556** p=**0.005**	r=-0.139 p=0.548	r=**0.470**● p=**0.021**	r=**-0.438** p=**0.032**	r=**-0.505**● p=**0.012**
RP	r=0.237 p=0.265	r=0.109 p=0.639	r=0.311 p=0.139	r=*-0.352* p=*0.092*	r=-0.311 p=0.138
%RP●	r=-0.114 p=0.595	r=0.109 p=0.638	r=-0.062 p=0.772	r=**-0.495** p=**0.012**	r=0.156 p=0.468
TN/TP	r=*-0.380* p=*0.067*	r=-0.082 p=0.725	r=*-0.348* p=*0.096*	r=0.329 p=0.117	r=**0.411** p=**0.046**
Ext. Coefficient	r=0.278 p=0.199	r=-0.142 p=0.550	r=0.131● p=0.550 (23)	r=0.106 p=0.623 (24)	r=**-0.483** p=**0.020**
Temperature n = 17, 20	r=0.283 p=0.227 (20)	r=-0.134 p=0.609 (17)	r=0.105 p=0.658 (20)	r=*-0.406* p=*0.075* (20)	r=**-0.765** (20) p<**0.0001**
%Oxygen n = 17, 20	r=0.225 p=0.340	r=-0.298 p=0.245	r=0.144 p=0.545	r=-0.122 p=0.609	r=**-0.616**● p=**0.004**
Conductivity● n = 17, 20	r=**-0.557** p=**0.011**	r=**0.564** p=**0.018**	r=**-0.510** p=**0.021**	r=*0.424* p=*0.062*	r=**0.678** p=**0.001**
pH●	r=0.308 p=0.187 (23)	r=*-0.453* p=*0.068* (20)	r=0.242 p=0.304	r=-0.293 p=0.210	r=**-0.601** p=**0.005**

Units: Temperature: °C, Conductivity: μS cm^{-1}, Nutrients: μg L^{-1}, Isotope signal: ‰. n = number of cases. ● Ranked variables.

Table 3.2.8 Comparison of metaphyton biomass versus other primary producers of the Rideau River on an areal basis (water column of 1 m).

	Min (gdw m^{-2})	**Max (gdw m^{-2})**
Metaphyton	0.70	616.9
Macrophytes*	0.76	217.4
Periphyton**	6.3	11.3
Phytoplankton***	0.15	1.5

* In littoral zones Makkay (2002)
** In riffle zones Chételat et al. (1999)
***In main channel Basu & Pick (1997)
Periphyton and phytoplankton chlorophyll-*a* were converted to dry weight based on the C:Chl-*a* ratio (37) of Descy & Gosselain (1994) and assuming half of the dry weight is carbon.

Table 3.2.9 Metaphytic mat composition per site. "Non-meta" corresponds to the non-metaphytic part of the whole mat whereas "Meta" corresponds to true metaphytic alga in the mat.

SITES	Meta	Non-Meta
1. Burrits Rapids	*Spirogyra*	*Elodea canadensis*
2. Murphy Drain	*Spirogyra*	*Elodea canadensis*
3. Libby Island	*Spirogyra*, *Oscillatoria* cf. *limnetica*	*Lemna trisulca*. Debris
4. Kars	*Spirogyra*, *Lyngbya*, Epiphytes: *Characium*	*Lemna trisulca*
5. Sanders Island	*Spirogyra*	*Potamogeton* spp. *Lemna trisulca*, *Ceratophyllum demersum*
6. Golf Course	*Cladophora*, *Oscillatoria*, *Lyngbya*	*Ceratophyllum demersum*, *Lemna trisulca*
7. BM 285	*Spirogyra*	*Lemna trisulca*, *Potamogeton* spp., *Ceratophyllum demersum*, *Elodea canadensis*
8. Manotick	*Spirogyra*	*Ceratophyllum demersum*, *Lemna trisulca*, *Elodea canadensis*
9. Bank Street	*Cladophora*, *Hydrodictyon*	Debris
10. St. Paul U.	*Cladophora*	*Ceratophyllum demersum*. Debris
11. St. Patrick Street	*Cladophora*, *Spirogyra*	Debris
12. Maple Park	*Spirogyra*, *Cladophora*, *Hydrodictyon*	*Elodea canadensis*, *Lemna trisulca*. Debris

Table 3.2.10 Pearson product-moment correlation with Bonferroni probabilities. Linear associations among nutrients and metaphyton isotopic signals. Variables were log-transformed or square root transformed for parametric correlations or ranked for Spearman correlations (n = 25). Italics are for slightly significant correlations.

	$\%N_{metaphyton}$	$\delta^{15}N_{metaphyton}$	$\%C_{metaphyton}$	$\delta^{13}C_{metaphyton}$●	$C/N_{metaphyton}$
TN	r=**-0.410** p=**0.042**	r=-0.206 p=0.322	r=**0.457** p=**0.022**	r=0.167 p=0.426	r=**0.594** p=**0.002**
NH_3	r=-0.154 p=0.461	r=0.317 p=0.122	r=-0.314 p=0.126	r=-0.259 p=0.211	r=0.036 p=0.864
NO_3+NO_2●	r=0.009 p=0.965	r=-0.122 p=0.563	r=-0.132 p=0.531	r=-0.244 p=0.240	r=-0.058 p=0.782
NO_3+NO_2/NH_3 ●	r=**0.455** p=**0.022**	r=-0.287 p=0.164	r=0.040 p=0.851	r=-0.054 p=0.799	r=**-0.404** p=**0.045**
TP	r=-0.161 p=0.442	r=0.012 p=0.954	r=**0.460** p=**0.021**	r=-0.030 p=0.888	r=*0.358* p=*0.079*
RP	r=0.030 p=0.888	r=*0.367* p=*0.071*	r=0.125 p=0.552	r=*-0.373* p=*0.067*	r=0.076 p=0.717
%RP	r=0.211 p=0.312	r=**0.473** p=**0.017**	r=-0.236 p=0.257	r=**-0.495** p=**0.012**	r=-0.243 p=0.242
TN/TP	r=-0.025 p=0.907	r=-0.146 p=0.486	r=**-0.412** p=**0.041**	r=0.187 p=0.372	r=-0.159 p=0.449
Ext. Coefficient	r=-0.192 p=0.368	r=0.009 p=0.965	r=*0.385* p=*0.063*	r=0.106 p=0.623	r=*0.372* p=*0.073*
Temperature	r=-0.251 p=0.272	r=-0.099 p=0.669	r=**0.535** p=**0.012**	r=**0.651** p=**0.001**	r=**0.456** p=**0.038**
%Oxygen	r=**-0.468** p=**0.032**	r=0.142 p=0.540	r=0.325 p=0.151	r=0.348 p=0.122	r=**0.595** p=**0.004**
Conductivity	r=**0.439** p=**0.047**	r=-0.014 p=0.953	r=-0.212 p=0.356	r=-0.274 p=0.229	r=**-0.524**● p=**0.015**
pH	r=-0.236 p=0.303	r=0.136 p=0.556	r=0.239 p=0.297	r=0.241 p=0.292	r=0.343 p=0.128

Units: Temperature: °C, Conductivity: µS cm^{-1}, Nutrients: µg L^{-1}, Isotope signal: ‰. ● Ranked variables.

Table 3.2.11 Correlations among isotopes signal in the metaphyton and in the sediments of 12 littoral zones in the Rideau River. Summer 2001.

	$\%N_{metaphyton}$	$\delta^{15}N_{metaphyton}$	$\%C_{metaphyton}$	$\delta^{13}C_{metaphyton}$●	$C/N_{metaphyton}$
$\%N_{sediment}$ n = 24	r=**-0.446** p=**0.029**	r=-0.251 p=0.237	r=0.038 p=0.860	r=0.009 p=0.966	r=**0.497** p=**0.014**
$\delta^{15}N_{sediment}$ n = 21	r=**0.511** p=**0.018**	r=0.087 p=0.707	r=0.236 p=0.303	r=0.060 p=0.796	r=**-0.501** p=**0.021**
$\%C_{sediment}$● n = 24	r=**-0.412** p=**0.046**	r=-0.249 p=0.241	r=0.013 p=0.953	r=-0.122 p=0.571	r=*0.395* p=*0.056*
$\delta^{13}C_{sediment}$● n = 24	r=*0.381* p=*0.066*	r=0.157 p=0.465	r=-0.341 p=0.103	r=-0.056 p=0.794	r=**-0.432** p=**0.035**
$C/N_{sediment}$● n = 24	r=0.257 p=0.226	r=-0.043 p=0.842	r=**-0.579** p=**0.003**	r=*-0.361* p=*0.083*	r=**-0.470** p=**0.020**

Units: Isotope signal: ‰; n = number of cases. ● Ranked variables.

Table 3.2.12 Correlation matrix among nutrient concentration of 12 littoral zones of the Rideau River. Sampling season: summer 2001, n = 25.

	TN	NH_3	NO_3+NO_2●	NO_3+NO_2/NH_3●	TP	RP	%RP
NH_3	r=-0.115 p=0.584						
NO_3+NO_2●	r=-0.251 p=0.226	r=0.118 p=0.576					
NO_3+NO_2/NH_3●	r=-0.221 p=0.288	r=**-0.662** p<**0.00***	r=**0.464** p=**0.020**				
TP	r=**0.851** p<**0.00***	r=0.041 p=0.845	r=-0.094 p=0.655	r=-0.008 p=0.969			
RP	r=0.323 p=0.116	r=**0.479** p=**0.015**	r=0.197 p=0.344	r=-0.102 p=0.629	r=**0.685** p<**0.00***		
%RP	r=-0.328 p=0.109	r=**0.583** p=**0.002**	r=**0.434** p=**0.030**	r=-0.052 p=0.805	r=0.057 p=0.786	r=**0.757** p<**0.00***	
TN/TP	r=**-0.624** p=**0.001**	r=-0.105 p=0.617	r=-0.020 p=0.924	r=-0.034 p=0.870	r=**-0.940** p=**0.00***	r=**-0.794** p<**0.00***	r=-0.217 p=0.298

Units: $\mu g\ L^{-1}$. *p < 0.0001. ● Ranked variables.

Figure 3.2.1 Metaphytic and planktonic chlorophyll-*a* of 12 sites sampled along the lower part of the Rideau River. Average and standard error of three samples per site for the metaphyton concentration and two samples for the planktonic chlorophyll-*a*.

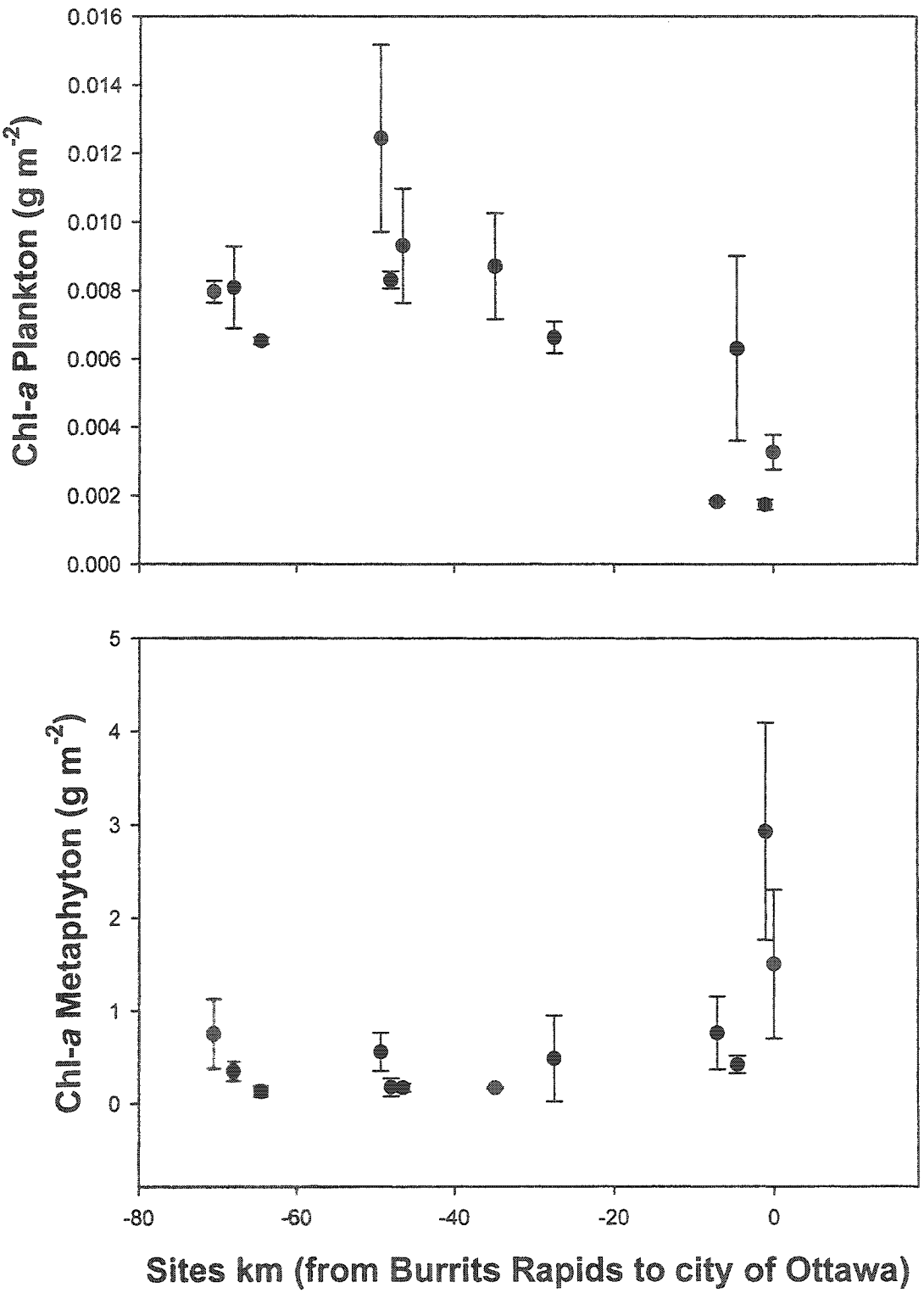

0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Chl-a Plankton (g m-2)
5
4
3
2
1
0
Chl-a Metaphyton (g m-2)
-80
-60
-40
-20
0
Sites km (from Burrits Rapids to city of Ottawa)

Figure 3.2.2 Longitudinal patterns of the metaphytic and planktonic biomass of the 12 sites sampling during the summer season 2001. In each site three samples were averaged and the standard error calculated for the metaphyton biomass and two for the plankton biomass.

