Cattail (*Typha* spp.) Biomass Harvesting for Nutrient Capture and Sustainable Bioenergy for Integrated Watershed Management

By

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Abstract

High levels of phosphorus loading in Lake Winnipeg, Manitoba, Canada are causing eutrophication and algal blooms of increasing intensity and frequency. Phosphorus is also a strategic and limited natural resource critical for plant growth, and essential for agriculture and global food security. This research study demonstrated an innovative environmental engineering approach to address multiple sustainable development challenges. Cattail (*Typha* spp.), a large competitive emergent aquatic plant, was harvested to capture and remove nutrients that would otherwise cause eutrophication in aquatic systems, and utilized as a biomass material for industry. Cattail reaches maturity in less than 90 days, and late summer/early fall harvests yielded average 15 to 20 t DM/ha, and captured 30 to 60 kg/ha/year of phosphorus. Once harvested, nutrients locked in plant tissue are prevented from being released into the environment via natural decomposition. Utilizing harvested biomass as a bioenergy feedstock provided a further benefit displacing fossil fuels for heating, and generated valuable carbon offsets. Cattail was compressed into densified fuel products, and combustion trials revealed an average calorific heat value of 17 MJ/kg to 20 MJ/kg, comparable to commercial wood pellets. Average ash content was 5 to 6%, and no major concerns were identified regarding combustion emissions and ash. Estimated greenhouse gas (GHG) mitigation potential from coal displacement was one tonne of cattail biomass generated 1.05 tonnes of CO_2 offsets. Additionally, up to 88% of total phosphorus was recovered in ash following combustion in solid fuel burners. Harvesting cattail biomass offers greatest feasibility if combined for multiple purposes: nutrient capture, habitat, bioenergy,

carbon offsets, water quality credits, and higher value end products and biomaterials (i.e. biochar). Economics of harvesting need to be further explored at the pilot and commercial scale for this novel renewable and sustainable ecological biomass feedstock. From an agricultural context, this biomass resource is presently undeveloped. It is a plant species prized for its nutrient capture and water quality benefits, and a biomass feedstock for bioenergy and high value end-products that grows on marginal agricultural land, not competing with prime land and food crops.

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Dedication

This PhD is dedicated to Christine, Vincent, Jessica, and Emma, who were integral partners on this journey and experience. From creation to finish. Showing me why the larger meaning of the research mattered.

Every journey begins with a single step…

“One day I was speeding along at the typewriter, and my daughter - who was a child at the time - asked me, "Daddy, why are you writing so fast?" And I replied, "Because I want to see how the story turns out!"

. . . Louis L'Amour

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1.1.1 Water Food Energy Nexus and the Bioeconomy

As we move further into the 21st century in the face of widespread concerns around water, energy, and food security, greater protection of our water resources and the increasing use of sustainable renewable inputs to industrial economies are inevitable and urgent. The concept that water, energy and food are intimately interconnected is well established, that actions in one area more often than not have impacts in one or both of the others (World Economic Forum, 2011). The World Economic Forum (2011) describes the demand for water, food and energy to rise by 30-50% in the next two decades, and that any strategy that focuses on one part of the water-food-energy nexus without considering its interconnections risks serious unintended consequences (World Economic Forum, 2011). Flooding, water supply and quality, nitrogen and phosphorus overloading, global food security, resource and energy scarcity, clean reliable sustainable alternative energy, and reduction in GHG and global carbon emissions, are some of the significant sustainable development challenges facing regions around the world. Often these issues are dealt with in isolation, but there are significant environmental and economic opportunities to address them in an integrated coherent approach. Natural ecosystems provide innovative solutions to address these multiple sustainable development challenges by harnessing natural processes and novel plant species that can deliver multiple environmental as well as economic co-benefits. Novel plant species or forms of ecological biomass for example, can be harvested to provide material inputs for industry, while simultaneously addressing environmental issues. Combining multiple environmental benefits and economic revenues will not only greatly increase the viability of environmental management, but sustainability of emerging bioeconomies - economic systems where the raw material for industry comes from harvested plant material or biomass (OECD 2012).

