Phytoremediation of nutrient polluted stormwater runoff: Water hyacinth as a model plant

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Abstract

Fox, L.J., 2009. Phytoremediation of nutrient polluted stormwater runoff: Water Hyacinth as a model plant. PhD Thesis, Wageningen University, Wageningen, The Netherlands. With summaries in English and Dutch, 103 pp.

Phytoremediation of nutrient polluted stormwater runoff using water hyacinth as a model plant was explored in greenhouse and field studies in south-eastern Virginia, USA. Under controlled greenhouse conditions, water hyacinths accounted for 60 – 85% of the N removed from solution. Net productivity, as measured by dry matter gain, increased initially with an increase in N rate then levelled out at N rates above 80 ppm. Water hyacinths accumulated between 0.3 and 7.9 g of N in plant tissue over four weeks, producing between 22.5 and 188 g of dry matter per 1.4 m^2 area. Tissue N accumulated in the plant tissue increased linearly with dry matter gain, but total nitrogen removal from the water increased exponentially with net dry matter gain or with an increase in canopy cover. Uptake by water hyacinth accounted for 17 – 79% of the P removed from solution. Plants were more vigorous, and canopy development was quicker and denser in the higher nutrient treatments. Water hyacinths accumulated between 0.02 and 1.7 g of P in plant tissue over four weeks for the same amount of dry matter per area as with N. Phosphorus accumulation in the tissue was significantly greater in higher level nutrient treatments.

The production ecology of water hyacinth was also examined under greenhouse conditions. High nitrogen (80 – 300 ppm) and phosphorus (9.4 – 70.6 ppm) levels in the water and light levels caused corresponding positive linear responses in biomass and canopy cover. The higher nutrient level treatments contained more plants and had better canopy cover and higher light interception values. Radiation use efficiency (RUE) values were higher in water hyacinths with more nitrogen in the tissue. Larger plants intercepted more light and were thus more productive leading to a faster increase in numbers of plants and the corresponding percent canopy cover, but also to an earlier and stronger crowding effect. While production trends were similar across two separate studies, variation was observed between the two studies, and this is attributed to seasonal differences in temperatures and light intensities which influenced the amount of light being intercepted and the efficiency with which the intercepted light was converted into dry matter. Temperatures were cooler and photosynthetically active radiation (PAR) readings were higher in the early season study.

A containment system for water hyacinths was designed and evaluated under field conditions. Floating containment corrals, constructed from PVC pipe and polyethylene netting, were deployed in a stormwater and irrigation retention pond along one shoreline. After eight weeks, the corrals remained anchored, UV light stable, and floating. Water

hyacinths experienced a 141-fold increase per corral. The corrals effectively contained the resultant biomass, were economical (approximately US $46.00 per corral), easy to construct, deploy, manoeuvre, and remove from the pond. The system is adaptable to diverse locations and can be expanded as needed.

Management, water and weather data was collected from two stormwater and irrigation runoff ponds at Bayville Golf Club (BGC), Virginia Beach, VA, USA and two ponds at Knotts Creek Nursery (KCN), Suffolk, VA, USA for two growing seasons for characterization purposes. Total dissolved N concentrations were consistently higher at KCN. In 2002, a drought year, N concentrations were generally low and within a narrow range (1.0 – 3.5 mg L^{-1} at BGC and 2.5 – 6.0 mg L^{-1} at KCN). There were more fluctuations in N concentration as depth increased. In 2003 rainfall was above average, and N concentrations were observed across a wider range (0.75 – 4.2 mg L^{-1} at BGC and 0.5 – 6.0 mg L^{-1} at KCN) over the season and were more consistent as depth increased. Both water temperatures and N concentrations fluctuated more dramatically at the inflow locations compared to the middles of the ponds.

The phytomechanisms most commonly utilized in the green industry are phytoextraction and phytodegradation; where plants either absorb and concentrate or absorb and metabolize pollutants, and both apply to the phytoremediation system proposed here. Using the N concentrations observed in the ponds, the N concentrations observed in the water hyacinths in the greenhouse studies, the average incoming light and radiation use efficiencies, it is possible to calculate the amount of biomass and area of pond coverage necessary to remediate a given amount of N. For all four ponds, the amount of biomass and coverage needed to remediate the highest N concentrations observed was 20% or less of the potential. Understanding a plants phytoremediation potential and how it can be applied in a larger ecosystem is essential to having a successful phytoremediation system.

Keywords: assimilation, biofiltration, bioremediation, best management practice (BMP), golf course, irrigation pond, nursery, nutrient pollution, phytoremediation, stormwater pond, stormwater runoff, water hyacinth (*Eichhornia crassipes* (Mart.) Solms), water quality

Preface

“Success is a journey not a destination. Happiness is a journey not a destination.”
Ben Sweetland

"Do what you can, with what you have, where you are."
Theodore Roosevelt.

As it takes a village to raise a child, so too does it take a village to complete a PhD. When I began my programme eight years ago at the urging of my department head Dr. Jerzy Nowak, and with the support of my family, friends, and colleagues, I had no idea the journey would unfold as it did. Looking back, I am amazed at the long, often curvy road, I travelled and at the lessons I experienced, both personally, professionally, and academically along the way. I would not have arrived at my destination if not for the “village”. I am very grateful for the overwhelming support I received on my journey, and I would like to acknowledge the following:

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Contents

CHAPTER 1

General introduction

Problem statement

Water is essential to life. A simple; yet profound statement, which connects us all at the most basic level. Sadly, it is no surprise then, that the most critical environmental issue worldwide is water quantity and quality. In the United States of America (USA) the Clean Water Act (CWA) of 1972 mandated clean water in lakes, rivers, streams, and aquifers. The Environmental Protection Agency (EPA) is charged with enforcing the CWA. Despite regulations, thousands of water bodies in the USA remain classified as "impaired", meaning that they contain pollutants at levels higher than is considered safe by EPA for the intended beneficial use of the water. Most of the impairment is attributed to polluted runoff (Ferguson, 1998; Wikipedia, 2009).

Stormwater runoff is water that originates during a precipitation or watering (irrigation) event that does not soak into the ground, but instead runs off impervious or water-saturated surfaces, transporting sediments and dissolved chemicals and nutrients into nearby waters (Schueler, 2000; University of Florida, 2009). Nutrient and sediment pollution of surface waters are the two largest threats to water quality (Bricker et al., 2007). Nutrients, primarily nitrogen (N) and phosphorus (P), enter surface water mainly through runoff and leaching from agricultural, commercial, and urbanized areas, but additional N comes from atmospheric deposition and precipitation, N_2 fixation in water and sediment, and N release from decomposing aquatic plants and animals (Carpenter et al., 1998).

Excess N and P degrade water quality, pose risks to humans and livestock, threaten rare habitats and ecosystems, and accelerate the natural eutrophication process in aquatic ecosystems. High levels of these nutrients from tributary waters have caused large hypoxic (oxygen depleted) zones in the Chesapeake Bay (Chesapeake Bay Foundation, 2006) and the Gulf of Mexico (NOAA, 2000) with subsequent adverse economic impacts.

Everyone is affected by degraded water resources, and every effort, no matter the scale or origin, to reduce the amount of nutrients contaminating our natural waters is important. Collectively, these efforts across agriculture, industry, and community will have a significant positive impact on our valuable water resources.

The role of the green industry

The green industry in the USA is comprised of commercial nurseries, sod producers, golf courses, arborists, and landscape designers and contractors. The industry has long recognized nutrient polluted runoff as an environmental issue (Urbano, 1989). Numerous studies and monitoring have been done throughout the industry to quantify sources and amounts of nutrient polluted runoff. Data collected primarily from nurseries (Cooper, 1993; Yeager et al., 1993) and golf courses (Gross et al., 1990; Cohen et al., 1999) has been used to support legislators and regulators so informed decisions can be made. That information has also been used to educate professionals and to promote the use of best management practices (BMP) within the industry to moderate impacts from polluted runoff (Cole et al.; 1997; Southern Nursery Association, 1997; Berghage et al., 1999; Cooper et al., 2004; Kohler et al., 2004; Taylor et al., 2006). Unfortunately, voluntary use of BMPs within the industry has been insufficient in addressing the nutrient issue, so federal, state, and local regulations governing water quality continue to increase.

Stormwater retention ponds

One of the most visible and widely utilized BMPs is the stormwater retention pond; found in most areas of agriculture and commercial and urban horticulture. In many areas, the amount of stormwater runoff allowed from a property is regulated. These ponds are used to manage runoff velocity, quantity, and quality. Frequently, these stormwater ponds have secondary benefits such as irrigation water storage and recreational uses such as boating, swimming, and fishing. The useful life expectancy for a stormwater pond was generally estimated at 18–20 years. While strong emphasis has been placed on using stormwater ponds to improve water quality, relatively little effort has been directed towards their long term maintenance and management. Consequently, many ponds experience accelerated eutrophication which decreases the useful life expectance to about 8–10 years. The aquatic ecosystem becomes unbalanced, and the pond no longer effectively manages runoff water volume or quality. Pond failure leads to flooding, public health issues, liability, economic loss, and environmental problems. Pond renovation generally entails dredging which adversely impacts the surrounding environment. Heavy equipment compacts soils and sections of vegetated buffer often have to be cut down for water access. These activities lead to pond bank destabilization and erosion. Dredge spoils are hauled to a landfill because application to another location on the site is often not possible. The renovation process is costly from both an environmental and economic perspective. An opportunity exists at this point in the hydrological cycle for scientific research to positively impact and improve water management practices relative to nutrient pollution.

The aquatic ecosystem

A stormwater pond ecosystem functions just like any other aquatic ecosystem. The two main differences are first, runoff into the system is more frequent due to irrigation events, and second, the system is small and often unable to adequately buffer frequent inflows of nutrient polluted runoff. Eutrophication is a natural process involving the physical, chemical, and biological changes associated with enrichment of a body of water due to increases in nutrients and sedimentation, and it occurs gradually over time as a body of water ages. Over-enrichment accelerates the eutrophication process resulting in excessive growth of organisms and decreasing oxygen concentration. Water temperatures cool with above normal vegetative cover. When vegetation dies and decays, nutrients are released back into the system to fuel more aquatic vegetative growth. The plant debris that doesn't decay sinks to the bottom and builds up causing the pond to become shallower. Ecosystem biodiversity decreases. Reduced water volume and oxygen content stress existing microorganism and fish populations. Like dominos the system begins to collapse. Is there a way to alleviate some of the nutrient loading pressure in these stormwater pond systems, slow the eutrophication process, and extend the useful life expectancy? Yes. BMPs such as irrigation cycling, fertilizer formulations, potting substrates, soil tests, vegetated drainage swales, and buffers can be used to reduce nutrient levels, keep the nutrients in place, and filter the polluted runoff before it goes into the stormwater pond. But, when these are not enough, what can be done after the nutrients get into the pond?

Phytoremediation

Phytoremediation is the process of using plants (*phyto*) to clean up (*remediate*) polluted soil or water. Plants are used to degrade, contain, immobilize, or extract pollutants. This age old natural process has been taken to the level of genetically engineered plants to remediate very specific and highly toxic environmental contaminants. EPA's National Risk Management Research Laboratory conducts programs on pollution prevention and control methods, including remediation. The lab's report, Introduction to Phytoremediation (U.S. EPA, 2000), provides one of the best evaluations of phytoremediation technologies. But, what about the most common and widespread contaminants N and P, and why couldn't more common plants be utilized for phytoremediation of those pollutants across a range of aquatic locations and situations within the green industry?

Water hyacinth as a model plant

Aquatic macrophytes are able to remove a variety of nutrients from polluted water, and floating water hyacinth has been of particular interest for remediation of pollutants, even though it's considered one of the world's most noxious weeds (Sculthorpe, 1967; Gopal, 1987). The characteristics that make it weedy also make it excellent for phytoremediation research. The plant is adaptable to a wide range of environmental factors including temperature, pH, and nutrient level, and the dense fibrous root system provides an extensive surface area for absorption, adsorption, and for micro-organism activity. Water hyacinths spend the majority of their lifecycle in a vegetative state and rapidly reproduce by vegetative propagation; which means an increase in biomass leads to an increase in filtering capacity. Water hyacinth can be a marketable ornamental crop, and it has the potential to be composted and used as an organic amendment or nutrient source. All of the above factors were considered when this plant was selected as the model plant for this research.

The potential of water hyacinth to remediate water

Water hyacinth's nutrient remediation ability has been examined in infested lakes, rivers (Gossett and Norris, 1971) and marshes (Mitsch, 1977). Systems using water hyacinths to remediate industrial wastewater (Jayaweera and Kasturiarachchi, 2004), effluent (Reddy and Smith, 1987; Basseres and Pietrasanta 1991), and landfill leachate (El-Gendy et al., 2004) have also been examined. Numerous other studies have been conducted to quantify water hyacinth's potential to accumulate N and P (Dunnigan et al., 1975; Boyd, 1976; Sato and Kondo, 1981; Reddy and Tucker 1983) and to even hyperaccumulate N (Reddy and DeBusk, 1985; Reddy et al., 1989). Most studies cultured the plants in a Hoagland type solution while observing the effects of varying N and P levels, the form of N, or the repeated application of N and P on the water hyacinths (Ower et al., 1981; Shiralipour et al., 1981; Tucker, 1981; Xie et al., 2004). Table 1 gives an overview of some of the literature on water hyacinth N and P phytoremediation potential.

Table 1

Water hyacinth phytoremediation potential: a literature comparison. fw=fresh dw=dry

Growth Rate g (dw) m^{-2} day^{-1}	Biomass g (dw) m^{-2}	Nitrogen concentration** mg l^{-1}	Nutrient uptake		Reference
			Nitrogen	Phosporus	
42.8	2500	2.38	3.69 g m^{-3}	2.02 g m^{-3}	Mitsch, 1977
46		56	42000 mg (dw)/tank	2500 mg (dw)/tank	Jayaweera and Kasturiarachchi, 2004
30.1	37	40	34 g kg^{-1}	11 g kg^{-1}	Reddy and Smith, 1987
		125	234 mg m^{-2} day^{-1}	23 mg m^{-2} day^{-1}	Basseres and Pietrasanta 1991
19.4		1.28	340 mg m^{-2} day^{-1}	43 mg m^{-2} day^{-1}	Boyd, 1976
25.5	410	28	1160 mg m^{-2} day^{-1}	200 mg m^{-2} day^{-1}	Sato and Kondo, 1981
53		10	2161 mg m^{-2} day^{-1}	542 mg m^{-2} day^{-1}	Reddy and Tucker 1983
		29	1278 mg m^{-2} day^{-1}	243 mg m^{-2} day^{-1}	Reddy and DeBusk, 1985
26.9	3000*	5.5	80 g m-2	20 g m^{-2}	Reddy et al., 1989
		36	1.25 mg $gfw^{-1}day^{-1}$	0.06 mg $gfw^{-1}day^{-1}$	Ower et al., 1981
30	15.4	10		5 mg g^{-1}dw	Shiralipour et al., 1981
38		14	700 mg m^{-2} day^{-1}		Tucker, 1981
	118.2	10	1190 mg m^{-2}	160 mg m^{-2}	Xie et al., 2004
	1549	8.5	3732 mg m-2		Billore et al., 1998

* based on an estimated dry matter content of 5%
** nitrogen concentration of nutrient growing solution

Phytoremediation in stormwater retention ponds

Water management strategies for the green industry need to be adaptive, and technology and practices need to be economically feasible, widely applicable, and easily implemented. Phytoremediation can meet all the criteria listed above, and in addition is non-invasive and more publicly acceptable than some other conventional water treatment methods. Using plants for phytoremediation in stormwater ponds could also serve other purposes. The phytoremediation system could provide additional production area at commercial nurseries. The plants utilized in the system could be sold or composted and used as an amendment in the container potting substrate or sold as a value added product. The system would also be aesthetically pleasing as well as functional, which is a factor at golf course sites. Taking the above into consideration, the potential benefits to the green industry and the opportunity for research in this area were obvious.

Research programme

The general research objective was to develop a phytoremediation system that would become a BMP to be utilized alone or in conjunction with other BMPs to address the very serious water quality degradation problem caused by excess N and P in stormwater runoff. A research programme was designed and implemented in 2001, with the goal of exploring the use of aquatic plants for phytoremediation of nutrient polluted stormwater runoff in retention ponds at production nurseries and golf courses. Specific objectives were set and matched with experiments that would create a comprehensive system for removal and recycling of the polluting N and P.

Specific objectives

- to assess water hyacinth phytoremediation potential of N and P as pollutants in stormwater runoff at commercial nurseries and golf courses;
- to examine water hyacinth production ecology and gain a clearer understanding of the factors influencing hyacinth production and their interaction;
- to design and evaluate an aquatic containment system for water hyacinths used for phytoremediation in stormwater retention ponds;
- to evaluate the quality of water hyacinth biomass produced;
- to develop a methodology for characterizing stormwater retention ponds at golf courses and ornamental plant production nurseries in the Chesapeake Bay area of the Eastern USA.

Permission was obtained to use two ponds at a private golf course in Virginia Beach, VA, USA, and two ponds at a commercial nursery in Suffolk, VA, USA, for five years of research. A series of experiments was designed and carried out under controlled greenhouse conditions and at the ponds to accomplish the program objectives. The results are presented in the subsequent chapters of this thesis.

Outline of the thesis

Chapters 2 and 3 are devoted to N and P, respectively, as the two primary water pollutants. Chapter 4 examines the production ecology of water hyacinth since that is so critical to successful phytoremediation, and Chapter 5 covers the containment system field work. Chapter 6 looks at pond characterization which is essential to applying and having an effective phytoremediation system. The water hyacinth biomass evaluation work is ongoing, and the study protocols are already being used in other research evaluating woody plants for phytoremediation potential.

CHAPTER 2

Nitrogen phytoremediation by water hyacinth (*Eichhornia crassipes* (Mart.) Solms)*

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Abstract

The phytoremediation potential of water hyacinth, *Eichhornia crassipes* (Mart.) Solms, was examined in two independent studies under nitrogen (N) rates of 0, 40, 80, 100, 150, 200, and 300 ppm. A modified Hoagland solution was added to ponds containing water hyacinths which were rated and measured weekly for four weeks. The hyacinths accounted for 60 – 85% of the N removed from solution. Net productivity, as measured by dry matter gain, increased with an increase in N rate until 80 ppm. Above that level dry matter productivity was similar. Tissue N increased linearly with dry matter gain, but total nitrogen removal from the water increased exponentially with net dry matter gain or with an increase in canopy cover. The relation between total N in plant tissue and N removal from the water was similar for the two experiments.

Keywords: assimilation, biofiltration, nutrient removal, phytoremediation

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Introduction

One of the most common environmental issues is nutrient pollution of surface waters, mainly from nitrogen (N) (NOAA, 2000). Nitrogen enters surface water primarily through runoff and leaching from agricultural and urbanized areas, but also from precipitation, N_2 fixation in water and sediment, and N release from decomposing aquatic plants and animals. Excess N degrades water quality, poses risks to humans and livestock, threatens rare habitats and ecosystems, and accelerates the natural eutrophication process in aquatic ecosystems. High levels of N from tributary waters have caused large hypoxic (oxygen depleted) zones in the Chesapeake Bay (Chesapeake Bay Foundation, 2006) and the Gulf of Mexico (NOAA, 2000) with subsequent adverse economic impacts.

In the United States of America in 1972, the Clean Water Act mandated clean water in lakes, rivers, streams, and aquifers. The increasingly stringent regulations governing water quantity and quality have resulted in the extensive use of stormwater retention ponds in most areas of agriculture and commercial and urban horticulture to manage runoff velocity, quantity, and quality. Some stormwater ponds have secondary benefits such as irrigation water storage and recreational uses. While strong emphasis has been placed on using stormwater ponds, relatively little effort has been directed towards their long term maintenance and management. Consequently, many ponds have experienced accelerated eutrophication, a process where water bodies receive excess nutrients through runoff. The nutrients stimulate excessive plant growth, and the aquatic ecosystem becomes unbalanced. Decaying vegetation negatively impacts water quality by reducing dissolved oxygen levels and releasing nutrients which fuel more vegetative growth. Organic matter that is not decomposed adds to the bottom sediments which accumulate until the pond no longer effectively manages runoff volume. The resultant flooding leads to issues of public health, liability, economic loss, and environmental problems. Pond renovation adversely impacts the surrounding environment and is very expensive. An inexpensive, site-adaptable phytoremediation system that uses floating water hyacinth (*Eichhornia crassipes* (Mart.) Solms) to remove N from runoff as it enters stormwater ponds is being evaluated as a method for slowing the eutrophication process and extending the life expectancy and functionality of stormwater ponds.

Phytoremediation is the process of using plants (*phyto*) to clean up (*remediate*) polluted soil or water. Aquatic macrophytes are able to remove a variety of nutrients from polluted water (Boyd and Vickers, 1971; Reddy and DeBusk, 1985; Moorhead et al., 1988), including the major agricultural pollutants N and phosphorus (P). The aquatic macrophyte, floating water hyacinth, has been of particular interest for water remediation. While water hyacinth is considered one of the world's most noxious weeds (Sculthorpe, 1967; Gopal, 1987), the characteristics that make it weedy also make it a good plant for remediation. The plant is adaptable to a wide range of environmental factors including pH, electrical conductivity (EC), and temperature (Mitsch, 1977; Desougi, 1984; El-Gendy et al., 2004). The dense fibrous root system provides an extensive surface area for absorption, adsorption, and for micro-organism attachment. Water hyacinths spend the majority of their lifecycle in a vegetative state and rapidly reproduce by vegetative propagation. Increased biomass leads to increased filtering capacity.

The plant absorbs and stores N in excess of what it requires for growth (hyper-accumulation or luxury uptake) (Reddy and Tucker, 1983; Reddy and Reddy, 1987; Alves et al., 2003). In the 1970s and 1980s, water hyacinth was used in numerous waste water treatment systems. Many studies have evaluated the efficacy of water hyacinth, however, results differ widely on the amount of N removed (Dunigan et al., 1975; Ower et al., 1981; Tucker, 1981).

The objective of this study was to assess water hyacinth phytoremediation potential of nitrogen, a common pollutant in stormwater runoff collected in urban stormwater retention ponds. Because of water hyacinth's invasive nature, and in order to complete the nutrient recycling cycle, subsequent studies were conducted to address the critical issues of containment, harvesting, and composting.

Materials and Methods

Location

This study was conducted at Virginia Polytechnic Institute and State University's Hampton Roads Agricultural Research and Extension Center, Virginia Beach, VA, USA.

Ponds

Sixty four ponds were constructed inside a polyethylene film covered greenhouse and arranged in 4 blocks, each with 2 parallel rows of 8 ponds. Each pond had dimensions of 1.2 m × 1.2 m × 17.8 cm. Pond frames consisted of concrete block covered with a cushion layer of woven geotextile SI 200 ST followed by an impervious layer of 40 mm Very Flexible Polyethylene (VFPE) (ACF Environmental, Richmond, VA, USA). Each pond was filled with 189 l of water from a well (Table 1), and the water level was marked on the side of each pond.

Treatment

The study was conducted twice: Study A 14 April through 12 May and Study B 30 August through 27 September, 2005. Treatment rates were based on 2 years of water analysis data from golf course and commercial nursery ponds in Southeastern Virginia (data not shown) and literature (Ower et al., 1981; Yeager et al., 1993; Jayaweera and Kasturiarachchi, 2004). A commercial fertilizer, Scotts Champion Water Soluble Fertilizer 17-4-17 with 4% Ca, 1.25% Mg (Scotts-Sierra Horticultural Products Company, Marysville, OH, USA), was used to approximate a Hoagland's solution (Table 1). Treatment rates were based on ppm N, and included treatments of 0, 40, 80, 100, 150, 200 ppm in both Studies A and B, and 300 in Study B. Ratios of the macro nutrients were 4.25N:1P:4.25K:1Ca:3Mg with corresponding amounts of the micro nutrients. Aliquots from a 200 ppm N (Study A) or 300 ppm N (Study B) stock solution were used to produce the different treatments, which were applied once at the initiation of the study. Because the fertilizer contained Mg, Cu, Mn, and Zn in water soluble form, Na-EDTA (Table 1) was added to each pond to prevent Fe from precipitating out of solution. An initial batch of hyacinths was purchased and grown in greenhouse ponds in Hoagland's solution at 100 ppm N for 5 weeks prior to each experiment to establish a uniform stock population. From that stock population four (Study A, average individual initial fresh weight 27 g) or five (Study B, average individual initial fresh weight 72 g) uniformly sized water hyacinths with no attached progeny were pulled and placed in each pond. Deionized (DI) water was added on a weekly basis to keep individual pond water volume constant.

Table 1

Component concentrations (mg l^{-1}) for pond fill water and nutrient stock solution.

	Concentration (mg l^{-1})	
Compound	Fill water	Stock solution
ammoniacal N (NH_4)	NA[a]	74
nitrate N (NO_3)	2	226
phosphate (P_2O_5)	1	71
potash (K_2O)	3	300
calcium (Ca)	17	71
magnesium (Mg)	6	22
boron (B)	0.03	0.23
copper (Cu)	NA	0.15
iron (Fe)	NA	1.50
manganese (Mn)	NA	0.84
molybdenum (Mo)	NA	0.15
zinc (Zn)	NA	0.24
Na-EDTA	NA	9.6

[a] values not assessed or below detection limit

Data

Study duration was 28 days, and the study was completed before flower initiation. Environmental, water, and plant data were collected.

Environment Air temperature and photosynthetically active radiation (PAR) (µmol m^{-2} s^{-1}) readings were taken hourly by a weather station placed inside the greenhouse (HOBO Micro Station Logger, Onset Computer Corporation, Cape Cod, MA, USA). The greenhouse sides were removed and a 50% shade cloth was added over the top of the greenhouse to offset higher summer temperatures and radiation levels during Study B.

Water Pond water temperature was recorded hourly (HOBO Water Temp Pro v1 data logger, Onset Computer Corporation, Cape Cod, MA, USA). Individual pond pH and EC were also recorded at the same time of day once weekly (Oakton pH/CON10 pH/Conductivity/°C hand-held waterproof meter, Oakton Instruments, Vernon Hills, IL, USA). Water samples were collected from each pond at the initiation and end of the study for nutrient analysis which included Total Kjedahl Nitrogen (TKN) (copper catalyst EPA Method 351.2), nitrate/nitrite (Nitrite EPA Method 353.2) and ammonia (EPA Method 350.1).

Plant For base line data, thirty whole plant samples were collected at the beginning of the study from the same propagation pond as the experiment plants. Plant canopy coverage was measured on a percent basis every seven days using the dot grid assessment method (Swiecki and Bernhardt, 2001). Total plant number (including four original plants in Study A and five in Study B) and total biomass (whole plants) weight for each pond were collected at the end of the study. A young water hyacinth plant was counted if it had begun to extend from the parent plant, had visible roots, and at least two leaves. The fresh weight data (not shown) was used as a check for other data. Pond biomasses were air dried to a constant weight then dry matter weight was measured for each biomass. A representative whole plant sample was taken from each pond biomass and ground to particle size ≤ 3 mm. Whole plant samples were used because the hyacinths would not be treated as partitioned in the subsequent composting (recycling) process. Tissue samples were analysed for Total Kjedahl Nitrogen (TKN) (copper catalyst EPA Method 351.2), nitrate/nitrite (Nitrite EPA Method 353.2) and ammonia (EPA Method 350.1). Total N uptake was calculated by adding TKN and nitrate/nitrite N. All analyses were performed by a US EPA certified laboratory.

Experimental design and data analysis

The study was a randomized complete block (RCB) with six (Study A) and seven (Study B) treatments and eight replications. Data were analysed using SAS (SAS version 9.3, Cary, NC 2005). Regression analysis and Tukey’s test for mean separation

($P = 0.05$) were performed. Data points of individual experimental units were graphed in some figures in order to observe data cluster patterns. Mean data values were graphed in other figures to show relationships.

Results and Discussion

Research conducted on N uptake by water hyacinth is generally divided between two types of systems; plants cultured in ponds with or without sediments. The culture solution is generally either a prepared nutrient solution such as Hoagland (Hoagland and Arnon, 1950) or polluted or waste/effluent water. In the present studies the ponds contained no sediment and a commercial water soluble fertilizer was used to simulate a Hoagland's solution.

Daily maximum and minimum air temperatures ranged from 34 °C to 9 °C (Study A), and 34 °C to 16 °C (Study B), respectively. Daily minimum and maximum water temperatures followed a similar pattern and ranged from 10 °C to 32 °C (Study A) and 19 °C to 35 °C (Study B). PAR readings were higher for Study A than for Study B as expected due to the early season timing and no shade cloth on the greenhouse. Daily total photon flux densities (PFD) in Study A ranged from 57 – 408 moles m^{-2} d^{-1} and in Study B ranged from 49 – 127 moles m^{-2} d^{-1}. PFD in Study B was lower given the late season timing and addition of a shade cloth to the greenhouse. Ponds in Study B required significantly more DI water to maintain a constant volume than ponds in Study A (Figure 1), this was a result of the later season higher average air and water temperatures and more aggressive vegetative growth. At the initiation of both studies the pH of all solutions (Figure 2) was close to neutral. After 2 weeks, pH increased for 0 ppm and 40 ppm N treatments and decreased for all treatments over 80 ppm N. Average EC values (Figure 2) showed the clear differences between treatments for both studies.

In both studies, water hyacinths grew and reproduced in all treatments. Water hyacinth biomass increased with increasing N level as expected, with a very close relationship evident between total number of plants and total biomass (data not shown). A significant growth effect was observed at N levels greater than 80 ppm (Table 2). While water hyacinths grew faster in Study B and produced more biomass, the 5-fold increase in dry matter from lowest to highest treatment was consistent across the two studies. While total N accumulation in the water hyacinth tissue was significantly greater for the 80 ppm N and higher treatments, it was not significantly different between those treatments in either study. Total nutrient depletion of the culture solution did not occur in any treatment in either Study A or B, but the N removal from the water significantly increased with an increase in the N level over the entire range (Study A) or until 100 ppm (Study B) (Table 2).

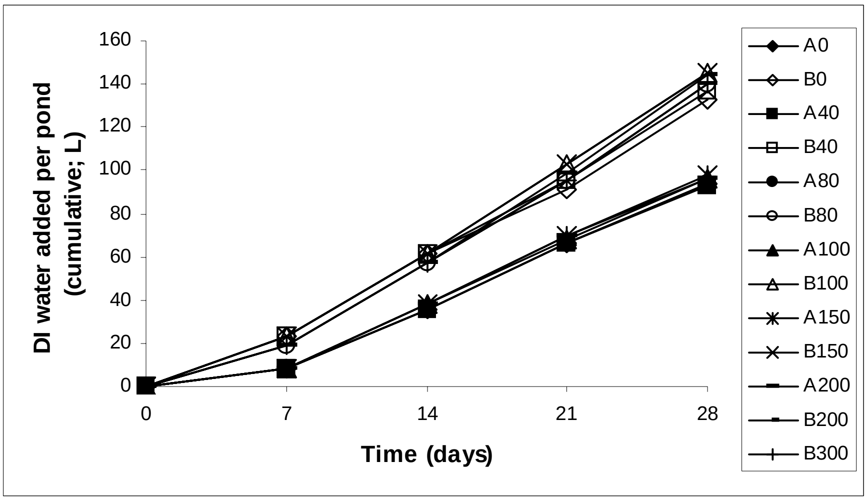


Fig. 1. Cumulative deionized (DI) water added per pond weekly to maintain constant water volume. Legend symbols represent Studies A and B and treatments in ppm N.