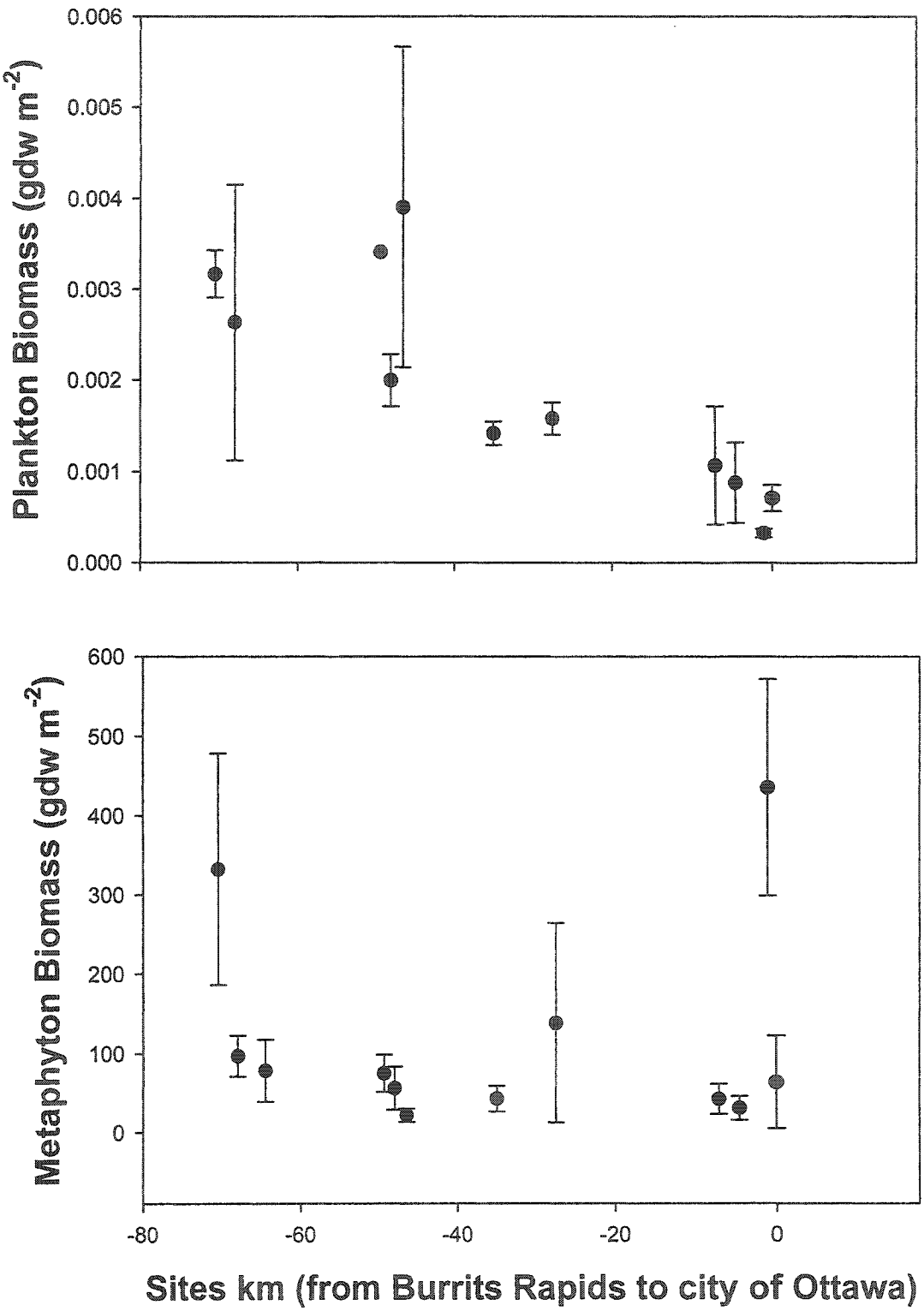

Plankton Biomass (gdw m-2)
0.006
0.005
0.004
0.003
0.002
0.001
0.000
Metaphyton Biomass (gdw m-2)
600
500
400
300
200
100
0
-80
-60
-40
-20
0
Sites km (from Burrits Rapids to city of Ottawa)

Figure 3.2.3 Longitudinal patterns of the nitrate + nitrite and the nitrate + nitrite to ammonia ratio. In each site two samples were averaged and the standard error calculated for both variables.

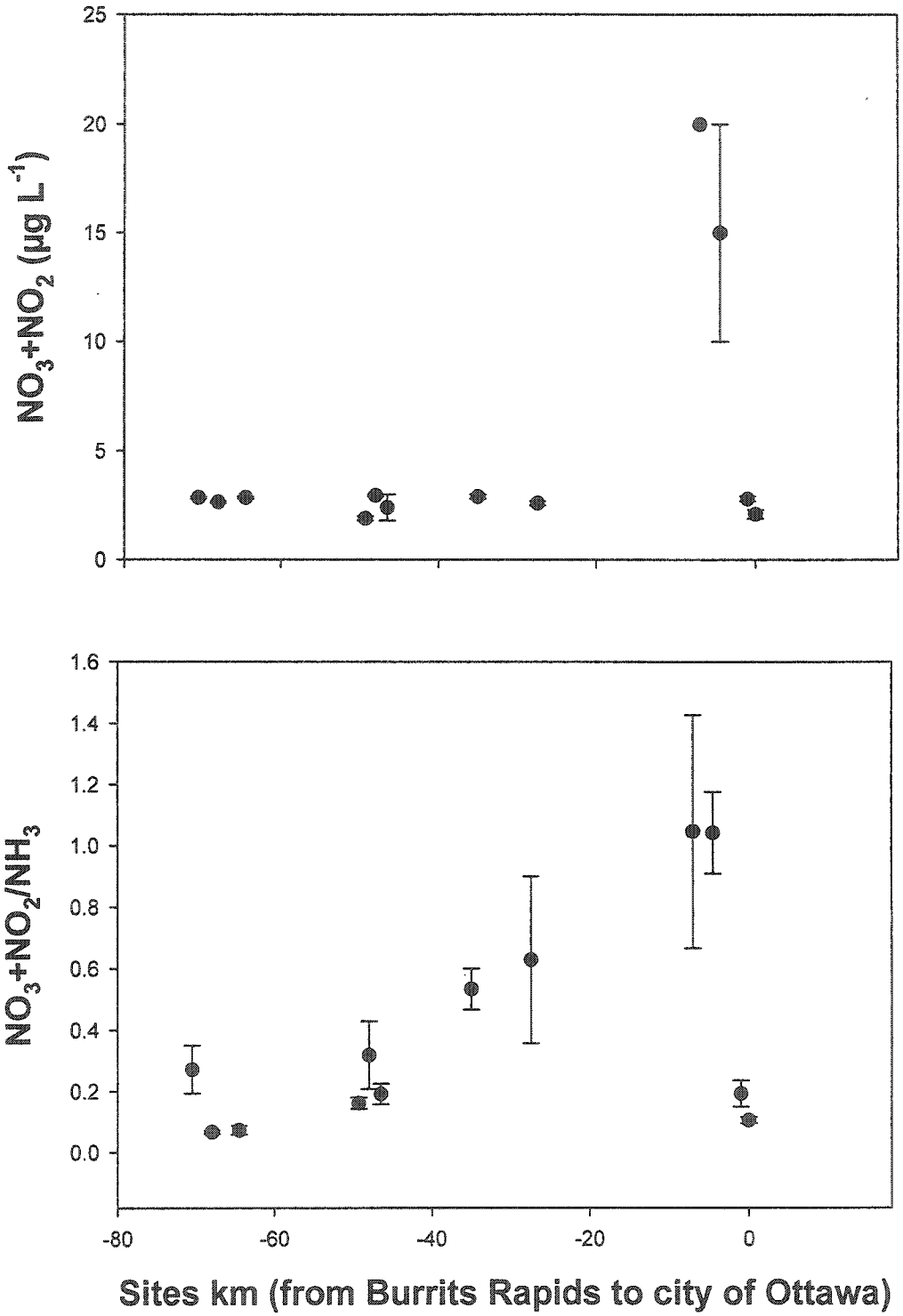

25
20
15
10
5
0
NO_3+NO_2 (µg L^{-1})
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
NO_3+NO_2/NH_3
-80
-60
-40
-20
0
Sites km (from Burrits Rapids to city of Ottawa)

Figure 3.2.4 Longitudinal pattern of the conductivity for ten sites located along the lower section of the Rideau River. At each site two samples were averaged and the standard error calculated.

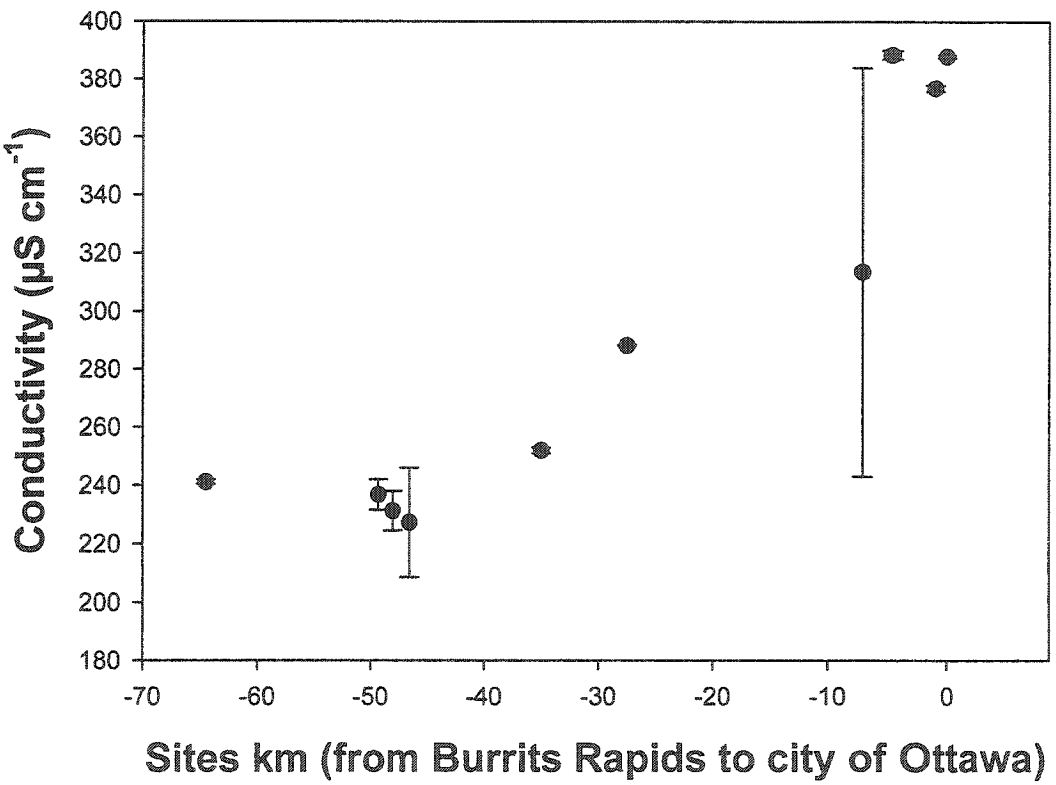

Conductivity (µS cm-1)
400
380
360
340
320
300
280
260
240
220
200
180
-70
-60
-50
-40
-30
-20
-10
0
Sites km (from Burrits Rapids to city of Ottawa)

Figure 3.2.5 Longitudinal pattern of $\delta^{15}N$, $\delta^{13}C$ and ratio carbon to nitrogen of sediments. Estimates represent the mean of two samples and include standard error.

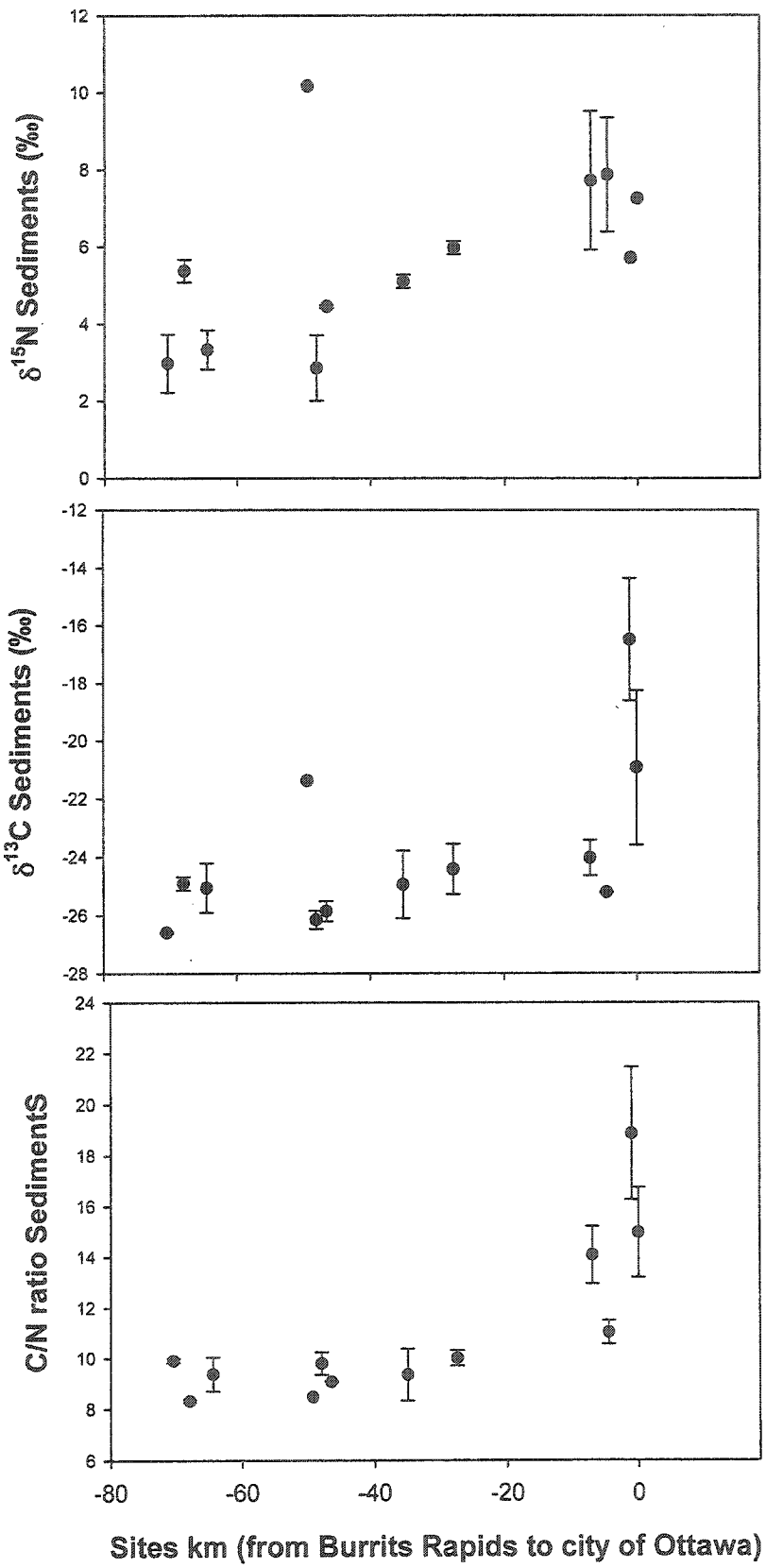

δ15N Sediments (‰)
δ13C Sediments (‰)
C/N ratio SedimentS
Sites km (from Burrits Rapids to city of Ottawa)

Figure 3.2.6 Longitudinal pattern of the organic matter in sediments. For some sites the average of two samples was estimated and the standard error calculated.