1.1.2 Wetland plants for nutrient capture and biomass bioenergy

Fresh water is one of the most important natural resources on our planet and is essential to human populations (Naiman et al. 1995), and yet, the quality of fresh water sources continues to decline at an astonishing rate due to human induced impacts and changing climates. Stresses such as urban expansion and development, resource extraction, industry, and agriculture can cause significant freshwater issues (McRae et al. 2000). Proper watershed management is critical to maintaining water quality and sustainability (Naiman et al. 1995, Gabor et al. 2001), emphasizing the importance of understanding the fundamental components that collectively make up our watersheds. Ecosystems provide critical ecological goods and services or EGS benefits through nutrient and contaminant removal, carbon storage, water storage and ground water recharge, reduction of flood impacts, and wildlife habitat and biodiversity (Kadlec and Knight 1996, Gabor et al. 2001, Mitsch and Gosselink 2007).

Wetlands and their aquatic plant communities are an important component of proper watershed management effectively reducing nutrient enrichment downstream (Gabor et al. 2001). They improve the quality of water flowing through them by removing and assimilating nutrients and toxins before reaching rivers and lakes. Unfortunately, over 70% of these natural filters, or Nature's Kidneys, have been drained and lost in Canada over the past century (Ducks Unlimited Canada 2012). Nutrient overloading or eutrophication of freshwater lakes is a serious water quality issue globally (UNEP 2011). Nutrients such as nitrogen (N) and phosphorus (P) are required to support living organisms, but become harmful to any water body when their loads exceed the water's natural capacity to manage them (Mitsch and Gosselink 2007). Excessive loading has a significant impact on fresh and marine waters by stimulating plant growth and promoting weed species and algal blooms that can reduce water quality, causing severe oxygen depletion when they decay (Mitsch and Gosselink 2007). UNEP (2011) recently emphasized how phosphorus, also an essential element for food production, is limited in global supply and that better insight is needed into the availability of this non-renewable resource and the environmental consequences associated with its use.

Natural systems have been successfully utilized around the world to address environmental issues through passive and active environmental engineering approaches (Kadlec and Knight 1996, Jiang et al. 2005, Vymazal 2006). Wetlands and riparian areas are very effective at reducing flooding, capturing nutrient rich runoff water from agricultural fields, preventing erosion and sediment buildup, and ultimately preventing nutrient loading and contamination. This is due in large part to the plants and microbes within these systems which actively absorb and cycle nutrients and contaminants while sequestering carbon from the atmosphere, producing a significant amount of plant biomass each year (Gabor et al. 2001). Managed and constructed wetland systems take advantage of these plants and microbes for treating nutrient enriched storm water, agricultural runoff, as well as wastewater from urban and rural sewage (US EPA 1993). Aquatic plants are prized for their nutrient absorbing capacity and are utilized for bioremediation of heavily contaminated sites (Jiang et al. 2005, McDonald 2006, Kadlec and Knight 1996).

In many European countries, wetland plants are often harvested or mowed to control the spread of invasive species and maintain productivity and biodiversity (Wyss 2004, Vymazal 2006, Wichtmann and Tanneberger 2009, Wichtmann et al. 2010, Wichtmann et al. 2012), but the harvested material is often left at the field edge as a waste material. The harvested plant material represents a valuable biomass feedstock for biomaterials or solid fuel to produce heat or electricity. Bioenergy is the production of energy from biological material, and globally it is considered a promising sustainable and renewable energy source to displace the use of carbon emitting fossil fuels and reduce global carbon and GHG emissions (Paine et al 1996). Demand for biomass fuel products and liquid biofuels continues to increase globally, driven by the need to reach legally-binding targets to cut carbon emissions as part of environmental policies (Schaps 2013).

Lake Winnipeg, in Manitoba, Canada, is the 10th largest freshwater lake in the world. It is also considered one of the most eutrophic and suffers from excessive loading of nutrients (i.e. nitrogen and phosphorus) from throughout its 1,000,000 km^2 watershed. High levels of phosphorus in Lake Winnipeg are causing algal blooms of increasing intensity and frequency that consume oxygen and can release dangerous toxins (Lake Winnipeg Stewardship Board 2005). Evidently, phosphorus, the noxious pollutant fouling Lake Winnipeg, is also a valuable natural resource important for plant growth, and critical for agriculture and global food security (Ulrich et al. 2009). The fact plants like *Typha* spp. (cattail in North America or bulrush in Europe) soak up these nutrients (i.e. phosphorus) that would otherwise flow into waterways and cause eutrophication and large-scale algal blooms represents a significant opportunity for watershed scale nutrient management, and a key driver for the regional bioeconomy. Harvesting novel plants such as cattail as a sustainable and renewable biomass feedstock for use in the biomass industry also delivers valuable ecological services through nutrient capture and reduction of nutrient loading (i.e. phosphorus) to downstream water bodies. Cattail is an extremely resilient and competitive, large emergent aquatic plant characteristic of wet environments in North America growing wherever standing water persists, and is prized for its nutrient capture and water quality benefits (Kadlec and Knight 1996). It also represents an under-utilized source of biomass that has the potential to be integrated into solid and cellulosic bioenergy systems to help meet increasing sustainable energy demands.