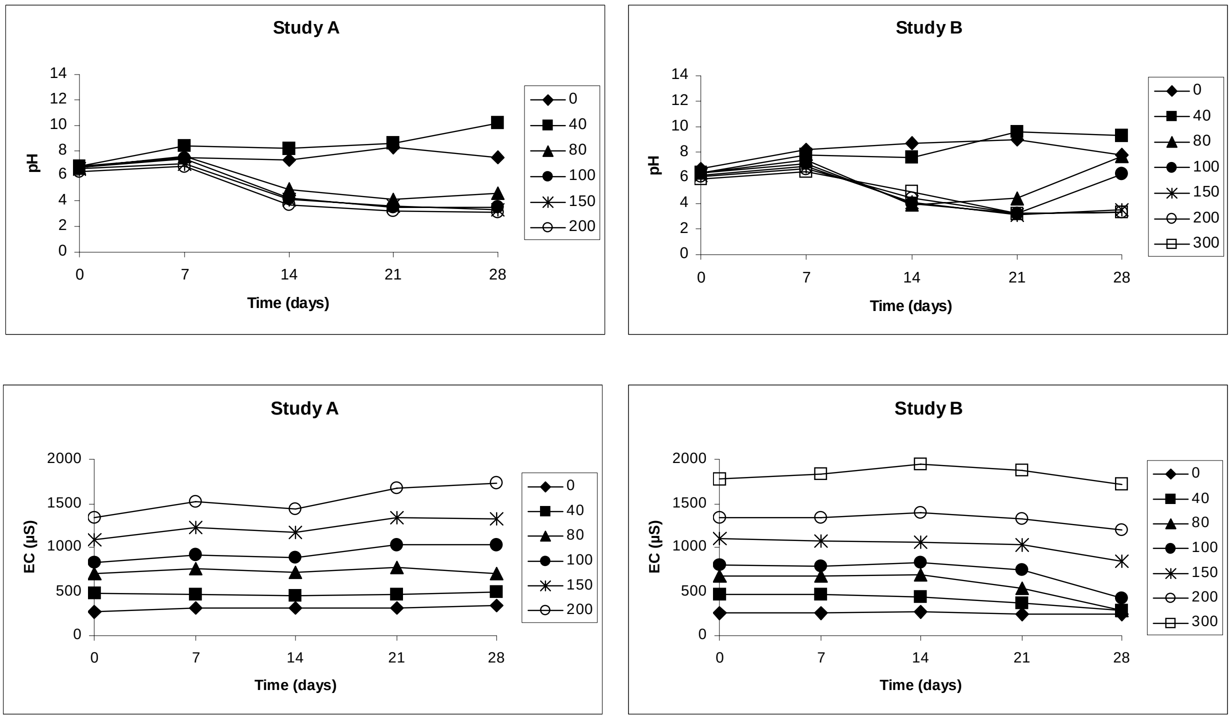


Fig. 2. Average pH and electrical conductivity (EC) values by treatment over time for Study A and Study B. Legend symbols represent treatments in ppm N.

Table 2

Final dry matter (DM), total nitrogen (N) in plant tissue, and N removal from water, means and separations for Studies A and B.

Study A							Study B						
	Means							Means					
TRT ppm N	DM g		Total N tissue g		N removal water g		TRT ppm N	DM g		Total N tissue g		N removal water g	
0	22.5	b[a]	0.28	c	0.47	f	0	32.5	c[a]	0.53	c	0.31	c
40	29.1	b	0.62	b	5.69	e	40	85.9	b	2.66	b	2.35	bc
80	101.9	a	3.49	a	9.31	d	80	181.8	a	6.10	a	5.45	ab
100	128.3	a	3.84	a	11.86	c	100	172.8	a	6.57	a	9.01	a
150	117.8	a	4.29	a	16.97	b	150	172.1	a	6.50	a	9.05	a
200	122.9	a	5.48	a	22.13	a	200	180.3	a	6.84	a	4.84	bc[b]
							300	188.0	a	7.88	a	9.26	a
	P<.0001		P<.0001		P<.0001			P<.0001		P<.0001		P<.0001	

[a] mean separation based on Tukey's test at $P < 0.05$

[b] initial values of treatment 200 were between initial values of treatments 100 and 300, and so were the final values; but the differences between final and initial values had a high coefficient of variation and on average were outlying.

The correlation between N concentration in plant tissue and plant dry matter of vegetative crops is well-documented in literature pertaining to agricultural crops (Biemond and Vos, 1992). This same relationship has also been well documented in water hyacinth (Mitsch, 1977; Shiralipour et al., 1981; Reddy et al., 1989). Total N concentration in the water hyacinth tissue correlated well with the final dry matter in both studies, as seen in the tight clustering of the data points and the R^2 values (Figure 3). The factors that influenced final dry matter also influenced total N concentrations suggesting that N was removed through multiple mechanisms. A strong linear correlation was evident between the net increase in water hyacinth tissue N and the net dry matter increase (Figure 4). The slope of the linear regression lines was similar for the two studies, suggesting a consistent nitrogen concentration in the tissue over studies.

Nitrogen added to each pond ranged from 40 mg L^{-1} (7.56 g) to 300 mg L^{-1} (56.73 g) (Table 2). Fifty-nine to 75% of the N was removed from the pond solution in Study A, while only 13−48% was removed in Study B (Figure 5). Water hyacinths accounted for up to 60% of the N removed from the pond solution in Study A and 85% in Study B (Table 2).

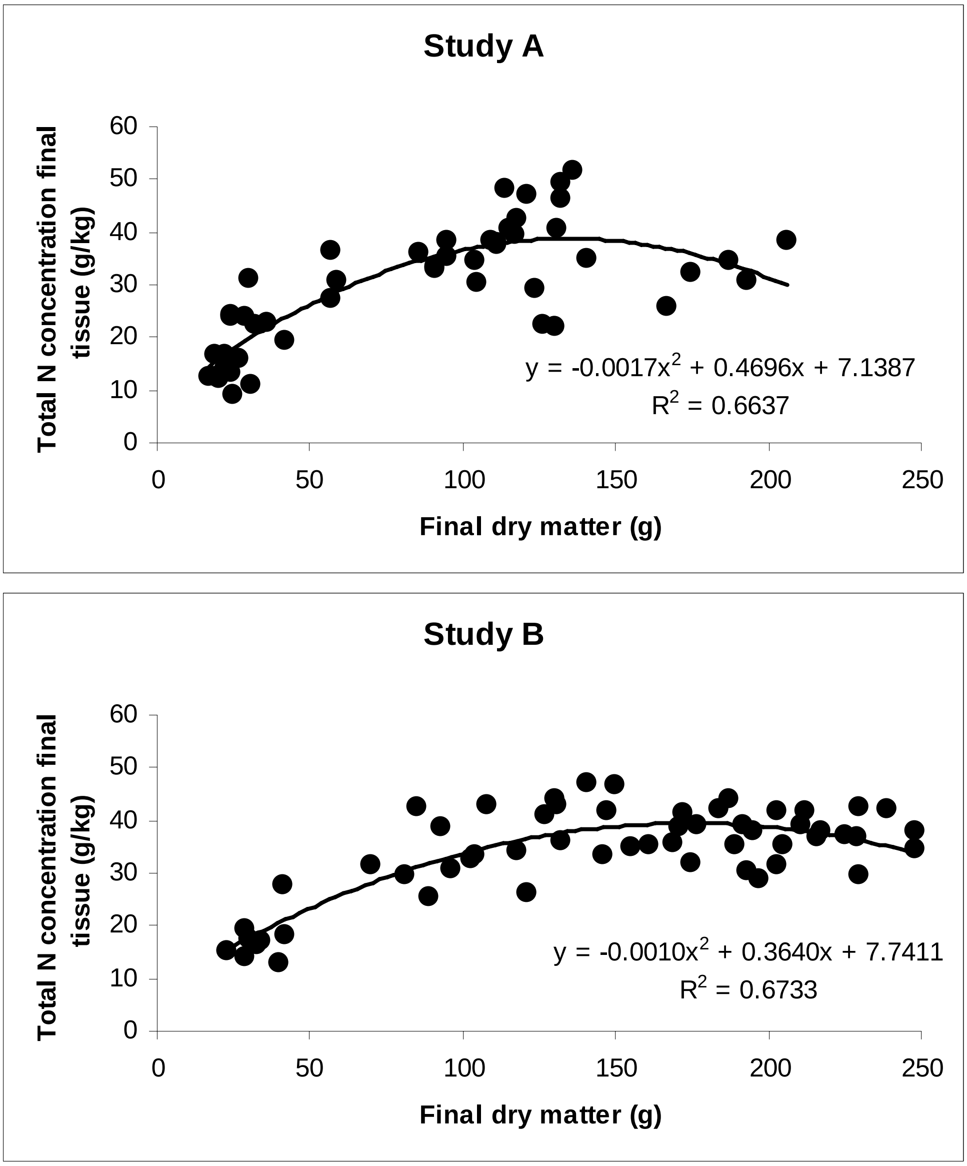
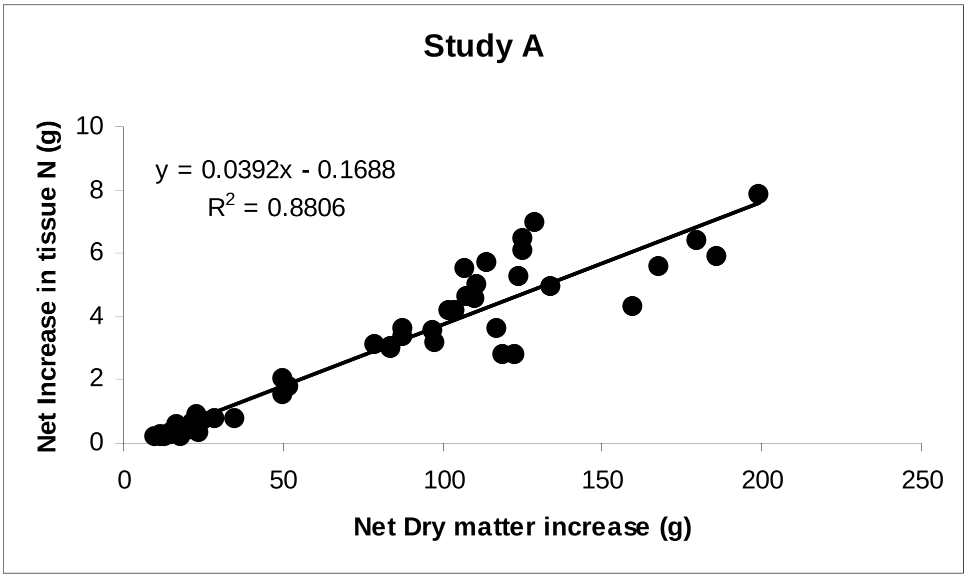


Fig. 3. Total nitrogen concentration in the final water hyacinth tissue versus final water hyacinth dry matter for Study A and Study B.

Power regression curves confirm that when water hyacinth dry matter increased, N removal from the pond solution increased. Initially N removal from the water corresponded closely to dry matter increase, but this did not hold at the higher level N treatments, especially in Study A. Although there was no additional growth or corresponding biomass increase, there was still variation in N removal from the pond solution. The relationships between water hyacinth canopy cover and N uptake from the pond solution (Figure 6) for both studies was similar to their N uptake dry matter relationship in Figure 5. Canopy cover is an indicator of N uptake. The power relationships for both studies in both Figures 5 and 6 clearly show the developmental effect on the water hyacinths as N is removed from solution.



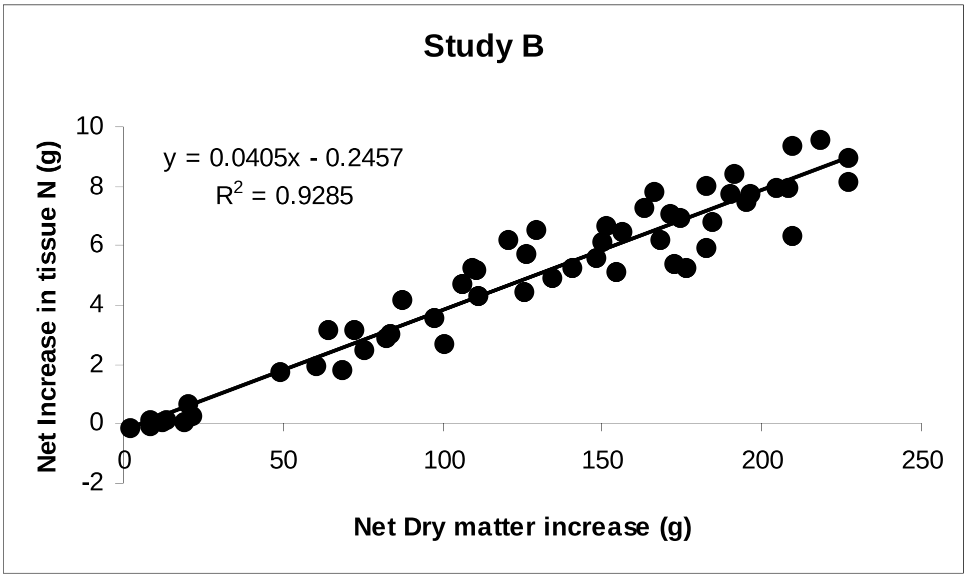


Fig. 4. Increase in tissue nitrogen versus dry matter for Study A and Study B.

While water hyacinths are known hyperaccumulators of nutrients, and they removed significant amounts of N, they did not account for the total amount of N removed from the pond solution. Processes other than plant uptake appeared to influence the N removal from the ponds, and plotting total N uptake in tissue against total N removal from water (Figure 7) confirms this.

The regression equations for both studies strongly deviated from the 1:1 line and the slope of the curves decreased with increasing total N removal. In Study A (with lower temperatures but much higher light levels on the canopy and the water), the discrepancy between total N uptake in plants and total N removal from water was much larger than in Study B. In addition to plant uptake, nitrification, denitrification, volatilization, and assimilation processes impact N removal from pond solutions

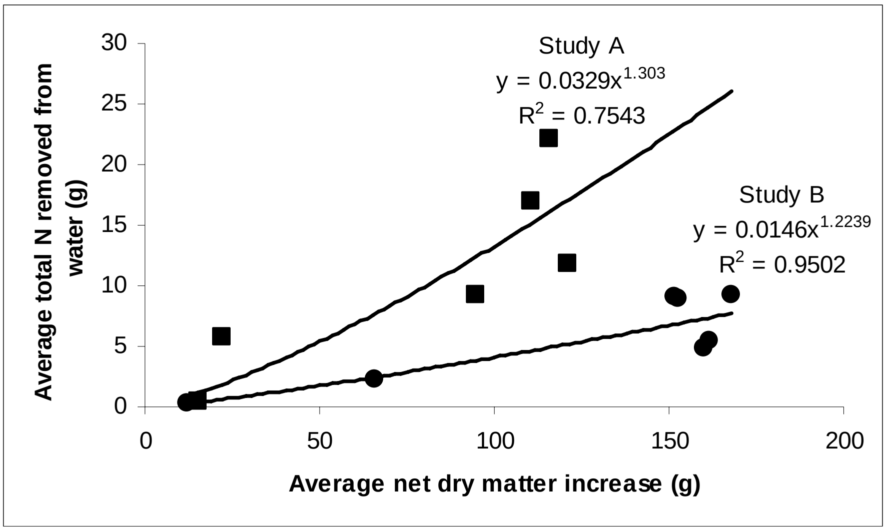


Fig. 5. Total nitrogen removed from pond solution versus net dry matter increase means for Studies A and B.

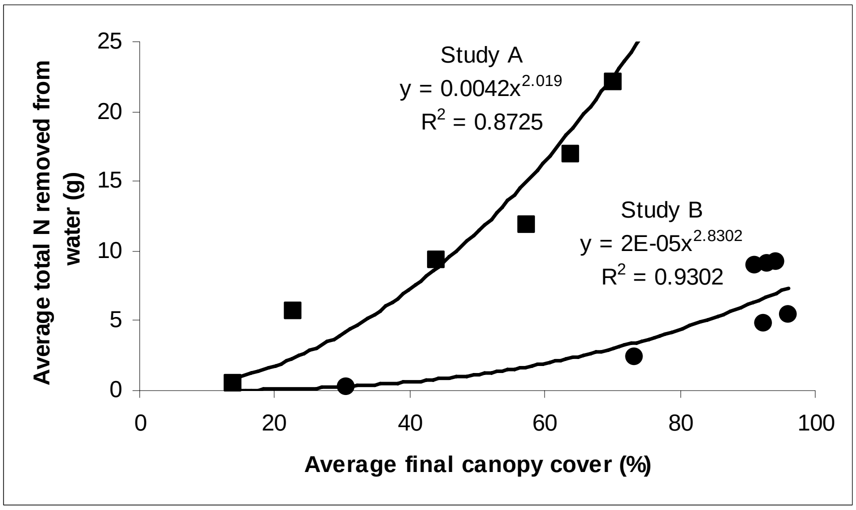


Fig. 6. Total nitrogen removed from pond solution versus final canopy cover means for Studies A and B.

(Schwarz et al., 1999). Since these studies were hydroponic, N loss from the denitrification process associated with sediment-based systems was not a factor. El-Gendy et al. (2004) reported that above pH 6.0, nitrogen transformations through nitrification and ammonia volatilization occur. In our studies, pH decreased for the higher N level treatments, eliminating nitrification and ammonia volatilization as significant sinks for the N removed in excess of what was observed in the water hyacinth tissue. These processes could have contributed to the N removal from the

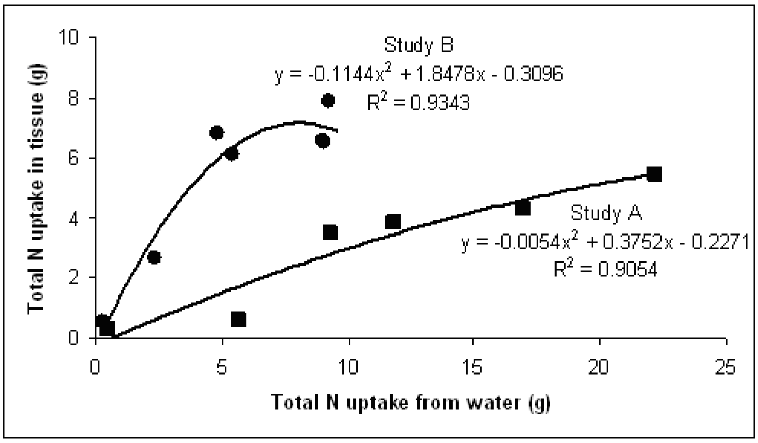


Fig. 7. Total nitrogen uptake in hyacinth tissue versus total nitrogen removed from pond solution means for Studies A and B.

pond solution in the lower ppm N treatments, though, where the pH was consistently above 6.0. Reddy and Reddy (1987) report that N assimilation by algae and aquatic macrophytes can contribute to significant losses of N from aquatic systems. Algae infested all treatments and replications in both studies. Denser algal growth was observed within the higher N treatments until hyacinth canopy coverage of pond surface area was almost complete. Algal growth was therefore considered a significant component in N removal in these studies, and a major factor in explaining the discrepancy between total N taken up by the plants and total N being removed from the water. The most likely mechanism to explain this discrepancy is denitrification enhanced by oxygen consumption and organic matter production by the algae as seen in Study B, which showed the smallest discrepancy, but where the water was replenished more frequently.

Conclusions

While information in the literature varies on the amount of N removed by water hyacinths, studies including this one show that these aquatic macrophytes are effective and efficient at nutrient phytoremediation. Other processes such as nitrification, denitrification, and volatilization also impact N removal in dynamic aquatic systems. How effectively and efficiently N is removed is relative to the individual system and end goals for nutrient removal. Nutrient removal from stormwater runoff can be achieved using water hyacinth in a contained system; however, water hyacinths alone cannot remediate 100% of the N in solution. Given that water hyacinths are invasive they should be used with caution and in conjunction with other practices under controlled conditions.

CHAPTER 3

Phosphorus phytoremediation by water hyacinth (*Eichhornia crassipes* (Mart.) Solms)*

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Abstract

Phosphorus (P) phytoremediation by water hyacinth, *Eichhornia crassipes* (Mart.) Solms, was examined in two independent studies, conducted under greenhouse conditions. Modified Hoagland solution with P (ammonium phosphate) rates of 0, 9.4, 18.8, 23.5, 35.3, 47.1 and 70.6 ppm was added to 189 L ponds containing four or five water hyacinth plants. Phosphorus content of the nutrient solution and hyacinth tissue were evaluated after a four week period. Electric conductivity and pH of the nutrient solution, and hyacinth canopy cover and biomass were evaluated weekly for four weeks. Plants were more vigorous, and canopy development was quicker and denser in the higher nutrient treatments. Water hyacinths accumulated between 0.02 and 1.7 g of P in plant tissue over four weeks, producing between 22.5 and 188 g of dry matter per pond. Phosphorus accumulation in the tissue was significantly greater in the 18.8 ppm and higher treatments than in the lower ppm treatments. Total nutrient depletion of the water did not occur in any treatment, in either study. Phytoremediation of the inorganic P by water hyacinth accounted for 17 − 79%.

Keywords: assimilation, biofiltration, nutrient removal, phytoremediation

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Introduction

Nutrient pollution of surface waters continues to be a critical environmental issue. Excess nutrients, primarily nitrogen (N) and phosphorus (P), degrade water quality and accelerate the eutrophication process in aquatic ecosystems. Since 1972 the United States' Clean Water Act has mandated clean water in lakes, rivers, streams, and aquifers (United States EPA, 1972). Increasingly stringent regulations governing runoff velocity, water quantity and quality have resulted in the extensive use of storm-water retention ponds in urbanized areas. These ponds frequently have additional uses such as irrigation, municipal water storage and recreational activities. While strong emphasis has been placed on the use of storm water ponds, relatively little effort has been directed towards their management and long term maintenance. Consequently, many ponds experience accelerated eutrophication from excessive N and P pollution.

Aquatic macrophytes are able to remove a variety of nutrients from polluted water (Boyd and Vickers, 1971; Reddy and DeBusk, 1985; Moorhead et al., 1988) and floating water hyacinth (*Eichhornia crassipses* (Mart.) Solms) has been of particular interest for water remediation. The characteristics that make water hyacinth one of the world's most aggressive weeds (Sculthorpe, 1967; Gopal, 1987) also make it good for remediation. Plants are adaptable to a wide range of environmental factors including pH, electrical conductivity (EC), and temperature (Mitsch, 1977; Desougi, 1984; El-Gendy et al., 2004). The dense fibrous root systems provide an extensive surface area for absorption, adsorption, and for micro-organism attachment. Water hyacinths spend the majority of their lifecycle in a vegetative state and rapidly reproduce through vegetative offshoots. As biomass increases, so does filtering capacity.

Previous studies have documented water hyacinths' ability to absorb and store nutrients in excess of what is required for growth (hyper-accumulation or luxury uptake) (Reddy and Tucker, 1983; Reddy and Reddy, 1987; Alves et al., 2003). However, earlier studies indicate that its nutrient removal efficacy can vary from site to site (Dunigan et al., 1975; Ower et al., 1981; Tucker, 1981).

The objective of this study was to assess accumulation of inorganic P by water hyacinth in order to evaluate its potential as a phytoremediation plant for the maintenance of urban storm water retention ponds. Because of water hyacinth's invasive nature, and in order to complete the nutrient recycling cycle, subsequent studies were conducted to address the critical issues of containment, harvesting, and composting.

Materials and Methods

This research was conducted at Virginia Polytechnic Institute and State University's Hampton Roads Agricultural Research and Extension Center, Virginia Beach, VA, USA. A detailed description of the materials and methods can be found in Fox et al.

(2008). Research pond (189 L per pond) fill water and nutrient stock solution compositions are listed in Table 1 in Chapter 2 (page 12). The study was conducted twice; Study A from April 14 to May 12, and Study B from August 30 to September 27, 2005. Both studies were terminated before hyacinth flower initiation.

Treatment rates were based on two years of water analysis data from golf course (Virginia Beach, VA) and commercial nursery ponds (Suffolk, VA) (data not shown) and literature (Ower et al., 1981; Yeager et al., 1993; Jayaweera and Kasturiarachchi, 2004). A commercial fertilizer, Scotts Champion Water Soluble Fertilizer 17-4-17 with 4% Ca, 1.25% Mg (Scotts-Sierra Horticultural Products Company, Marysville, OH, USA), was used to approximate a Hoagland's solution (Hoagland and Arnon, 1950). Phosphorus (ammonium phosphate) rates were 0, 9.4, 18.8, 23.5, 35.3, 47.1 in both Studies A and B, and 70.6 ppm in Study B. Aliquots from a stock solution were used to produce the different treatments, which were applied once at the initiation of the study. From a stock population of water hyacinths, four (Study A, average individual initial fresh weight 27 g) or five (Study B, average individual initial fresh weight 72 g) uniformly sized water hyacinths with no attached progeny were pulled and placed in each pond. Deionized (DI) water was added weekly to keep individual pond water volume constant. Air temperature and photosynthetically active radiation (PAR) (μmol m^{-2} sec^{-1}) data were recorded hourly by a weather station (HOBO Micro Station Logger, Onset Computer Corporation, Cape Cod, MA, USA) placed inside the greenhouse. The greenhouse sides were removed, and a 50% shade cloth was added over the poly top of the greenhouse to reduce irradiation and lower the ambient temperature during Study B.

Water samples were collected from each pond at the initiation and end of the study for nutrient analysis. Percent plant canopy coverage was measured weekly using the dot grid assessment method (Swiecki and Bernhardt, 2001). Total plant number (including four original plants in Study A and five in Study B) and total biomass (whole plants) weight for each pond were assessed at the conclusion of the study. Water and tissue samples were analysed for Total Phosphorus (TP) by digesting with ammonium persulfate in autoclave (121 °C, 15 – 20 psi, 30 minutes), followed by flow injection analysis colorimetry (EPA Method 365.1) (United States EPA, 1993). All analyses were performed by a US EPA certified laboratory.

The study was designed as a randomized complete block (RCB) with six (Study A) and seven (Study B) treatments and eight replications. Data were analysed using SAS (SAS version 9.3, Cary, NC, 2005). Regression analysis and Tukey's test for mean separation (P = 0.05) were performed. Data points of individual experimental units were graphed in some figures in order to observe data cluster patterns. Mean data values were graphed in other figures to show relationships.

Results and Discussion

Daily minimum and maximum air temperatures ranged from 9 to 34 °C during Study A (April/May), and from 16 to 34 °C during Study B (August/September). Daily minimum and maximum water temperatures followed a similar pattern, ranging from 10 to 32 °C, and 19 to 35 °C, in Studies A and B, respectively. Daily total photon flux densities (PFD) in Study A ranged from 57 – 408 moles m^{-2} d^{-1} and in Study B ranged from 49 – 127 moles m^{-2} d^{-1}. PFD in Study B was lower given the late season timing and addition of a shade cloth to the greenhouse. Ponds in Study B required significantly more DI water to maintain a constant volume than ponds in Study A (Figure 1), because of the higher average air and water temperatures later in the season and vigorous plant growth (Table 1) and transpiration. At the initiation of both studies the pH of all solutions (Figure 2) was close to neutral. After two weeks, pH increased for 0 ppm and 9.4 ppm P treatments and decreased for the higher P concentration treatments. Average EC values (Figure 2) showed clear differences between treatments for both studies.

In both studies, water hyacinths grew and reproduced across all treatments and replications. Plant biomass increased with increasing P concentration, with a very close relationship evident between total number of plants and total biomass (data not shown). A significant effect on plant growth was observed at P levels 18.8 ppm or greater (Table 1). While water hyacinths grew faster in Study B and produced more biomass, the 5-fold increase in dry matter from lowest to highest treatment was consistent across the two studies. Phosphorus accumulation in the water hyacinth tissue was significantly greater for the 18.8 ppm P and higher concentrations than for

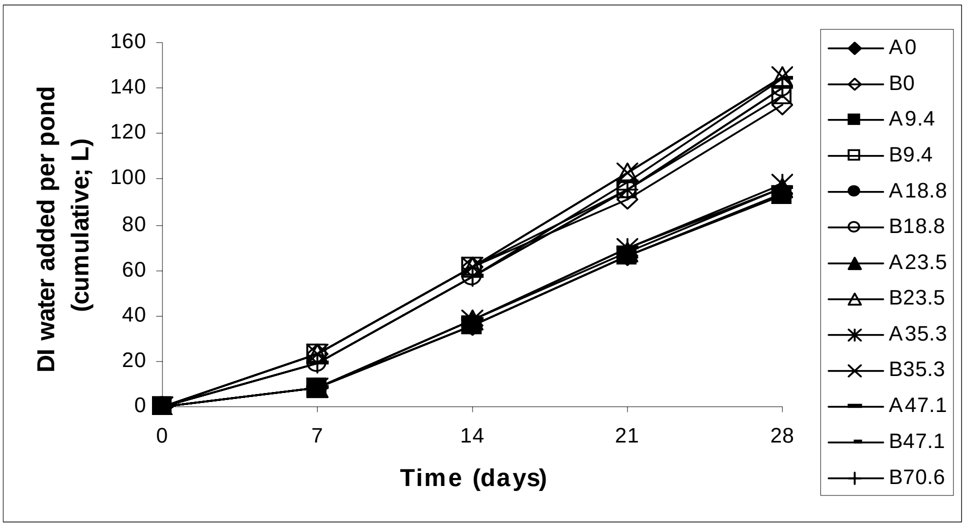

Fig. 1. Cumulative deionized (DI) water added per pond weekly to maintain constant water volume. Legend symbols represent Studies A and B and treatments in ppm P.

Table 1

Dry matter (DM), final canopy coverage (CC), total phosphorus (P) in plant tissue, and P uptake from water means and separations for Studies A and B.

	Study A (Means)									Study B (Means)							
TRT ppm P	**DM g**		**CC %**		**Total P tissue g**		**P uptake water g**		**TRT ppm P**	**DM g**		**CC %**		**Total P tissue g**		**P uptake water g**	
0	22.50	b*	14.00	d	0.02**	d	0.00**	f	0	32.50	c	30.63	c	0.05**	d	0.00**	e
9.4	29.10	b	22.75	c	0.14	c	0.79	e	9.4	85.90	b	73.25	b	0.41	c	1.03	bc
18.8	101.90	a	43.88	b	0.63	b	1.41	d	18.8	181.80	a	96.00	a	1.02	b	1.29	b
23.5	128.30	a	57.38	ab	0.71	b	1.70	c	23.5	172.80	a	91.13	ab	1.13	b	1.58	a
35.3	117.80	a	63.75	ab	0.74	b	2.17	b	35.3	172.10	a	93.00	a	1.26	b	0.83	cd
47.1	122.90	a	70.25	a	0.90	a	2.64	a	47.1	180.30	a	92.38	ab	1.46	a	0.72	d
	P<.0001		*P*<.0001		*P*<.0001		*P*<.0001		70.6	188.00	a	94.25	ab	1.73	a	1.35	ab
										P<.0001		*P*<.0001		*P*<.0001		*P*<.0001	

* mean separation based on Tukey's test at $P<0.05$.