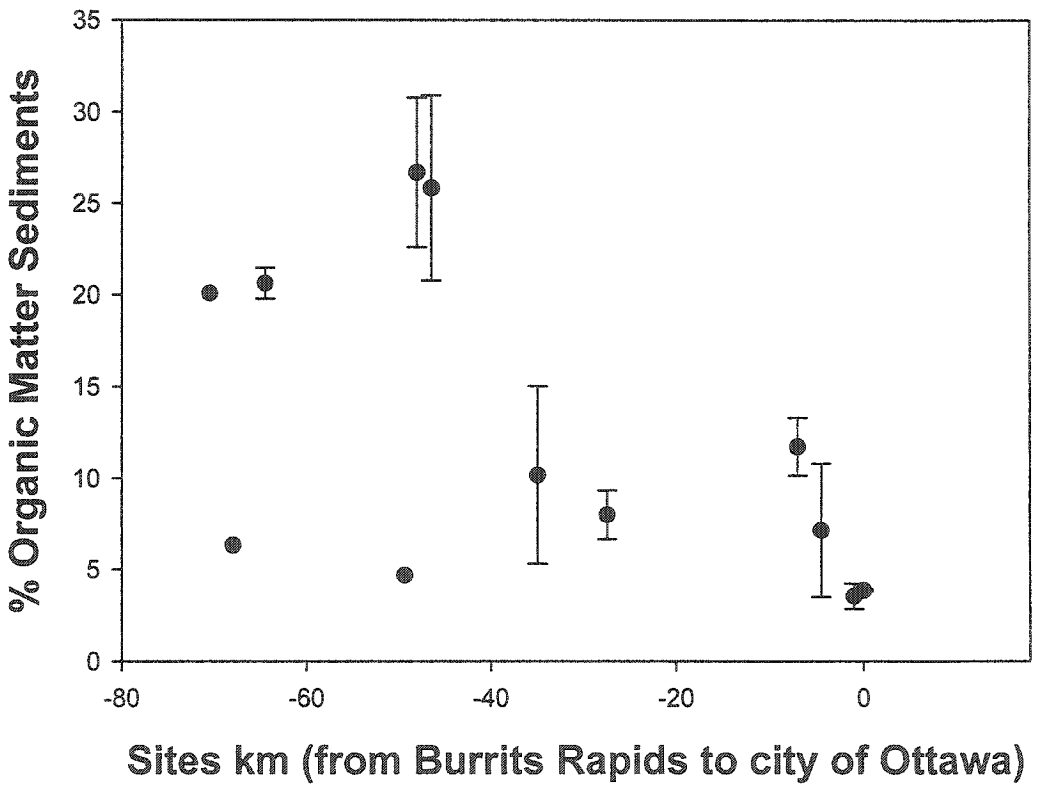

% Organic Matter Sediments
35
30
25
20
15
10
5
0
-80
-60
-40
-20
0
Sites km (from Burrits Rapids to city of Ottawa)

Figure 3.2.7 Longitudinal pattern of NH_3, TN and TP from Burrits Rapids to the city of Ottawa. Two samples were taken per site; the averages were calculated as well as the standard errors.

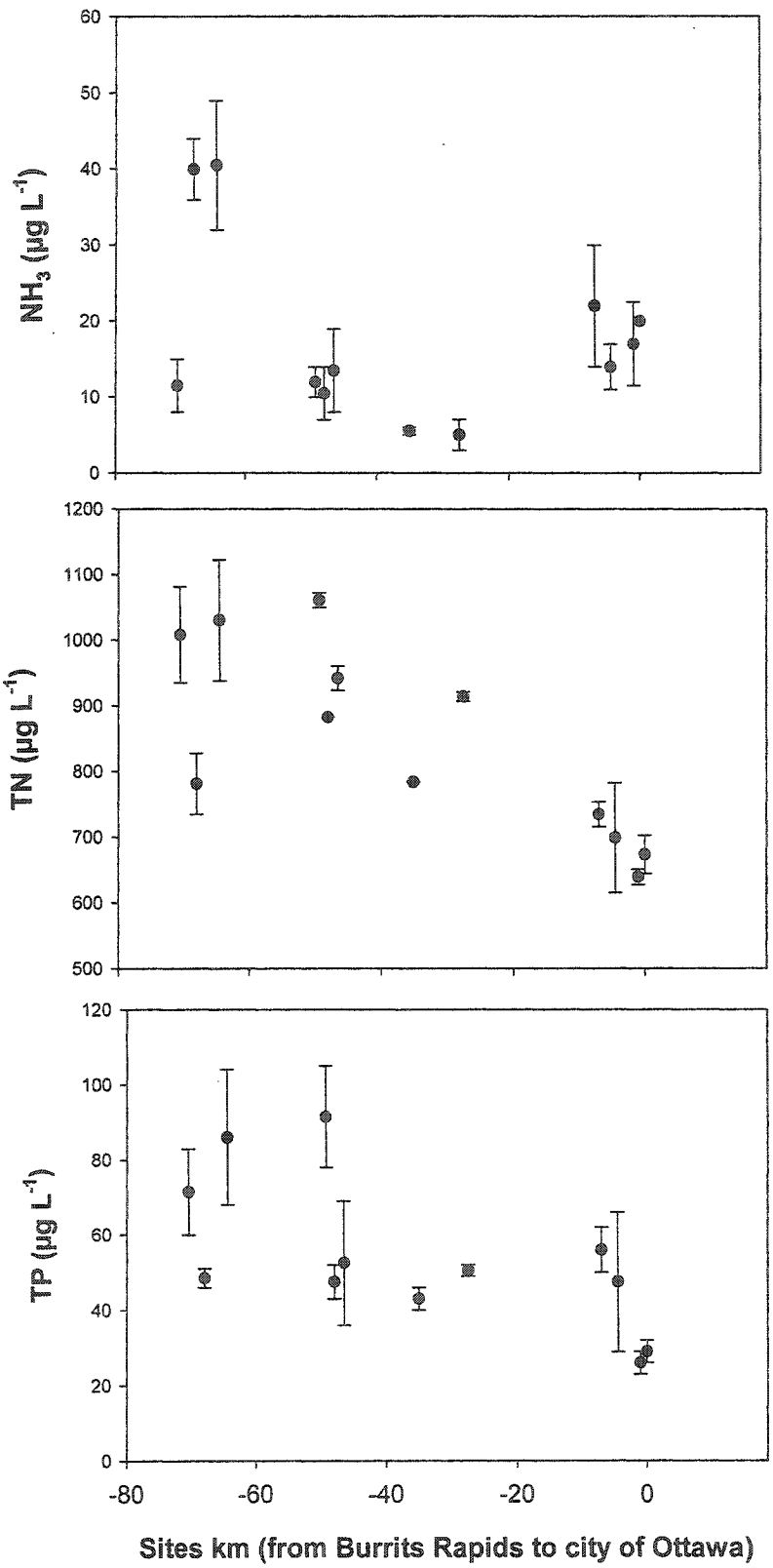

NH3 (µg L-1)
TN (µg L-1)
TP (µg L-1)
Sites km (from Burrits Rapids to city of Ottawa)

Figure 3.2.8 Longitudinal pattern of $\delta^{15}N$, $\delta^{13}C$ and ratio carbon to nitrogen of the metaphyton. Estimates represent the mean of two samples and include standard error.

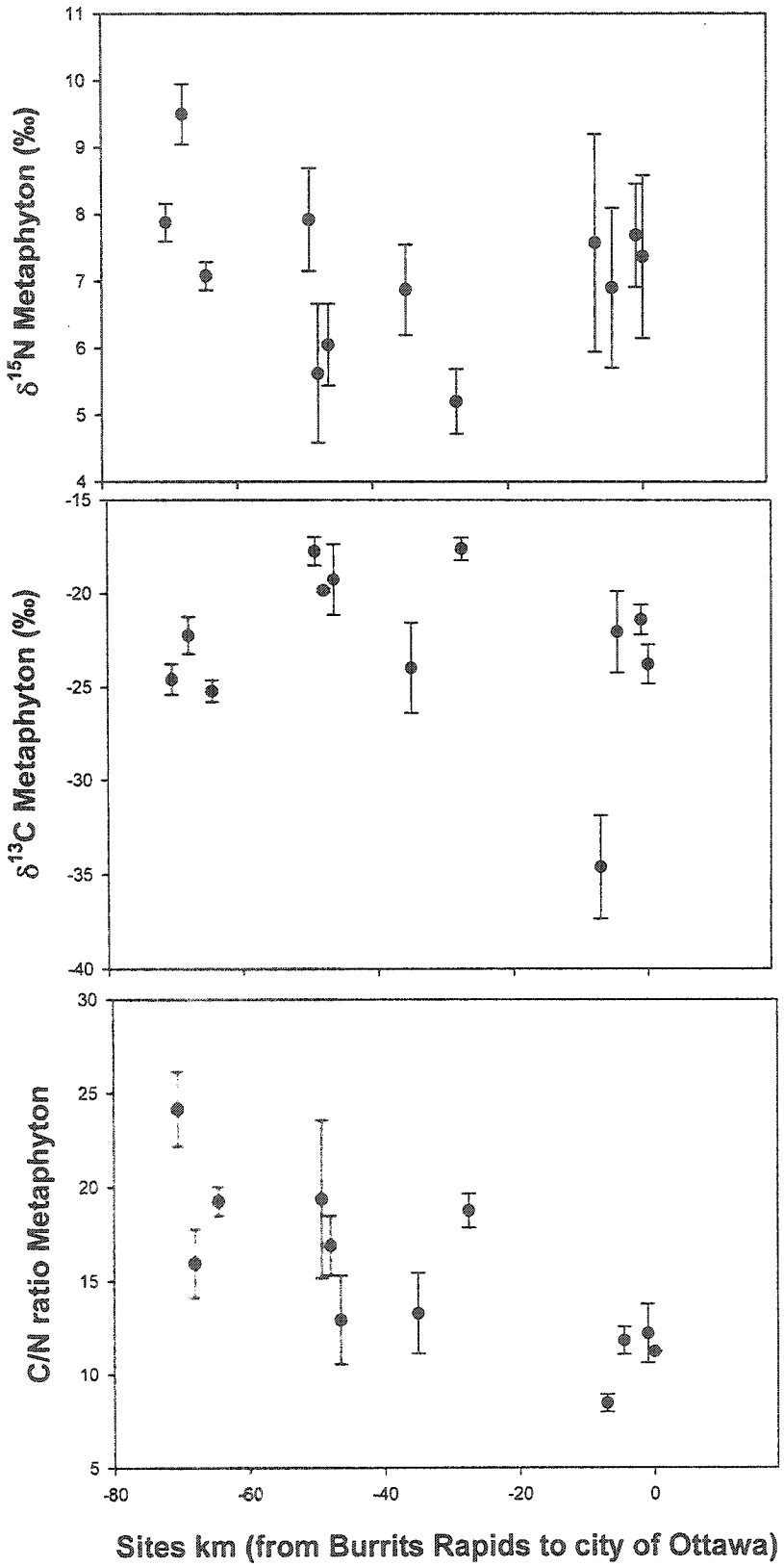

δ15N Metaphyton (‰)
11
10
9
8
7
6
5
4
δ13C Metaphyton (‰)
-15
-20
-25
-30
-35
-40
C/N ratio Metaphyton
30
25
20
15
10
5
-80
-60
-40
-20
0
Sites km (from Burrits Rapids to city of Ottawa)

Figure 3.2.9 Comparison among ascribed land-use grouping for the ratio carbon to nitrogen of the metaphyton, total nitrogen and total phosphorus of the water column. The values were log transformed (TN and TP in $\mu g\ L^{-1}$) or squared root (C/N_{meta}) for parametric nested-ANOVA. Least squares means with the same letter are not significantly different at 5%. AG group corresponds to sites adjacent to agricultural land; RG corresponds to light-residential sites and UG to the urban group.

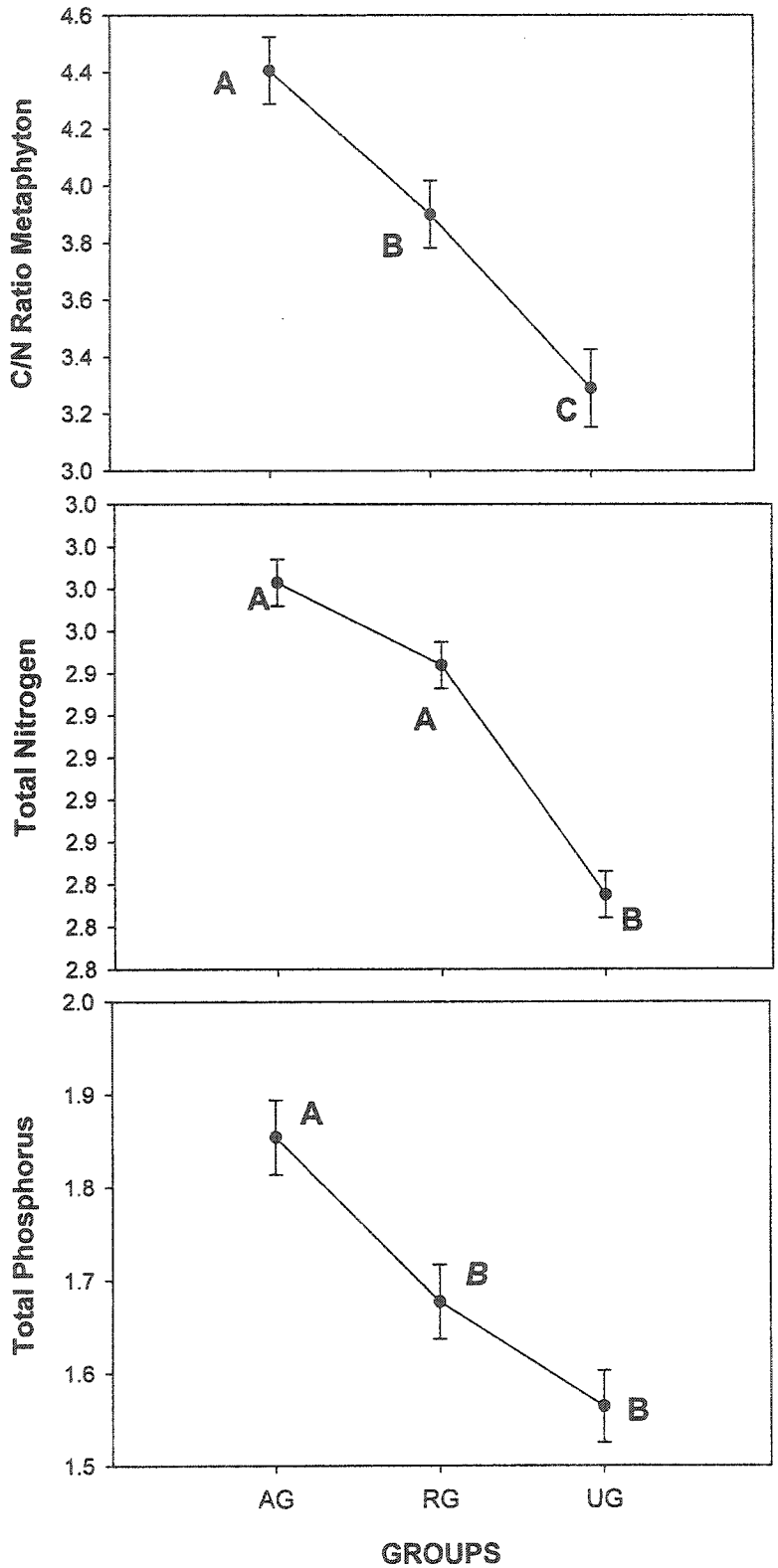

C/N Ratio Metaphyton
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
A
B
C
Total Nitrogen
3.0
3.0
3.0
2.9
2.9
2.9
2.9
2.9
2.8
2.8
2.8
A
A
B
Total Phosphorus
2.0
1.9
1.8
1.7
1.6
1.5
A
B
B
AG
RG
UG
GROUPS

Figure 3.2.10 Comparison among ascribed land-use grouping for the chlorophyll-*a*, $\delta^{15}N$ of sediments and conductivity of the water column. The values were log transformed (conductivity and Chl-*a* in $\mu S\ cm^{-1}$ and $g\ m^{-2}$, respectively) or squared root ($\delta^{15}N_{sed}$ in ‰) for parametric nested-ANOVA. Least squares means with the same letter are not significantly different at 5%. AG group corresponds to sites adjacent to agricultural land; RG corresponds to light-residential sites and UG to the urban group.