1.1.3 Introduction to study objectives

The purpose of this study is to evaluate the harvesting of cattail (*Typha* spp.) for multiple combined benefits: to capture and remove nutrients thereby reducing nutrient loading (i.e. phosphorus) to aquatic systems, use of the harvested cattail biomass as a renewable and sustainable biomass feedstock for energy production and reduction in global carbon (GHG) emissions, and recovery of phosphorus – a valuable strategic resource critical for global food security. This study demonstrates an innovative solution to harvest novel plant species, or forms of ecological biomass, to address multiple environmental issues much more strategically and profitably while delivering higher environmental and economic values. We can address environmental issues profitably rather than at a cost, and produce revenue while maximizing environmental benefits.

1.2 Manitoba Context: Innovative Solutions for Lake Winnipeg

1.2.1 The Lake Winnipeg Watershed

The Lake Winnipeg watershed encompasses a highly drained and modified geographic region across Provincial and US borders, draining an area of approximately 1 million km^2 (Figure 1.1). This region is prone to flooding in the spring with an abundance of dissolved nutrients transported in flood waters. Consequently nutrient loading to the lake is made worse by dramatic spring flood events (McCullough et al. 2012). An overabundance of phosphorus in Lake Winnipeg causes algae blooms that wash ashore on beaches. Of concern is the increasing size and frequency of algae blooms in the north and south basins of the lake (Lake Winnipeg Stewardship Board 2005). The phosphorus within the Lake Winnipeg watershed comes from a complex diversity of sources: runoff from sewage, agricultural crop fertilizer and livestock, and large urban centers. Much of the watershed encompasses the heavily modified and drained landscape of the prairie agricultural region where many of the natural wetlands, prairies, and riparian areas have been lost, resulting in a loss in natural EGS benefits such as water and nutrient retention (Ducks Unlimited Canada 2012).

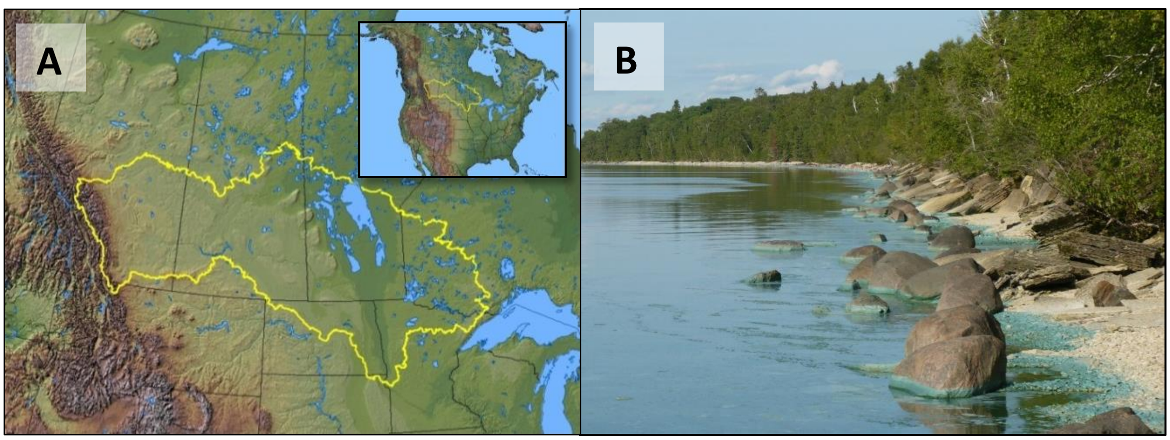


Figure 1.1. A) The Lake Winnipeg watershed encompasses a highly drained and modified landscape. B) Overabundance of phosphorus causes algae blooms.