** data were natural log transformed prior to statistical analysis.

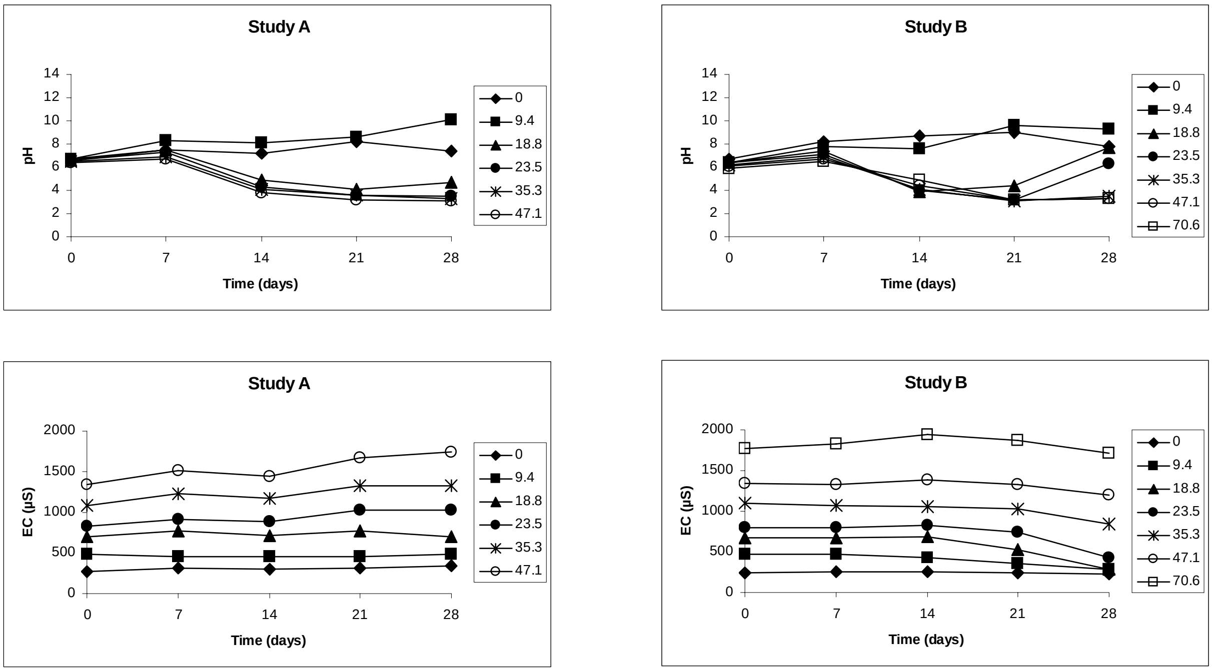

Fig. 2. Average pH and electrical conductivity (EC) values by treatment over time for Study A and Study B. Legend symbols represent treatments in ppm P.

the 0 and 9.4 ppm concentrations. Total nutrient depletion of the water did not occur in any treatment in either Study A or B. Uptake by water hyacinths accounted for 17 to 44% of the P removed from water in Study A and 39 to 79% in Study B.

The P uptake patterns for Study A and Study B were similar to the nitrogen uptake patterns (Fox et al., 2008) observed in the same studies. Amounts of P removed from the pond water increased when final canopy cover by the water hyacinth increased in both studies (Figure 3). Also the levels of P in the water hyacinth tissue increased with an increase in final canopy cover (Figure 3). In Study B, the tissue based values and the water based values were similar. The amount of nutrients removed from the water was reflected in the water hyacinth tissue, and water hyacinth canopy development was quicker and denser, especially in the higher nutrient treatments. In Study A, canopy coverage developed more slowly. A large difference between the P removed from the water and what was taken up in the water hyacinth tissue was observed in Study A. More light (Petrucio and Esteves, 2000), higher algae concentrations leading to assimilation, and a wider fluctuation of ambient temperatures earlier in the season could account for the larger difference between the tissue and water values in Study A and for the difference between studies (Gopal, 1987; Petrucio and Esteves, 2000). Precipitation of phosphorus as $FePO_4$ or as other compounds due to water pH conditions (Jayaweera and Kasturiarachchi, 2004) could also be a contributing factor, especially in the lower rate treatments.

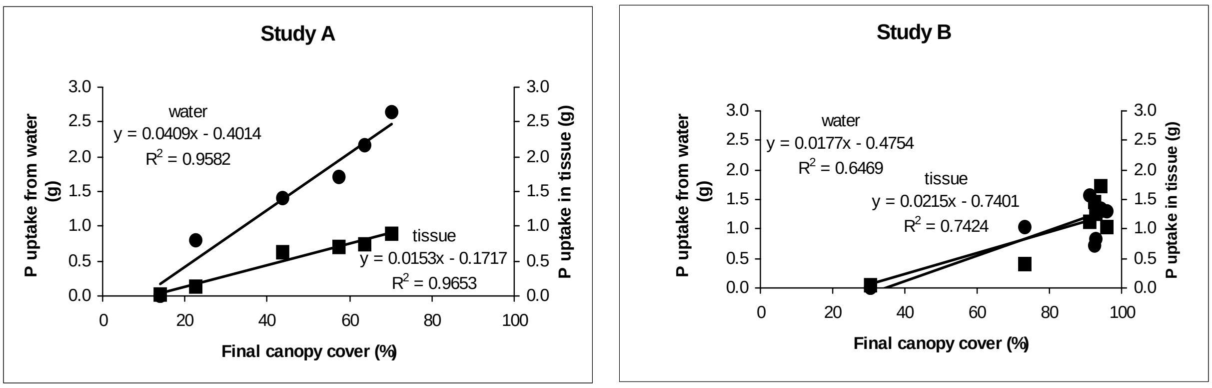

Fig. 3. P uptake from water and P uptake in water hyacinth tissue versus final canopy cover for Studies A and B.

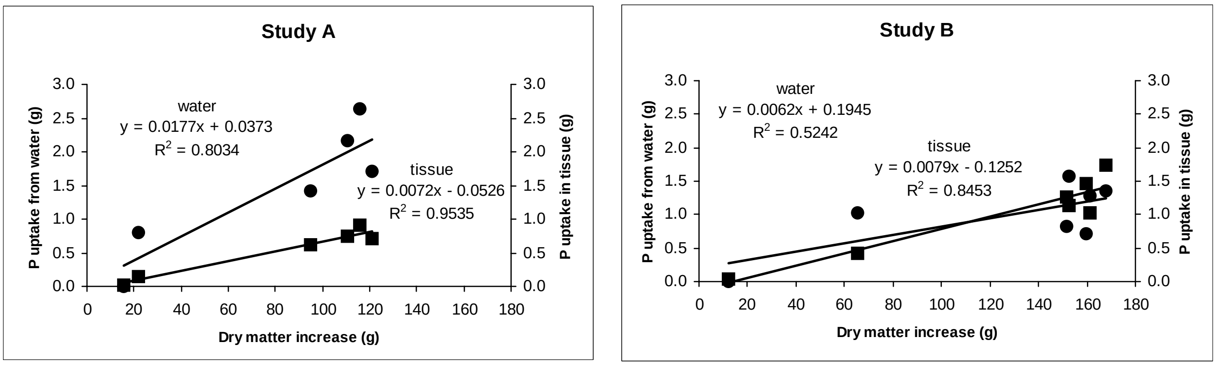

Fig. 4. P uptake from water and P in water hyacinth tissue versus dry matter increase for Studies A and B.

The P uptake from water and the P uptake in tissue showed similar relations with dry matter increase as they did with final canopy cover for both studies (Figure 4), and these relations again reflected the differences between the two studies associated with differences in processes of assimilation, temperature fluctuation, and P precipitation from the water.

The relatively constant P content in water hyacinth tissue over a wide range of P concentrations in pond water is seen across both studies when plotting total P concentration in the final tissue to final dry matter and also when plotting the net P increase in tissue against the net dry matter increase (Figure 5). Treatments with no or low P concentrations (0 and 9.4 ppm) in the water showed lower and more variable P concentrations in the water hyacinth tissue than the higher P treatments. When water hyacinth dry matter increased P uptake was consistent per unit of dry matter, so the dry matter increase was affected in a similar way to the P concentration in the dry matter content.

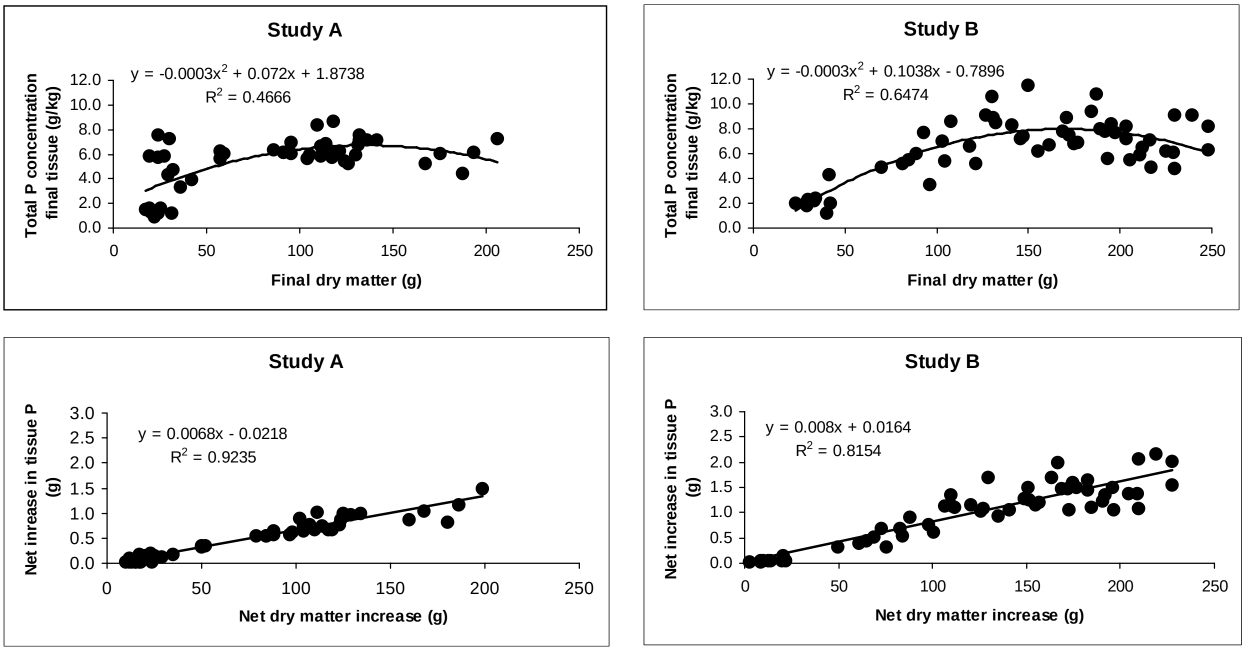

Fig. 5. Total P concentration in water hyacinth tissue versus final dry matter and net increase in tissue P versus net increase in dry matter for Studies A and B.

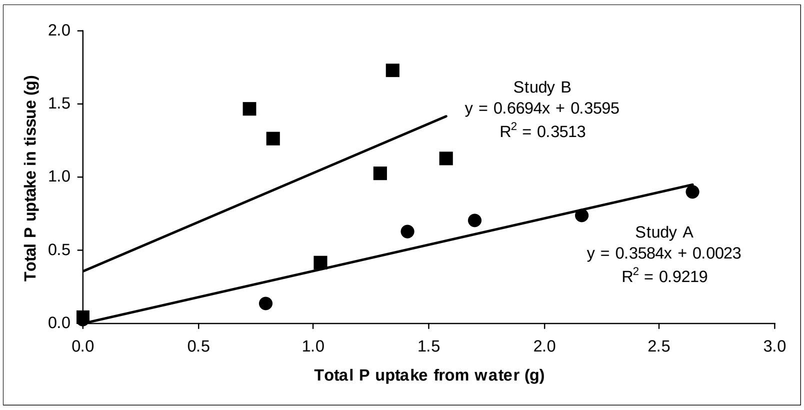

Fig. 6. Total P uptake in water hyacinth tissue versus total P uptake from water for Studies A and B.

When plotting the total P uptake in tissue against the total P removed from the water (Figure 6), a strong linear relationship is evident in Study A. However, only a small proportion of what was removed from the water accumulated in water hyacinth tissue in Study A. In Study B, the relation was weaker while most of the P removed from the water accumulated in the plant tissue. The authors propose that much of the P precipitated out of solution due to pH extremes (Figure 7) and thus, became unavailable to the water hyacinth plants. It is not clear, however, why this pH effect was stronger in Study A than in Study B.

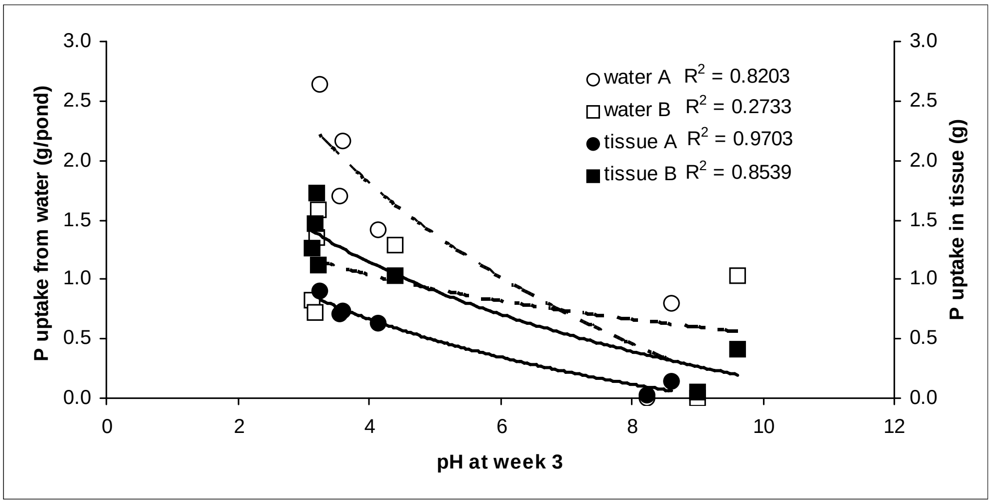

Fig. 7. Influence of pH on P uptake from water and P uptake in water hyacinth tissue for Studies A and B.

Conclusions

Two P phytoremediation studies conducted with water hyacinth demonstrated that this aquatic macrophyte can remove 17 – 79% of P from water at P concentration levels between 9.4 and 70.6 ppm. Phosphorus remediation is strongly influenced by the individual system, environmental factors, and the end goals for nutrient removal. Successful phytoremediation of stormwater runoff can be achieved using water hyacinth; however, water hyacinths alone cannot remediate 100% of P in solution. Given that water hyacinths are invasive they should be used with caution and in conjunction with other practices under controlled conditions. Using water hyacinths as the example, and with the increased availability of floating island and wetland systems, it is now possible to utilize a wider range of other non-invasive aquatic macrophytes for phytoremediation.

CHAPTER 4

Production ecology of water hyacinth (*Eichhornia crassipes* (Mart.) Solms)*

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Abstract

The relationships between water nutrient level and growth conditions on production of water hyacinth were examined in two studies. High nitrogen (80 – 300 ppm) and phosphorus (9.4 – 70.6 ppm) levels in the water and light levels caused corresponding positive linear responses in plant growth as determined by biomass accumulation and canopy cover. Daily total photon flux densities (PFD) in Study A ranged from 57 – 408 moles m^{-2} d^{-1} and in Study B ranged from 49 – 127 moles m^{-2} d^{-1}. Larger plants intercepted more light and were thus more productive leading to a faster vegetative multiplication rate and the corresponding higher percent canopy cover, as well as an earlier and stronger crowding phenomenon. In both studies treatments with the higher nutrient levels generated more plants and had better canopy cover and higher light interception values. The higher light interception resulted in better accumulation of nutrients in the tissue. Radiation use efficiency (RUE) values were also higher in water hyacinths with more nitrogen in the tissue.

Keywords: biofiltration, bioremediation, phytoremediation, water quality

* *Submitted*

Introduction

Water hyacinth (*Eichhornia crassipes* (Mart.) Solms) is a floating aquatic macrophyte with such a prolific growth habit that it is considered an invasive weed world wide (Mehra et al., 1999). While it does reproduce by seed, its primary means of multiplication is through vegetative offshoots produced at the ends of stolons which extend from the parent plant. Water hyacinth grows and multiplies rapidly enough to double the number of plants every 11 – 18 days under favourable environmental conditions (Reddy and Tucker, 1983; Gopal, 1987). Just 10 plants have the potential to increase to 655,360 in eight months (Penfound and Earle, 1948). Also water hyacinth leaves have a large exposed surface area that effectively captures light (Reddy and DeBusk, 1984; Reddy, 1988).

Due to its rapid growth, high multiplication rate and large ability to absorb and hyper-accumulate high levels of nutrients water hyacinth has great potential in phytoremediation of nutrient polluted waters (Reddy and DeBusk, 1985; Reddy et al., 1989, 1990). It has already been used in waste water treatment programmes, and more recently, tested in remediation of polluted storm water runoff in retention ponds (Fox et al., 2008).

Factors that limit growth of water hyacinth include: water salinity higher than 0.2%, nutrient availability, physical disturbance, natural enemies (*Neochetina* spp. Weevils), unfavourable water temperatures (below 13 °C and above 40 °C), and insufficient light (PAR ~2000 µE m^{-2} s^{-1}) (Wilson et al., 2001; Williams et al., 2005; Wilson et al., 2005). Biomass, canopy cover, and number of plants are good measures of the performance of water hyacinth (Agami and Reddy, 1990; Wilson et al., 2001). There are well documented relationships between N concentration in the leaves and growth rate (Aoyama and Nishizake, 1993), and between leaf architecture and photosynthetic efficiency (Reddy and DeBusk, 1984; Reddy, 1988).

The use of water hyacinths for phytoremediation of nitrogen and phosphorus in surface water runoff has created a need to study its production ecology. A clearer understanding of the factors influencing hyacinth production, and their interaction, will lead to the development of recommendations that maximize its remediation efficiency. The objective of this research was to examine plant production response to nutrient and light effects. This was done by creating different growth conditions through nutrient supply manipulation and then analysing the associations between growth phenomena.

Materials and Methods

Location

This study was conducted at Virginia Polytechnic Institute and State University's Hampton Roads Agricultural Research and Extension Center, Virginia Beach, VA, USA.

Ponds

Sixty four ponds were constructed inside a polyethylene film covered greenhouse and arranged in 4 blocks, each with 2 parallel rows of 8 ponds. Each pond had dimensions of 1.2 m × 1.2 m × 17.8 cm. Pond frames consisted of concrete block covered with a cushion layer of woven geotextile SI 200 ST followed by an impervious layer of 40 mm Very Flexible Polyethylene (VFPE) (ACF Environmental, Richmond, VA, USA). Each pond was filled with 189 l of water from a well (see Table 1 in Chapter 2, page 12), and the water level was marked on the side of each pond.

Treatments

The study was conducted twice; Study A 14 April through 12 May and Study B 30 August through 27 September, 2005. Treatment rates were based on 2 years of water analysis data from golf course and commercial nursery ponds in Southeastern Virginia (data not shown) and literature (Yeager et al., 1993). A commercial fertilizer, Scotts Champion Water Soluble Fertilizer 17-4-17 with 4% Ca, 1.25% Mg (Scotts-Sierra Horticultural Products Company, Marysville, OH, USA), was used to approximate a Hoagland's solution (see Table 1 in Chapter 2) (Hoagland and Arnon, 1950). Treatment rates were based on ppm N, and included treatments of 0, 40, 80, 100, 150, 200 ppm in both Studies A and B, and 300 in Study B. Ratios of the macro nutrients were 4.25N:1P:4.25K:1Ca:3Mg with corresponding amounts of the micro nutrients. Aliquots from a 200 ppm N (Study A) or 300 ppm N (Study B) stock solution were used to produce the different treatments, which were applied once at the initiation of the study. Because the fertilizer contained Mg, Cu, Mn, and Zn in water soluble form, Na-EDTA (Table 1 in Chapter 2) was added to each pond to prevent Fe from precipitating out of solution. An initial batch of hyacinths was purchased and grown in greenhouse ponds in Hoagland's solution at 100 ppm N for 5 weeks prior to each experiment to establish a uniform stock population. From that stock population four (Study A, average individual initial fresh weight 27 g) or five (Study B, average individual initial fresh weight 72 g) uniformly sized water hyacinths with no attached progeny were pulled and placed in each pond. Deionized (DI) water was added on a weekly basis to keep individual pond water volume constant.

Data

Study duration was 28 days, and the study was completed before flower initiation. Environmental, water, and plant data were collected.

Environment Air temperature and photosynthetically active radiation (PAR) (μmol m^{-2} sec^{-1}) readings were taken hourly by a weather station placed inside the greenhouse (HOBO Micro Station Logger, Onset Computer Corporation, Cape Cod, MA, USA). The greenhouse sides were removed and a 50% shade cloth was added over the top of the greenhouse to offset higher summer temperatures and radiation levels during Study B.

Water Pond water temperature was recorded hourly (HOBO Water Temp Pro v1 data logger, Onset Computer Corporation, Cape Cod, MA, USA). Individual pond pH and EC were also recorded at the same time of day once weekly (Oakton pH/CON10 pH/Conductivity/°C hand-held waterproof meter, Oakton Instruments, Vernon Hills, IL, USA). Water samples were collected from each pond at the initiation and end of the study for nutrient analysis which included Total Kjedahl Nitrogen (TKN) (copper catalyst EPA Method 351.2), nitrate/nitrite (Nitrite EPA Method 353.2), ammonia (EPA Method 350.1), and Total Phosphorus (EPA Method 365.1).

Plant For base line data, thirty whole plant samples were collected at the beginning of the study from the same propagation pond as the experiment plants. Plant canopy coverage was measured on a percent basis every seven days using the dot grid assessment method (Swiecki and Bernhardt, 2001). Total plant number (including four original plants in Study A and five in Study B) and total biomass (whole plants) weight for each pond were collected at the end of the study. A young water hyacinth plant was counted if it had begun to extend from the parent plant, had visible roots, and at least two leaves. The fresh weight data (not shown) was used as a check for other data. Pond biomasses were air dried to a constant weight then dry matter weight was measured for each biomass. A representative whole plant sample was taken from each pond biomass and ground to particle size $\leq$ 3 mm. Whole plant samples were used because the hyacinths would not be treated as partitioned in the subsequent composting (recycling) process. Tissue samples were analysed for Total Kjedahl Nitrogen (TKN) (copper catalyst EPA Method 351.2), nitrate/nitrite (Nitrite EPA Method 353.2), ammonia (EPA Method 350.1), and Total Phosphorus (EPA Method 365.1). Total N uptake was calculated by adding TKN and nitrate/nitrite N. All analyses were performed by a US EPA certified laboratory.

Calculations Amount of light intercepted was calculated by multiplying the canopy cover per pond averaged across the eight treatment replications by the accumulated photosynthetically active radiation (PAR) then converting to MJ PAR m^{-2}. Light use efficiency (RUE) was calculated by dividing final total biomass per pond by the cumulative intercepted PAR per pond. Accumulated thermal time was calculated by taking the average of the daily maximum and minimum temperatures compared to a base temperature (10 °C) and was measured for the duration of each study.

Statistical analysis

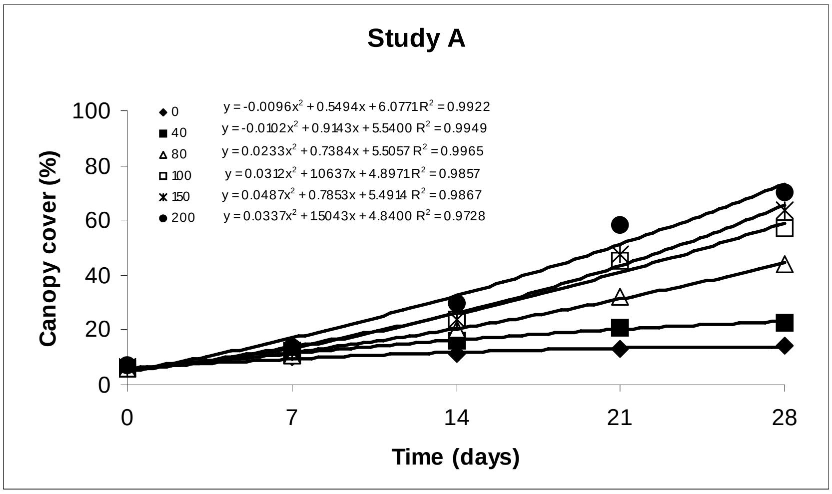
The study was a randomized complete block (RCB) with six (Study A) and seven (Study B) treatments and eight replications. Data were analysed using SAS (SAS version 9.3, Cary, NC, 2005). Regression analysis and Tukey's test for mean separation (P = 0.05) were performed. Data points of individual experimental units were graphed in some figures in order to observe data cluster patterns. Mean data values were graphed in other figures to show relationships.

Results

Daily minimum and maximum air temperatures ranged from 9 °C to 34 °C (Study A), and 16 °C to 34 °C (Study B), respectively. Daily minimum and maximum water temperatures followed a similar pattern and ranged from 10 °C to 32 °C (Study A) and 19 °C to 35 °C (Study B). Accumulated thermal time was 478 °C for Study A and 689 °C for Study B. On average, temperatures were 7.5 °C higher in Study B compared to Study A. Daily total photon flux densities (PFD) in Study A ranged from 57 – 408 moles m^{-2} d^{-1} and in Study B ranged from 49 – 127 moles m^{-2} d^{-1}. PFD in Study B was lower given the late season timing and addition of a shade cloth to the greenhouse.

Nutrient levels had a significant effect on the rate of water hyacinth propagation (Table 1). Far fewer plants were observed at the lowest nutrient levels compared with plant numbers observed at the higher nutrient levels. The percent plant canopy cover and dry matter values corresponded, and this pattern was consistent across both studies. Also, as nutrient levels increased there was a corresponding faster curvilinear increase in plant canopy cover over time (Figure 1). The canopy cover reached 70% in Study A and 94% in Study B for the highest nutrient levels, but the pattern in the increase over time and across nutrient levels was the same across the two studies, and consistent with what has been reported in the literature (Agami and Reddy, 1990; Wilson et al., 2001). The highest percent canopy cover was observed in the highest level nutrient treatments. Distinct differences in the percent of canopy cover were observed between all treatments by day 14 in Study A. These differences remained until the end of the study. Distinct differences in the percent of canopy cover between the lowest nutrient level and all other levels was observed by day 14 in Study B and between the two lowest level treatments and the highest level treatments collectively, by the end of the study. A study effect was observed and can be seen in the mean separation differences in canopy cover values between the studies (Table 1).

Higher numbers of plants generally indicate higher canopy cover values. Treatment effects on both variables were strongly correlated in both studies. Figure 2a (Study B) shows a positive asymptotic relationship where the final percent canopy cover increases as the final number of plants increases, but the rate at which it increases slows so that eventually the canopy cover is not increasing at all as it approaches 100%. Study A has a similar relationship, though not as strong compared with Study B. The five initial plants in Study B were larger and more vigorous than the initial four plants in Study A. The larger higher number of initial plants in Study B would lead to a faster increase in numbers of plants and the corresponding percent canopy cover, but



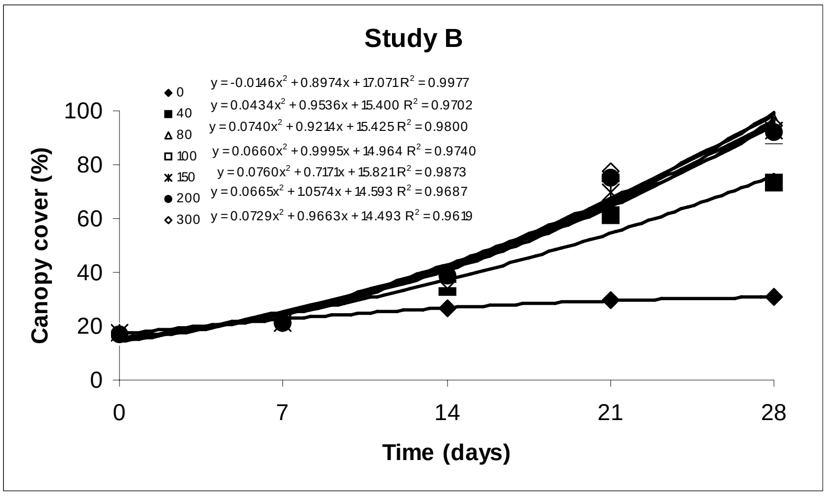


Fig. 1. Percent (%) canopy cover of water hyacinth over four weeks across nutrient treatments for Studies A and B.

Table 1
Final number of plants, final canopy coverage (CC), dry matter (DM), nitrogen (N) uptake from water, total nitrogen (N) in plant tissue, phosphorus (P) uptake from water, and total phosphorus in plant tissue means and separations for Studies A and B.

Study A (Means)

TRT ppm N	TRT ppm P	# Plants		CC %		DM g		N uptake water g		Total N tissue g		P uptake water g		Total P tissue g	
0	0	16	b*	14.00	d	22.50	b*	0.47**	f	0.28**	c	0.00**	f	0.02**	d
40	9.4	40	b	22.75	c	29.10	b	5.69	e	0.62	b	0.79	e	0.14	c
80	18.8	120	a	43.88	b	101.90	a	9.31	d	3.49	a	1.41	d	0.63	b
100	23.5	144	a	57.38	ab	128.30	a	11.86	c	3.84	a	1.70	c	0.71	b
150	35.3	134	a	63.75	ab	117.80	a	16.97	b	4.29	a	2.17	b	0.74	b
200	47.1	141	a	70.25	a	122.90	a	22.13	a	5.48	a	2.64	a	0.90	a
		P<.0001		*P*<.0001		*P*<.0001		*P*<.0001		*P*<.0001		*P*<.0001		*P*<.0001	

Study B (Means)

TRT ppm N	TRT ppm P	# Plants		CC %		DM g		N uptake water g		Total N tissue g		P uptake water g		Total P tissue g	
0	0	28	c	30.63	c	32.50	c	0.31**	c	0.53**	c	0.00**	e	0.05**	d
40	9.4	83	b	73.25	b	85.90	b	2.35	bc	2.66	b	1.03	bc	0.41	c
80	18.8	170	a	96.00	a	181.80	a	5.45	ab	6.10	a	1.29	b	1.02	b
100	23.5	156	a	91.13	ab	172.80	a	9.01	a	6.57	a	1.58	a	1.13	b
150	35.3	162	a	93.00	a	172.10	a	9.05	a	6.50	a	0.83	cd	1.26	b
200	47.1	168	a	92.38	ab	180.30	a	4.84	bc***	6.84	a	0.72	d	1.46	a
300	70.6	191	a	94.25	ab	188.00	a	9.26	a	7.88	a	1.35	ab	1.73	a
		P<.0001		*P*<.0001		*P*<.0001		*P*<.0001		*P*<.0001		*P*<.0001		*P*<.0001	

* mean separation based on Tukey's test at $P<0.05$.