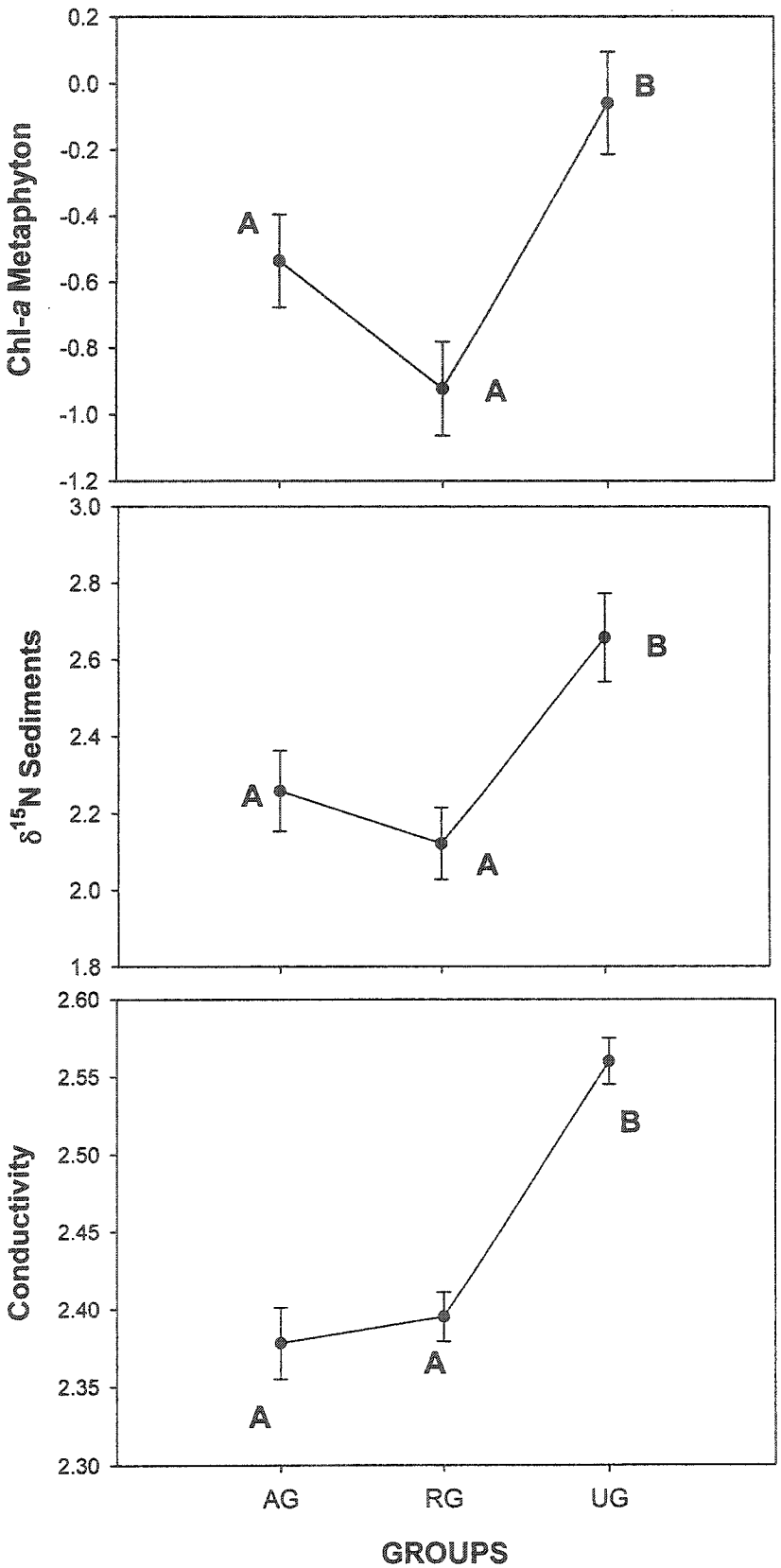

Chl-a Metaphyton
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
A
A
B
δ15N Sediments
3.0
2.8
2.6
2.4
2.2
2.0
1.8
A
A
B
Conductivity
2.60
2.55
2.50
2.45
2.40
2.35
2.30
A
A
B
AG
RG
UG
GROUPS

Figure 3.2.11 Comparison among ascribed land-use grouping for metaphyton biomass, the $\delta^{15}N$ of metaphyton and NH_3 in the water. The values were log transformed (metaphyton biomass and NH_3 in gdw m^{-2} and $\mu g\ L^{-1}$, respectively) or squared root for parametric nested-ANOVA (metaphyton $\delta^{15}N$ signal in ‰). Least squares means with the same letter are not significantly different at 5%. AG group corresponds to sites adjacent to agricultural land; RG corresponds to light-residential sites and UG to the urban group.

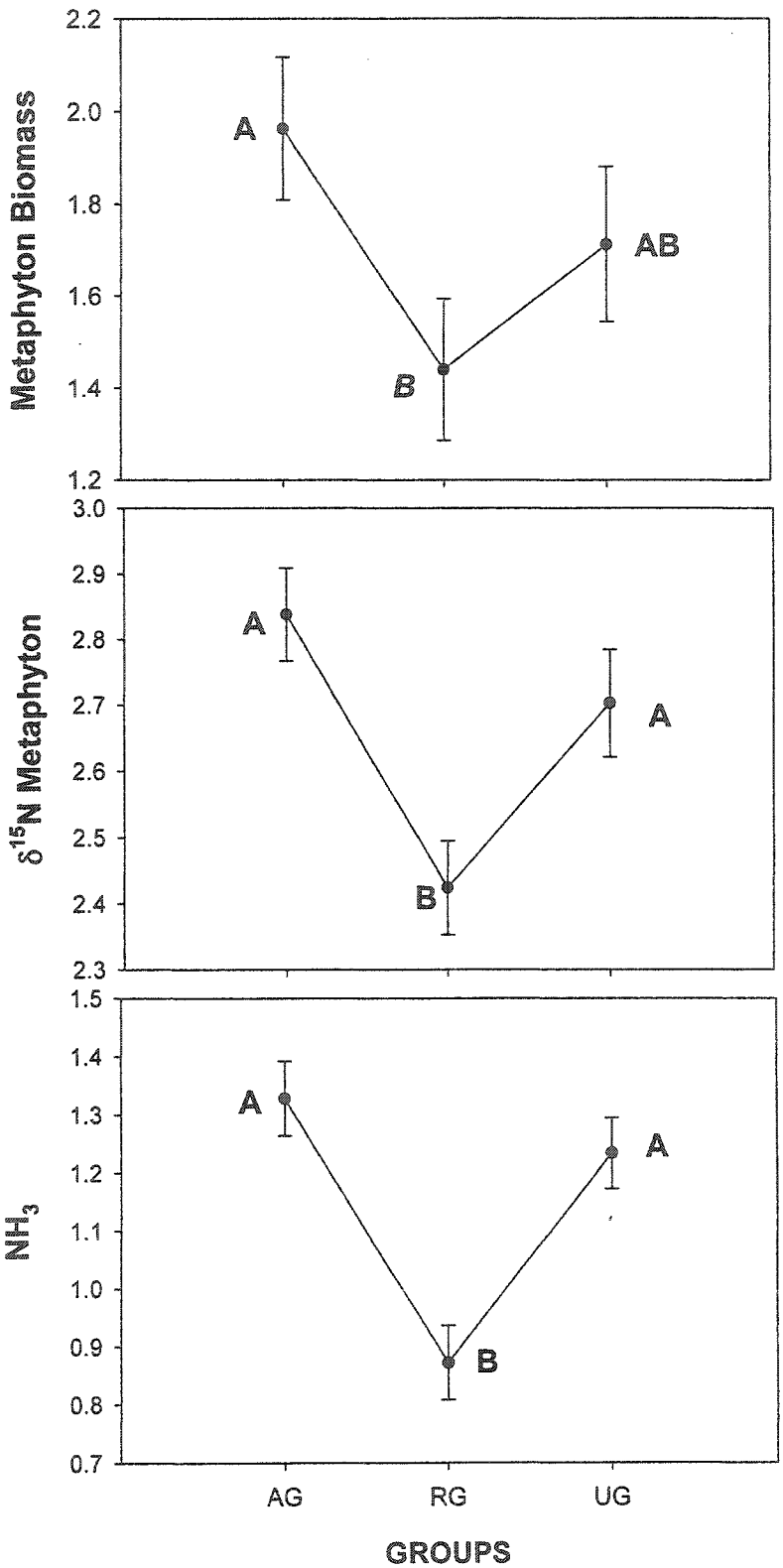

Metaphyton Biomass
2.2
2.0
1.8
1.6
1.4
1.2
A
B
AB
δ15N Metaphyton
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
A
B
A
NH3
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
A
B
A
AG
RG
UG
GROUPS

Figure 3.2.12 Comparison among ascribed land-use grouping for the $\delta^{13}C$ of metaphyton (‰). The values were ranked for a non-parametric nested-ANOVA. Least squares means with the same letter are not significantly different at 5%. The AG group corresponds to sites adjacent to agricultural land; RG corresponds to light-residential sites and UG to the urban group.

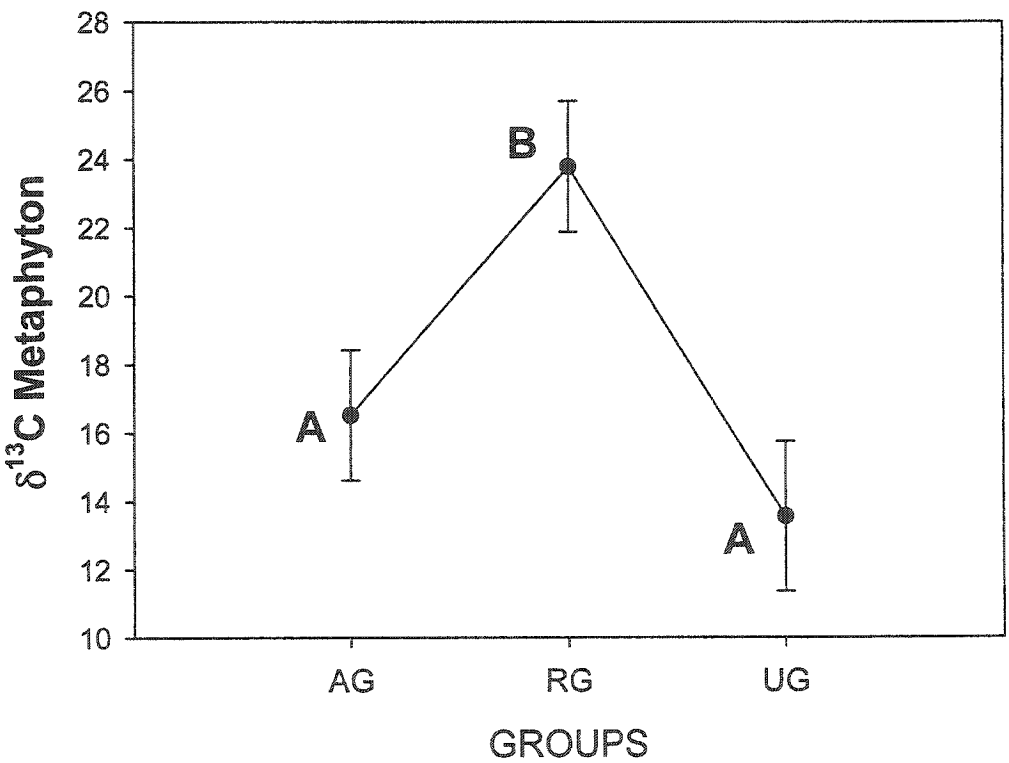

28
26
24
22
20
18
16
14
12
10
δ13C Metaphyton
B
A
A
AG
RG
UG
GROUPS

Figure 3.2.13 Linear association between the chlorophyll-*a* of metaphyton and plankton communities along 12 littoral zones of the Rideau River.