Because of the ecological significance of Lake Winnipeg further environmental protection measures need to be taken to protect and restore the lake to an ecologically healthy condition. The Manitoba Government's aggressive goal to reduce nutrient levels in Lake Winnipeg by 50% is identified in Bill 46 the Save Lake Winnipeg Act, by protecting wetlands, controlling runoff, and reducing nutrient loading within the watershed. Exploring innovative solutions has been identified as a key objective of the Government of Manitoba to accomplish these goals (Government of Manitoba 2011a).

1.2.2 Netley-Libau Marsh: Lake Winnipeg's Coastal Wetland

Netley-Libau Marsh lies at the mouth of the Red River along the south end of Lake Winnipeg (Figure 1.2). At 250 km^2 in size, it is one of the largest freshwater coastal wetlands in Canada. It is comprised of shallow lakes, channels and wetland areas through which the Red River flows on its way to Lake Winnipeg. It is designated an Important Bird Area by Bird Studies Canada and the Canadian Nature Federation providing important habitat for wildlife. The area is traditionally used for agriculture and recreation, but more significantly, the wetland provides an array of diverse ecological goods and services. A healthy coastal wetland acts as a natural filter and can store and remove a significant amount of nitrogen and phosphorus from runoff (Neely and Baker 1989, Kadlec and Knight 1996). Unfortunately, EGS benefits have been compromised by drainage, dredging, flooding, and water management over decades, with a significant loss of habitat, gradual loss of plant communities, erosion of channels and islands, and subsequent decline in wildlife populations (Grosshans et al. 2004). Nevertheless, revitalization through restoration and management of this important coastal wetland could help restore degraded environmental benefits. Nutrient capture is an important and overlooked function of this marsh that is understood as a key component of a Lake Winnipeg basin nutrient management strategy.

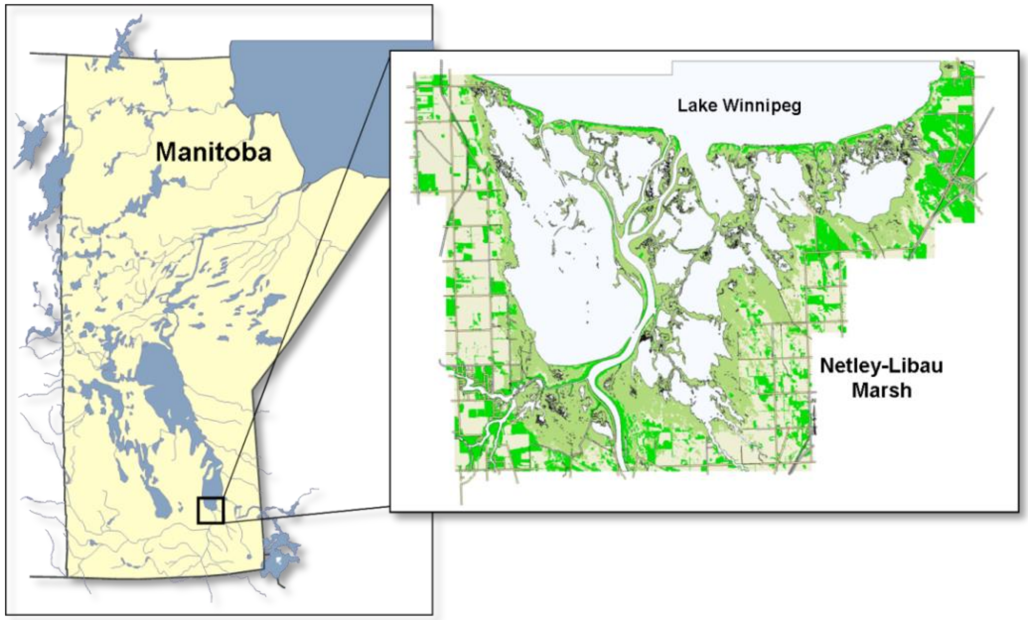


Figure 1.2. Location of Netley-Libau Marsh, at the south end of Lake Winnipeg, Manitoba, Canada at the mouth of the Red River (source: Grosshans et al. 2004).