** data were natural log transformed prior to statistical analysis.

*** initial values of treatment 200 were between initial values of treatments 100 and 300, and so were the final values; but the differences had a high coefficient of variation and on average were outlying.

also to an earlier and stronger crowding effect. It follows then that as plant numbers and canopy cover increase, dry matter values are impacted. Strong linear relationships were observed in both studies relative to these factors (Figure 2b and Figure 2c). The relationships are more clearly defined as evidenced by the tighter clustering of data points around the trend lines for Study B (as illustrated by higher R^2 values).

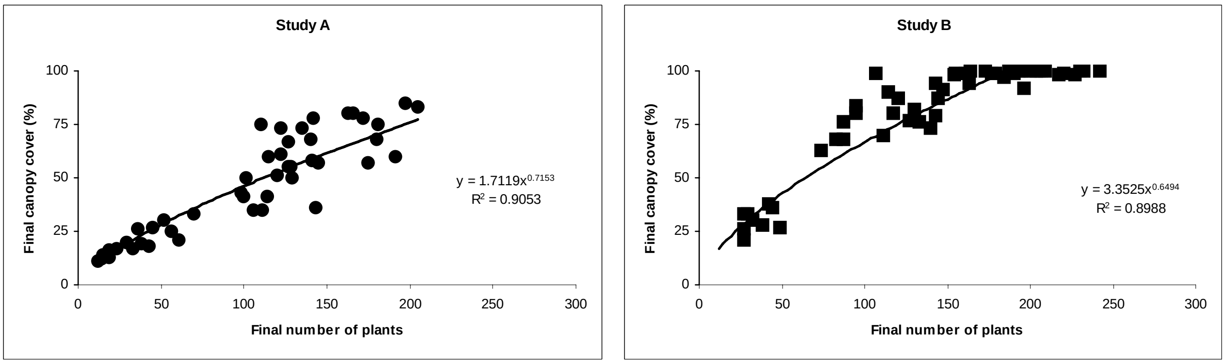


Fig. 2a. Final percent (%) canopy cover of water hyacinths versus the final number of plants per pond for Studies A and B at the end for four weeks.

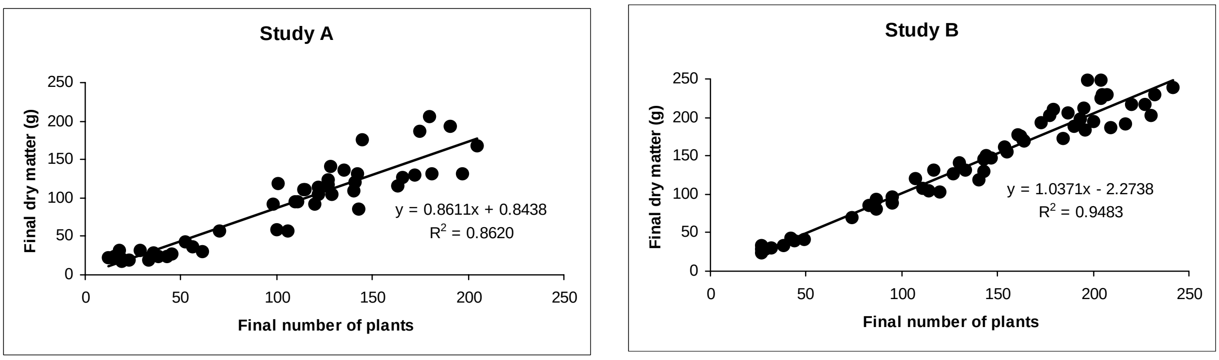


Fig. 2b. Final dry matter (g) of water hyacinths versus final number of plants for Studies A and B at the end for four weeks.

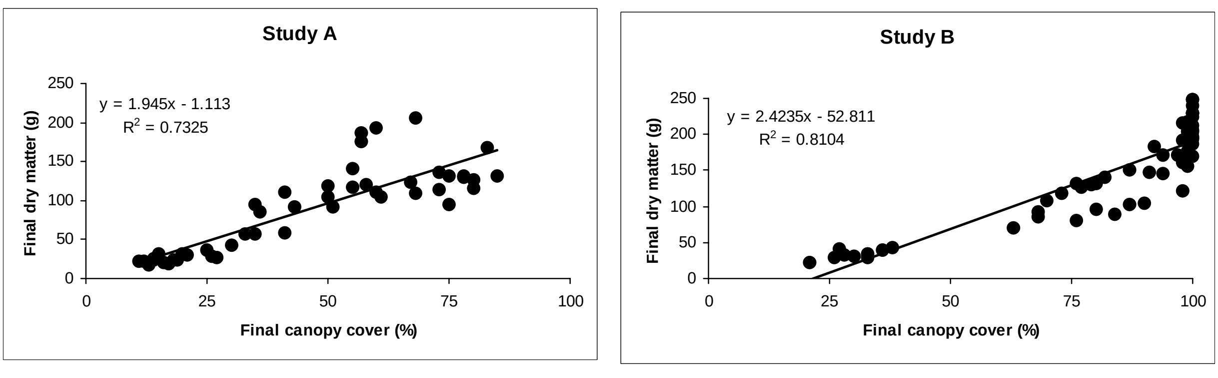


Fig. 2c. Final dry matter (g) of water hyacinths versus final percent (%) canopy cover of plants for Studies A and B at the end for four weeks.

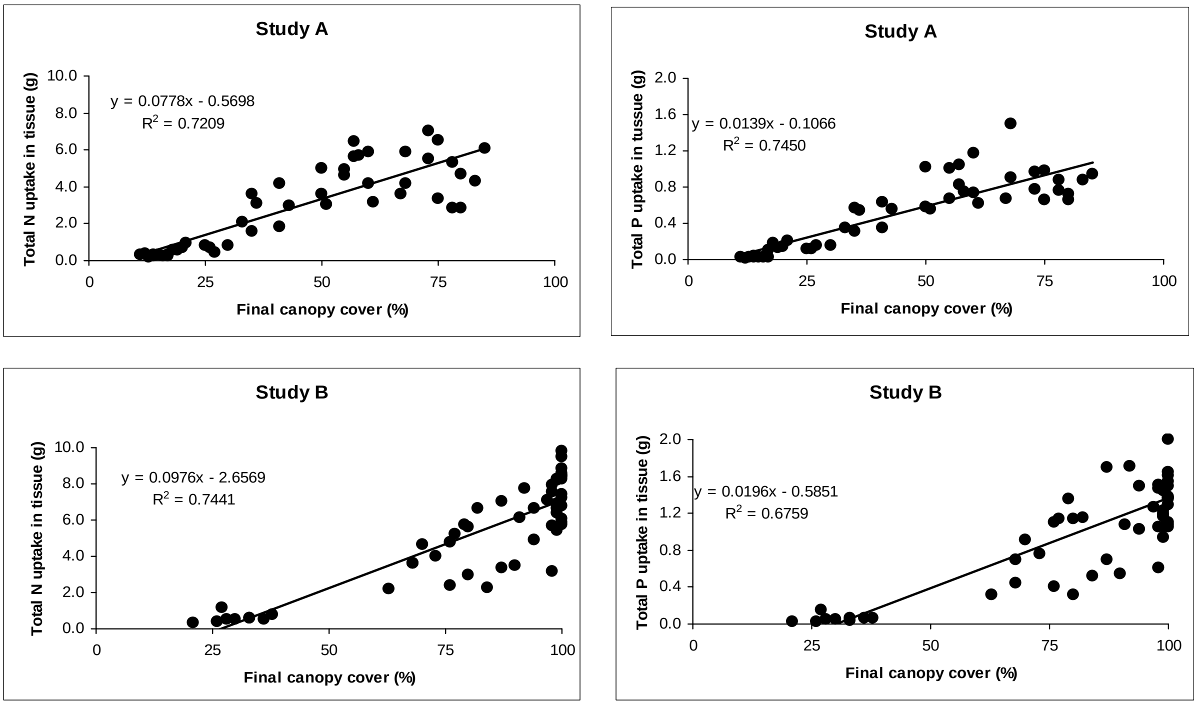


Fig. 3. Total nitrogen (N) and phosphorus (P) uptake (g) in water hyacinth tissue versus percent (%) canopy cover of plants in Studies A and B.

As water hyacinth canopy cover increased in response to the nutrient treatments there was a corresponding increase in uptake of N and P (Figure 3). The highest percent canopy cover was observed in the highest level nutrient treatments, where the highest nutrient uptake values were observed. This pattern was consistent across both studies for both N and P. While P tissue values were much lower than those for N, the tissue nutrient to percent canopy cover relationships were all more or less linear. The variation in water hyacinth canopy cover accounted for 67 – 75% of the variation of the nutrient uptake.

Both studies had approximately the same value for intercepted light (Figure 4a) for the lower nutrient level treatments. The initial radiation use efficiency (RUE) values were also close for the two studies for the lower level treatments. In both studies, the higher nutrient level treatments which contained more plants and canopy cover, had higher intercepted light values. The light interception values were higher in Study A due to more light being available earlier in the growing season. If the broken stick model is applied to the RUE values in Figure 4a, it shows that a plateau was reached when nitrogen concentrations in the water were 100 ppm and above. Nutrient levels had a larger effect on RUE in Study B than in Study A. Light intensity strongly impacted RUE which is reflected in the differences in the two studies: with lower light intensities the RUE is usually much higher as in Study B.

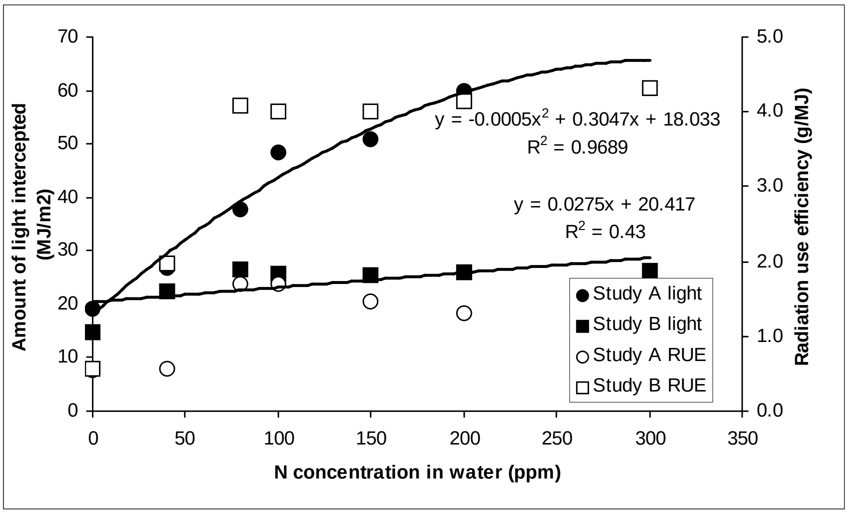


Fig. 4a. Amount of light intercepted (MJ m^{-2}) and radiation use efficiency (g MJ^{-1}) versus nitrogen (N) concentration (ppm) in water hyacinth treatment solution. Curve fits for amount of light only.

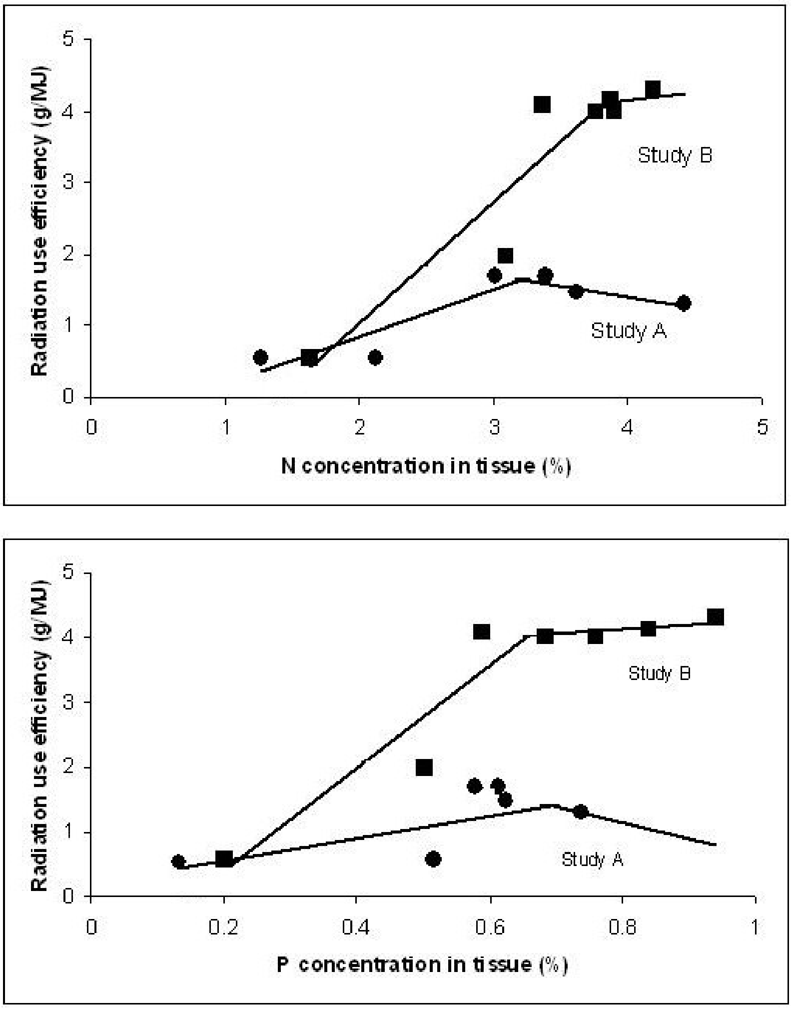


Fig. 4b. Radiation use efficiency (RUE) (g MJ^{-1}) versus nitrogen (N) and phosphorus (P) concentrations (%) in water hyacinth tissue for Studies A and B.

The effect of nitrogen level on RUE is consistent across both studies, but is smaller in Study A because of the narrower range associated with the light saturation occurring in this study. When there was more nitrogen in the water hyacinth tissue, the RUE values were higher (Figure 4b). Because phosphorus supply and uptake are related to nitrogen supply and uptake (Sato and Kondo, 1980; Tucker and DeBusk, 1981; Aoyama and Nishizake, 1993), similar patterns were observed for the relation between these variables and RUE.

When more light was intercepted by the plant canopy then more nutrients were accumulated in the tissue (Figure 4c). These relationships were stronger in Study A than in Study B. Figure 5 shows the nitrogen and phosphorus uptake relationships in water hyacinth tissue and pond water. Nutrient accumulation in the tissue is consistent across the two studies as expected, with the slope for Study A only slightly higher than for Study B. The relationship between phosphorus and nitrogen uptake from the water is also consistent across the two studies though there is greater difference in the slopes with more scatter around the trend lines.

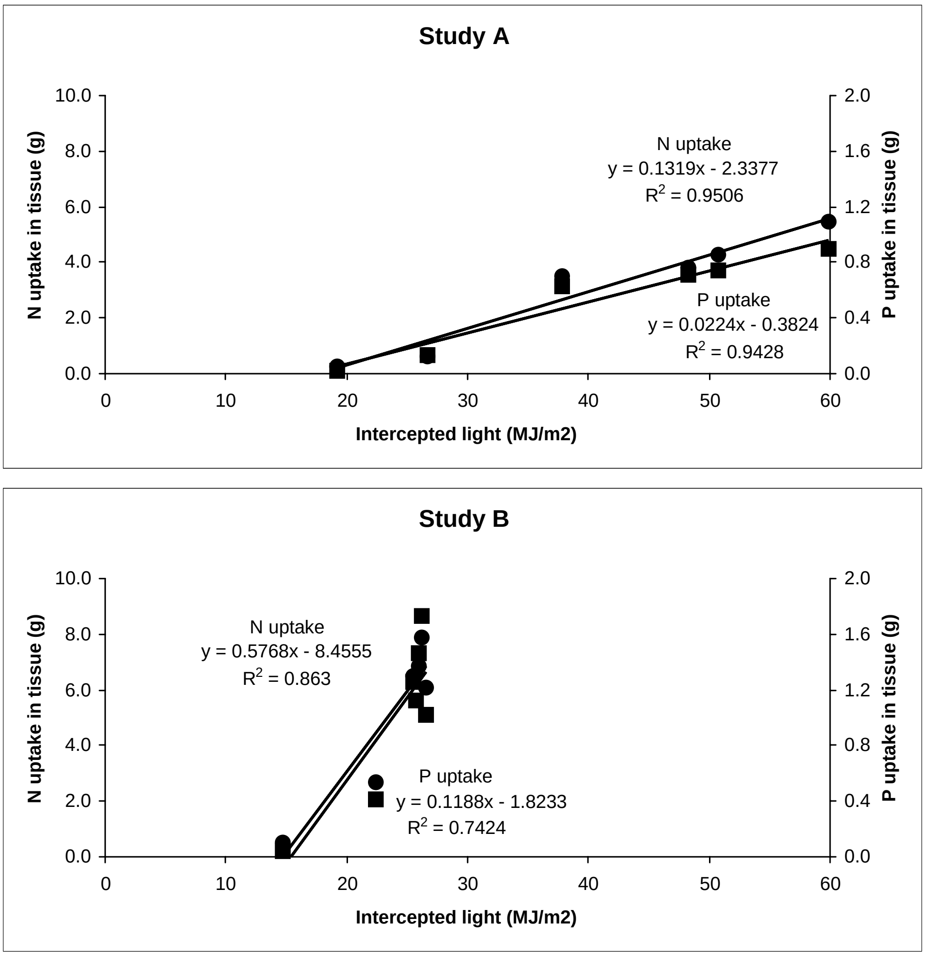
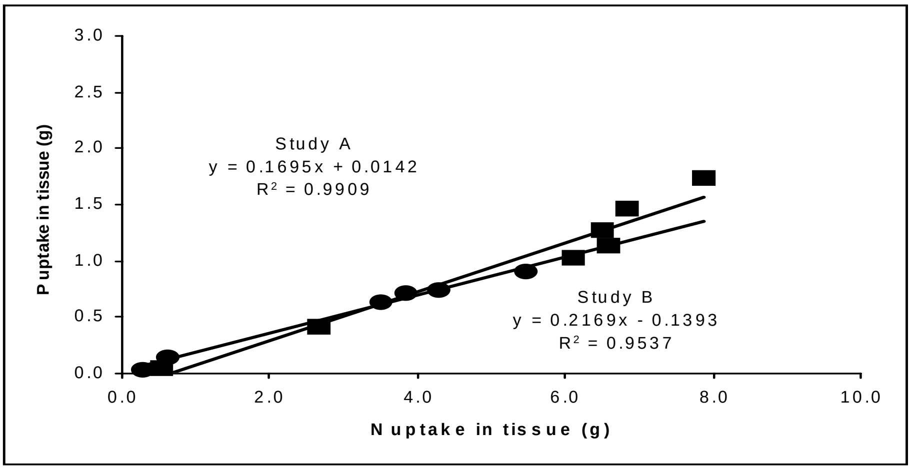


Fig. 4c. Nitrogen (N) and phosphorus (P) uptake (g) in water hyacinth tissue versus intercepted light (MJ m^{-2}) for Studies A and B.



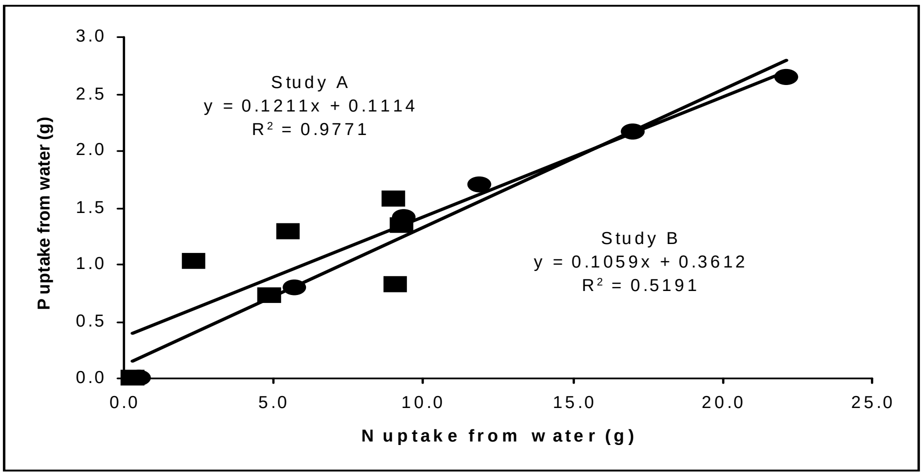


Fig. 5. Phosphorus (P) and nitrogen (N) uptake (g) in water hyacinth tissue and from nutrient treatment solution for Studies A and B.

Discussion

Ambient and water day/night temperature differentials were larger in Study A than Study B. But, with the exception of a few low nighttime values early in Study A, water temperatures were well within the range for successful hyacinth production for both studies; 13 °C – 40 °C (Williams et al., 2005). This is important because day/night temperature differentials facilitate the plant biochemical reactions which influence nutrient uptake and plant growth (Black et al., 1969; Berry and Björkman, 1980). The generally higher average air and water temperatures in Study B compared to Study A also impacted plant growth. The temperature differentials, the generally warmer temperatures, along with the higher accumulated thermal time later in the season, caused the water hyacinths to be more robust, to grow faster, and to develop canopy coverage quicker in Study B.

While biomass and surface area covered are commonly accepted ways to measure water hyacinth production, plant nutrient content is slightly more accurate since linear relationships between N content and growth rate (Aoyama and Nishizake, 1993) are well documented. Nutrient levels had a significant effect on the rate of water hyacinth propagation. As expected, plants with higher levels of nutrients in the water grew faster, were more numerous, and had higher percent canopy coverage. The mechanism through which treatment influenced dry matter was an increase in the production of plants but not necessarily the individual plant size; because despite the size and vigour differences in the plants in Study B, there was approximately the same dry matter yield in both studies. Although dry matter amount is closely correlated to water hyacinth plant canopy cover (Center and Spencer, 1981; Reddy and DeBusk, 1984), it is not necessarily always correlated to plant numbers.

Part of the differences between studies can be attributed to a slight crowding effect because canopy cover was approaching the maximum limits in Study B, where the accumulated thermotime was significantly higher. As crowding occurs, the water hyacinth leaf elongates and the orientation becomes more vertical affecting exposed leaf surface area and influencing photosynthetic efficiency (Reddy, 1988; Williams et al., 2005). The variation in water hyacinth canopy cover accounted for 67 – 75% of the variation of the nutrient uptake. The remaining variation is most likely explained by differences in the amount of light being intercepted or the efficiency with which the intercepted light was converted into dry matter. Photosynthetically active radiation (PAR) readings were higher for Study A than for Study B as expected due to the early season timing and no shade cloth on the greenhouse. Water nutrient levels and intercepted light strongly influenced activity during the vegetative period and thus water hyacinth biomass production (Urbanc-bercic and Gaberscik, 1989). Because phosphorus supply and uptake are related to nitrogen supply and uptake (Sato and Kondo, 1980; Tucker and DeBusk, 1981; Aoyama and Nishizake, 1993), similar patterns were observed for the relation between these variables and RUE. Given the values of light and temperature it was not surprising to have such high levels of RUE in Study B. Differences in RUE are expected due to the range of nitrogen treatments because low nitrogen in the water results in low nitrogen in the leaf tissue which impedes photosynthesis. Low light levels, low tissue N levels, and high rates of plant processes lead to high RUEs. Light became a limiting factor at the end of the study; influenced by the shade cloth on the greenhouse and the late season timing of the study. A large difference in the temperature: PAR ratio was observed between the two studies; almost four fold higher in Study A, which again, impacted photosynthesis and, thus, production (Berry and Björkman, 1980; Haxeltine and Prentice, 1996), but was also responsible for the much lower RUE values in Study A.

In order to understand water hyacinth production ecology it is necessary to understand the effect of edaphic factors that influence production and their interaction. The dynamic relationships between nutrient supply, light, and temperature, are key to any water hyacinth management plan; whether it is for increased production for biofuel (Hronich et al., 2008) or phytoremediation or for reduced production for weed control.

CHAPTER 5

A containment system for water hyacinth (*Eichhornia crassipes* (Mart.) Solms) used for aquatic phytoremediation

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Abstract

A containment system for water hyacinths was designed and evaluated in a test pond at a golf course in Virginia Beach, Virginia, USA. Floating containment corrals of 1.7 m^2 were constructed from PVC pipe and polyethylene netting and deployed in the pond along one shoreline. Water hyacinths were placed in each corral and allowed to reproduce for eight weeks. The corrals remained anchored, UV light stable, and floating. Water hyacinths grew rapidly, 141-fold increase per corral in eight weeks. The corrals did not adversely influence hyacinth reproduction, and they effectively contained the resultant biomass regardless of mesh size or guard feature. The corrals were economical (approximately US $46.00 per corral), easy to construct, deploy, maneuver, and remove from the pond. The system is adaptable to diverse locations and can be expanded as needed.

Keywords: biofiltration, nutrient runoff, stormwater retention ponds, water quality

Introduction

Phytoremediation is the process of using plants (*phyto*) to clean up (*remediate*) polluted soil or water. Floating water hyacinths (*Eichhornia crassipes* (Mart.) Solms) can be used in stormwater retention or irrigation ponds as biological filters to absorb excess nutrients, primarily nitrogen and phosphorus, and improve water quality. While water hyacinth's aggressive reproductive rate makes the species invasive, this characteristic also makes the species desirable for phytoremediation provided it can be contained. A containment system for water hyacinths was developed and evaluated in a test pond at a golf course in Virginia Beach, Virginia. Floating containment corrals of 1.7 m^2 were constructed from PVC pipe and polyethylene netting and deployed in the pond along one shoreline. Water hyacinths were placed in each corral and allowed to reproduce for eight weeks. The corrals remained anchored, UV light stable, and floating. Water hyacinths grew rapidly, but were successfully contained. The corrals were economical (approximately US $46 per corral), easy to construct, deploy, maneuver, and remove from the pond. The system is adaptable to diverse locations and can be expanded as needed.

The Chesapeake Bay Watershed covers 165,000 km^2 over parts of six states. One of the largest and most productive estuaries in the world, the Chesapeake Bay is surrounded by a rich diversity of agricultural operations, and an expanding urban population. Nutrient over-enrichment of surface waters contributes significantly to water quality and habitat degradation in tributaries and the Bay (Chesapeake, 2006). Increasingly stringent regulations governing water quantity and quality have resulted in the extensive use of stormwater retention ponds in all areas of agriculture and urban horticulture to manage runoff velocity, quantity, and quality, and to provide a way to store water for irrigation. The issue of nutrient polluted runoff from golf courses (Gross et al., 1990; Cohen et al., 1999) and nurseries (Yeager et al., 1993; Berghage et al., 1999; Taylor et al., 2006) has been well documented. Research has been conducted on the use of wetland plants as filters in buffer zones and constructed wetlands (Cooper, 1993; Cole et al., 1997; Carpenter et al., 1998; Cooper et al., 2004; Kohler et al., 2004). In a similar manner aquatic plants can be used for phytoremediation in retention and irrigation ponds at nurseries, golf courses, and residential, municipal, and industrial sites.

Floating water hyacinth (*Eichhornia crassipes*) has been documented as an effective biofilter for removing excess nutrients, particularly N and P, from ornamental ponds and waste water systems (Dunigan et al., 1975; Mitsch, 1977; Reddy and DeBusk, 1985; Reddy and Smith, 1987; El-Gendy et al., 2004; Jayaweera and Kasturiarachchi, 2004). While water hyacinth's aggressive reproductive rate makes the species invasive (Sculthorpe, 1967; Gopal, 1987), this characteristic also makes the species desirable for use as a phytoremediation tool provided it can be contained. An inexpensive, site adaptable containment system is necessary to make the phytoremediation effort economical (Linacre et al., 2005). The containment system would keep the water hyacinths at the location(s) where the most nutrient polluted runoff is coming into a pond in order to intercept and filter the nutrients effectively. The water hyacinths must also be contained effectively so they do not escape into the aquatic ecosystem and become an invasive weed. Based on literature (Pantulu, 1984) and the authors' work with several prototypes, containment corrals were developed and evaluated for this purpose.

Materials and Methods

Location

Pond five at greens complex/hole number five of Bayville Golf Club, Virginia Beach, VA, USA.

Containment System

Twelve floating corrals were constructed of white 4 in schedule 40 co-extruded cellular polyvinyl chloride (PVC) pipe as shown in Figure 1. The PVC pipe came in 6 m lengths which were cut into 1.2 m lengths. To create a square containment corral with final dimensions of 1.7 m^2, four lengths of PVC pipe 1.2 m and four 90° PVC elbows were glued together using PVC cement. Black Durethene polyethylene netting (formerly ADPI Enterprises, now Conwed Plastics) was attached to the bottom of each corral with 33 in Fastenal Industrial plastic cable ties. Six corrals had netting with a diamond mesh size of 4.8 cm^2 and six with 11.6 cm^2. The mesh was used to prevent hyacinths from escaping underneath the PVC. Three corrals from each group also had 20.3 cm of netting (same mesh size as on the bottom of the corral) attached around the corral perimeter, to form a 'fence-like containment guard' above the floating PVC pipe to prevent hyacinth escape over the top of the PVC. The four treatments included small mesh with and without guard and large mesh with and without guard. Corrals with guards cost US $49.58, and corrals without guards cost US $45.55.

Deployment

Containment corrals were deployed in early May 2004. Each corral was anchored in place 1 m from shore by two submerged 20.3 cm concrete blocks. Each block was attached with 1.2 m 0.6 cm nylon rope and a carabiner to two (opposite) sides of each corral. Each corral was connected to the adjacent corral with a carabiner to prevent lateral movement and to form a line of floating corrals parallel to the shoreline greens complex of hole number five.

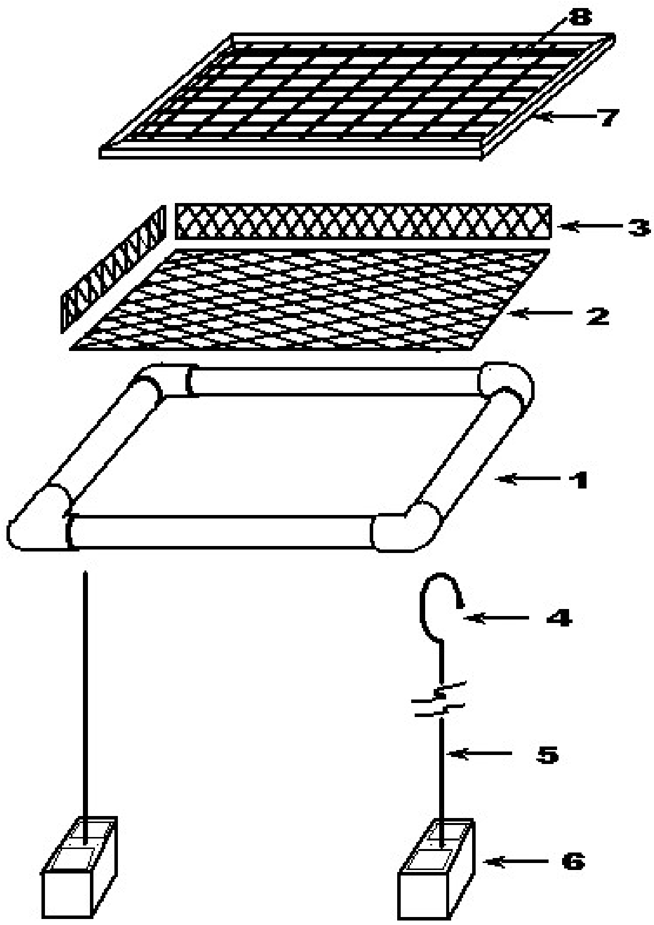

Fig. 1. Aquatic phytoremediation containment corral. PVC frame (1), polyethylene netting underlay (2), polyethylene netting guard (3), carabiner on rope around corral frame (4), nylon rope (5), concrete block anchor (6), grid overlay frame (7), 100 count grid (8).