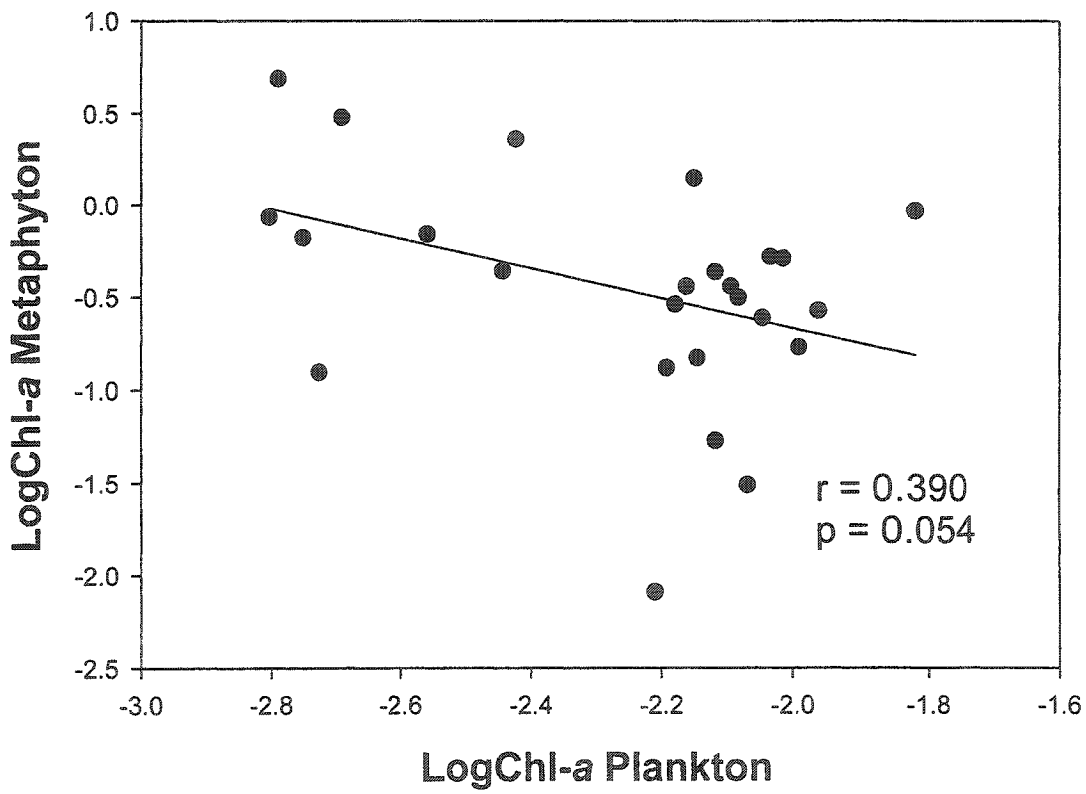
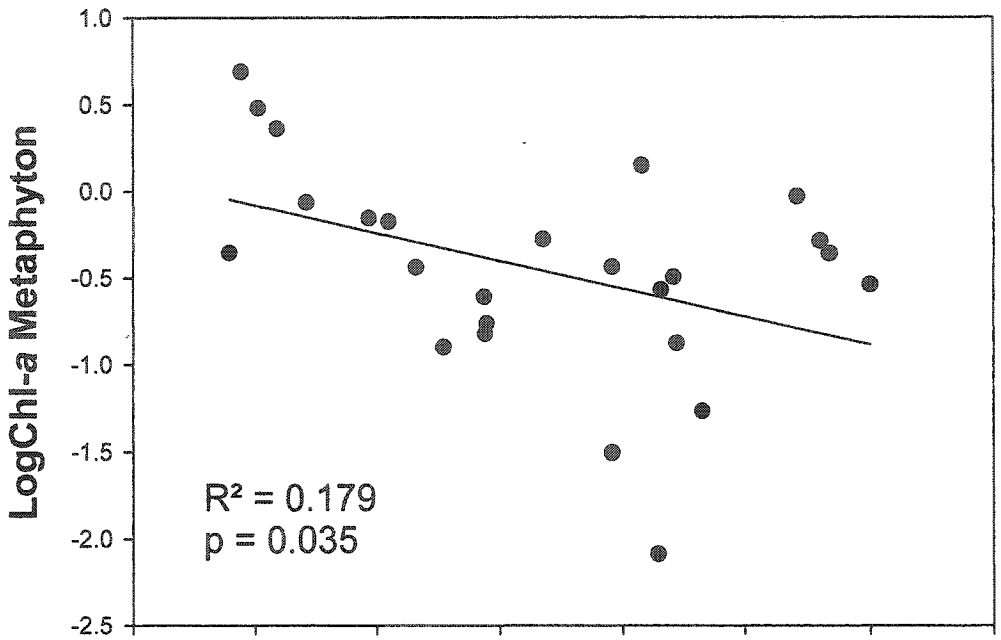

1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-2.8
-2.6
-2.4
-2.2
-2.0
-1.8
-1.6
LogChl-a Metaphyton
LogChl-a Plankton
r = 0.390
p = 0.054

Figure 3.2.14 Linear regression between total nitrogen in the water column and the chlorophyll-*a* of metaphyton and plankton communities for 12 littoral zones of the Rideau River.


LogChl-a Metaphyton
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
R² = 0.179
p = 0.035

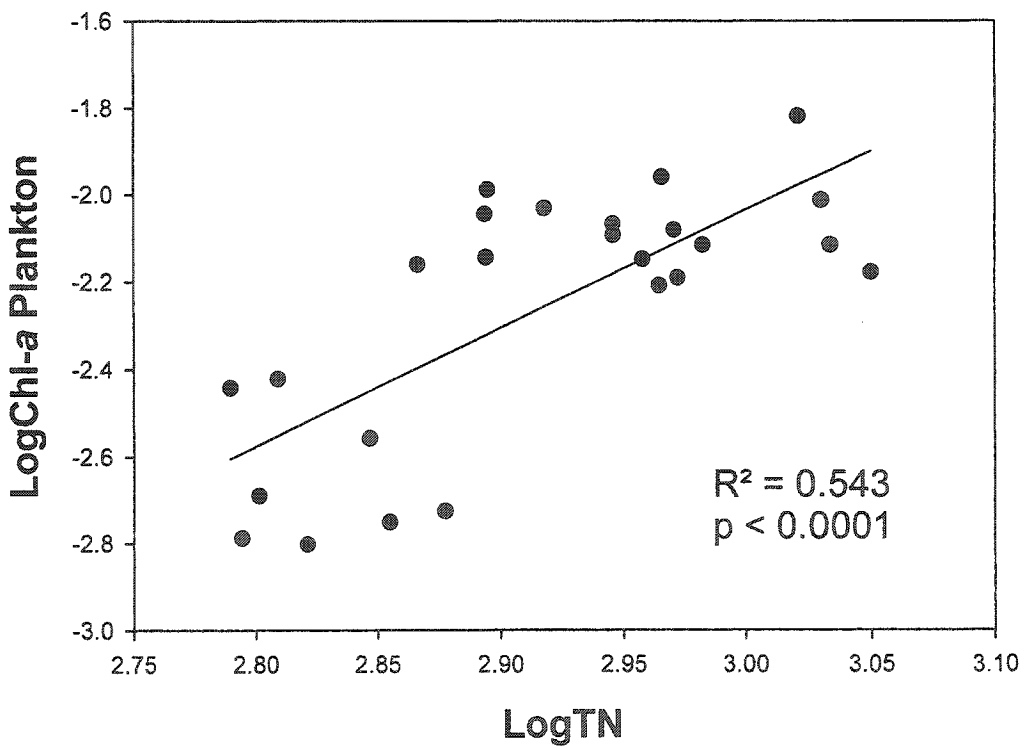

LogChl-a Plankton
-1.6
-1.8
-2.0
-2.2
-2.4
-2.6
-2.8
-3.0
2.75
2.80
2.85
2.90
2.95
3.00
3.05
3.10
LogTN
R² = 0.543
p < 0.0001

Figure 3.2.15 Linear regression between the ration nitrate + nitrite to ammonia in the water column and the biomass of metaphyton and plankton communities for 12 littoral zones of the Rideau River.

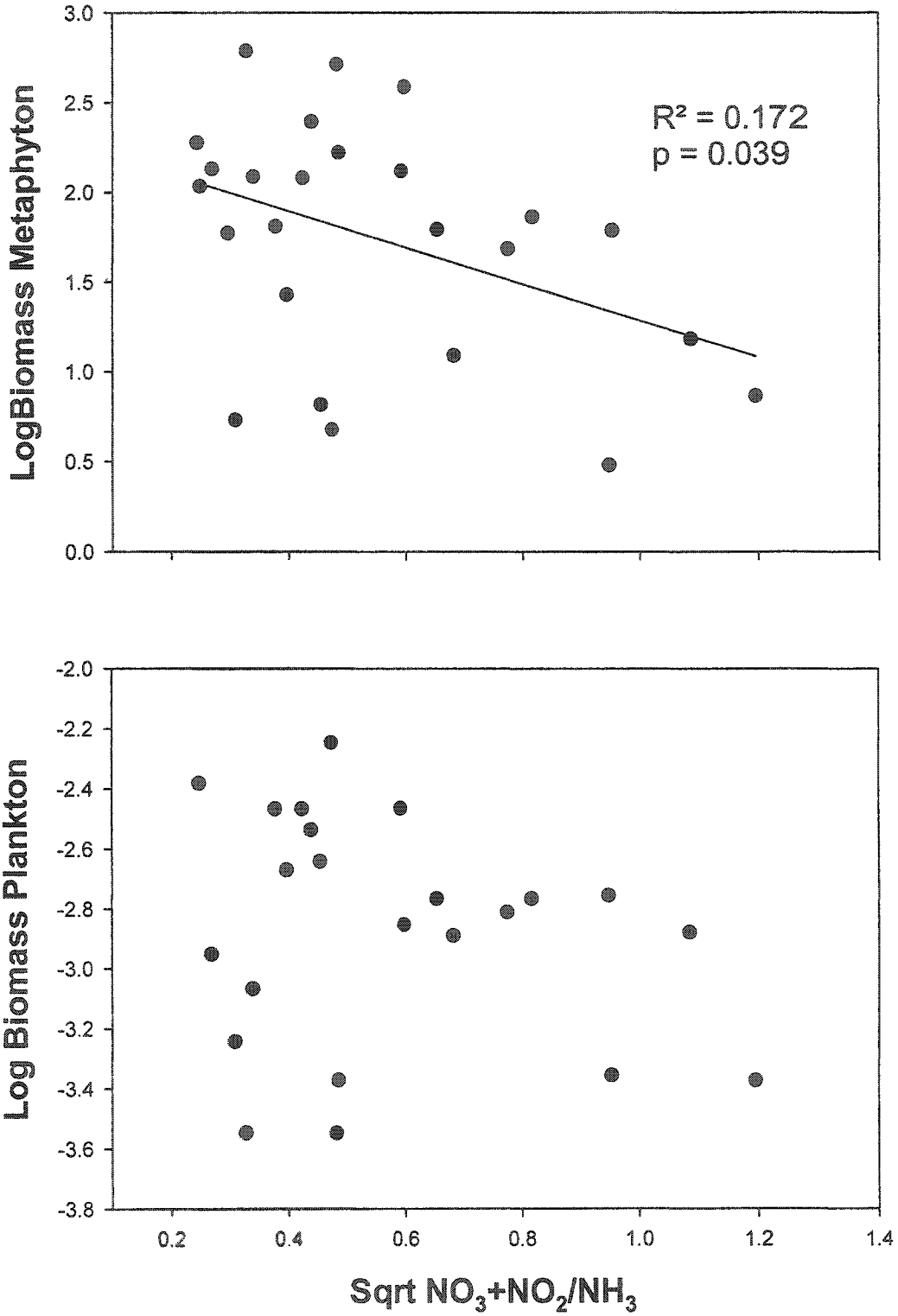
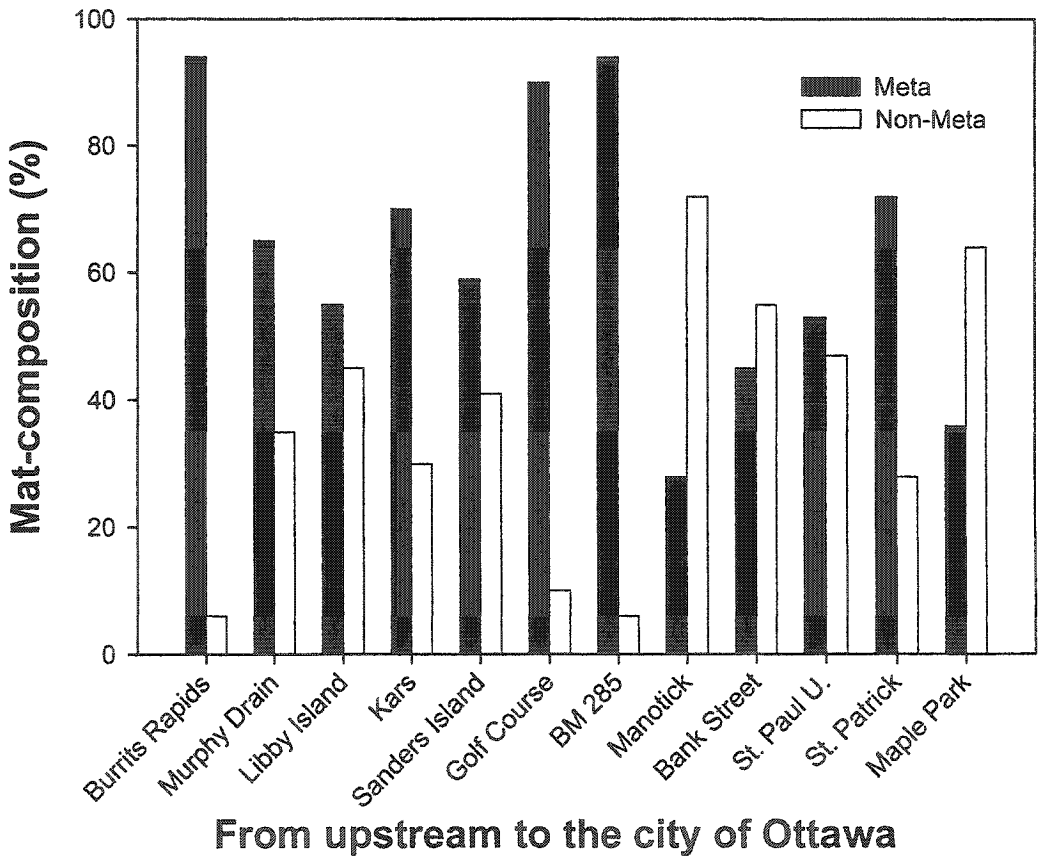

LogBiomass Metaphyton
3.0
2.5
2.0
1.5
1.0
0.5
0.0
R² = 0.172
p = 0.039
Log Biomass Plankton
-2.0
-2.2
-2.4
-2.6
-2.8
-3.0
-3.2
-3.4
-3.6
-3.8
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Sqrt NO3+NO2/NH3

Figure 3.2.16 Composition in percentage of the whole mat per site. Meta corresponds to the metaphytic filamentous algae whereas the Non-Meta refers to the non-metaphytic part of the mat.


100
80
60
40
20
0
Mat-composition (%)
Meta
Non-Meta
Burrits Rapids
Murphy Drain
Libby Island
Kars
Sanders Island
Golf Course
BM 285
Manotick
Bank Street
St. Paul U.
St. Patrick
Maple Park
From upstream to the city of Ottawa

Chapter 4.0

Discussion

In this chapter, I examine the main physical and chemical factors that influence metaphyton in the Rideau River, Ontario, from both a temporal and spatial perspective. Subsequently, I discuss the stable isotope signals of metaphyton and their relationship to land use along the lower reaches of the river. Finally, I elaborate on the potential interactions between metaphyton and other primary producers in the littoral zones of rivers.

4.1 First hypothesis: The role of nutrients in metaphyton development

The first hypothesis that I addressed was that the biomass of metaphyton is positively related to nutrient concentrations in the Rideau River. I predicted that due to the nutrient requirements of primary producers for nitrogen and phosphorus, the biomass of metaphyton would be greater in littoral areas with high nutrient concentrations.