1.2.3 Cattail (*Typha* spp.) - Ecological Biomass for Multiple Benefits

Cattail (*Typha* spp.) is a large robust and prolific emergent plant found in wetlands, ditches, and on marginal agricultural land across North America. The most widespread species is broad-leaf cattail *Typha latifolia*, extending across the temperate and northern hemisphere, as well as narrow-leaf cattail *Typha angustifolia*, and their hybrid *T. x glauca.* Southern cattail or *T. domingensis* is found throughout temperate and tropical regions of the world, such as the Florida Everglades (Li et al. 2010). *Typha* spp. (hereafter referred to as cattail) is extremely productive and competitive and grows wherever standing water persists. It sequesters carbon from the atmosphere and takes up nutrients from the sediment as it grows, incorporating these components into plant biomass. They can grow to a height of over 2 meters and produce considerable standing plant biomass within a single growing season. It primarily spreads by underground rhizomes but also produces large volumes of seed that colonize open areas and mudflats. Cattail is also very effective in absorbing nutrients and is commonly used in constructed wetlands for wastewater treatment (Lakshman 1979, Cheng et al. 2002, Martin et al. 2003, Cicek et al. 2006). Studies of nutrient uptake in treatment tanks used to purify untreated raw municipal wastewater demonstrate the extraordinary ability of cattails for water quality improvement, and suggest harvesting cattail in natural eutrophic systems to reduce downstream nutrient loading could be significant (Lakshman 1979, 1984, Weng et. al. 2006).

Cattail was also explored as an alternative energy crop for bioenergy production by the US Department of Energy and the Saskatchewan Research Council in the 1970s (Lakshman 1984, Pratt et al. 1984, 1988, Dubbe et al. 1988, and Garver et al. 1988). The economics of harvesting solely for bioenergy, however, was not considered viable at that time. Although it was determined to be an excellent bioenergy feedstock with excellent energy properties for solid fuel (Dubbe et al. 1988) and ethanol (Lakshman 1984), it was too difficult and costly to be used as a planted energy crop. Cattail was more recently evaluated for storm water retention and bioenergy in Sweden (Wyss 2004) and in Canada (Cicek et al. 2006) and it was concluded this fast-growing and ubiquitous plant could become ecologically and economically important for bioenergy production. By considering modern environmental and economic benefit analysis beyond simple heat production, the benefits of harvesting cattail biomass could be significant (Venema et al. 2005, Cicek et al. 2006, Grosshans et al. 2011). The International Institute for Sustainable Development (IISD) has most recently demonstrated at a commercial pilot scale the harvesting of cattail for nutrient capture and bioenergy, and that the harvested material can be utilized for higher value bioproducts, biochar, beyond simply an alternative sustainable low-carbon fuel source to displace the use of fossil fuels (i.e. coal) for heat and energy (Grosshans et al. 2011, Grosshans and Greiger 2013).

1.3 Introduction to the concepts: Wetlands for Water Quality, Biomass Production, and Bioenergy

1.3.1 Wetland plants for water quality

Wetlands improve water quality by retaining, removing and assimilating nutrients, suspended sediments, pathogens, pesticides, heavy metals, and contaminants (Kadlec and Knight 1996, Mitsch and Gosselink 2007). A wetland's ability to trap and filter nutrients and toxins relies in part on its aquatic plant community (Mitsch and Gosselink 2007). Larger emergent wetland plants assimilate large amounts of nutrients from the sediment and organic layers into accumulated biomass. They also slow water flow, which helps retain nutrients by physical sedimentation into the organic litter and sediment layers where they are later taken up by the plants. Plants also provide a combination of aerobic and anaerobic conditions that facilitate chemical transformations, and organic litter or peat accumulation that also permanently buries nutrients (Wang and Mitsch 2000).

A plant's ability to absorb nutrients makes them potential tools to remove nutrients and toxins from aquatic systems (Lakshman 1979, Smith et al. 1988, Koottatep and Polprasert 1997). Larger emergents such as cattail, giant reed (*Phragmites* spp.), and reed canary grass (*Phalaris* spp.) are often mowed to control the spread of these highly invasive species (Wyss 2004, Wichtmann and Tanneberger 2009). But harvesting these plants could have significant nutrient removal benefits because of their large stores of absorbed nutrients (Lakshman 1979, Smith et al. 1988, Koottatep and Polprasert 1997). If these plants are harvested when they retain enough nutrients, this could capture significant stored nutrients and ultimately reduce nutrient loading to downstream lakes (Martin and Fernandez 1992, Vymazal 2006). Harvesting nutrient rich biomass material prevents nutrients from being re-released into the aquatic system as naturally occurs from dead decomposing plant material (Toet et al. 2005, Morris et al. 1986).