Observations

Ten water hyacinths were placed in each corral on 7 May 2004. The study lasted for eight weeks. Pressure treated wood was used to create a frame equal in size to the corrals, and pink nylon cord to create a 100 square grid within the frame. Each week the grid was placed over each corral and photographed. Percent canopy cover was assessed by counting the number of grid squares containing foliage. Total biomass fresh and dry matter weights were collected at the end of eight weeks for each corral. Observations were also made on corral UV light stability, water hyacinth containment, float integrity, anchoring, and ease of corral deployment and removal from the pond.

Experimental design and data analysis

The study design was a randomized complete block with four treatments and three replications. Data were analysed using SAS (SAS version 8.1, Cary, NC). A repeated measures analysis was performed on the canopy cover data. Other data were analysed using Tukey's test with the level of significance at $P = 0.05$.

Results and Discussion

At the end of eight weeks, no differences in canopy cover or biomass weights were observed between treatments (data not shown). Water hyacinth reproduction was initially slow, increased from week three to seven, and began to level out by week eight as shown in Figure 2. The slow start is attributed to a temperature and pH acclimation from the production pond to the experiment pond. Experiment pond water temperature and pH are shown in Figure 3. Water hyacinth's dry matter weight went from an average of 15 g to 2.1 kg (per corral); a 141-fold increase in eight weeks. The corrals did not adversely influence hyacinth reproduction, and they effectively contained the resultant biomass regardless of mesh size or guard feature.

Corrals remained UV stable, buoyant, and anchored through the eight weeks. One person could easily deploy the corrals into the pond and readily maneuver the corrals in the pond for initial setup or to make additions if necessary. The corrals were constructed of readily available supplies and were cost efficient (approximately US $46 per corral) compared to other prototypes. They were also uncomplicated to assemble, and easy to transport in the back of a pickup truck.

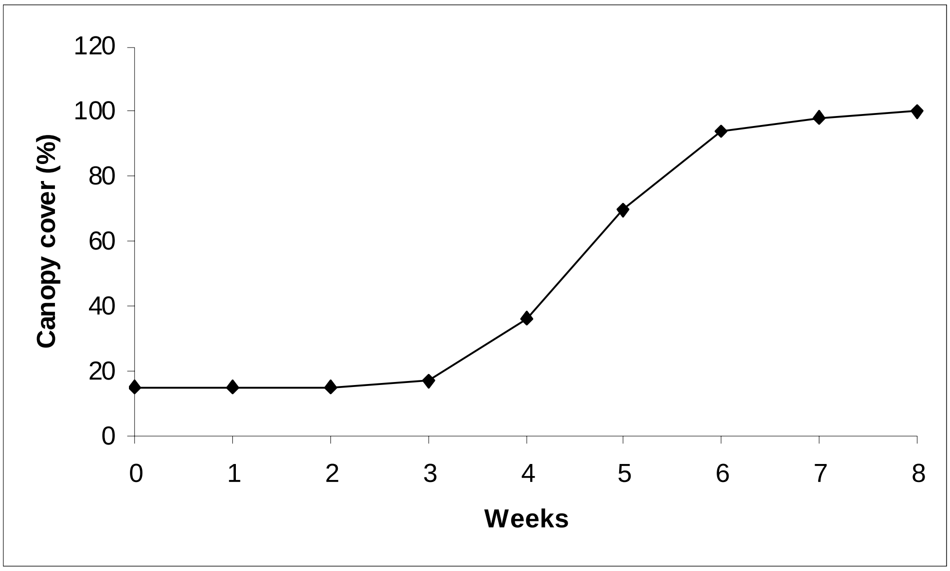

Fig. 2. Water hyacinth canopy cover over eight weeks.

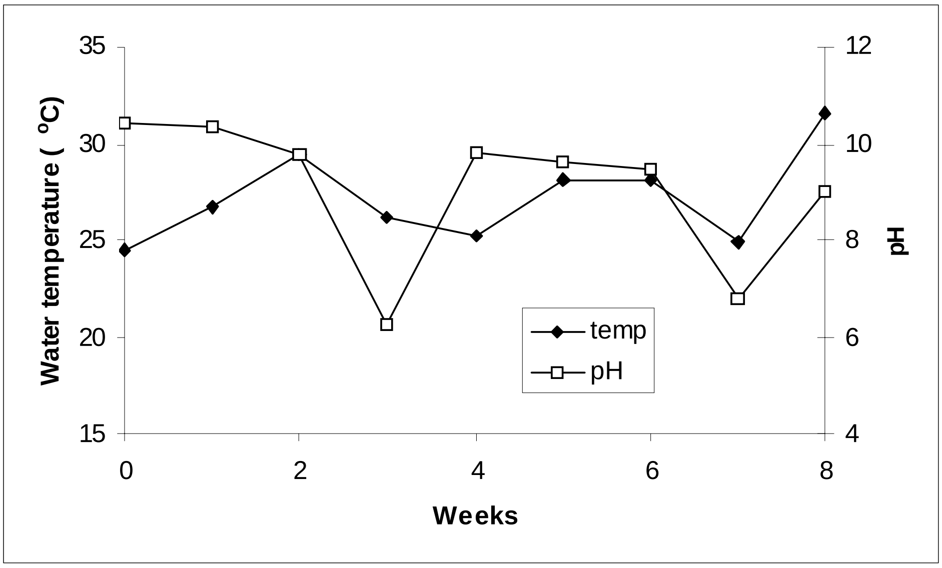

Fig. 3. Pond water temperature and pH measured 10 in below corrals over eight weeks.

Water hyacinth biomass should be thinned periodically during the growing season to prevent overcrowding and competition which causes reduced filtration capacity. The thinning interval is dependent on the growth rate, but should generally occur when the water hyacinth canopy achieves 100% cover of the corral confines. In non-temperate zones, the entire system should be removed at the end of the growing season. Water hyacinths should not be allowed to senesce in the pond, releasing the filtered nutrients and contributing to the eutrophication of the aquatic ecosystem. Also, the PVC corrals could be damaged by freezing weather.

Initial concern existed about water hyacinth and corral removal from the pond due to the amount and weight of the water hyacinth biomass. The most efficient removal method was to unhook the anchor blocks, float the corrals to shore, and lift each corral out of the pond, water hyacinths included. Weights averaged 45.4 kg per corral and water hyacinth unit. Four people, one on each corner to prevent twisting of the corral, could lift a corral of water hyacinths onto shore. After approximately 15 minutes enough water had drained from the biomass so two people could easily lift a corral. Removal of the corral and water hyacinths could also be accomplished with a forklift, provided equipment and access to the pond were available. Corrals were loaded onto a pickup truck, then hauled and dumped at a composting site. Water hyacinth roots easily separated from the corral mesh during the dumping process. At this point, corrals could be stored for winter or redeployed in the pond. Manual removal of the water hyacinths separate from the corrals was viewed as too labour intensive and time prohibitive. Anchoring the corrals to stakes in the pond or on shore is recommended in order to reduce cost of supplies and amount of labour. For a large scale phytoremediation containment system, the use of floating booms or turbidity barriers with curtains (similar to barriers used for oil spill containment) was also examined. While water hyacinth containment was effective, removal of the hyacinths from the pond was labour intensive and cost prohibitive. Where water hyacinth is illegal or the threat of invasiveness outweighs the benefits of its use, other aquatic species could be substituted into this floating containment system. A compartmentalized system allowed the most flexibility for site adaptation and expansion as well as cost effectiveness and ease of removal.

CHAPTER 6

Irrigation pond characterization and analysis: Impact of weather and management*

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Abstract

Weather and management practices were monitored to assess the impact on water quality at four stormwater retention ponds used for irrigation. Two ponds were located at Bayville Golf Club (BGC), an intensely maintained private golf club in Virginia Beach, VA, USA (USDA zone 8) and two were located at Knotts Creek Nursery (KCN), a commercial nursery specializing in container grown perennials, in Suffolk, VA, USA (USDA zone 7) over two growing seasons (2002 – 2003). Total dissolved N concentrations were examined at increasing depths to 305 cm and over time at the pond inflows and in the middles. More types of fertilizers were applied more frequently at BGC, but N concentrations were consistently higher at KCN. In 2002, a drought year, water temperatures fluctuated little over the season or with depth. N concentrations were generally low and within a narrow range (1.0 – 3.5 mg L^{-1} at BGC and 2.5 – 6.0 mg L^{-1} at KCN). There were more fluctuations in N concentration as depth increased. In 2003 rainfall was above average. Water temperatures fluctuated more over the season and with increasing depth. N concentrations were observed across a wider range over the season (0.75 – 4.2 mg L^{-1} at BGC and 0.5 – 6.0 mg L^{-1} at KCN) and were more consistent as depth increased. Both water temperatures and N concentrations fluctuated more dramatically at the inflow locations compared to the middles of the ponds. Overall, regardless of the amount of fertilizer applied, with low runoff volume from either natural storm events or irrigation, N concentrations in the ponds remained low. With increased runoff volume, N concentrations were higher a in general and at increasing depths. Fertilizer choice and application timing, rate, and location directly impact nutrient pollutant levels in stormwater and irrigation ponds, especially during times of increased runoff volume and frequency.

* *Submitted*

Keywords: best management practice (BMP), golf course, nursery, nutrient runoff, stormwater runoff, water pollution

Introduction

The protection and preservation of water resources is a key management requirement in the green industry in the United States (Urbano, 1989), and in the states surrounding the Chesapeake Bay, in particular. Nitrogen (N) and phosphorus (P) polluted runoff continue to threaten water quality (Carpenter et al., 1998, CBF, 2007). Regulations are becoming increasingly stringent on stormwater runoff from commercial entities such as nurseries and golf courses. As a result, best management practices like vegetated drainage ditches and buffers, constructed wetlands, and retention ponds are used to filter nutrient polluted runoff (Berghage et al., 1999; Cole et al., 1999; Cooper et al., 2004; Kohler et al., 2004; Taylor et al., 2006). Runoff ponds are commonly used at nurseries and golf courses because the collected water can be used for irrigating high value nursery crops and intensively managed golf greens. Runoff from these areas, though, can carry nutrients, pesticides, sediments, and other pollutants that accumulate in these ponds (Gross et al., 1990; Yeager et al., 1993; Cohen et al., 1999), with N being the primary pollutant. Therefore, it is important to understand the amounts of N that accumulate in the ponds, the way in which N is dispersed throughout a pond, and how the environment and nutrient management practices influence these processes. The generated knowledge can then be used to place an aquatic phytoremediation system or improve the efficiency of one (Reddy and DeBusk, 1985; Reddy and Smith, 1987).

This paper presents physical descriptions of four stormwater and irrigation retention ponds; two golf course ponds and two commercial nursery ponds located in the Chesapeake Bay area of Southeastern Virginia, USA. Data is presented on environmental conditions, including rainfall and ambient temperatures, nutrient management practices, including nutrient applications and irrigation, and N distribution in the ponds. The data was collected over two growing seasons, one rather dry year and one rather wet year.

Materials and Methods

Permission was secured from Bayville Golf Club (BGC) in Virginia Beach, VA and Knotts Creek Nursery (KCN) in Suffolk, VA to utilize two ponds on each property. The properties are 64 km apart. BGC is in USDA cold hardiness zone 8, and KCN is in zone 7 (US National Arboretum, 2009).

Each pond was surveyed to generate a topographic map and section view. Pond storage capacity was also calculated from the survey information.

Water sampling was conducted every two weeks from July through October of 2002 and from May through October of 2003. A PVC pole was driven into the floor of the pond at the inflow and the middle point of each pond, and a floating marker buoy was attached so samples could be collected at the same point each time. Water samples were collected with a 1.5 L water sampler (single line trigger mechanism, Forestry Suppliers, Jackson, MS, USA) at depths in 25 cm increments. The deepest sample also gave an indication of the water table level on each sampling date. Samples were frozen immediately and batch processed and analysed at the end of each season.

Total nitrogen (N) was determined using copper catalyst EPA Method 351.2. Pond water temperature was recorded at the same time water samples were collected and at the same depths (Oakton pH/CON10 pH/Conductivity/°C hand-held waterproof meter, Oakton Instruments, Vernon Hills, IL, USA). Ambient temperature and rainfall were recorded continuously over the period of the study at each location (HOBO Weather data logger, Onset Computer Corporation, Cape Cod, MA, USA).

Information on management of the area surrounding the ponds was collected from records of the superintendent at BGC and the owner at KCN.

Results

Pond descriptions

Pond contour maps and cross sections are in Figure 1 (BGC) and Figure 2 (KCN).

BGC is a 108 hectare private 18 hole golf course located on the Lynnhaven River at the Chesapeake Bay. The property has seven runoff collection ponds that are used for irrigation and aesthetic purposes. Pond 1 is adjacent to hole 1 and Pond 5 to hole 5 on the course. Each hole is a greens complex usually comprised of the greens (hybrid bermudagrass), bermudagrass roughs and bunkers, and mixed cool season grass (mainly fescues) naturalized buffer areas with some shrub vegetation (*Baccharis halimifolia*, groundsel-bush; *Myrica cerifera,* wax myrtle; and *Salix nigra*, black willow). Pond 1 is surrounded predominantly by a mixed cool season grass naturalized buffer, that is mowed once a year in February, with limited shrub vegetation (< 10%). Normal pool (normal water level) is defined as the lowest crest level of an overflow for a pond that has a fixed overflow (Water Words Dictionary, 2009). Pond 1 has a maximum depth of 3 meters, a surface area at normal pool of 0.73 hectares, and a volume at normal pool or 12.72 million litres. Pond 5 is also surrounded by a mixed cool season grass naturalized buffer, that is mowed once a year in February, but it has more shrub vegetation (~ 60%). Pond 5 has a maximum depth of 3 meters, a surface area at normal pool of 0.69 hectares, and a volume at normal pool of 12.45 million litres.

KCN is a three hectare commercial production nursery specializing in container grown perennials. It is located between Bennett's Creek and Knotts Creek which flow into the Nansemond River, then into the James River, and finally into the Chesapeake Bay. The production areas are comprised of geotextile fabric covered ground with overhead irrigation. The production areas drain into vegetation-free collection swales which then drain into the ponds. Approximately two hectares of production area drain into Pond 1 and one hectare into Pond 2. Both ponds are used for irrigation. Pond 1 is completely surrounded by a mature mixed hardwood tree buffer which shades most of the water. Pond 1 has a maximum depth of 4 meters, a surface area at normal pool of 0.13 hectares, and a volume at normal pool of 2.65 million litres. Pond 2 is surrounded

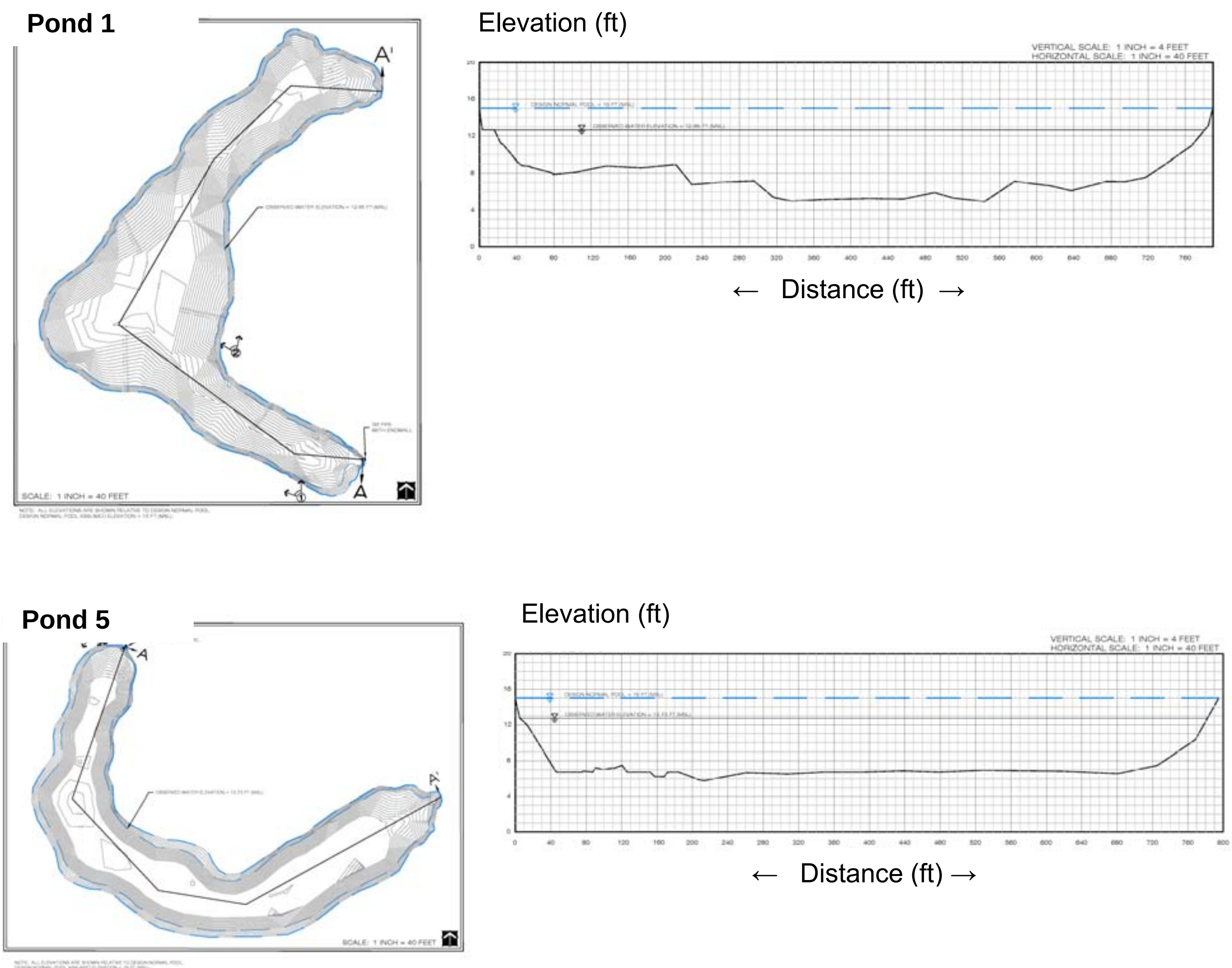


Fig. 1. Bayville Golf Club, Virginia Beach, VA, USA. Pond 1 - maximum depth 3 m, surface area at normal pool 0.73 ha, volume at normal pool 12.72 million litres. Pond 5 - maximum depth 3 m, surface area at normal pool 0.69 ha, volume at normal pool 12.45 million litres.

entirely by a mixed herbaceous naturalized buffer that is mowed once a year in February. Pond 2 has a maximum depth of 2 meters, a surface area at normal pool of 0.09 hectares, and a volume at normal pool of 0.87 million litres.

Management practices

At BGC is a typically managed golf course in that it is maintained intensively for the purposes of playability and aesthetics, but they have been recognized for their environmentally conscientious management practices, especially as they impact water quality. Fertilizer products are diverse and applications are very specific to targeted areas (Table 1). The naturalized buffer areas are mowed once a year with the clippings left in place. Irrigation is on an as needed basis to keep the turf as dry as possible to

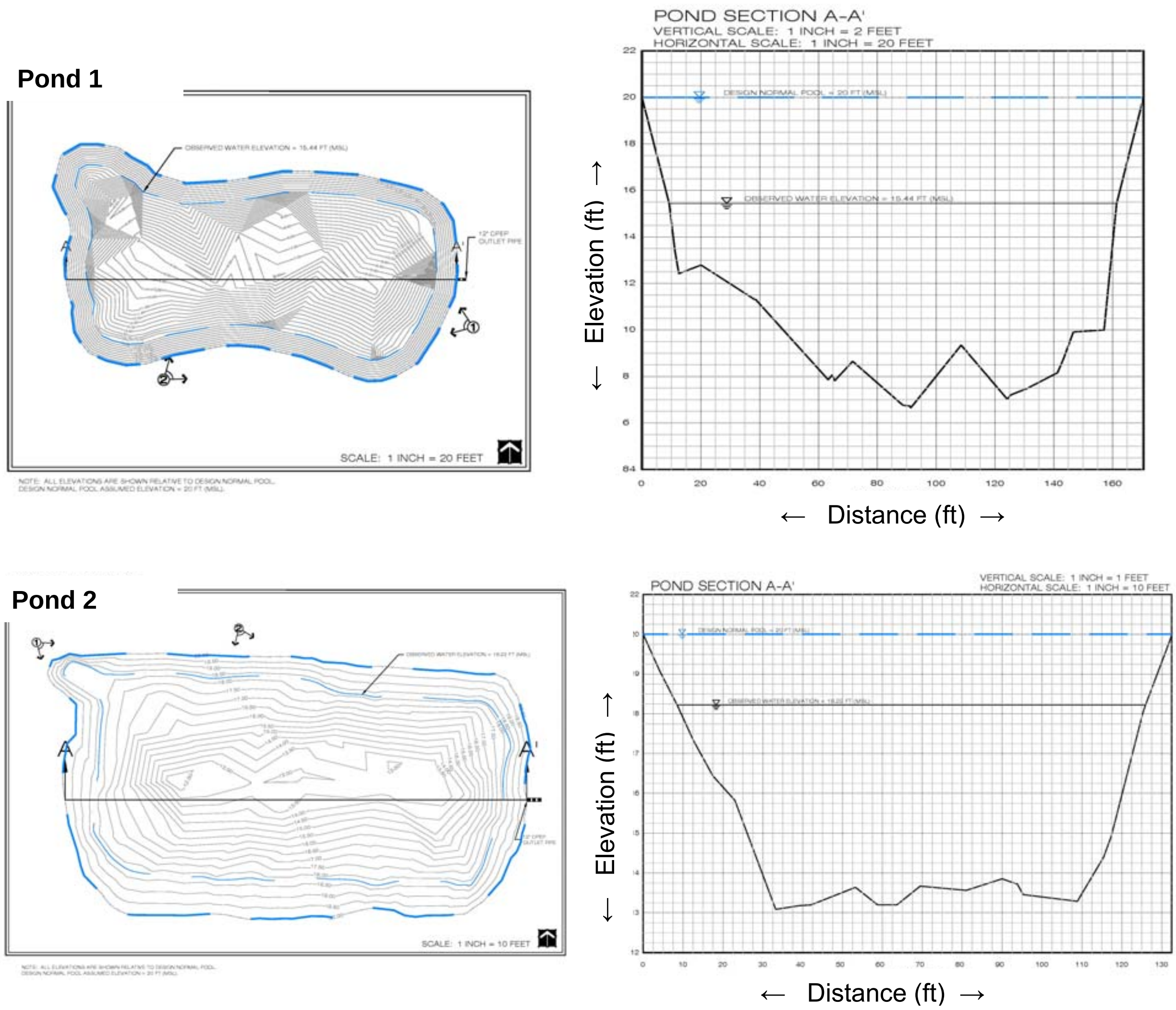


Fig. 2. Knotts Creek Nursery, Suffolk, VA, USA. Pond 1 - maximum depth 4 m, surface area at normal pool 0.13 ha, volume at normal pool 2.65 million litres. Pond 2 - maximum depth 2 m, surface area at normal pool 0.09 ha, volume at normal pool 0.87 million litres.

prevent disease pressure. Irrigation occurs May through September at 10–15 mm of water per week based on wind, dew point, and evapotranspiration rates, when there is no natural rainfall.

At KCN an eight to nine month slow release fertilizer is incorporated into the potting substrate at the time of planting. Container grown plants then receive one application of quick release liquid fertilizer through the irrigation system to 'quick start' them until the slow release nutrients become available. Irrigation occurs April

Table 1

Fertilizer applications and rain events for Ponds 1 and 5 at Bayville Golf Club (BGC) and Ponds 1 and 2 at Knotts Creek Nursery (KCN) for 2002 and 2003.

2002

BGC Pond 1, greens 2601 m^2, bermudagrass 8.5 ha, bunkers 0.4 ha cool season grasses 1.2 ha
BGC Pond 5, greens 1858 m^2, bermudagrass 6 ha, bunkers 0.4 ha, cool season grasses 0.4 ha

Day of year	Date	Fertilizer (formulation, manufacturer)	Area fertilized	Pond 1	Pond 5	Rain event
				kg	kg	mm
121	1 May	0-0-28, Lesco	greens	47	34	
122	2 May	19-19-19, Home Field	bunker edges	45	45	
143	23 May	30-4-10, Home Field	bermudagrass rough	953	680	
161	10 Jun	4-2-0 organic, Harmony	bermudagrass rough	9525	6804	
189	8 Jul	6-2-12 organic, Harmony	greens	44	31	
198	17 Jul	20-20-20, Prolific	greens	4	3	
205	24 Jul					41
206	25 Jul	20-20-20, Prolific	greens	4	3	
220	8 Aug	20-20-20, Prolific	greens	4	3	
224	12 Aug	20-20-20, Prolific	greens	4	3	
244	1 Sep					20
259	16 Sep					128
262	19 Sep	14-28-10, Anderson's	greens	51	37	
273	30 Sep	19-19-19, Home Field	cool season grasses	14	5	
275	2 Oct	5-0-30, Home Field	bermudagrass rough	953	680	
284	11 Oct					91
297	24 Oct	5-0-30, Home Field	bermudagrass rough	953	680	

KCN Pond 1, collects runoff from 2 ha of production area
KCN Pond 2, collects runoff from 1.2 ha of production area

Day of year	Date	Fertilizer (formulation, manufacturer)	Area	Pond 1	Pond 2	Rain event
74	15 Mar	21-4-7, Scotts	container pads	2835	1701	
		8-4-6, Crop Prod. Srvcs.	container pads			
195	14 Jul					57
240	28 Aug					58

Table 1

Continued.

2003

BGC Pond 1, greens 2601 m^2, bermudagrass 8.5 ha, bunkers 0.4 ha cool season grasses 1.2 ha
BGC Pond 5, greens 1858 m^2, bermudagrass 6 ha, bunkers 0.4 ha, cool season grasses 0.4 ha

Day of year	Date	Fertilizer (formulation, manufacturer)	Area	Pond 1	Pond 5	Rain event
118	28 Apr	30-4-10, Home Field	bermudagrass rough	667	476	
142	22 May					24
143	23 May					26
154	3 Jun	30-4-10, Home Field	bermudagrass rough	1048	748	
165	14 Jun					25
170	19Jun					49
181	30 Jun	6-2-12 organic, Harmony	greens	33	24	
189	8 Jul	6-2-12 organic, Harmony	greens	44	31	
195	14 Jul					58
200	19 Jul					28
209	28 Jul	30-4-10, Home Field	bermudagrass rough	1048	748	
222	10 Aug	20-20-20, Prolific	greens	4	3	
226	14 Aug	20-20-20, Prolific	greens	4	3	
229	17 Aug					62
239	27 Aug	20-20-20, Prolific	greens	4	3	
254	11 Sep	0-0-50, Home Field	bermudagrass rough	953	680	
255	12 Sep					27
256	13 Sep					25
261	18 Sep					57
275	2 Oct	0-0-50, Home Field	bermudagrass rough	953	680	
		20-20-20, Prolific	greens	4	3	
279	6 Oct	20-20-20, Prolific	greens	4	3	
282	9 Oct	20-20-20, Prolific	greens	4	3	

KCN Pond 1, collects runoff from 2 ha of production area
KCN Pond 2, collects runoff from 1.2 ha of production area

Day of year		Fertilizer (formulation, manufacturer)	Area	Pond 1	Pond 2	Rain event
74	15 Mar	21-4-7, Scotts	container pads	3118	1871	
		8-4-6, Crop Prod. Srvcs.	container pads			
142	22 May					33
143	23 May					26
166	15 Jun					37
200	19 Jul					26
211	30 Jul					24
216	4 Aug					39
220	8 Aug					20
247	4 Sep					102
255	12 Sep					52
261	18 Sep					105
267	24 Sep					23

through October at a rate of approximately 205 mm per week as needed when there is no natural rainfall. The rate is reduced from November through March to 127 mm on an as needed basis. Because the potting substrate is very porous (2:1 aged pinebark:Biocomp 5S (peanut hulls/sphagnum/composted pinebark)) irrigation is applied daily (36 mm) in a split application with half in the morning and half in the afternoon.

Rainfall

Average yearly rainfall for Virginia Beach is 1143 mm and for Suffolk is 1219 mm (NOAA, 2009; SERCC, 2009). Data and sample collection was done July through October in 2002 and May through October in 2003. Historical average rainfall for those four months of 2002 was 445 mm for Virginia Beach and 635 mm for Suffolk; and for those six months of 2003 was 485 mm for Virginia Beach and 686 mm for Suffolk. Actual rainfall totals for the two locations were: for 2002, 422 mm at BGC in Virginia Beach, and 249 mm at KCN in Suffolk; for 2003, 813 mm at BGC and 864 mm at KCN. Rainfall in 2002 was below average for both locations, with severe drought conditions experienced at the KCN location. Rainfall in 2003 was considerably above average at both locations (Figure 3). For the purpose of this paper a rain event is considered any event producing 20 mm or more of rainfall within 24 hours. Four such events occurred at BGC and only two at KCN in 2002, while 11 events occurred at BGC and 12 at KCN in 2003 (Table 1).

Pond depth

Average pond depths were: BGC Pond 1 at 2.2 m, Pond 5 at 2.5 m, KCN Pond 1 at 3.4 m, and Pond 2 at 2.0 m. In 2002, the ponds at BGC were approximately 0.08 m below normal pool level. The ponds at KCN were approximately 0.2 m and 0.06 m below normal pool level in Pond 1 and Pond 2, respectively. In 2003, the ponds at both locations remained at normal pool level. During the drought year, the shallow state of the ponds caused the water to almost stagnate and the water temperatures and N concentrations to fluctuate very little over the season and with increasing depth. In 2003, the deeper state of the ponds and more frequent inflows of runoff caused the water temperatures and N concentrations to fluctuate widely over the season and with increasing depth. Deeper ponds can buffer temperature and nutrient level changes better than more shallow ponds.