This hypothesis was only in part accepted. On a temporal scale, at the one river site, a significant relationship was observed between total phosphorus in the water column and the metaphyton biomass (Table 3.1.3). In addition, seasonally, the metaphyton was negatively related to NO_3+NO_2/NH_3 at Manotick. In contrast, on the longitudinal scale of the Rideau, the only significant relationship between metaphyton biomass and nutrients

was the negative one with NO_3+NO_2/NH_3 ratio (Table 3.2.5). The lack of a relationship between TP and TN along the river is not because nutrient concentrations did not vary: there was as much longitudinal as temporal variation in TP levels (36 - 105 along the river *vs.* 21 - 81 $\mu g\ L^{-1}$ at Manotick). One problem with the longitudinal study is that because the metaphyton biomass is the result of several days of growth, the water nutrient concentrations taken at the time of sampling may not reflect the actual concentrations over the growth period.

The ratio NO_3+NO_2/NH_3 was proposed by Wetzel (1983), as a measure of polluted or unpolluted lakes in regions draining calcareous sedimentary landforms. This author suggested that ratios in the range of 1:10 could indicate some sewage or agricultural applications of nitrogen fertilizers. Wetzel (1983) also proposed the ratio 25:1 for natural sources of nitrate. However, the latter seems unlikely since nitrate in rivers has been proposed as an indicator of anthropogenic impact because of a strong correlation between nitrate and human population densities (Caraco & Cole 1999). The Rideau River, localized in a calcareous sedimentary basin, had an average NO_3+NO_2/NH_3 ratio of 0.38, suggesting sewage contamination or/and agricultural applications of nitrogen fertilizers, but the ratio ranged from 0.06 to 0.90. The ratio increased towards downtown Ottawa to values that, according to Wetzel, would indicate a lack of pollution (1:1). Clearly, further study is required to evaluate the utility of this ratio in assessing anthropogenic impacts.

The overall pattern of the NO_3+NO_2/NH_3 ratio and NO_3+NO_2 concentrations in the Rideau River could be due to changes in river morphology and the distribution of

wetlands as well as differences in loading along the river. Wetlands tend to lose nitrogen because of high denitrification rates. The Rideau has a large wetland area upstream around Kilmarnok Island that would be important in regulating the N retention upstream; further downstream past Kars the river channel becomes deeper with less littoral zones (Preece 2001, Fig. 2.1). The NO_3+NO_2 and NH_3 concentration increased at the urban sites indicating either increased loading from urban runoff or less capacity to process inorganic forms because of a lack of littoral zones and greater depth. Depth appears to be an important variable in controlling nitrogen retention in rivers, presumably because of its effects on denitrification (Alexander et al. 2000).

Metaphyton, aside from obtaining their nutrients from the water column, may access sediment stores of nutrients at some stage in their life cycle. Although there was no significant relationship between metaphyton biomass and the percent nitrogen content of the sediments, the metaphytic chlorophyll-*a* was negatively associated with percent nitrogen and carbon in sediments. It should be noted that both, the percent nitrogen and carbon of the sediments were positively associated with TN and TP in the water column (Table 3.2.7). In littoral zones (as well as in shallow lakes), the sediment-water contact ensures a rapid return of most sedimented material into the water column. In addition, the relatively high sediment temperatures in summer lead to an increase in mineralization rates, and consequently to an increased release of nutrients from the sediment (Jeppesen et al. 1997, Scheffer 1998). The availability of nutrients in the sediments depends on the chemical condition of the water-sediment interface (Gunnars & Blomqvist 1997), but also on the retention time. If the retention time is short in the littoral zones, the nutrient

concentration in the water column resembles the concentration in the inflowing water more closely (Scheffer 1998, Preece 2001).

The nutrient concentration was generally similar between the littoral zones and main channel of the river, excepting TN and NO_3+NO_2, which showed concentrations slightly different (higher and lower, respectively). The lower concentration of NO_3+NO_2 likely denotes primary producer consumption or enhanced denitrification in shallow waters (Wetzel 1983, Alexander et al. 2000). Consumption of nitrate could be due to both higher plants (macrophytes) and algae, which are both present in the littoral zone. Most algae take up ammonium preferentially over nitrate when supplied with both; but when ammonium is no longer available, nitrate reductase is produced in plants and algae to allow for the reduction of nitrate following uptake (South & Whittick 1987).

The overall similarity in nutrient concentrations in both the littoral zones and the main channel may mean that the water residence time or low current was more important for the metaphyton community than water column nutrient levels at the scale of an individual river. In these littoral areas the residence time is unknown but water currents are close to zero (Preece 2001). In the case of macrophyte communities, Makkay (2002) found that physical factors related to current velocity, slope, and substrate type were more important than the chemical characteristics of sites within the Rideau.

The relationships between nutrients and metaphyton chlorophyll-*a* concentrations were somewhat different than the relationships with metaphyton biomass (Tables 3.1.3,

3.2.5 & 3.2.6). The chlorophyll-*a* levels reflect more the physiological state of the metaphyton. As observed by Turner et al. (1995), samples with high biomass but low chlorophyll-*a* concentration would suggest senescence, but those with low biomass and high chlorophyll-*a* concentrations likely indicate active growth. The former situation was observed at an upstream site.

Because the chlorophyll-*a* molecule contains nitrogen, this may explain why a significant negative relationship was observed between TN (as well as sediment N and marginally with NO_3+NO_2/NH_3) and metaphyton chlorophyll-*a* (but not biomass) along the river. Along the river, consumption of nitrogen by metaphyton for chlorophyll synthesis might lead to negative relationships. However, at Manotick, there was no significant relationship with TN but a negative relationship with NO_3+NO_2/NH_3 was observed, as along the entire river.

Another measure of the physiological state of the metaphyton is the carbon to nitrogen ratio. Generally, algal cells with C/N ratios above 12 can be considered nitrogen deficient (Healey 1975). Cells growing at rates close to their maximum rates take up the major nutrient ions in a fixed ratio, the Redfield ratio (cited in Harris 1986). This is the C: N: P ratio for balanced growth and is usually assumed to be 106C: 16N: 1P by atoms (Harris 1986). Most of the sites along the Rideau point to nitrogen deficiency in the metaphyton, with the exception of the most downstream urban sites (Fig. 3.2.8) where nitrate tended to be high despite decreases in the total nitrogen (Fig. 3.2.7). These were also the sites with the lower biomass to chlorophyll-*a* ratio as discussed above. Consistent

with potential nitrogen limitation is also the fact that the mean water column TN/TP ratio was far from the expected Redfield ratio of 16:1. Some sites in the Rideau River were potentially N limited (TN/TP = 10) whereas at others, P was likely the limiting nutrient (TN/TP = 31) (e.g. Hecky et al. 1993). Thus, perhaps to control metaphyton in the Rideau, the nitrogen loading to the system must be considered as well as phosphorus.

There have been some interesting experimental studies on wetlands where metaphyton communities have been stimulated through the addition of nutrients. Murkin et al. (1994) found that nutrient additions to marsh enclosures stimulated metaphyton that was absent from control enclosures. Nutrient additions were in line with loading from a cattle feedlot. Interestingly, when the marsh enclosures contained no emergent aquatic plants, metaphyton increased only under the high nutrient loading and increased later in the summer. Water column nutrients between treatments were quite similar among the vegetated treatments and only the unvegetated treatments showed differences between the nutrient loadings.

McDougal et al. (1997) designed an experiment in wetlands of Delta Marsh Manitoba to test if two large nutrient spikes ("pulse" additions) would have the same effect on wetland primary production as many smaller additions ("press") comprising the same total load. "Pulse" loading might occur naturally due to runoff from seasonal storms or chemical spills, whereas "press" loading may simulate nutrient inputs from groundwater. In both cases, nutrients increased metaphyton biomass which appeared earlier in the year relatively to controls. The authors did not find any significant

difference between "pulse" and "press" treatments, but the metaphyton composition and distribution was markedly different. Pulse enclosures consisted mostly of diffuse masses of *Cladophora* sp., whereas in press enclosures, the metaphyton was mainly a surface-floating mat of *Enteromorpha intestinalis*. As found in the present study, the metaphyton biomass surpassed the macrophyte biomass particularly in the nutrient treatments. The metaphyton biomass was 49, 165, and 129 g m^{-2} in control, press and pulse treatments, respectively; whereas for the submerged macrophytes, biomass was 106, 68, and 91 g m^{-2}, respectively; over the same period of time.

Despite the lack of strong and consistent relationships between metaphyton and nutrients in the Rideau, the documented relationship between nutrients (e.g. TP) and phytoplankton in rivers (e.g. Basu & Pick 1996, Van Niewenhuyse & Jones 1996) was in fact observed. In comparison to the metaphyton, the phytoplankton community was linearly related to more variables with higher coefficients of correlation (Tables 3.2.5 & 3.2.6). This may be due to the fact that phytoplankton with relatively smaller cell sizes have shorter generation time (< 1 day- 3 days) than filamentous metaphyton, and therefore more rapid nutrient uptake and physiological responses (e.g. Rosemarin 1975). Thus, the phytoplankton biomass is more likely to reflect the immediate conditions of the various physical and chemical variables at a given point in time.

4.2 The second and third hypotheses: stable isotope signals, land use and sources of nutrients

I hypothesized that the signal of $\delta^{15}N$ in metaphyton would be different depending on the adjacent or upstream nutrient source. I predicted that the metaphyton in agricultural areas would have a lighter isotope signal due to high nutrient concentrations in these areas. Nitrogen fertilizers, manufactured from atmospheric N_2 tend to have low $\delta^{15}N$ signals. In addition, with high ambient inorganic nitrogen concentrations, discrimination against the heavier isotope would be more pronounced. In contrast, the metaphyton in urban areas was expected to have a heavier $\delta^{15}N$ signal due to dominance of nitrogen coming from human sources (combined stormwater), which has high $\delta^{15}N$ signal.

This hypothesis was rejected since there were no significant differences between the metaphyton signal of the agricultural sites versus those of the urban sites. Contrary to what was expected, the isotopic signals were high and were of similar value in both these two land-use groups. To my knowledge, the metaphyton community has not been used as a tracer of nutrient sources and there is no baseline of comparison. Neither is there a source apportionment budget for the river. However, depending on the land use, differences in isotopic signals and nutrient loading have been reported. In a recent study of the $\delta^{15}N$ signal of nitrate, Chang et al. (2002) reported a heavier signal for the isotopic value in agricultural areas (crop and livestock) (+3.0 to +13.0 ‰), than in urban and undeveloped areas (fallow pastures, wetlands) (–1.4 to +6.0 ‰), although there was overlap in the signals. Smith et al. (1996) reported that nitrate loading was highest coming off agricultural lands under corn and soybean cultivation (NO_3 = 326; TP = 57.1 kg km^{-2} $year^{-1}$), urban areas had intermediate values (NO_3 = 192; TP = 41.7), whereas

agricultural fields with mixed crops had the lowest values (NO_3 = 107; TP = 23.1). In the present study, the nitrate did not vary strongly along the Rideau (except for two urban sites), which may explain the lack of correlation of this nutrient with the metaphytic $\delta^{15}N$ signal.

The lack of significant difference in $\delta^{15}N$ signal between the agricultural and urban sites may be because the metaphyton community at the agricultural sites was obtaining nutrients from an already heavy isotopic source. This could be due to agricultural land fertilized with manure and the presence of livestock. Alternatively, the isotopic composition of fertilizers may have changed following application as nitrogen compounds interact with the soil organic matter and microbes or experience partial volatilization, leaving inorganic forms of N enriched in $\delta^{15}N$ (Macko & Ostrom 1994).

In the present study, the $\delta^{15}N$ signal of the sediments at the agricultural sites, when grouped by land used, were in fact significantly lower than the urban sites (5.11 and 7.07 ‰, respectively). Cloern et al. (2002) found that $\delta^{15}N$ of soils and sediments around and within San Francisco Bay (marshes and tributary river systems) were reflecting different land uses. The most $\delta^{15}N$ depleted soils were from diverse croplands and the most $\delta^{15}N$ enriched soils were from pastures with grazing cattle. Interestingly, the isotopic composition of surficial sediments of the Bay had similar means to upland soil samples (cited in Cloern et al. 2002).

In contrast, there was a significant seasonal variation in the $\delta^{15}N$ signal of the metaphyton at Manotick (Fig. 3.1.4); the $\delta^{15}N$ signal of the metaphyton was highest in the spring (~ 9 ‰) and declined to low values in late summer (3 ‰). Nitrate and the metaphyton $\delta^{15}N$ signal followed the same pattern (Fig. 3.1.2 *vs.* Fig. 3.1.4) and the two variables were highly correlated whereas no correlation was observed with either ammonia or total nitrogen. Considering that discrimination in uptake occurs against the heavier isotope, one might expect that with higher bulk concentrations of nitrate the stable isotope signature of the metaphyton would be lower in the spring (hypothesis 3, Chapter 1). In fact, the opposite was observed suggesting that the source of nitrate was more enriched in $\delta^{15}N$ in the spring. Much of the spring nitrate peak would be due to run-off from agricultural fields and livestock farms, or leakage from septic systems at Manotick (a growing community with no centralized sewage treatment). Nitrate is highly mobile in soils, easily leached and typically would be high during the high discharge of spring. High $\delta^{15}N$ of nitrate can indicate soil-derived nitrate (Chang et al. 2002).

Aside from reflecting different sources of inorganic N, the $\delta^{15}N$ signal of the metaphyton could also be a reflection of the physiological state of the population. The metaphyton community along the Rideau varied in physiological state. In this context, the agricultural and light residential groups were nitrogen limited (based on C/N ratios). In contrast, the urban group showed less N limitation, despite the decreasing TN. In addition, the metaphytic chlorophyll-*a* was lower at the agricultural sites despite the high metaphytic biomass, whereas at the urban sites, the biomass was lower and the chlorophyll-*a* higher. Thus, the metaphyton community at the agricultural sites was on

average likely declining at the time of sampling while at the urban sites it was actively growing.

Growth rate can affect the observed fractionation even if the sources remain the same. Wada & Hattori (1978) reported that the $\delta^{15}N$ signal of phytoplankton is a function of substrate concentration and growth rate. More recently, in a field study of the effects of flow and light on stable isotope signatures of periphyton, MacLeod and Barton (1998) concluded that growth rates were important in determining the overall signals. Periphyton grown under high light conditions of summer was generally more enriched in $\delta^{15}N$ (and $\delta^{13}C$) than periphyton grown under low light or at lower temperatures in autumn. Growth rate differences or differences in the physiological state of the metaphyton may largely explain the observed stable isotope signals. In support of this argument, the chlorophyll-*a* and biomass in the metaphyton were positively related with the $\delta^{15}N$ signal of the metaphyton biomass (Tables 3.2.5 & 3.2.6). Clearly, additional controlled experiments are necessary for an accurate interpretation of stable isotope signals in natural systems.

While the $\delta^{15}N$ signals from metaphyton were of primary interest in this study, the stable isotopes of carbon were also analyzed. Carbon signals have generally been used in ecological studies to identify the source of organic carbon to food webs (e.g. Michener & Schell 1994, Doucett et al. 1996, Grey et al. 2000).