Harvesting wetland plants to remove stored nutrients has shown success in natural and cultivated stands. Pratt et al. (1984) through fertilization experiments indicated nutrients such as nitrogen and phosphorus are taken up and removed by harvesting cattail plants. Most studies of harvesting have been primarily in experimental settings (Lakshman 1979, Liu et al. 2003, Weng et al. 2006) and constructed and semi-engineered wetlands receiving relatively high nutrient loads from treated or secondary waste water effluent (Pratt et al. 1984, Toet et al. 2005, Jiang et al. 2005, Vymazal 2006). It has been suggested much greater success could be obtained from harvesting in tertiary or polishing treatment wetlands and eutrophic natural wetland systems compared to the high nutrient loadings from treatment wetlands (Toet et al. 2005, Cicek et al. 2006, Vymazal 2006). Martin and Fernandez (1992) do indicate periodic harvesting of aboveground cattail biomass after leaf drying would remove elements from the water in the long term. Harvesting plants is used for bioremediation to mitigate pollutant concentrations in contaminated water and soils with plants that are able to contain, degrade, or eliminate nutrients, metals, pesticides, solvents, and various other contaminants from the media that contain them (McDonald 2006, Wani et al. 2012).

1.3.2 Wetlands and bioenergy - Ecological Biomass for the Biomass Industry

Traditional uses of harvested wetland plants are for building and thatching materials (Boar and Leeming 1997, Ozesmi 2003), paper pulp (Bates et al. 1994), animal fodder (Yakubovskii 1975), mulch (Calado and Duarte 2000), or even fibreboard (Fraunhofer 2012). Harvesting wetland plants for energy is not a new concept. Peat from fens and bogs, cattails, and reeds have been used as a solid fuel for burning and heat production for centuries (Bjork and Graneli 1978, Graneli 1984, Allirand and Gosse 1995, Cheng et al. 2002). More recently, high efficiency conversion of wetland plants for bioenergy (i.e. cattails and reeds) has been evaluated at the research scale (Pratt et al. 1988, Lakshman 1984, Reddy and Smith 1987, Xu et al. 1999; SAFTI 2003, Cicek et al. 2006).

Bioenergy is low-carbon energy produced from biological material, and has the potential to provide significant amounts of heat and electrical energy to address future energy demands by producing far fewer GHG emissions (Paine et al 1996). This is certainly evident in Europe, where biomass has been actively promoted and utilized for the past several decades at a commercial scale to offset coal for energy production (Faaij 2004). Government policies to reduce greenhouse gas emissions are driving the need for renewable and sustainable alternative energy options to generate energy with minimal amounts of net-carbon emissions (Cook and Beyea 2000, Duncan 2004). Harvested plant material provides valuable biomass to produce cleaner bioenergy. Wood as charcoal is still the most common form of fuel for simple heating and cooking applications in developing countries, although it is considered an unsustainable practice (Caro et al 2011). In Senegal 2.5 million trees are cut down annually for charcoal nationwide, which is currently driving the exploration for more sustainable options (Caro et al 2011). Dry biomass can be directly burned to produce heat energy, but in industrialized nations, newer high efficiency technologies utilize biomass as low-carbon solid fuel substitutes to carbon emitting fossil fuels to produce cleaner emission heat, energy, and combined heat and power (CHP). Biomass energy is considered to be a low carbon source of energy since CO_2 absorbed from the atmosphere by the plants during growth is returned back to the atmosphere during combustion. A further economic benefit is gained through reduced GHG emissions and carbon offset credits to be sold on global carbon markets (Cicek et al. 2006).