Temperature

Ambient temperature trends for both locations for both years are reported in Figure 3. In 2002 for the months of July through October, BGC had an average daily maximum

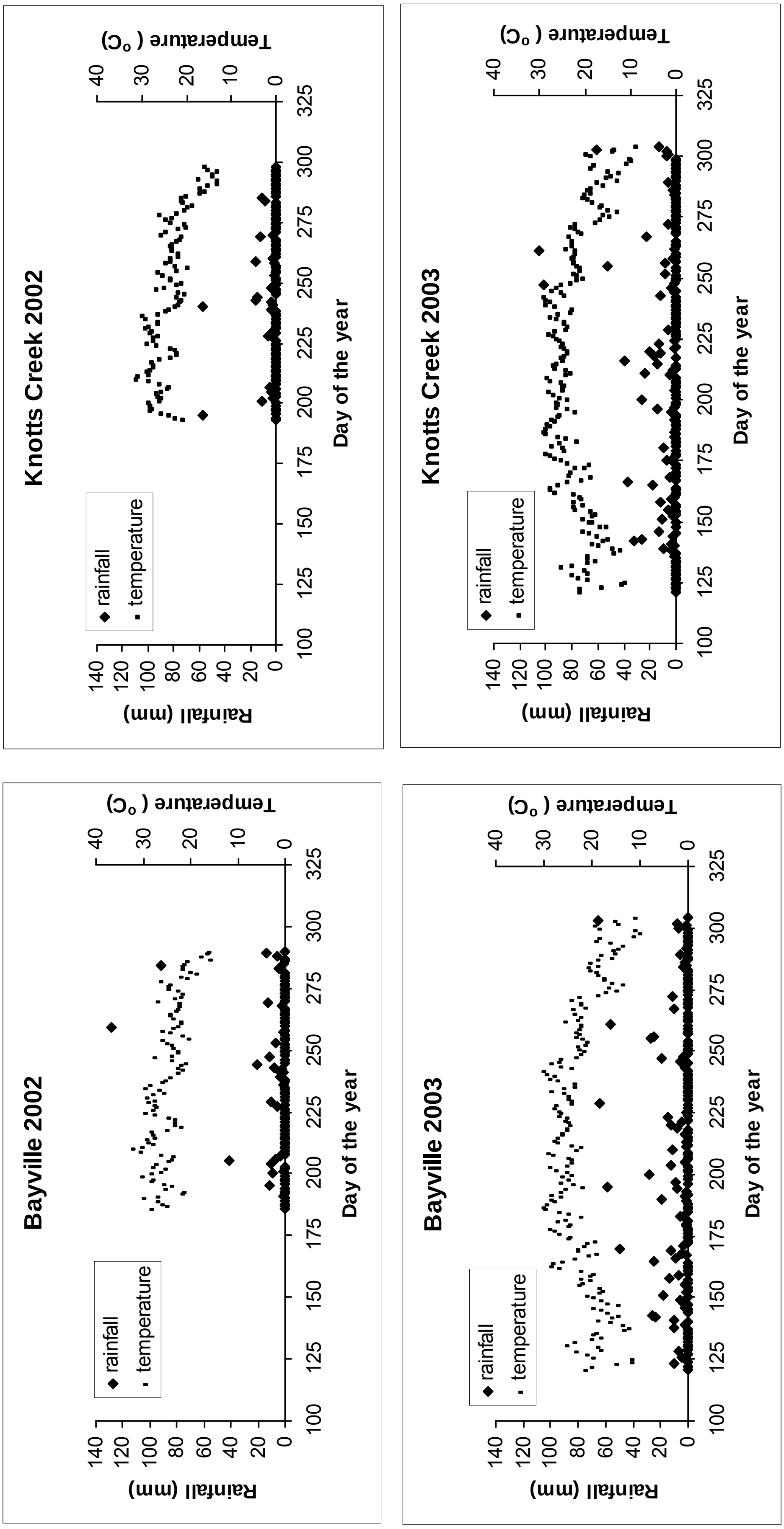


Fig. 3. Daily rainfall (mm) and average daily temperature (°C) trends over four months in 2002 and six months in 2003 at Bayville Golf Club and Knotts Creek Nursery, Virginia, USA.

temperature of 32 °C, an average daily minimum temperature of 15 °C, and an average daily mean temperature of 25 °C. KCN had an average daily maximum temperature of 31 °C, an average daily minimum temperature of 13 °C, and an average daily mean temperature of 24 °C. In 2003 for the months of May through October: BGC had an average daily maximum temperature of 30 °C, an average daily minimum temperature of 10 °C, and an average daily mean temperature of 23 °C. KCN had an average daily maximum temperature of 29 °C, an average daily minimum temperature of 8 °C, and an average daily mean temperature of 25 °C.

Water levels were low in 2002; therefore only the temperature data for the four pond middle locations is reported in Figure 4. At BGC water temperatures were warmest on the 5 July date in both ponds. There was also a distinctive trend of the water temperatures cooling at increasing depths on that date. On the later sampling dates, the water temperatures were generally around 25 °C, and they remained consistent as depth increased. At KCN the 12 July water temperatures in Pond 1 followed the same trend as the 5 July readings at BGC. The range of temperatures in Pond 1 over the sampling dates was wider than at BGC. KCN Pond 2 had a narrower range of temperatures over sampling dates than Pond 1, but not as narrow as at BGC. Water temperatures cooled slightly as water depth increased in both ponds.

Rainfall was above average during the growing season in 2003, so inflow and middle of the pond water temperature data is reported for all four ponds at more sampling depths and dates (Figure 5). At BGC water temperatures ranged between 16 °C and 29 °C at the inflow and middles of both ponds. Generally, water temperatures cooled slightly as depth increased in both locations in both ponds on most sampling dates. Of particular note though, are the drastic temperature decreases as pond depth increases on 1 May at the middle of both ponds, on 26 June at the inflows and middles of both ponds, and 24 July at the middle of Pond 1. At KCN water temperatures ranged between 16 °C and 25 °C at the inflow and middle of Pond 1, and between 16 °C and 29 °C at the inflow and middle of Pond 2. The trend of drastically decreasing water temperatures with increasing depth occurs more frequently in the KCN ponds; sometimes as much as 12 °C in 2.8 m. This trend occurs mainly on sampling dates earlier in the season, although it’s visible on the August dates at the middles of both ponds, though not as strong.

Nitrogen concentration and distribution

Total dissolved Nitrogen (N) concentrations at 102 cm deep were examined at the middles of all ponds both years (Figure 6). At BGC, N concentrations remained below 4.0 mg L^{-1} in both ponds for both years. In 2002, N concentrations were slightly higher earlier in the growing season and declined to below 2.0 mg L^{-1} by the end of the

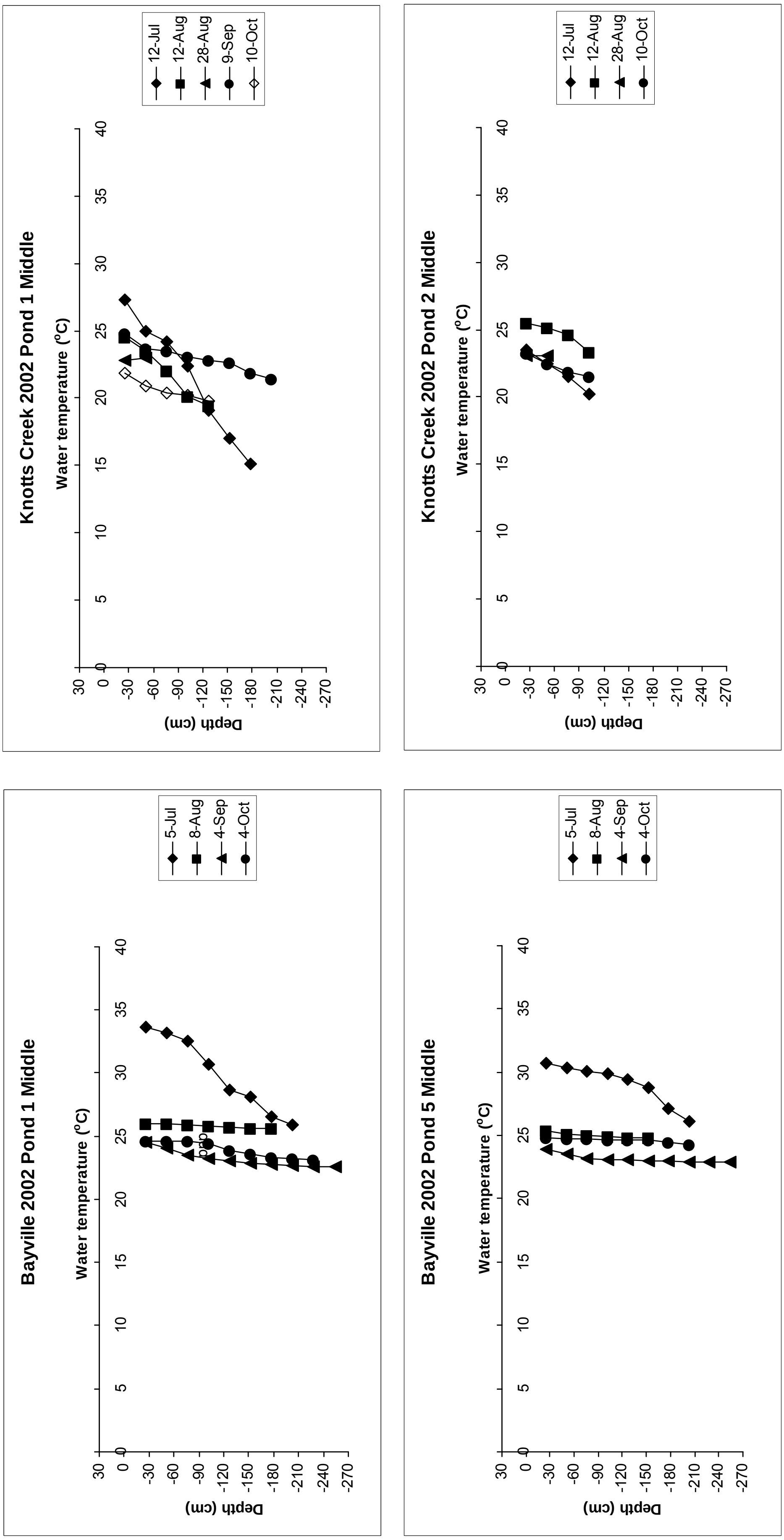
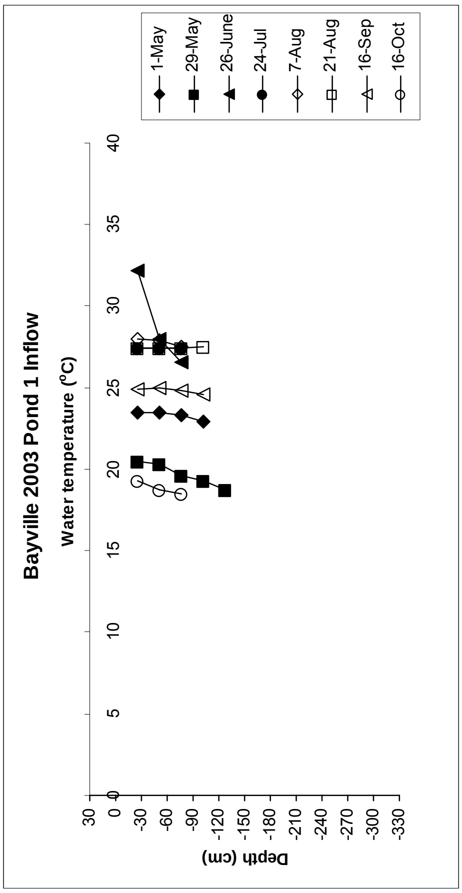
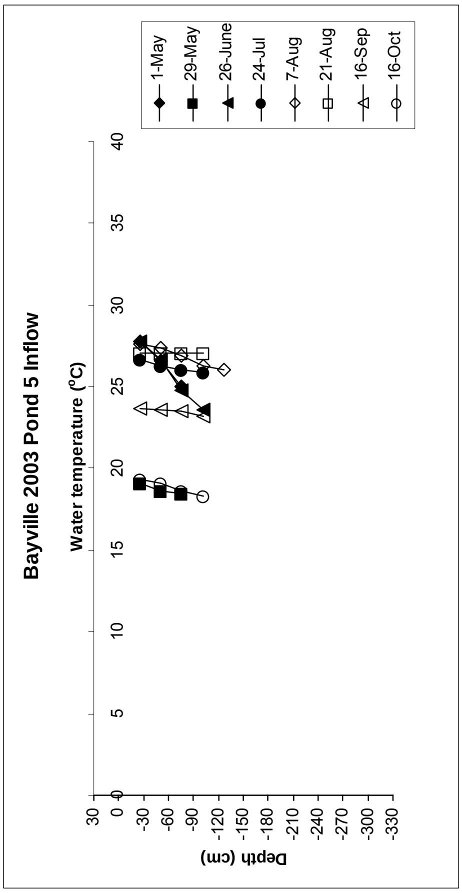
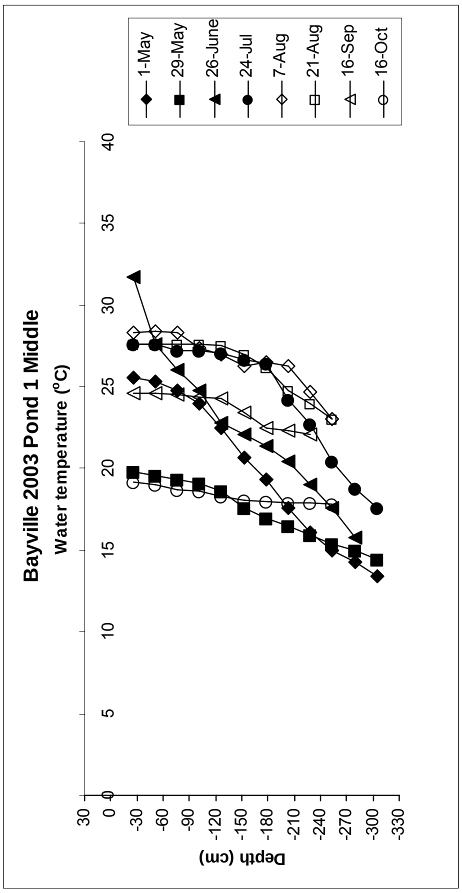
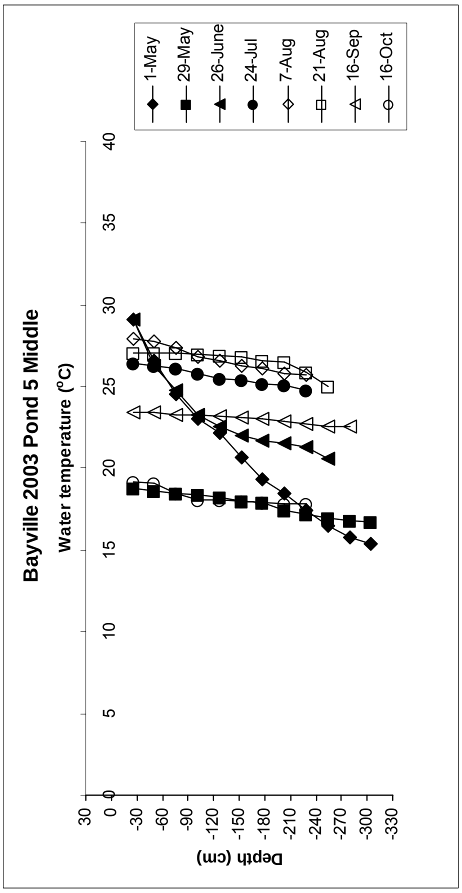


Fig. 4. Water temperature (°C) at increasing depths at the middle of the pond at BGC Ponds 1 and 5 and at KCN Ponds 1 and 2 for 2002.


Bayville 2003 Pond 1 Inflow
Water temperature (°C)
Depth (cm)
1-May
29-May
26-June
24-Jul
7-Aug
21-Aug
16-Sep
16-Oct


Bayville 2003 Pond 5 Inflow
Water temperature (°C)
Depth (cm)
1-May
29-May
26-June
24-Jul
7-Aug
21-Aug
16-Sep
16-Oct


Bayville 2003 Pond 1 Middle
Water temperature (°C)
Depth (cm)
1-May
29-May
26-June
24-Jul
7-Aug
21-Aug
16-Sep
16-Oct


Bayville 2003 Pond 5 Middle
Water temperature (°C)
Depth (cm)
1-May
29-May
26-June
24-Jul
7-Aug
21-Aug
16-Sep
16-Oct

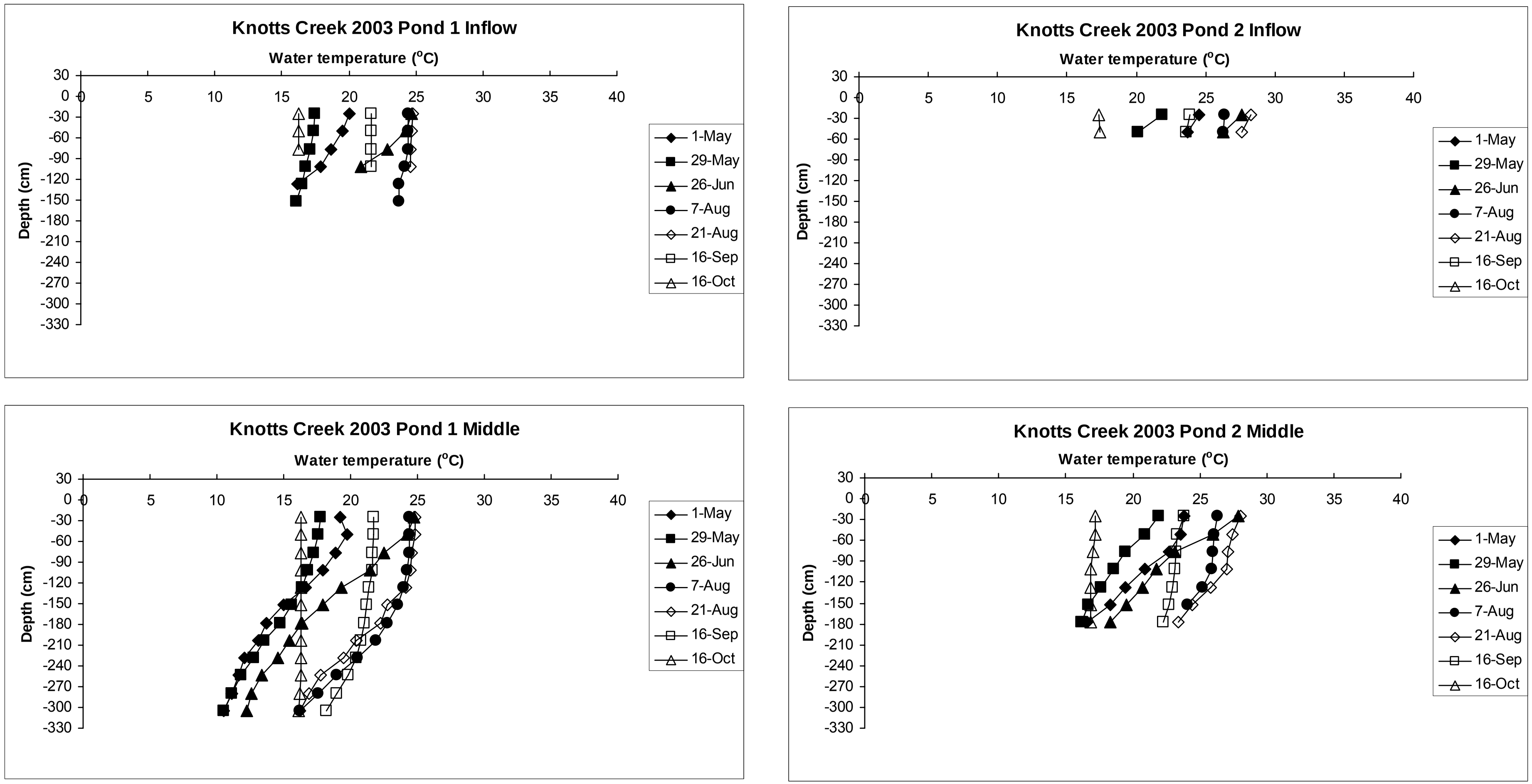


Fig. 5. Water temperature (°C) at increasing depths at inflow and middle of pond at BGC Ponds 1 and 5 and at KCN Ponds 1 and 2 for 2003.

season. In 2003, N concentrations were higher earlier in the season, declined to below 2.0 mg L^{-1} midseason, and had a significant peak, with a 3 mg L^{-1} increase, day 259 (16 September), before returning to below 2.0 mg L^{-1}. At KCN in 2002, N concentrations initially increased in Pond 1 and decreased in Pond 2 to remain between 4.0 and 5.0 mg L^{-1} the rest of the season. In 2003, N concentrations were lower, and consistently between 1.8 and 3.0 mg L^{-1} until the peak, again with a 3 mg L^{-1} increase, at day 259 like at BGC. That peak is attributed to hurricane Isabel and over 100 mm of rainfall.

Total dissolved Nitrogen (N) concentrations were examined at 51 cm deep at the inflows of all ponds both years (Figure 7). The relationships between N concentrations in the two ponds at both BGC and KCN are difficult to examine for 2002 because the severe drought conditions limited the number of samples collected. N concentrations followed very similar patterns in both ponds at BGC each year. Almost no fluctuation was observed in 2002 due to the lack of runoff, and N concentrations remained below 2.0 mg L^{-1}. While more fluctuation was observed in 2003, N concentrations remained below 3.0 mg L^{-1} with the exception of the peak caused by hurricane Isabel at day 259. At KCN, no samples were collected from the inflow for Pond 2 in 2002. N concentrations in Pond 1 increased from 3.5 mg L^{-1} to 5.0 mg L^{-1} where they remained consistent the rest of the season. In 2003, the N concentration fluctuated more, but remained below 3.0 mg L^{-1} with the exception of the peak from hurricane Isabel. While the fluctuation patterns at BGC and KCN for 2003 were similar to those observed at the 102 cm depth, they were more dramatic. This was attributed to the dilution effect as runoff flowed out into the pond.

Using the highest N concentrations observed in the ponds (3 mg L^{-1}), water hyacinth N uptake capacity (Fox et al., 2008), pond volume, and the average incoming light and radiation use efficiencies, it is possible to calculate the amount of biomass and area of pond coverage necessary to remediate a given amount of N. The amount of biomass and coverage needed to remediate the highest N concentrations observed in the ponds at BGC was 20%, and at KCN was 6% or less of the total surface area.

Total dissolved N concentrations were also examined at increasing water depths on specific sampling dates over the growing season. Three trends were observed. First, N concentrations stayed the same as depth increased. Second, N concentrations increased as depth increased, and third N concentrations decreased as depth increased. All three trends were seen in each pond.

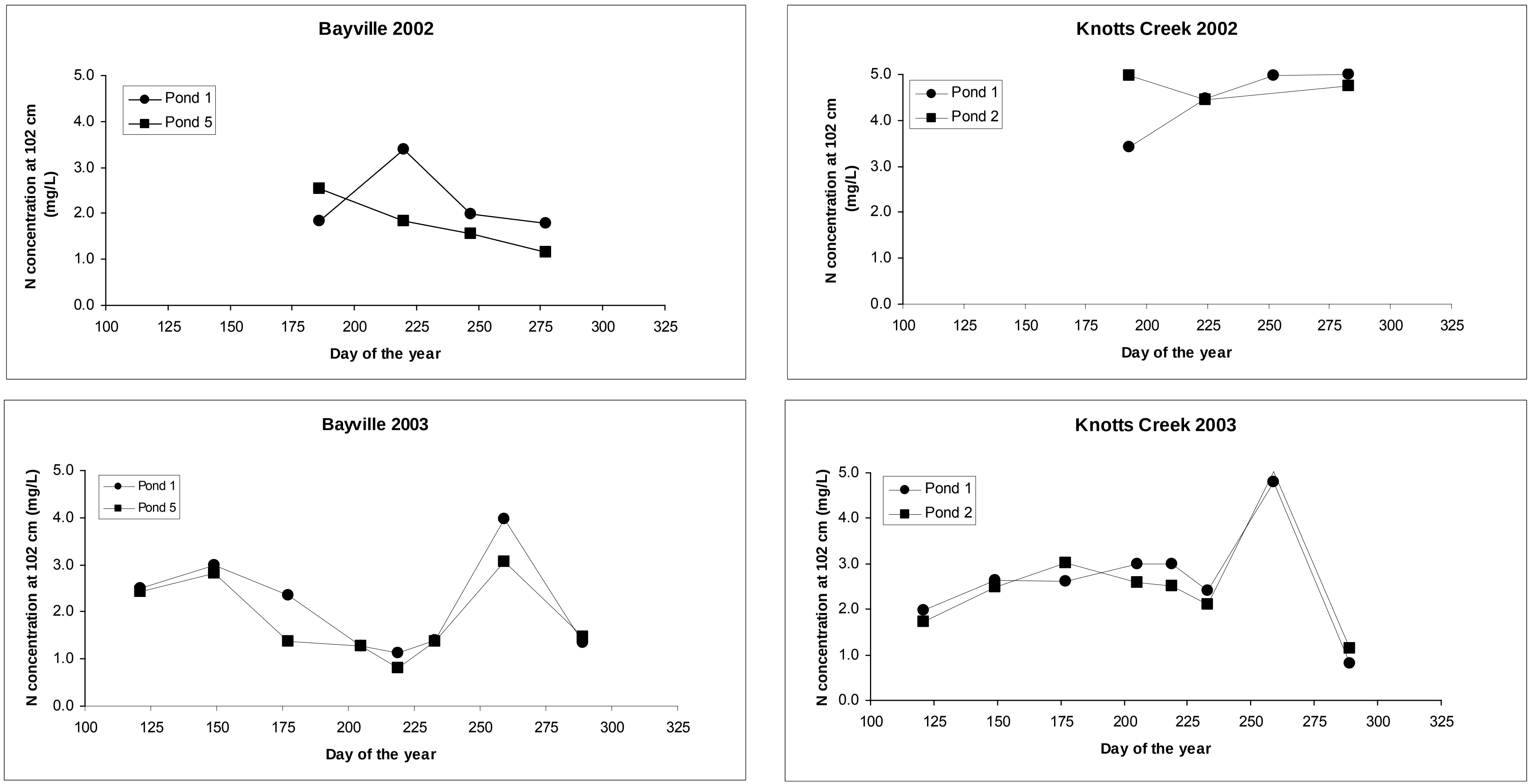


Fig. 6. Total dissolved Nitrogen concentrations (mg L^{-1}) at 102 cm depth at middle sampling locations in BGC Ponds 1 and 5 and in KCN Ponds 1 and 2 for 2002 and 2003.

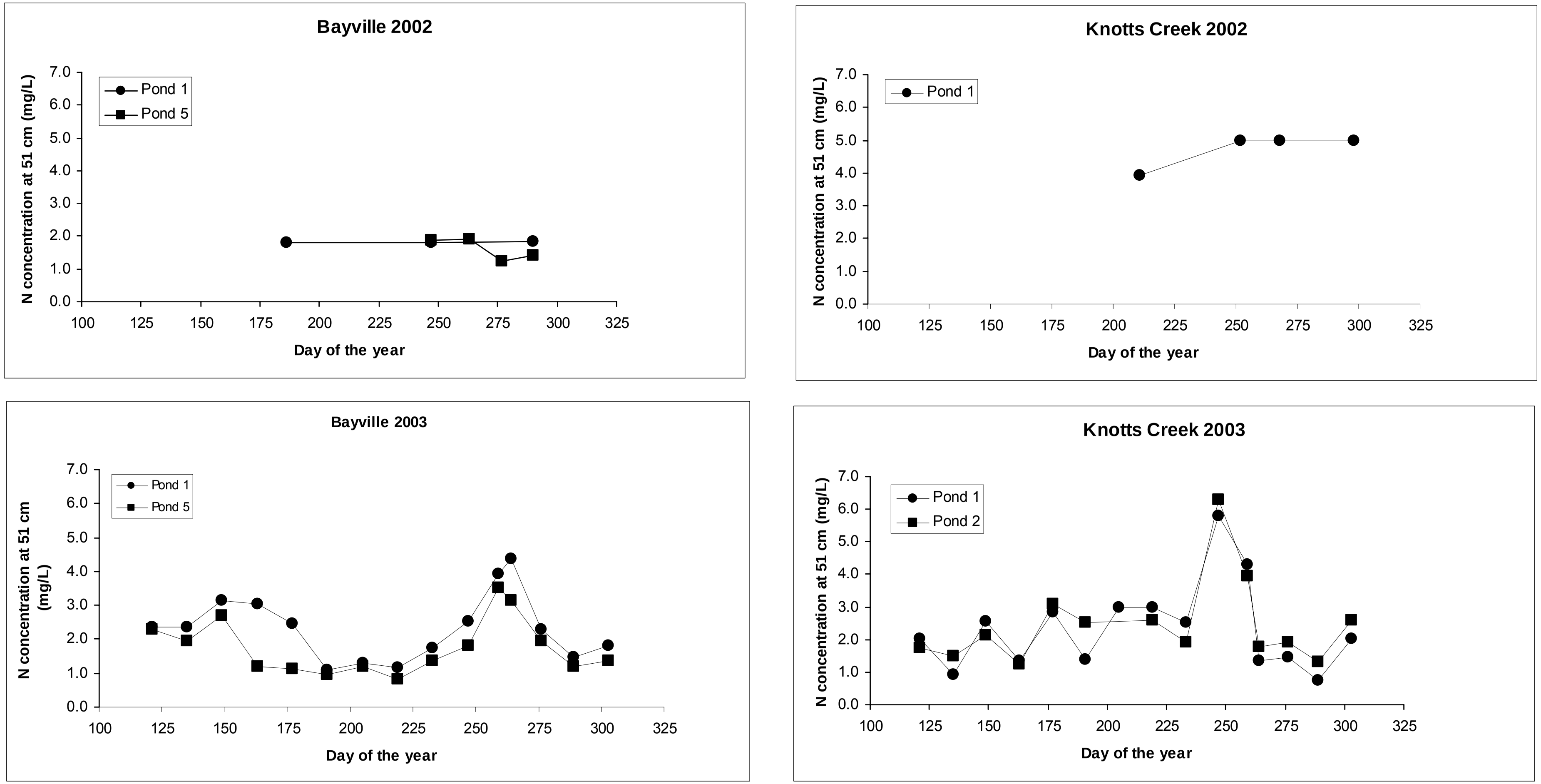


Fig. 7. Nitrogen concentration (mg L^{-1}) patterns at 51 cm depth at inflow sampling location in BGC Ponds 1 and 5 and in KCN Ponds 1 and 2 for 2002 and 2003.

Only the N concentrations for the middles of the ponds were graphed for 2002 (Figure 8). At BGC in Pond 1, N concentrations are between 1.5 and 3.5 mg L^{-1}, while in Pond 5 they are between 0.75 and 2.75 mg L^{-1}. On the 5 July sampling date for Pond 1, N concentrations initially decrease with increasing depth, then dramatically increase at depths greater than 152 cm. For the same date for Pond 5, N concentrations increase slightly with increasing depth, then dramatically at depths greater than 152 cm, the same as in Pond 1. As there was no rain event prior to sampling on this date, the high N concentrations are attributed to suspended solids close to the pond floor possibly exacerbated by the sampling process. At the 4 October date in Pond 1, N concentrations decreased with increasing depth from 3.2 to 1.7 mg L^{-1}. In Pond 5, they were consistently between 1.0 and 1.5 mg L^{-1} and were the lowest of all the dates. N concentrations were fairly consistent as depth increased for the middle season sampling dates for both ponds.