The $\delta^{13}C$ (as well as the percent carbon) of the metaphyton was positively associated with temperature along the river perhaps indicating the intrinsic interaction

between availability of free CO_2 and algal uptake, and reflecting the overall productivity of sites (Gu et al. 1996). The $\delta^{13}C$ of the metaphyton varied along the river, but without any pattern either seasonal or longitudinal. However, the heavier values of $\delta^{13}C$ at different sites (and even seasonally) might indicate carbon limitation and therefore an indiscriminate carbon uptake (O'Leary 1981, O'Leary et al. 1992, Goericke et. al 1994). Also, as with the $\delta^{15}N$ data, there were no differences between the urban and agricultural sites (-22.65 to -24.7 ‰, respectively) and the residential sites had lowest values (~20.0 ‰).

Several studies have noted that planktonic $\delta^{13}C$ signals are different from benthic algal signals and that this is related to diffusion problems (Neil & Cornwell 1992; Hecky & Hesslein 1995). It is possible that the differences observed in the metaphyton are due to differences in growth stage as they are alternatively benthic and pelagic in habit. However, the experiments of McLeod and Barton (1998) tend to minimize the importance of the benthic boundary layer in affecting the $\delta^{13}C$ signal in periphyton.

4.3 Interactions between metaphyton, phytoplankton and macrophytes

The metaphyton community is a conspicuous element of the Rideau River. Floating mats are commonly observed throughout the summer and into the fall. The metaphyton community of the Rideau was characterized by filamentous green algae. The mats were three-dimensional structures and some vertical structure likely developed: when *Cladophora* was present it was generally located on the bottom of mats. In late

summer, filamentous cyanobacteria (*Lyngbya*) were only a minor component of the floating mats.

From the literature, *Cladophora* and *Spirogyra* seem to have high nutrient requirements relative to planktonic or benthic algae (e.g. diatoms: 0.5-1 μg P L^{-1} (Bothwell 1989) versus *Cladophora*: 60 μg P L^{-1} (Wong & Clark 1976)). However, according to Borchardt et al. 1994, *S. fluviatilis* thrives best under low steady supplies of phosphorus. Nevertheless, further study is required to understand the uptake kinetics for the filamentous taxa found in this study.

Spirogyra (Zygnemataceae) was by far the dominant filamentous green alga and it underwent several sexual cycles throughout the spring and summer of 2001. Under high nutrient conditions, high pH (8.0) and high temperature (25 °C), species of *Spirogyra* can undergo sexual reproduction every 15 days (Agrawal & Chaudhary 1994). Lack of nitrogen in the medium and high population density of cells stimulated sexual reproduction of Zygnematales in axenic cultures (Pickett-Heaps 1975). Yin-Xin and Ying-Kit (2000) examined the reproductive cycle of five common Zygnemataceae (*Zygogonium, Temnogametum, Mougeotia, Spirogyra, Zygnemopsis*) from eighteen acidic Ontario lakes and concluded that their reproduction and growth was related to temperature. In their study, higher temperatures (> 20 °C) triggered sexual reproductive structures by mid-June and the sexual reproductive cycle was completed by mid-September. When temperatures were below 20 °C, the filament color changed from green to yellowish-brown. This was also observed on the Rideau River in the present study.

When compared with other primary producers in the river (phytoplankton, epilithic periphyton, macrophytes), the metaphyton biomass was considerable (Table 3.2.8). McDougal et al. (1997) found a maximum metaphyton biomass of 350 g m^{-2} in wetland enclosures that were nutrient enriched. In the Rideau, the maximum biomass recorded was higher than this value (616 g m^{-2}). As found in the McDougal et al. (1997) study, the metaphyton biomass in the littoral zones exceeded the highest macrophyte biomass reported for the Rideau.

Metaphyton were usually associated with macrophytes. The two communities co-existed in the Rideau, however, metaphyton tended to develop earlier than macrophytes. When collecting the metaphyton, considerable time was spent separating algal filaments from small floating macrophytes such as *Lemna*. Metaphyton use the macrophytes as anchoring points but whether they derive any nutrients from macrophytes is not known. Macrophytes take up nutrients mainly from the sediments (Carignan & Kalff 1990) and possibly release a fraction for uptake by the filamentous algae. The marsh experiments of Murkin et al. (1994) support the idea that macrophytes can influence the development of metaphyton but the underlying mechanisms were not identified. Whether metaphyton can be detrimental to macrophytes is also not clear, but large floating mats would tend to reduce light penetration and impair submerged macrophyte photosynthesis.

Antagonistic interactions between macrophytes and algae have long been suspected, but the nature of these interactions remains unclear (Scheffer 1998). In

laboratory experiments, Fitzgerald (1969) found that cultures of various aquatic plants remained free of epiphytes or competing phytoplankton when nitrogen was limiting. This points to the potential role of nitrogen in determining the balance between macrophytes, metaphyton and phytoplankton, in littoral zones and shallow lakes.

Allelochemicals have also been implicated in affecting algal-macrophyte interactions. Both inhibitory and stimulating effects have been reported. Jasser (1995) found that the presence of macrophytes increased biomass of green algae, especially *Chlorella* sp. and *Chlamydomonas* sp., in field experiments. In contrast, Mohamed (2002) reported that *Oscillatoria agardhii* exhibited high growth and microcystin production as a result of the allelochemicals produced by *Spirogyra* when it was grown at high concentrations of an aqueous *Spirogyra* extract. Thus, the presence of metaphyton along littoral zones of lakes or rivers could be a biotic factor to take into consideration when monitoring cyanobacterial blooms.

Generally, a healthy shallow water aquatic ecosystem is characterized by the dominance of macrophytes (Scheffer 1998). When the metaphyton biomass exceeds macrophyte biomass, this could indicate a disruption in the trophic dynamics independently of any change in nutrient loading. A lack of herbivore grazers or a change in the herbivore community may contribute to an overabundance of metaphyton. In acidified lakes, a lack of grazers (crayfish) at low pH has been suggested as one reason for the dominance of metaphytic green algae in littoral zones (France et al. 1991).

Within the littoral zone, the metaphyton biomass exceeded by several orders of magnitude the phytoplankton biomass of the littoral zone. Interestingly, there was a significant negative association between phytoplankton and metaphyton chlorophyll-*a* within the littoral zone (Fig. 3.2.13). This could be the result of competition for resources (nutrients, light) or may simply reflect the complex interactions that have been reported between macrophytes and phytoplankton in shallow lakes (Scheffer 1998). In addition, the planktonic algal biomass and chlorophyll-*a* concentrations were generally lower in the littoral zone than in the main channel, also suggesting a negative impact of metaphyton or macrophytes on phytoplankton. Preece (2001) examined the role of hydraulic "dead" zones on plankton development in the Rideau and found similar planktonic chlorophyll-*a* levels between littoral zones and the main channel; however, differences in the size structure with more net plankton were evident in the littoral and these were likely fragments of metaphyton.

In this study, the littoral zone was often different than the main channel of the river in terms of physical and chemical characteristics as well as in biotic structure. On average, the pH was higher in the littoral zone than in the main channel. The higher pH in the littoral zones is due to consumption of CO_2 during times of high primary production (Wetzel 1983). In addition, the oxygen levels were higher during daytime, possibly as a consequence of the higher abundance of both metaphyton and macrophytes. From this study, it was not possible to determine the relative importance of these two communities in influencing littoral processes. Nevertheless, several studies have shown that algae in

wetlands can be more important in energy transfer to higher trophic levels than macrophytes (Hamilton et al. 1992, Murkin et al. 1994).

The theory of the alternation of stable (equilibrium) states of ecosystems, as first described for shallow lakes (Scheffer 1989), may apply to the littoral zone of rivers. In shallow lakes, two possible "alternate states" have been described. One state is a macrophyte-dominated system where phytoplankton biomass is low and water clarity is high. The other is a phytoplankton-dominated system where algal levels are high enough to reduce water clarity, thus impeding the growth of attached plant vegetation. Both systems can exist at a similar and often intermediate level of nutrient enrichment. Some critical level of turbidity can cause a lake to rapidly shift from the one equilibrium state to the other (Scheffer et al. 1993). Generally though, at very high nutrient levels, algae out-compete macrophytes which then disappear from the system. The Rideau is macrophyte dominated in the shallow littoral areas but the present abundance of metaphyton may be indicative of increased nutrient levels and the earlier stages of a state shift. Metaphyton have the advantage that they can access nutrients both from the sediments and from the water column depending on their growth stage. If nutrient levels were to increase even more and if soil erosion were to increase, planktonic algae could eventually out-compete the macrophytes.

Conclusions

From the results of this study, conditions for the presence of large metaphyton communities in rivers include: 1) shallow littoral zones with minimal current, 2) the presence of macrophytes (as a substratum), and 3) moderate to high nutrient concentrations (particularly dissolved inorganic nitrogen).

The presence of the metaphyton community in the Rideau River is likely triggered by more than one factor since the association of the metaphytic variables with nutrients was weak or null. Several researchers have pointed out that there are some fundamental reasons why rigid strong inference is of limited use in ecology (Quinn & Dunham 1983, Roughgarden 1983). The most basic argument is that strong inference assumes that the competing hypotheses to explain observed phenomena are general and mutually exclusive, whereas in ecosystems several independent mechanisms often contribute to an observed phenomenon that could also, in theory, be explained by each mechanism alone (Scheffer 1998). One of the mechanisms will often dominate, but this dominance will differ from case to case and may even shift in time. Perhaps, not surprisingly, the metaphyton biomass was related to nutrients at the seasonal scale, but this relationship was not as evident on the longitudinal scale of the river.

Stable isotopes in ecology are useful if the signal source can be identified. The potential source must have an isotopic signal different from other sources, and the signature must either change predictably or remain constant (Lajtha & Marshall 1994). In

this study, the nitrogen isotopic signal of the metaphyton at the agricultural and urban sites overlapped. Perhaps the $\delta^{15}N$ signal was reflecting nutrient sources, but the chemical and biological processes between the water column, sediment and soil make inferences about the source difficult. Dissolved inorganic nitrogen forms were some of the nutrients that likely affected the metaphyton development in the Rideau. Future riverine studies should include the stable isotopic signal of nitrate and ammonia from different compartments such as land runoff, the water column, sediments, groundwater, and soils. In the river, the spatial and temporal scale should be expanded since the growth rate of the metaphyton seems to have a significant effect on the stable isotope signals.

Chapter 5.0

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Appendix 1.1 Water nutrient concentration (μg L^{-1}), extinction coefficient (m^{-1}), temperature (C), dissolved oxygen (mg L^{-1}), percent dissolved oxygen (%), pH, metaphyton biomass (gdw m^{-2}), metaphytic chlorophyll-*a* (g m^{-2}), metaphyton biomass nitrogen and carbon content (%) and isotopic signal (‰), measured on 5 dates at Manotick site during spring-summer 2001.

Julian Day	Biomass	Chl-*a*	NH_3	NO_3+NO_2	TN	RP	TP	Temp	% DO	DO	pH
121	0.70	0.013	51	80	506	6	20	15.32	111.20	11.27	8.11
121	6.09	0.002	45	90	553	5	20	15.32	111.20	11.27	8.11
133	3.21	0.054	7	3	577	8	26	18.24	145.87	14.20	8.57
133	17.91	0.239	4	3	771	8	46	18.20	135.95	12.97	8.41
133	8.78	0.078	8	20	554	8	21	18.39	112.26	10.69	8.29
170	388.79	1.409	7	3	908	4	49	25.30	126.64	10.42	8.46
170	3.02	0.008	3	2.7	921.7	4	52	25.63	135.29	11.03	8.54
227	104.57	0.766	30	2.5	681.5	26	52	25.82	109.35	8.92	8.40
227	435.36	6.580	26	2.9	848.9	24	81	25.98	98.75	8.03	7.87
244	36.92	0.152	28	2.6	808.6	26	73				
244	27.07	0.130	27	3	634	27	50				

Julian Day	Ext. Coef.	% N	$\delta^{15}N$	% C	$\delta^{13}C$	C/N
121	0.48	4.11	8.29	44.60	-18.70	10.84
121	0.48	4.17	9.17	45.12	-18.79	10.83
133	1.49	3.45	6.87	39.27	-23.60	11.38
133	2.67	3.69	5.97	37.22	-23.50	10.09
133	2.16	3.60	6.26	37.74	-23.21	10.48
170	1.42	2.04	7.04	34.18	-16.03	16.74
170	1.70	2.21	4.72	43.42	-18.21	19.65
227	3.44	2.32	4.64	35.27	-21.51	15.21
227	0.98	2.27	5.37	34.99	-23.71	15.39
244	3.05	2.38	3.61	43.81	-19.03	18.43
244	3.42	2.74	3.21	41.10	-15.28	15.00

Appendix 1.2 Raw data for comparison between variables at the littoral zone and main channel of Manotick site. For units see appendix 1.1. Conductivity (Conduc) is in $\mu S\ cm^{-1}$.

Littoral Zone						Main Channel					
Date	**Temp**	**% DO**	**DO**	**pH**	**Conduc**	**Date**	**Temp**	**% DO**	**DO**	**pH**	**Conduc**
133	18.4	115.7	11	8.24	268.7	133	19.11	139.4	13.06	8.56	268
133	17.96	200	20	9.1	252.7	133	19.08	140.5	13.22	8.6	266.8
133	18.22	119	11.35	8.35	268.3	133	19.53	145.5	13.51	8.64	267.4
133	18.16	188.8	18.03	8.6	265.2	133	19.34	163.5	15.25	8.76	261
133	18.46	109.6	10.4	8.22	273	133	20.22	179	16.4	8.9	259.4
133	18.37	111.2	10.67	8.31	269	133	20.14	189.9	18.34	9.03	255.8
133	18.36	114.1	10.85	8.31	269.1	133	20.34	148.9	13.61	8.68	266.1
133	18.37	128.9	12.54	8.56	265.7	133	19.93	139.2	12.59	8.3	267.3
133	18.37	96.3	9.16	8.01	271	133	17.92	92.4	8.87	7.9	270.6
133	18.25	92.7	8.84	7.34	304.8	133	17.29	86.4	8.4	7.83	270.8
170	25.51	130.8	10.71	8.44	289	133	16.87	81.5	7.99	7.78	274.3
170	25.08	122.5	10.12	8.48	288	133	19.55	94.2	8.74	7.91	273.1
170	25.73	139.3	11.3	8.52	288	133	19.33	95.2	8.87	7.95	272.2
170	25.52	131.3	10.75	8.55	288	133	18.86	93.5	8.74	7.92	270.3
227	26.23	115.3	9.34	8.65	235.1	133	18.19	92.7	8.85	7.87	270.5
227	25.41	103.4	8.5	8.14	240.6	133	17.51	87.7	8.48	7.84	272.5
227	26.33	120.6	9.75	8.29	240.2	133	17.5	86.5	8.37	7.84	272.8
227	25.62	76.9	6.3	7.45	245	170	25.7	125.1	10.15	8.39	289
						170	25.36	113.5	9.38	8.31	290
						170	25.01	109.8	9.07	8.27	291
						170	24.52	100.8	8.41	8.19	291
						170	20.9	48.2	4.3	7.85	305
						227	26.08	84.8	6.89	7.29	242.8
						227	26.1	84.7	6.88	7.32	242.9
						227	26.05	84.4	6.86	7.34	242.8
						227	26.02	85	6.91	7.38	242.7
						227	25.55	77.5	6.36	7.33	244
						227	24.76	37.1	3.08	6.96	257.9
						227	22.63	1.9	0.17	6.92	277.2

Appendix 1.3 Raw data for comparison of metaphyton biomass, chlorophyll-*a*, nitrogen and carbon content and isotopic signals among sampled dates. For units see Appendix 1.1.