At KCN in 2002, N concentrations in Pond 1 were between 2.5 and 6.0 mg L^{-1} and in Pond 2 between 3.5 and 5.0 mg L^{-1}, with the exception of the unusually high concentrations, 10.0 mg L^{-1}, observed on 28 August in both ponds just after a major rain event of 58 mm. The 12 July and 12 August N concentrations follow the increasing N with increasing depth trend in both ponds. The 10 October concentrations are consistent as depth increases in both ponds.

With more rainfall in 2003, a more comprehensive picture of N concentrations relative to pond depth emerges. For BGC in both ponds at both locations the N Concentrations were between 1 and 4 mg L^{-1} overall (Figure 9). The concentrations on the early season May dates were generally between 2 and 3 mg L^{-1}, while the concentrations on the later season dates, August through October were generally between 1 and 2 mg L^{-1}. September was the exception, with N concentrations between 3 and 4.5 mg L^{-1} due to hurricane Isabel. At the inflows of both ponds, 1 May concentrations initially increased with increasing depth, and then decreased. The 10 May concentrations were consistent with increasing depth in both ponds. The later season date concentrations, August through October were consistent at increasing depth in Pond 1, but seemed to increase slightly at increasing depths in Pond 5. In the middles, 1 May concentrations increased with depth in Pond 1. They increased initially and then were consistent with increasing depth in Pond 2. The 29 May concentrations were consistent with increasing in both ponds. The 24 July concentrations were also consistent as depth increased in both ponds with the exception of the dramatic increase that occurred at the deepest levels in Pond 1, which is attributed to suspended sediment. Early August concentrations were consistent as depth increased in both ponds. Those on 21 August showed an initial slight decrease followed by an increase as depths increased. October concentrations were consistent with increasing depth.

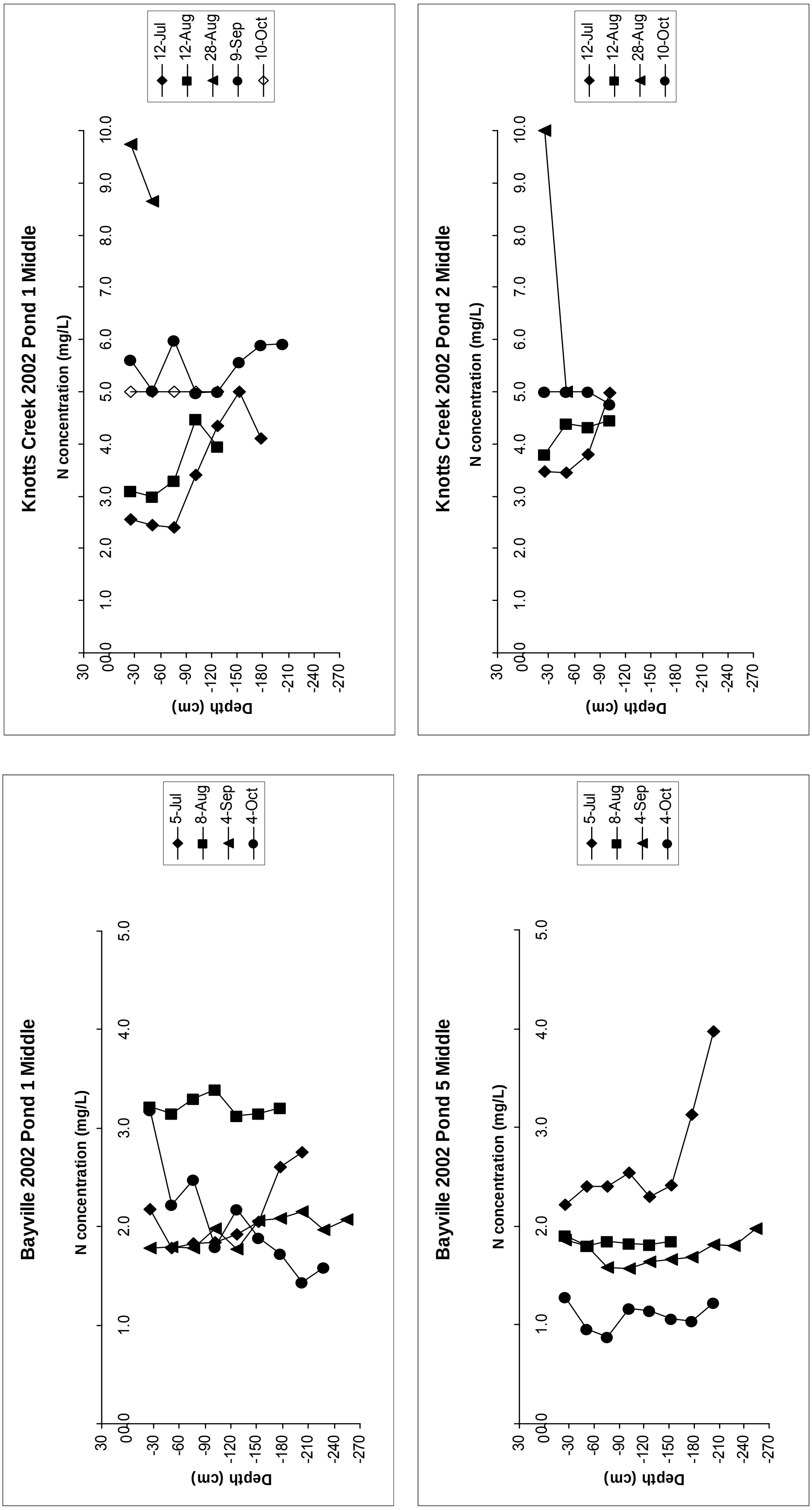


Fig. 8. Total dissolved nitrogen concentration (mg L^{-1}) patterns at increasing depths at the middle sampling location on selected sampling dates in BGC Ponds 1 and 5 and in KCN Ponds 1 and 2 for 2002.

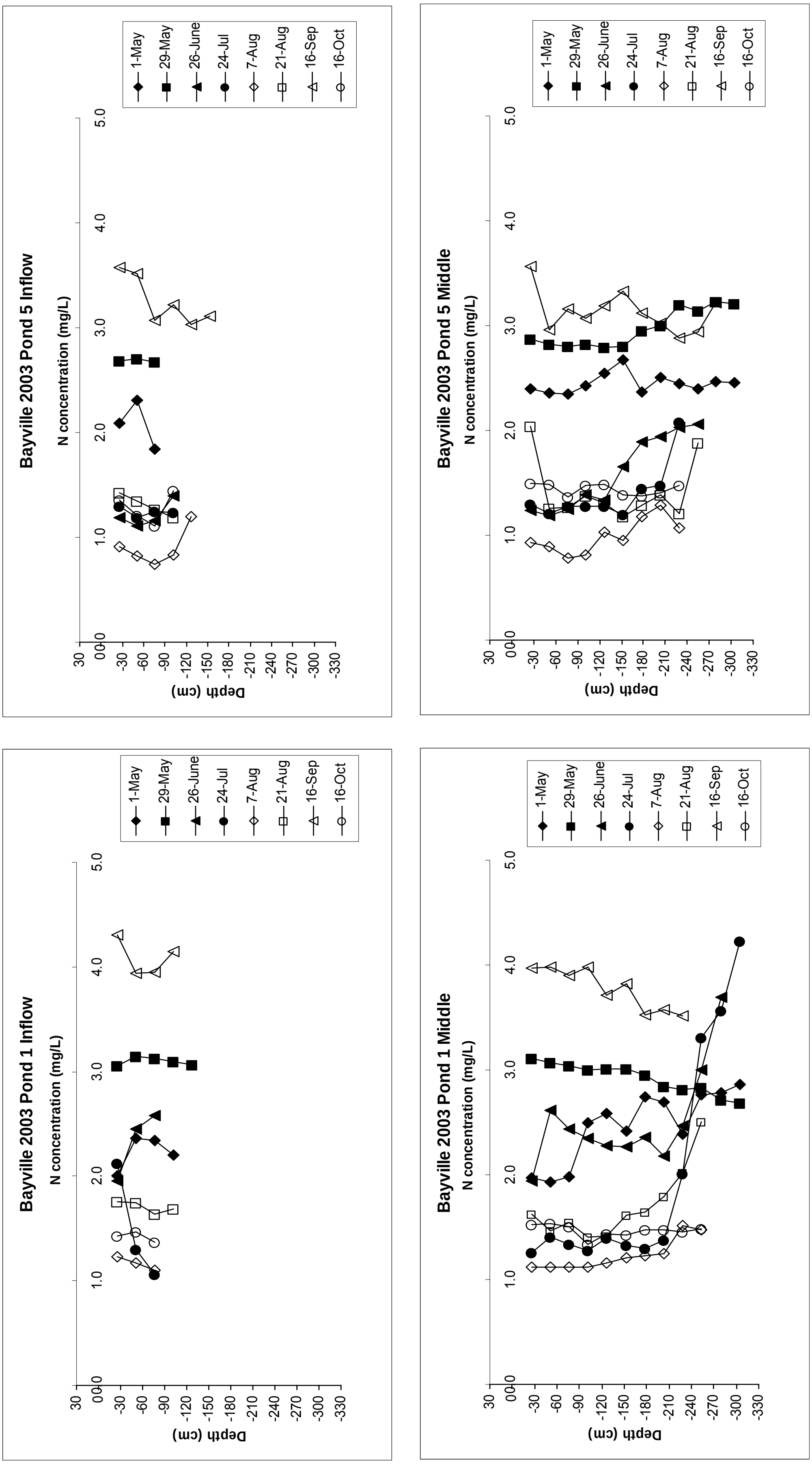


Fig. 9. Total dissolved nitrogen concentrations (mg L^{-1}) at increasing depths at the inflow and middle sampling locations on selected sampling dates in BGC Ponds 1 and 5 for 2003.

For KCN in both ponds at both sampling locations, the N concentrations were between 0.5 and 3 mg L^{-1} overall (Figure 10). Again the exception was the high N concentrations (4 – 5 mg L^{-1} at the inflows and 5 – 6 mg L^{-1} at the middles) in September. KCN received almost twice as much rainfall as BGC during hurricane Isabel. N concentrations for 1 May through 21 August generally remained between 2.0 and 3.0 mg L^{-1} at the inflows and middles of both ponds. October concentrations were lowest, around 1.0 mg L^{-1} at both locations in both ponds. There was a general overall trend at KCN for N concentrations to be consistent at increasing depths. Notable differences include: 1 May where a slight increase was observed at increasing depths in both ponds, and 26 June where an initial decrease followed by an increase was observed in Pond 1.

Discussion

Four stormwater retention ponds used for irrigation located in southeastern Virginia, USA, were characterized and examined over two growing seasons relative to weather and management strategies and the implications for water quality. Two ponds were located at an intensively managed golf course right on the Chesapeake Bay (USDA zone 8), and two were located at a commercial nursery specializing in container grown perennials 64 km inland (USDA zone 7). Obviously weather and management practices influenced amount and quality of runoff being collected in these ponds. Pond size, depth, and openness also influence water temperatures and N concentrations and distribution in the pond.

During the four months data was collected in 2002, rainfall was well below average. Pond volumes were low. Water temperatures fluctuated little over the season or with depth. N concentrations were generally low and within a narrow range. There were more fluctuations in N concentration as depth increased. All of these conditions are attributed to lack of water inflow into the ponds. During the six months data was collected in 2003, rainfall was above average leading to an entirely different situation. Pond volumes were usually at normal capacity. Water temperatures fluctuated more over the season and with increasing depth due to the influx of cooler water. N concentrations were observed across a wider range over the season. This can be attributed to the increased volume and frequency of nutrient polluted runoff inflow into the ponds. Overall, N concentration values were very similar as depth increased. Fluctuations in temperature and N concentrations were more dramatic at the pond inflows compared to the middles as expected. The ponds at BGC were larger, deeper and more open where the ponds at KCN were smaller, with Pond 1, deeper and mostly shaded and Pond 2, the smallest and shallowest. Larger deeper ponds have better temperature and nutrient buffering capacities, and open ponds are more subject to

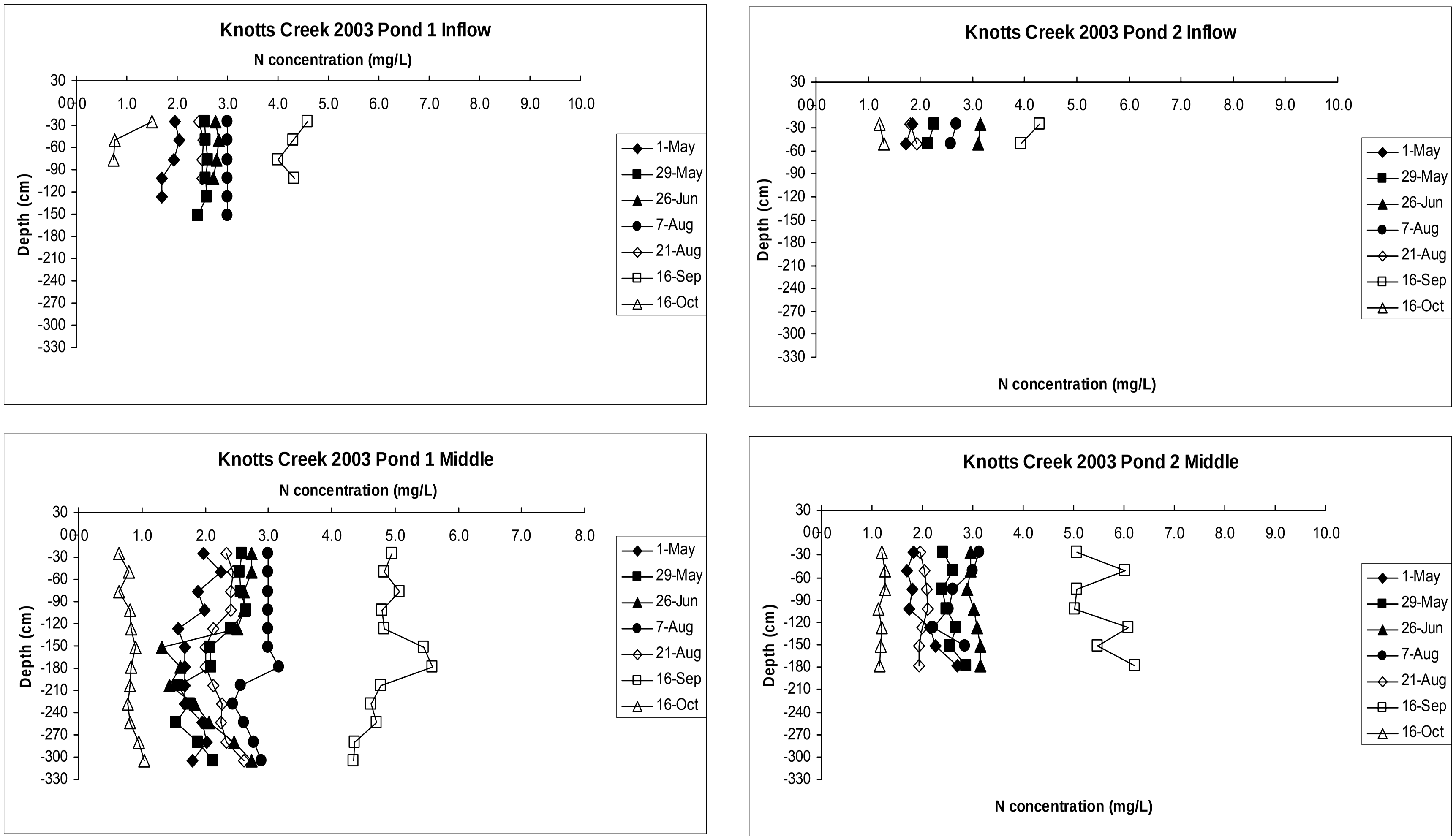


Fig. 10. Total dissolved nitrogen concentrations (mg L^{-1}) at descending depths at the inflow and middle sampling locations on selected sampling dates in KCN Ponds 1 and 2 for 2003.

passive solar heating which also impacts water temperatures.

More types of fertilizers were used and with more frequency at BGC than at KCN which would seem to increase the potential for nutrient polluted runoff; however, they were applied to solidly vegetated areas in relatively low doses over an extended time. While fewer types of fertilizers were used at KCN, container substrate is notoriously porous requiring frequent irrigation. Applications through an overhead irrigation system also cause fertilizer to fall on unvegetated space between the containers. Both of these factors lead to higher N concentrations and runoff volumes. Irrigation was applied more frequently at KCN, and considering the above circumstances, it was not surprising to find considerably higher N concentrations in the ponds at KCN compared to BGC. Rain events significantly influenced nutrient runoff and subsequent amounts in ponds. This was very apparent with the unique event, hurricane Isabel in September 2003, which caused some interesting, but not unexpected effects. KCN received twice as much rainfall as BGC. Pond water temperatures decreased dramatically with the excessive and cooler inflow.

Fertilizer choice and application timing, rate, and location directly impact nutrient pollutant levels in stormwater and irrigation ponds, especially during times of increased runoff volume and frequency.

CHAPTER 7

General discussion

Water quality and the global perspective

Water is the foundation of life. An estimated 110,000 km^3 of water fall as precipitation every year (Speidel and Agnew 1982; L'Vovich et al., 1990; Schwarz et al., 1990). As the human population around the world continues to increase, and more land is developed, the demand for fresh water increases. The amount of water withdrawn globally by humans and the land area under irrigation have risen exponentially over the last 100 years, and it is estimated that more than half of the accessible fresh water runoff is already being used by humans (Jackson et al., 2000). There is a distinction between renewable and non-renewable water resources, an understanding of which is critical to developing and implementing water management strategies. Surface and ground water are closely linked. What affects the quantity and quality of one often affects the other. When more than 75% of groundwater is considered non-renewable (Shiklomanov, 1997), the need to protect and preserve our surface water resources becomes even more apparent and urgent. While a global perspective on water use is important, regional and local water management practices are critical to ensuring the availability and sustainability of our essential water resources. The need has never been more urgent to link research to water management. In this chapter, water quality issues in the green industry in the USA, the use of phytoremediation, and where this research fits into the larger picture, are reviewed and discussed.

Water quality and water management the United States perspective

The U.S. Environmental Protection Agency (EPA) is an independent federal agency that was established in 1970 and charged with protecting the United State's (US) land, air, and water resources. EPA is chiefly responsible for the environmental policy of the US. Through national environmental laws, EPA formulates and implements actions to balance human activities and the sustainability of natural systems. In other words, EPA coordinates programmes aimed at reducing pollution and protecting the environment. In 1972, the Clean Water Act (CWA) became the first comprehensive national clean water legislation, and was a response to growing public concern over serious and widespread water pollution. The CWA mandated clean water in lakes, rivers, streams, and aquifers, and established the goals of eliminating releases of high amounts of toxic substances to waters and ensuring that surface waters meet standards necessary for human activities. It provides a comprehensive framework of standards, technical tools and financial assistance to address the many causes of pollution and poor water quality, including municipal and industrial wastewater discharges, polluted runoff from urban and rural areas, and habitat destruction. Even with legislation, regulations, programmes and funding, water pollution is still a major problem in the US.

Pollution is generally categorized into point and non-point sources. Point source pollution has been relatively easy to identify, measure, and regulate. Currently, non-point source pollution is considered the major threat to waters in the US (U.S. EPA, 1990, 1996). It is generally intermittent, seasonally and weather influenced, and widespread in nature; making it difficult to quantify and regulate. Polluted stormwater runoff is a major contributor to the non-point source pollution problem. It is water that originates during a precipitation event that does not soak into the ground, but instead runs off impervious or water-saturated surfaces, transporting sediments and dissolved chemicals and nutrients into nearby waters (Schueler, 2000; University of Florida, 2009). Reducing the impact of polluted stormwater runoff requires research, education, and implementation of management practices at many levels.

Water quality and management issues in the green industry

Non-point source pollution is often a result of agricultural activities and urban development. Agriculture and related industries are the largest "withdrawers" of surface water runoff in the United States (Jackson et al., 2000), and along with urban activities, they are also the major sources of nitrogen (N) and phosphorus (P) pollutants in aquatic ecosystems (Carpenter et al., 1998). As part of the "related industries", the green industry (commercial nurseries, sod producers, golf courses, arborists, and landscape designers and contractors) has long recognized nutrient polluted runoff as an environmental issue (Urbano, 1989). But, while many people in the green industry agree that water quality is the top issue, and that economic growth should be sacrificed to preserve and protect the environment, there is limited consensus on what to do exactly. Some think the government should increase regulations, while others feel there are already a sufficient number of regulations that just need to be enforced. Some feel that education is the solution; that when people know how important water quality is, they will do the right thing and their collective actions with make the difference. Still others feel that the green industry should be a leader in protecting and conserving resources since their livelihood depends on it.

Numerous studies and monitoring have been done throughout the industry to quantify sources and amounts of nutrient polluted runoff. Data collected primarily from nurseries (Cooper, 1993; Yeager et al., 1993) and golf courses (Gross et al., 1990; Cohen et al., 1999) has been used to support legislators and regulators so informed decisions can be made. That information has also been used to educate professionals and to promote the use of best management practices (BMP) within the industry to moderate impacts from polluted runoff generated through both storm and or watering (irrigation) events (Cole et al.; 1997; Southern Nursery Association, 1997; Berghage et al., 1999; Cooper et al., 2004; Kohler et al., 2004; Taylor et al., 2006). Also, different groups have taken proactive steps, like the Southern Nursery Association and its Best Management Practices (BMP) guide which recommends production practices for moderating impacts from runoff (Southern Nursery Association, 1997). Individual companies train employees in proper fertilizer use, plant use, and integrated pest management. Many in the green industry also try to educate their clients about water quality. If the demand for the "perfect landscape" is reduced, then the inputs required to achieve it, but which have adverse effects on water quality, will also be reduced. All of the above actions are necessary and good, but it has not been enough. Unfortunately, voluntary use of BMPs within the industry has been insufficient in addressing the nutrient issue, so federal, state, and local regulations governing water quality continue to increase. As one green industry manager so appropriately said: "The issue brought forward here is, 'Which has more importance – the environment or progress?' These two issues cannot be separated. The horticulture industry, and any industry that works with the land, must realize that to keep our long-term investment progressing, we must work with the environment. If we don't, we as a living entity will not exist." (Urbano, 1989). The green industry has a long standing and strong relationship with university and extension personnel. And so, the opportunity is there to make connections across segments of the industry and research disciplines, to utilize research to support policy and regulation, to develop cost effective practical technologies and practices that can be implemented, and to make a positive contribution towards improved water quality.

Why phytoremediation?

No process is more indicative of working with the environment than phytoremediation, which is the process of using plants (*phyto*) to clean up (*remediate*) polluted soil or water. This age old natural process has today been taken to the level of genetically engineered plants to remediate very specific and highly toxic environmental contaminants. The above mentioned water trends and green industry attitudes, create numerous opportunities for research in the area of phytoremediation, especially for use in the green industry.

Through the EPA, water quality research areas have been and continue to be prioritized. Realistic goals have been defined, but efforts still need to be cross-cutting and integrated in areas of climatology, hydrology, limnology, ecology and social sciences. Management strategies need to be adaptive, and technology and practices need to be economically feasible, widely applicable, and easily implementation. Phytoremediation can meet all the criteria listed above, and in addition is non-invasive and more publicly acceptable than other conventional treatment methods. Data that supports this is accumulating rapidly. Perhaps the most relevant data is on the cost effectiveness of phytoremediation compared to other treatment methods (Gren, 1995). A highly successful and often cited example is New York City's investment of over one billion dollars to purchase land in the Catskill Mountains around the watershed that supplies the city's drinking water. Using plants to restore and preserve watershed habitat and protect water quality cost one-fifth the price of a new filtration plant and requires limited maintenance (Chichilnisky and Heal, 1998).

Phytoremediation mechanisms

The EPA considers phytoremediation to be a set of technologies that use plants to degrade, contain, immobilize, or extract pollutants. EPA's National Risk Management Research Laboratory conducts programmes on pollution prevention and control methods, including remediation. The lab's report, Introduction to Phytoremediation (U.S. EPA, 2000), provides one of the best evaluations of phytoremediation technologies along with system selection and design considerations, including plant selections. Phytoremediation research is generally divided into two categories, exploration of mechanisms and evaluation of applications. An understanding of the mechanisms is necessary in order to recommend an application for a specific situation. Following are brief descriptions of the major mechanisms/forms of phytoremediation.

Phytoextraction is the uptake of pollutants through plant roots. Pollutants are concentrated and can be removed by removing the plants.

Phytostabilization is the use of plants to prevent pollutant movement. Pollutants are absorbed, adsorbed, or precipitated within the plant root zone.

Phytodegradation (*phytotransformation*) is the use of plants metabolic processes to break down pollutants. The resultant process by-products are generally harmless.

Phytovolatilization is the uptake of pollutants and release of a modified form of the pollutant into the atmosphere through transpiration.

Phytohydraulics is the use of plants to remove groundwater to control the movement of pollutants.

Phytoremediation use in the green industry

Phytoextraction was the process utilized in the greenhouse studies, but many times a combination of these processes is utilized in applications in the green industry. Phytoextraction and phytodegradation are commonly used in applications such as:

riparian buffers, wetlands, and bioremediation basins. Buffers are areas of vegetation adjacent to bodies of water that slow down and filter intercepted runoff. Riparian usually means the inclusion of trees in the buffer. Buffers can be used in “water front” landscapes in which case they are generally planted with ornamental plants and are usually less than 15 m in width. Buffers can be used around stormwater and irrigation ponds at commercial nurseries and at golf courses. Vegetated drainage ditches are a type of modified buffer used at nurseries to filter irrigation runoff. Plant mixture and width are extremely variable in these situations. Wetlands are basically an aquatic based buffer. Again, runoff is intercepted and filtered before moving into a main body of water. Wetlands require a large area and a totally different selection of plants. Sometimes wetlands are stepped so that there is a chain of them for polluted runoff to filter through. This allows more time for the system to accomplish the remediation. Gren (1995) wrote that wetland restoration may be the most cost effective method of decreasing non-point N pollution. Bioremediation basins include practices like stormwater retention ponds, dry detention ponds, and infiltration basins or swales (called rain gardens in residential landscapes). These basins collect runoff water and hold it temporarily. The combination of plants, soil, and microorganisms filter polluted water before it is released into natural water bodies, used for irrigation, or leaches into the ground to recharge aquifers. It is obvious that the basic concept of phytoremediation can be implemented in numerous and diverse ways. Either individually or in combination, these practices can be used by the green industry to improve water quality.

Phytoremediation in stormwater ponds

Stormwater ponds are one of the most widely utilized BMPs in the green industry for managing runoff from both storm and irrigation events. Thus, it made sense to examine the use of aquatic plants to remediate the polluted runoff coming into these ponds before the water was subsequently released back into natural waterways. Since many of these ponds have secondary purposes such as irrigation water storage and recreational uses, not only the environment, but plant health and social and economic impacts would be positive. In addition, the useful life expectancy of the stormwater ponds could be extended by slowing the eutrophication process. Using plants for phytoremediation in stormwater ponds could also serve other purposes. The phytoremediation system could provide additional production area at commercial nurseries. The plants utilized in the system could be sold or composted and used as an amendment in the container potting substrate or sold as a value added product. The system would also be aesthetically pleasing as well as functional, which was a consideration at golf course sites.

Water hyacinth for phytoremediation

Water hyacinth was an excellent model plant to use for this research. Its nutrient remediation ability has been examined in numerous locations and situations (Table 1 in Chapter 1). The plant is adaptable to a wide range of environmental conditions experienced across the green industry such as temperature, pH, and nutrient levels. The dense fibrous root system provides an extensive surface area for absorption, adsorption, and for micro-organism activity which would enhance the aquatic ecosystem of the pond. Water hyacinths spend the majority of their lifecycle in a vegetative state and rapidly reproduce by vegetative propagation; which means an increase in biomass leads to an increase in filtering capacity. Water hyacinth is easy to obtain, and is a marketable ornamental crop in the United States. It can be composted and used as an organic amendment or nutrient source in nursery production or in the landscape. The testing protocols and recommendations for use could also be applied to other aquatic macrophytes. All of the above factors were considered when this plant was selected.

Research programme and results

Both an exploration of phytoremediation using the phytoextraction mechanism and an evaluation of applications in the field were done with this thesis research. Chapters 2 and 3 of this thesis cover the use of the aquatic macrophyte, water hyacinth, to remediate N and P, the two primary pollutants that degrade water quality. Other studies on the uptake of nutrients by water hyacinth have wide-ranging results due to the variability in culture parameters (plant density, temperature, and solar radiation), and in concentrations and ratios of plant nutrients. There is general agreement through the literature; however, on a number of points:

- that water hyacinths grow at a wide range of nutrient levels,
- that tissue N and P levels correlate to nutrient levels in the growing solution,
- that N uptake correlates to P availability,
- that water hyacinths utilize all forms of N, and
- that they can accumulate N at levels in excess of what they use for growth (luxury consumption).

Most studies examine the water hyacinth nutrient relationship at constant or increasing nutrient levels, and a Hoagland-type base growing solution is always utilized to preclude the chance of nutrient deficiencies.

The focus of the work in Chapters 2 and 3 is on examining the relationship when nutrient levels are excessive and infrequent such as with nutrient polluted stormwater runoff at production nurseries and golf courses. The setup of the greenhouse studies and particular treatments were designed to accommodate the first two research objectives. It was logical then to apply different strength nutrient solutions once to a constant volume of water in order to observe the phytoremediation potential under documented conditions more commonly experienced in the stormwater retention ponds; particularly at commercial nurseries where complete fertilizers are generally applied. Thus; when N and P levels increased, so did the other nutrients. Obviously, this setup could lead to pH fluctuations or nutrient deficiencies or toxicities. The point was to examine water hyacinth's phytoremediation ability under these real and often extreme conditions. The experiments were successful, and the hyacinths accounted for 60-85% of the N and 17-79% of the P removed from solution. The results fall within the range observed in other studies (Dunigan et al., 1975; Mitsch, 1977; Shiralipour et al., 1981; Reddy and DeBusk, 1985; Reddy and Smith, 1987; Basseres and Pietrasanta, 1991; Jayaweera and Kasturiarachchi, 2004).

Once nutrient uptake amounts were established and it was confirmed that water hyacinths could perform under these extreme conditions, their ecology was examined through the relationships between water nutrient level and growth conditions on production. Chapter 4 deals with the second research objective of production ecology of water hyacinth. The sixty four study ponds had dimensions of 1.2 m × 1.2 m × 17.8 cm to prevent any crowding effect in the higher nutrient treatments. Ponds were lined with polyethylene and filled with 189 l of well water because of the physical volume of water needed. The well water had a low buffering capacity, and the commercial fertilizer used to simulate a Hoagland solution contained Mg, Cu, Mn, and Zn in water soluble form. So Na-EDTA was added to prevent precipitation of any micronutrients, particularly Fe, when the pH fluctuated (pH range of 3-9) from the treatment or from hyacinth activity. The ponds were maintained at a constant volume by adding DI water so there was no confounding effect on the treatments from additional nutrients that could have come from additional well water. A nutrient solution pH range of 5.1 to 5.9 is ideal with a pH of 5.3 being optimal for nutrient uptake by the plant (Muckle, 1993; Lea-Cox et al., 1999). These values are slightly more acidic than the widely recognized soil pH/nutrient availability recommendations. Water hyacinths will grow under a wide range of environmental conditions including pH, and they have the ability to influence the microenvironment around root hairs so they can continue to take up nutrients even during unfavourable pH conditions (Purchase, 1977; Reddy, 1988).