Julian Day	Biomass	Chl-*a*	% N	$\delta^{15}N$	% C	$\delta^{13}C$	C/N
121	0.70	0.013	4.14	8.73	44.86	-18.75	10.84
121	1.76	0.015	4.05	8.98	45.31	-18.58	11.18
121	6.09	0.002	3.97	8.43	45.12	-18.64	11.36
133	4.80	0.114	3.00	6.15	41.39	-22.55	13.79
133	8.78	0.079	4.38	6.68	38.10	-36.24	8.71
133	17.91	0.240	3.52	5.30	32.95	-23.23	9.37
133	3.21	0.054	3.62	6.47	34.81	-23.74	9.61
133	3.11	0.047	2.96	6.76	30.45	-24.38	10.29
170	388.79	1.409	2.21	4.72	43.42	-18.21	19.65
170	3.02	0.008	1.91	5.31	32.70	-16.79	17.12
170	22.69	0.031	2.04	7.04	34.18	-16.03	16.74
227	104.57	0.767	2.31	5.40	35.03	-23.69	15.17
227	435.36	6.581	3.06	4.29	41.09	-12.49	13.45
227	167.32	1.226	2.94	6.78	34.69	-24.78	11.79
244	36.92	0.153	2.74	3.21	41.10	-15.28	15.00
244	27.07	0.130	2.70	3.40	41.59	-20.81	15.40
244	28.29	0.142	2.38	3.61	43.81	-19.03	18.43

Appendix 2.1 Physical and chemical variables measured for main channel and adjacent littoral zone (surface and bottom) along the Rideau River. For units and labels see Tables 2.1, 3.2.2. & 3.2.4.

Littoral Zones

Sites	Temp	% DO	DO	pH	Conduc
4	27.15	170.8	13.61	9.03	229
4	26.43	121.4	9.85	8.78	234
4	26.71	136.9	10.91	8.62	242
4	26.7	139.1	11.08	8.63	242
5	26.33	148.5	12.05	8.97	219
5	23.79	92.3	7.77	8.6	230
5	26.77	135.2	10.77	9.05	225
5	23.88	96.5	8.12	8.63	251
6	24.16	115.3	9.71	8.36	142
6	22.98	95.6	8.2	8.17	275
6	23.97	111.1	9.35	8.58	245
6	23.51	107	9.09	8.45	247
6	24.36	106.6	8.97	8.5	246
6	23.88	91.5	7.7	8.44	248
7	26.01	138.7	11.25	8.76	249
7	24.04	112.5	9.47	8.45	257
7	26.12	133.2	10.81	8.72	251
7	25.62	114.2	9.35	8.75	251
8	25.51	130.8	10.71	8.44	289
8	25.08	122.5	10.12	8.48	288
8	25.73	139.3	11.3	8.52	288
8	25.52	131.3	10.75	8.55	288

Appendix 2.1 Continued.

Main Channel

Sites	Temp	% DO	DO	pH	Conduc
4	25.73	125.4	10.96	8.46	234
4	25.72	123.3	10.78	8.55	234
4	25.56	114.6	10.02	8.57	235
4	25.33	119.2	9.85	8.55	235
4	24.35	99.5	8.38	8.31	240
4	21.7	37.1	3.24	8.01	258
5	25.39	120.4	9.95	8.69	232
5	25.3	117.1	9.68	8.6	243
5	24.93	104.4	8.63	8.59	244
5	24.68	103.4	8.54	8.52	244
5	24.16	93.8	7.9	8.48	245
5	23.49	71.8	6.1	8.31	247
5	22.09	53.4	4.67	8.03	260
6	25.8	109.0	8.84	8.38	246
6	24.65	107.7	8.9	8.44	245
6	23.78	111.5	9.39	8.42	245
6	23.36	90.0	7.72	8.15	248
6	23.03	77.4	6.64	8.04	250
6	22.07	57.8	5.05	7.88	274
6	21.14	37.5	3.34	7.77	279
7	24.45	92.8	7.81	8.31	254
7	24.38	91.5	7.7	8.32	254
7	24.23	88.6	7.46	8.31	254
7	23.8	84.0	7.07	8.22	254
7	23.56	70.8	5.96	8.1	257
7	22.25	49.2	4.3	7.91	277
8	25.7	125.1	10.15	8.39	289
8	25.36	113.5	9.38	8.31	290
8	25.01	109.8	9.07	8.27	291
8	24.52	100.8	8.41	8.19	291
8	20.9	48.2	4.3	7.85	305

Appendix 2.2 Physical, chemical and biological variables measured during spring-summer 2001 at 12 sites along the Rideau River. At each site, two samples were collected. NA = not available (missing sample). BD = below detection. For units and labels see Tables 2.1, 3.2.2. & 3.2.4.

Sites	Groups	MetaBiom	Chl-*a*Meta	PhyBiom	Chl-*a*Phy	NH_3
1	1	248.00	0.32	0.0029	0.0083	15
1	1	131.90	0.44	0.0034	0.0076	8
2	1	135.37	0.36	0.0011	0.0069	36
2	1	108.13	0.53	0.0042	0.0093	44
3	1	59.20	0.13	NA	0.0064	32
3	1	189.57	0.29	NA	0.0066	49
4	1	120.48	0.93	0.0034	0.0152	10
4	1	64.58	0.52	0.0034	0.0097	14
5	2	62.15	0.36	0.0017	0.0081	7
5	2	6.56	0.03	0.0023	0.0086	14
6	2	26.92	0.27	0.0021	0.0110	19
6	2	4.77	0.05	0.0057	0.0076	8
7	2	48.65	0.17	0.0015	0.0103	5
7	2	12.30	0.15	0.0013	0.0072	6
8	2	388.79	1.41	0.0014	0.0071	7
8	2	3.02	0.01	0.0018	0.0062	3
9	3	73.16	0.67	0.0017	0.0018	30
9	3	7.36	0.13	0.0004	0.0019	14
10	3	15.26	0.24	0.0013	0.0090	17
10	3	61.26	0.44	0.0004	0.0036	11
11	3	616.80	3.02	0.0003	0.0020	28
11	3	520.65	4.90	0.0003	0.0016	12
11	3	167.38	0.86	0.0004	0.0016	11
12	3	122.48	2.30	0.0009	0.0038	20
12	3	5.39	0.70	0.0006	0.0028	20

Appendix 2.2 Continued.

Sites	Groups	RP	TP	TN	NO_3+NO_2	Temp
1	1	13	60	935	2.9	NA
1	1	17	83	1081	2.8	NA
2	1	16	46	735	2.6	NA
2	1	14	51	828	2.7	NA
3	1	13	68	938	2.8	21.91
3	1	20	104	1122	2.9	22.20
4	1	9	78	1049.8	1.8	26.79
4	1	20	105	1072	2	26.71
5	2	8	52	883	3	25.06
5	2	5	43	882.9	2.9	25.33
6	2	5	36	924	3	23.57
6	2	8	69	960.8	1.8	23.74
7	2	6	46	785	3	25.03
7	2	5	40	783.8	2.8	25.87
8	2	4	49	907.5	2.5	25.30
8	2	4	52	921.7	2.7	25.63
9	3	35	62	716	20	20.10
9	3	15	50	754	20	19.81
10	3	20	66	783	20	22.95
10	3	9	29	616	10	23.16
11	3	4	24	633	3	21.51
11	3	5	22	622.8	2.8	21.52
11	3	3	32	662.6	2.6	21.56
12	3	6	32	644.3	2.3	21.92
12	3	5	26	702.9	1.9	22.05

Appendix 2.2 Continued..

Sites	Groups	% DO	DO	pH	Conduc	Ext. Coef.
1	1	NA	NA	NA	NA	6.66
1	1	NA	NA	NA	NA	6.22
2	1	NA	NA	NA	NA	4.37
2	1	NA	NA	NA	NA	6.31
3	1	134.35	11.91	8.62	240.3	1.51
3	1	133.50	11.77	8.53	241.85	2.10
4	1	146.11	11.73	8.91	231.5	4.09
4	1	137.99	11.00	8.63	242	2.88
5	2	120.41	9.91	8.79	224.5	3.06
5	2	115.81	9.44	8.84	238	6.79
6	2	105.47	8.95	8.27	208.6	3.15
6	2	109.02	9.22	8.51	246	2.93
7	2	125.58	10.36	8.61	253	2.84
7	2	123.72	10.08	8.73	251	3.04
8	2	126.64	10.41	8.46	288.5	1.42
8	2	135.29	11.02	8.53	288	1.70
9	3	92.60	8.42	8.11	243	2.04
9	3	85.80	7.80	8.20	384	NA
10	3	85.10	7.30	7.67	390	5.78
10	3	101.84	8.69	7.99	387	1.02
11	3	115.18	10.19	8.30	374.6	1.75
11	3	97.50	8.61	8.24	378	1.59
11	3	103.89	9.12	8.21	378	1.11
12	3	113.23	9.90	8.56	387.5	2.59
12	3	115.12	10.06	8.46	388.5	3.86

Appendix 2.2 Continued.

Sites	Groups	% N Sed	δ^{15}N Sed	% C Sed	δ^{13}C Sed	C/N Sed
1.00	1.00	1.08	3.73	10.63	-26.62	9.82
1.00	1.00	1.00	2.22	10.04	-26.56	10.00
2.00	1.00	0.32	5.67	2.67	-25.13	8.26
2.00	1.00	0.37	5.08	3.12	-24.67	8.37
3.00	1.00	1.10	2.82	11.01	-25.90	10.04
3.00	1.00	1.27	3.84	11.07	-24.20	8.70
4.00	1.00	0.28	10.17	2.35	-21.38	8.48
4.00	1.00	NA	NA	NA	NA	NA
5.00	2.00	1.79	2.01	16.76	-26.47	9.35
5.00	2.00	1.23	3.71	12.62	-25.83	10.24
6.00	2.00	1.20	4.49	10.58	-25.50	9.10
6.00	2.00	1.40	4.42	12.67	-26.20	9.05
7.00	2.00	0.47	5.28	4.87	-23.78	10.38
7.00	2.00	0.27	4.93	2.27	-26.10	8.34
8.00	2.00	0.43	6.15	4.43	-23.55	10.32
8.00	2.00	0.53	5.81	5.14	-25.27	9.71
9.00	3.00	0.24	9.51	3.69	-23.42	15.22
9.00	3.00	0.51	5.92	6.59	-24.64	12.96
10.00	3.00	0.42	9.34	4.41	-25.22	10.57
10.00	3.00	0.46	6.39	5.30	-25.19	11.50
11.00	3.00	0.23	5.71	3.31	-20.49	14.16
11.00	3.00	0.11	BD	2.04	-15.69	19.36
11.00	3.00	0.08	BD	1.95	-13.26	23.09
12.00	3.00	0.35	7.25	4.68	-23.60	13.20
12.00	3.00	0.09	BD	1.52	-18.25	16.76

Appendix 2.3 Metaphyton biomass (gdw m^{-2}), chlorophyll-*a* (g m^{-2}), nitrogen and carbon content (%) and metaphyton biomass isotopic signals (‰) for 12 sites along the Rideau River. For sites and groups labels see Tables 2.1 & 3.2.4.

Sites	Groups	Chl-*a*	Biomass	% N	$\delta^{15}N$
1	1	0.32	248.00	1.35	7.50
1	1	0.44	131.90	1.47	8.42
1	1	1.50	616.92	1.74	7.71
2	1	0.36	135.37	1.94	10.36
2	1	0.53	108.13	3.01	9.32
2	1	0.16	48.16	2.31	8.82
3	1	0.13	59.20	1.90	6.92
3	1	0.10	61.05	1.99	7.37
3	1	0.01	5.00	1.82	7.47
3	1	0.29	189.57	2.04	6.55
4	1	0.93	120.48	3.19	8.39
4	1	0.52	64.58	2.64	8.95
4	1	0.22	41.31	1.44	6.42
5	2	0.36	62.15	2.47	7.46
5	2	0.13	100.34	1.94	3.87
5	2	0.03	6.56	1.93	5.54
6	2	0.19	12.50	3.50	5.73
6	2	0.18	43.88	3.93	7.50
6	2	0.27	26.92	1.90	4.58
6	2	0.05	4.77	3.45	6.41
7	2	0.17	48.65	3.47	8.22
7	2	0.15	12.30	4.18	6.25
7	2	0.18	68.03	2.16	6.15
8	2	1.41	388.79	1.98	6.17
8	2	0.01	3.02	2.21	4.72
8	2	0.03	22.69	2.21	4.72
9	3	1.48	47.12	BD	BD
9	3	0.67	73.16	3.64	9.20
9	3	0.13	7.36	5.01	5.95
10	3	0.24	15.26	3.26	4.72
10	3	0.44	61.26	3.09	8.82
10	3	0.57	16.32	2.90	7.17
11	3	4.90	520.65	2.97	8.29
11	3	0.86	167.38	3.11	6.15
11	3	3.02	616.80	2.03	8.60
12	3	2.30	122.48	3.01	8.58
12	3	0.70	5.39	3.11	6.15

Appendix 2.3 Continued.

Sites	Groups	% C	$\delta^{13}C$	C/N
1	1	36.35	-24.21	27.10
1	1	36.68	-26.16	25.02
1	1	35.53	-23.37	20.37
2	1	36.69	-20.29	18.98
2	1	38.00	-23.58	12.65
2	1	37.45	-22.80	16.21
3	1	37.57	-24.73	19.78
3	1	36.88	-26.50	18.91
3	1	38.22	-25.79	21.00
3	1	35.03	-23.83	17.31
4	1	45.82	-18.45	14.29
4	1	40.24	-18.53	16.06
4	1	39.81	-16.22	27.73
5	2	33.39	-19.70	13.73
5	2	35.09	-20.03	18.06
5	2	36.36	-19.75	18.85
6	2	41.70	-16.66	11.91
6	2	37.85	-22.76	9.62
6	2	37.81	-15.35	19.89
6	2	35.24	-22.21	10.21
7	2	39.41	-25.55	11.36
7	2	45.40	-19.22	10.86
7	2	37.96	-27.13	17.57
8	2	33.44	-16.41	16.93
8	2	43.42	-18.21	19.65
8	2	43.42	-18.21	19.65
9	3	BD	BD	BD
9	3	32.41	-31.88	8.89
9	3	39.90	-37.36	7.96
10	3	42.68	-17.71	13.18
10	3	32.95	-24.62	10.60
10	3	33.45	-23.76	11.61
11	3	29.44	-21.46	10.11
11	3	34.61	-22.71	11.17
11	3	30.82	-19.97	15.30
12	3	33.84	-24.81	11.24
12	3	34.61	-22.71	11.17