Chapter 5 covers the containment system field work. It is necessary to be aware of the larger ecosystem when deliberately using plants for remediation. Extreme care must be taken when applying a biological to an ecosystem, so that there aren't unintended consequences. In the case of this research, the concern was that the hyacinths could escape and become a weed problem in natural waters.

Chapter 6 looks at pond characterization, which was essential to creating an effective phytoremediation system. Chapter 6 answers the key questions about amounts of nutrients and frequency of inflow into nursery and golf course ponds. Combined with data from the greenhouse studies, the questions of how many hyacinths to apply and how efficient will they be at remediating the polluted runoff can be addressed. Using the highest increase in N concentrations observed in the four ponds, the highest tissue N concentrations in the water hyacinths in the greenhouse studies, and the pond volumes and surface areas, calculations were made to determine the percent area of pond coverage necessary to remediate a given amount of N. The percent of total surface area coverage needed to remediate the highest increase in N concentration of 3 mg L^{-1} ranged from 6% at one of the KCN ponds to 20% at one of the BGC ponds. In an ideal world, those hyacinths should be able to accomplish the remediation in less than three days. However, these numbers are specific to these two locations, based on the site data collected over two years, and data generated from controlled greenhouse studies. In the real world, each pond situation will be different, and the percent coverage relative to the pond surface area, volume, nutrient runoff potential and frequency, and growing conditions. The reality is that the calculations only provide an estimate, and that actual remediation amounts will probably never reach full potential due to the numerous environmental factors that influence the aquatic ecosystem. Also, in some cases the recommended percent hyacinth coverage could exceed the generally acceptable levels of 40-60 percent vegetative coverage for healthy aquatic ecosystems. Excessive vegetative coverage adversely impact water temperature, light penetration, and oxygen levels.

Methodological issues

There are three major methodological issues that require further discussion:

1. Fluctuations in pH and in EC values. A major difference between growing plants in soil and growing plants hydroponically is that the nutrient solutions are not buffered in either pH or nutrient supply. To overcome this problem, nutrient concentrations in solution are generally higher than those found in soil solution (Mengel and Kirkby, 2001), and the solution is changed frequently (Parker and Norvell, 1999). If the solution is not changed, then nutrients are depleted through plant uptake at different rates which in turn cause pH and EC fluctuations (Muckle, 1993). Such is the case in stormwater ponds. Solution pH and EC fluctuations are generally related to the uptake of cations and anions, especially nitrate and ammonium which are the two common N sources in fertilizers and thus in nutrient polluted runoff into stormwater ponds. If the solution becomes strongly acidic or strongly alkaline, then many nutrients

become limited or unavailable (Utah State, 2001) (Figure 1). This is especially true with micronutrients, which is why they are used in chelated form in the water soluble fertilizers. A common example is when the pH is above 9 and iron oxidizes, precipitates out of solution, and causes an iron deficiency in the plant. In the greenhouse studies, where the pH fluctuated from 3-9 because of treatment or hyacinth activity, Na-EDTA was added to prevent precipitation of any micronutrients, particularly iron. The greenhouse studies were 28 days in duration. The observed pH and EC changes were similar across treatments and occurred in the middle to late stages of the study as nutrients were absorbed through plant uptake and as the volume of solution per plant ratio decreased. In order to mimic environmental conditions of the stormwater ponds, the nutrient solution was not changed, buffered, or pH adjusted for any of the greenhouse studies.

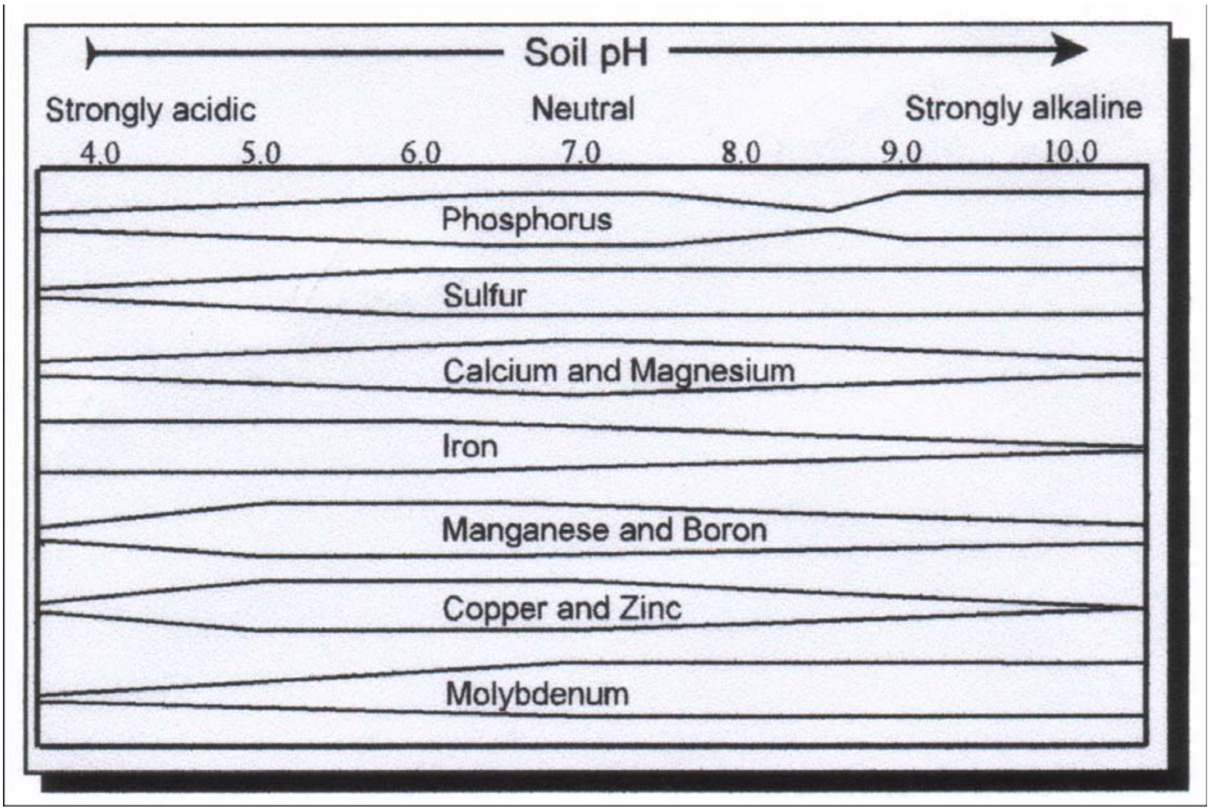


Fig. 1. The effect of pH on nutrient availability. Wider bars indicate greater nutrient availability at that pH.

2. The fact that the nutrient levels were not varied separately, but that the full concentration of the nutrient solution was varied. Most commercial applications of fertilizer such as at nurseries or golf courses are based on nitrogen as that is the most soluble and mobile nutrient. At production nurseries, the fertilizers applied are generally complete and include micronutrients, where golf courses

often mix applications of complete fertilizers with specialty or custom fertilizers. A complete commercial fertilizer was used to simulate a Hoagland solution on a large volume basis and to mimic common industry fertilizer application practices. Thus, when different strength nutrient solutions based on amount of nitrogen or phosphorus were applied to the greenhouse study ponds, the amounts of all the other nutrients increased accordingly. This experimental setup eliminated the possibility of nutrient deficiencies based on Liebig's Law of the Minimum, which states that a plant's development is limited by the one essential mineral that is in the relatively shortest supply. This setup also supported Mitscherlich's Law of Physiological Relations, which states that as plant yield approaches its maximum, the rate of change with additional fertilizer approaches zero. Those results are seen in the asymptotic graphs in Chapter 1.

3. The fact that in the ecology paper (Chapter 4), the cause of variation in what was plotted against the x and y axis was the nutrient level and not another factor. The variations in relationships between plant numbers, dry weights, and canopy covers were a result of the different nutrient concentrations. These relationships were examined because recommendations for using water hyacinth, or any other species, for phytoremediation cannot be responsibly made without an understanding of its growth habit and production ecology which are highly dependent on water nutrient concentrations. Understanding not only what and how a plant will remediate, but how that plant reacts within an aquatic system is critical to the success of the whole phytoremediation process.

What is the potential of phytoremediation?

Phytoremediation has great potential. Data on site specific environmental conditions and production practices, combined with data from research studies, can be used to generate recommendations for a phytoremediation system for a commercial nursery or golf course operation. Time of year to apply, location in the stormwater pond, and quantity of water hyacinths (or other aquatic plants) to use can be specified. Harvesting intervals to maintain maximum remediation potential can be recommended, and amount of nutrients removed and time to accomplish the removal can be calculated. Most nurseries and golf courses already keep detailed management records that could be used to create a customized phytoremediation system which could easily be adapted as management practices change.

Research application

The results from this thesis work have directly impacted Bayville Golf Club and Knotts Creek Nursery in many ways. Each site manager has gained a better understanding of their nutrient runoff issues. They have made adjustments to their management strategies which have reduced both the concentrations of nutrients in the runoff and the overall amount of runoff. Bayville has even experimented with expanding the original phytoremediation system. The application timing of a phytoremediation system is important to the success of it. When plants are used for phytoremediation under optimal growing conditions, they are more efficient and the system is more successful. Therefore, the application timing needs to be a match between optimal plant growth conditions and peak pollution inflow. Knowing weather conditions, how water flowed into the ponds, and what the management practices are impact the size and location of the phytoremediation system. The more information about a site, its uses, management activities, etc. that is available, the more successful the integration of phytoremediation practices into the system. It is also very necessary to understand that a system of this type would only be one part of a broader comprehensive nutrient management plan. The protocols from the research studies are already being used in other research evaluating woody plants for phytoremediation potential. The results can be utilized to make recommendations for improving naturally existing and engineered phytoremediation systems. These recommendations can be used as examples and guidelines across businesses and locations in the green industry. With my background in landscape design, plant production, weed science, and now phytoremediation, I can work with diverse groups in the green industry to design water management strategies and to help develop industry standards and policies.

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Summary

Since water is essential to life, it is no surprise that the most critical environmental issue worldwide is water quantity and quality. Pollution from nutrients and sediment are the two largest threats to surface water quality. Nitrogen (N) and phosphorus (P), enter surface water mainly through runoff and leaching from agricultural, commercial, and urbanized areas and degrade water quality, pose risks to humans and livestock, threaten rare habitats and ecosystems, and accelerate the natural eutrophication process in aquatic ecosystems; all with subsequent adverse economic impacts. In the United States of America (USA) in 1972, the Clean Water Act mandated clean water in lakes, rivers, streams, and aquifers. The green industry (commercial nurseries, sod producers, golf courses, arborists, and landscape designers and contractors) in the USA has long recognized nutrient polluted runoff as an environmental issue and promoted the use of best management practices (BMP) to moderate impacts from runoff, but these efforts have been insufficient to address the nutrient issue. A more aggressive approach is necessary. An opportunity exists for scientific research to positively impact and improve water management practices relative to nutrient pollution. The intent of this research was to explore phytoremediation using aquatic plants as a potential new tool for managing nutrient polluted runoff and improving water quality.

Phytoremediation is the process of using plants (*phyto*) to clean up (*remediate*) polluted soil or water. Aquatic macrophytes are able to remove a variety of nutrients from polluted water, and floating water hyacinth has been of particular interest for remediation of pollutants, especially N. It was selected as the model plant for the research. Both an exploration of phytoremediation mechanisms and an evaluation of applications in the field were done with this thesis research.

Chapter 2 covers the use of water hyacinth to remediate N in solutions with increasing nutrient concentrations (including other nutrients than N). The water hyacinths accounted for 60–85% of the N removed from solution. Net productivity, as measured by dry matter gain, increased initially with an increase in N rate then levelled out at N rates above 80 ppm. Water hyacinths accumulated between 0.3 and 7.9 g of N in plant tissue over four weeks, producing between 22.5 and 188 g of dry matter per 1.4 m^2 area. Tissue N accumulated in the plant tissue increased linearly with dry matter gain, but total nitrogen removal from the water increased exponentially with net dry matter gain or with an increase in canopy cover.

Chapter 3 covers the use of water hyacinth to remediate P in solutions with increasing nutrient concentrations (including other nutrients than P). Uptake by water

hyacinth accounted for 17 – 79% of the P removed from solution. Plants were more vigorous, and canopy development was quicker and denser in the higher nutrient treatments. Water hyacinths accumulated between 0.02 and 1.7 g of P in plant tissue over four weeks for the same amount of dry matter per area as with N. Phosphorus accumulation in the tissue was significantly greater in higher level nutrient treatments.

Chapter 4 examines the production ecology of water hyacinth under greenhouse conditions. High nitrogen (80–300 ppm) and phosphorus (9.4–70.6 ppm) levels in the water and light levels caused corresponding positive linear responses in biomass. The higher nutrient level treatments contained more plants and had better canopy cover and higher light interception values. Radiation use efficiency values were higher in water hyacinths with more nitrogen in the tissue. Larger plants intercepted more light and were thus more productive leading to a faster increase in numbers of plants and the corresponding percent canopy cover, but also to an earlier and stronger crowding effect. While production trends were similar across two separate studies, variation was observed between the two studies, and this is attributed to seasonal differences in temperatures and light intensities which influenced the amount of light being intercepted and the efficiency with which the intercepted light was converted into dry matter. Temperatures were cooler and photosynthetically active radiation (PAR) readings were higher in the early season study. Recommendations for using water hyacinth, or any other species, for phytoremediation cannot be responsibly made without an understanding of its growth habit and production ecology. Understanding not only what and how a plant will remediate, but how that plant reacts within a system is critical to the success of the whole process.

Chapter 5 covers the containment system field work. A containment system for water hyacinths was designed and evaluated. Floating containment corrals were constructed from PVC pipe and polyethylene netting and deployed in the pond along one shoreline. Water hyacinths were placed in each corral and allowed to reproduce for eight weeks. The corrals remained anchored, UV light stable, and floating. Water hyacinths grew rapidly, 141-fold increase per corral in eight weeks. The corrals did not adversely influence water hyacinth reproduction, and they effectively contained the resultant biomass regardless of mesh size or guard feature. The corrals were economical (approximately US $46.00 per corral), easy to construct, deploy, manoeuvre, and remove from the pond. The system is adaptable to diverse locations and can be expanded as needed. It is necessary to be aware of the larger ecosystem when deliberately using plants for remediation. Extreme care must be taken when applying a biological to an ecosystem, so that there aren’t unintended consequences. In the case of this research, the concern was that the water hyacinths could escape and become a weed problem in natural waters.

Chapter 6 covers characterization of the stormwater runoff retention ponds. Management, water and weather data was collected from two stormwater and irrigation runoff ponds at Bayville Golf Club (BGC), Virginia Beach, VA, USA and two ponds at Knotts Creek Nursery (KCN), Suffolk, VA, USA for two growing seasons for characterization purposes. Weather and management practices were monitored to assess the impact on water quality at four stormwater retention ponds used for irrigation. BGC is an intensely maintained private golf club, and KCN is a commercial nursery specializing in container grown perennials. Total dissolved N concentrations were examined at increasing depths to 305 cm and over time at the pond inflows and in the middles. More types of fertilizers were applied more frequently at BGC, but N concentrations were consistently higher at KCN. In 2002, a drought year, water temperatures fluctuated little over the season or with depth. N concentrations were generally low and within a narrow range (1.0 – 3.5 mg/L at BGC and 2.5 – 6.0 mg/L at KCN). There were more fluctuations in N concentration as depth increased. In 2003 rainfall was above average. Water temperatures fluctuated more over the season and with increasing depth. N concentrations were observed across a wider range (0.75 – 4.2 mg/L at BGC and 0.5 – 6.0 at KCN mg/L) over the season and were more consistent as depth increased. Both water temperatures and N concentrations fluctuated more dramatically at the inflow locations compared to the middles of the ponds.

The phytomechanisms most commonly utilized in the green industry are phytoextraction and phytodegradation; where plants either absorb and concentrate or absorb and metabolize pollutants, and both apply to the phytoremediation system developed in this research. Using the N concentrations observed in the ponds, the N concentrations observed in the water hyacinths in the greenhouse studies, the average incoming light and radiation use efficiencies, it is possible to calculate the amount of biomass and area of pond coverage necessary to remediate a given amount of N. For all four ponds, the amount of coverage needed to remediate the highest N concentrations observed was 20% or less of the total pond surface area.

While water hyacinth was used as the model plant, the phytoremediation capacity research protocols and the containment system are intended for use with other aquatic plants. The practical results of the research are: first, recommendations for use of aquatic plants for phytoremediation of nutrient polluted stormwater runoff in retention ponds at commercial nurseries and golf courses and second, to develop an inexpensive, expandable, site-adaptable containment system for aquatic plants used for phytoremediation. Ultimately, the recommendations and system would become another BMP that could be utilized alone or in conjunction with other BMPs to address

the very serious water quality degradation problem caused by excess N and P in runoff.

Samenvatting

Water is essentieel voor al het leven op aarde. Het hoeft dus geen verbazing te wekken dat overal op deze wereld het meest kritieke milieuvraagstuk juist de beschikbaarheid van goed water is. Vervuiling door eutrofiëring en ongewenste sedimentatie bedreigen in belangrijke mate de kwaliteit van het oppervlaktewater. Stikstof (N) and fosfor (P) komen vooral in het oppervlaktewater terecht via het afvloeien en wegsijpelen van water afkomstig van landbouwgronden, industriegebieden of stedelijke gebieden. Hierbij veroorzaken N en P een verslechtering van de waterkwaliteit. N en P vormen een risico voor mens en dier, bedreigen zeldzame leefgebieden en ecosystemen en versnellen het proces van natuurlijke eutrofiëring in aquatische ecosystemen. Dit alles heeft vervolgens negatieve economische gevolgen.

In de Verenigde Staten van Amerika (USA) schreef de Clean Water Act van 1972 schoon water in meren, rivieren, beken en waterhoudende bodemlagen voor. De groene sector (bestaande uit commerciële kwekers, producenten van graszoden, golfbaanbeheerders, boomspecialisten, landschapsarchitecten en loonwerkers) in de USA heeft zich al lang geleden gerealiseerd dat afstromend overtollig regenwater dat vervuild is met nutriënten een belangrijk milieuprobleem vormt. De sector bevorderde daarom ook de toepassing van zogenaamde Best Management Practices (BMP; of wel de meest geëigende en milieubewuste praktijken) om de negatieve effecten van afstromend overtollig regenwater te verminderen. Deze inspanningen hebben echter het nutriëntenprobleem onvoldoende kunnen adresseren. Een agressievere benadering is noodzakelijk. Dat maakt wetenschappelijk onderzoek relevant naar de mogelijkheden om het waterbeheer te verbeteren en aldus de waterverontreiniging met nutriënten terug te dringen. Het doel van het in dit proefschrift beschreven onderzoek was om te verkennen in hoeverre fytoremediatie met behulp van waterplanten kon worden benut om oppervlakkig afstromend en met nutriënten vervuild water te beheersen en de waterkwaliteit te verbeteren.

Fytoremediatie is het proces van het benutten van planten (*Fyto*) om verontreinigde bodem of vervuild water schoon te maken (*remediatie*). Waterplanten zijn in staat om verschillende nutriënten uit het vervuilde water op te nemen. Drijvende waterhyacinten kunnen heel efficiënt verontreinigingen uit het water opnemen, vooral N. De waterhyacint werd dan ook gekozen als modelplant voor ons onderzoek. Het onderzoek betrof zowel een verkenning van de mechanismen van fytoremediatie als ook de toepassing in de praktijk.

In hoofdstuk 2 wordt aangegeven in hoeverre de waterhyacint in staat is effectief N op te nemen uit oplossingen met verschillende concentraties nutriënten (inclusief andere nutriënten dan N). Van de hoeveelheid verwijderde stikstof bleken de waterhyacinten 60–85% opgenomen te hebben. De nettoproductie, vastgesteld op basis van de toename in het gewicht aan droge stof, nam aanvankelijk toe met een toename van de stikstofconcentratie in de voedingsoplossing, maar bij concentraties boven de 80 ppm, vlakte de toename af. In vier weken tijd hoopten waterhyacinten tussen de 0.3 en 7.9 g N in plantmateriaal op, terwijl ze in die periode tussen de 22.5 en 188 g droge stof per 1.4 m^2 wateroppervlak produceerden. De hoeveelheid N in het plantmateriaal nam lineair toe met de toename in droge stof, maar de totale hoeveelheid N die uit het water werd verwijderd nam exponentieel toe met de netto toename van droge stof en met de toename in waterbedekking door het gewas.

In hoofdstuk 3 wordt aangegeven in hoeverre de waterhyacint in staat is effectief P op te nemen uit oplossingen met verschillende concentraties nutriënten (inclusief andere nutriënten dan P). Van de hoeveelheid verwijderde P bleken de waterhyacinten 17–79% opgenomen te hebben. De planten waren levenskrachtiger en de ontwikkeling van het bladerdek was sneller en vollediger bij de rijkere voedingsoplossingen. In vier weken tijd hoopten waterhyacinten tussen de 0.02 en 1.7 g P in plantmateriaal op, terwijl ze in die periode tussen de 22.5 en 188 g droge stof per 1.4 m^2 wateroppervlak produceerden. De hoeveelheid P in het plantmateriaal was groter op de rijkere voedingsoplossingen.

In hoofdstuk 4 werd de productie-ecologie van de waterhyacint onder kascondities onderzocht. Hogere N (80–300 ppm) en hogere P (9.4–70.6 ppm) niveaus in het water and hoge lichtniveaus resulteerden in meer biomassa. Bovendien hadden de gewassen op voedingsoplossingen met hoge nutriëntenconcentraties meer planten en meer waterbedekking en onderschepten ze dus meer straling. De waarden van de berekende lichtbenuttingscoëfficiënt lagen hoger bij waterhyacinten die meer N in het plantmateriaal hadden opgehoopt. Grotere planten onderschepten meer licht en waren daarom productiever en dat leidde tot een snellere toename in het aantal planten en in de waterbedekking. Het leidde echter ook tot een vroeger en sterker effect van de toename in plantdichtheid. Hoewel de trends in productie voor de twee verschillende studies vergelijkbaar waren, waren er ook verschillen. Deze verschillen waren een gevolg van seizoensinvloeden. Temperaturen waren lager en de hoeveelheden straling waren hoger in de eerste studie. Hogere temperaturen en lagere hoeveelheden straling in de tweede studie veroorzaakten een lagere hoeveelheid onderschepte straling en een hogere efficiëntie waarmee deze straling werd omgezet in droge stof. Aanbevelingen over het gebruik van waterhyacint, of een andere plantensoort, voor fytoremediatie kunnen alleen maar op verantwoorde wijze worden gedaan indien we voldoende inzicht hebben in de groeiwijze en de productie-ecologie van de soort. Het begrijpen van wat en hoe de plant remedieert en hoe een plant zich in een systeem gedraagt, is van doorslaggevend belang voor het gehele proces.

Hoofdstuk 5 behandelt het beheersen van de expansie van de plant in de praktijk. We ontwikkelden en evalueerden een systeem om de uitbreiding van de plant binnen de perken te houden. Van pijpen van PVC en van netten van polyethyleen werden drijvende kralen gemaakt die de uitbreiding moesten beteugelen. Deze kralen werden uitgetest langs één van de oevers van een vijver. In elke kraal werden waterhyacinten geplaatst en deze werd een periode van 8 weken gegund om zich te vermenigvuldigen. De kralen bleven verankerd, bleken UV-licht stabiel en bleven drijven. De waterhyacinten in de kralen groeiden snel, met een 141-voudige toename per kraal in acht weken. De kralen hadden geen negatief effect op de reproductie van de waterhyacint. Bovendien waren ze goed in staat om – ongeacht de maasgrootte van de netten of de borging – de zich ontwikkelende biomassa binnen de perken te houden. De kralen waren goedkoop (ongeveer 44 US dollar per kraal). Bovendien konden ze gemakkelijk worden gemaakt, ingezet, verplaatst, en uit de vijver verwijderd. Het systeem kan aan de omstandigheden worden aangepast en indien nodig worden opgeschaald. Het is noodzakelijk om rekening te houden met het gehele ecosysteem indien planten bewust worden ingezet voor fytoremediatie. Het uitzetten van een levend organisme in een ecosysteem kan alleen met de grootste omzichtigheid worden gedaan; voorkomen dient te worden dat er onbedoelde bijeffecten optreden. In dit onderzoek waren we bezorgd of de waterhyacinten konden ontsnappen en een onkruidplaag konden gaan vormen in de natuurlijke wateren.

In hoofdstuk 6 worden enkele vijvers gekarakteriseerd die zijn aangelegd om het overtollig regenwater dat afvloeit op te vangen en vast te houden. Voor twee vijvers (bedoeld voor berging van overtollig en afvloeiend regenwater en voor irrigatie) op de golfbaan van de Bayville Golf Club (BGC), Virginia Beach, VA, USA, en twee vijvers bij de Knotts Creek Nursery (KCN), Suffolk, VA, USA en gedurende twee groeiseizoenen werden gegevens betreffende het beheer, de watergiften en de weersomstandigheden verzameld om deze vijvers nader te karakteriseren. Weersomstandigheden en beheersmaatregelen werden vastgelegd om de invloed daarvan op de waterkwaliteit van deze vier vijvers die zowel voor waterberging als voor irrigatie werden gebruikt, vast te stellen. BGC is een privé golfbaan die intensief wordt beheerd. KCN is een commerciële kwekerij die zich gespecialiseerd heeft in meerjarige potplanten. De concentratie van de totale hoeveelheid opgeloste stikstof werd op verschillende diepten (tot op 305 cm) en op verschillende tijdstippen bepaald, zowel op het punt van toevloed als in het midden van de vijvers. Op BGC werden meer types kunstmest toegediend dan op KCN en dat gebeurde bovendien in hogere frequenties. De N concentraties waren echter op KCN consistent hoger dan op BGC. In het droge jaar 2002 fluctueerden de temperaturen maar licht gedurende het groeiseizoen en ook de diepte had geen groot effect op de watertemperatuur. De stikstofgehalten in het water waren meestal laag en lagen binnen nauwe grenzen (1.0 – 3.5 mg/L op BGC and 2.5 – 6.0 mg/L op KCN). De stikstofgehalten fluctueerden echter meer op grotere diepten. Het jaar 2003 was natter dan normaal. De temperaturen in het water vertoonden een sterkere fluctuatie gedurende het groeiseizoen en met de diepte. De stikstofconcentraties vertoonden ook grotere verschillen gedurende het groeiseizoen (0.75 – 4.2 mg/L op BGC and 0.5 – 6.0 mg/L op KCN) maar werden constanter naarmate het monster dieper was genomen. In dit jaar fluctueerden zowel de watertemperatuur als de stikstofconcentraties meer bij het punt van invoer van overtollig regenwater dan in het midden van de vijvers.

De fytomechanismen die het meest algemeen worden gebruikt in de groene sector zijn fytoextractie (waarbij planten contaminanten absorberen en concentreren) en fytodegradatie (waarbij planten contaminanten absorberen en metaboliseren). Beide mechanismen speelden een rol in ons onderzoek. Op basis van de stikstofconcentraties zoals die werden waargenomen in de vijvers, en stikstofconcentraties in het plantenmateriaal zoals die werden gevonden in de kasproeven, de hoeveelheid invallende straling en de lichtbenuttingsefficiënties kan worden uitgerekend hoeveel biomassa en hoeveel waterbedekking in de vijvers noodzakelijk is om tot afdoende remediatie van een bepaalde hoeveelheid stikstof te komen. Voor alle vier de vijvers bleek dat slechts 20% of minder van de beschikbare oppervlakte van de vijver bedekt hoefde te zijn met waterhyacint om deze remediatie te realiseren.

Wij gebruikten de waterhyacint als modelplant. Echter de onderzoeksprotocollen voor het onderzoeken van de fytoremediatiecapaciteit en het systeem om de waterplanten binnen de perken te houden kunnen ook worden toegepast op andere (drijvende) waterplanten. Voor de praktijk zijn de volgende resultaten van belang:

1. op basis van het onderzoek kan worden aanbevolen om waterplanten te gebruiken voor fytoremediatie van vijvers die het met nutriënten verontreinigd afvloeiend overtollig regenwater bergen en zoals die gebruikt worden bij golfbanen en kwekerijen.
2. we hebben een goedkoop systeem voor het vasthouden van (drijvende) waterplanten die worden ingezet voor fytoremediatie ontworpen dat kan worden opgeschaald en kan worden aangepast aan de eisen die de locatie stelt.

Uiteindelijk moet de aanbevelingen en het ontwerp gezamenlijk leiden tot een nieuw BMP dat op zichzelf staand of samen met andere BMPs kan worden ingezet om het grote probleem van de waterverontreiniging met overmatige stokstof en fosfor in afstromend overtollig regenwater.

Curriculum vitae

Laurie Jo Fox was born in Richmond, Virginia, USA on August 13th, 1968. After completing basic education, she was accepted into the horticulture program at North Carolina State University in Raleigh, NC, where she obtained her BS degree in 1990 majoring in landscape design and ornamental plant production. Laurie also obtained her MS degree in 1993 from North Carolina State majoring in weed science. Her thesis work involved off target injury of herbicides to landscape trees. While in school Laurie gained practical work experience through jobs at a commercial nursery and private design and maintenance company. After graduation she accepted a position with the North Carolina Cooperative Extension Service as a horticulture agent covering the areas of commercial vegetable and ornamental horticulture production and urban horticulture for Robeson and Scotland Counties. When the opportunity became available in 1996 to cover the Weed Scientist Extension Specialist position while that faculty member was on sabbatical, Laurie became a faculty member in the Plant Pathology, Physiology, and Weed Science Department at Virginia Tech University based at the Hampton Roads Agricultural Research and Extension Center (AREC) in Virginia Beach, VA. Her work for that year focused on evaluating herbicides for weed management in container produced landscape ornamentals. In 1997 Laurie shifted to a Horticulture Associate position in the Horticulture Department and remained at the AREC. Her research and extension efforts refocused to sustainable practices for urban landscapes and water quality issues. She conducted studies evaluating wastewater (treated effluent) for landscape irrigation. Laurie began her PhD work in 2001 when she was accepted into the programme in the Crop and Weed Ecology Group of the Department of Plant Sciences at Wageningen University, Wageningen, The Netherlands, under the supervision of Prof. dr. ir. P.C. Struik. Her supervisors at Virginia Tech University were Dr. J.E. Nowak and Dr. B.L. Appleton. The PhD research focused on phytoremediation of nutrient polluted runoff using water hyacinth. Laurie plans to continue her phytoremediation research in conjunction with Dr. Appleton focusing on woody ornamental plants for urban landscapes.