Typical biomass sources include waste timber wood, sawdust from manufacturing, agricultural residues (i.e. straw, flax chives, corn stover), and planted energy crops like switch grass and miscanthus (Zub and Brancourt-Hulmel 2010). But there is an identified need to expand the portfolio of renewable sustainable biomass sources for use as feedstocks in the bioenergy and biofuel industries (USDOE 2011). Feedstock sustainability is a significant risk to the biomass industry, and developing biomass into a sustainable source of affordable biopower and fuels will require the flexibility to use a wide variety of sustainable biomass resources (USDOE 2011). Exploration of higher value uses and end products beyond simple heat production, i.e. biochar, cellulosic ethanol, biofibres, or bioplastics, and economic instruments through carbon offset markets can significantly improve cost: benefit economics. A market protocol for biomass combustion in Alberta relates to avoided GHGs from switching to biomass from fossil fuels as well as avoided GHGs by combusting biomass vs. undergoing anaerobic decomposition (Government of Alberta 2007). In addition, identifying novel plant species that are utilized for environmental remediation, such as cattail and reeds, which are viable biomass feedstocks will position biomass as not only a low-carbon fuel source but one that delivers multiple environmental and economic co-benefits. Economic sustainability of the biomass industry is greatly improved when multiple EGS benefits and economic values are considered. Cattails, which are very effective in capturing nutrients and toxins (Lakshman 1984, Pratt et. al. 1984, 1988), represents a renewable and sustainable source of biomass for bioenergy, biomaterials, and high value end-products. Exporting cattail biomass as a revenue generating feedstock would be a welcome by-product from wetland management or municipal ditch maintenance, which are all managed at a cost to local governments (Cheng et al. 2002). In addition, utilizing plant species that grow on marginal agricultural land provides landowners a greater economic value from otherwise unproductive marginal agriculture land and does not compete with prime agricultural lands and food crops, which addresses the ongoing food vs. fuel debate and current criticisms with bioenergy and biofuels around the globe (UN 2013). Primary food crops (i.e. sugar cane and corn) are used to produce ethanol, while oilseeds (i.e. soybeans, canola, and palm oil) are used to produce biodiesel (Duncan 2004). Major criticisms surround the competition it places on world demand for food crops and animal forage (Evans 2008).

1.3.3 Demand for global biomass supplies

The demand for biomass fuel products and biofuels continues to increase globally in order to reduce global carbon emissions since switching from coal to biomass for use in power plants results in low carbon emissions. Biomass is typically compressed into densified pellets, logs, briquettes, or cubes for efficient transport, storage and burning for bioenergy. China and Europe's demand for biomass fuel pellets to produce electricity represents the largest global demand, with European demand expected to triple by 2020 as governments, notably Britain, Sweden, Denmark, and the Netherlands, offer subsidies for greener energy sources to replace dirtier coal in electricity generation (Schaps 2013). The demand for pellets in Europe is estimated to reach 29 million tonnes in 2020, up from 8 million tonnes in 2010 (Schaps 2013). This demand for densified biomass represents a potential opportunity to grow the North American market to meet global demands. Use of biomass in Canada is growing and it is anticipated this growth will continue with federal and provincial renewable energy policies and regulations to reduce the use of coal (Sawyer 2011).

1.3.4 Harvesting in wetlands - Wet Agriculture

Harvesting in wetland environments presents some serious logistical challenges. Various equipment has been used in the past to harvest plants from wetlands either for biodiversity management, energy production, or nutrient removal, and specialized equipment has been developed in Europe for these specialized wet agriculture purposes (De Vries Cornjum 2013, Pisten Bully 2013, LogLogic 2013, Seiga 2013, and Reeda 2013). Several studies indicate winter ice covered conditions provide suitable conditions for harvesting in wetlands for management and bioenergy purposes producing dry feedstock for burning (Granelli 1984, Cicek et al. 2006), but whether enough nutrients remain in dead aboveground biomass to effectively remove N and P for nutrient capture is relatively unknown. Additionally, snow and ice conditions often present some serious challenges, preventing harvesters from accessing wetland areas. Effects of harvesting in Canadian wetland environments is also relatively unknown. Other challenges include volume of harvested material, drying, moisture content, general quality of the biomass for energy, calorific value, and the energy conversion technology. Because wetland systems differ quite dramatically from one area to the next, and the goals of wetland biologists, nutrient managers, and bioenergy producers differ, the impacts and priorities need to optimally merge the discrete functions of wetland management, water treatment, and bioenergy production (Martin et al. 2003).

1.3.5 Manitoba Biomass potential

The Federal and Provincial governments of Canada are taking steps to reduce GHG emissions, by 2020 to 607 Megatonnes (Mt). Manitoba's coal tax of $10 per tonne of CO_2 equivalents (Government of Manitoba 2012a), and a mandate to eliminate coal for heat production by 2014, requires an immediate need for alternative energy sources for industries, communities, and small coal users in MB to reduce their reliance on coal. In Manitoba approximately 3% of the energy used comes from coal burning, which represents about 385,000 MT of coal, 40% of which is used for industrial and commercial heating (Figure 1.3).

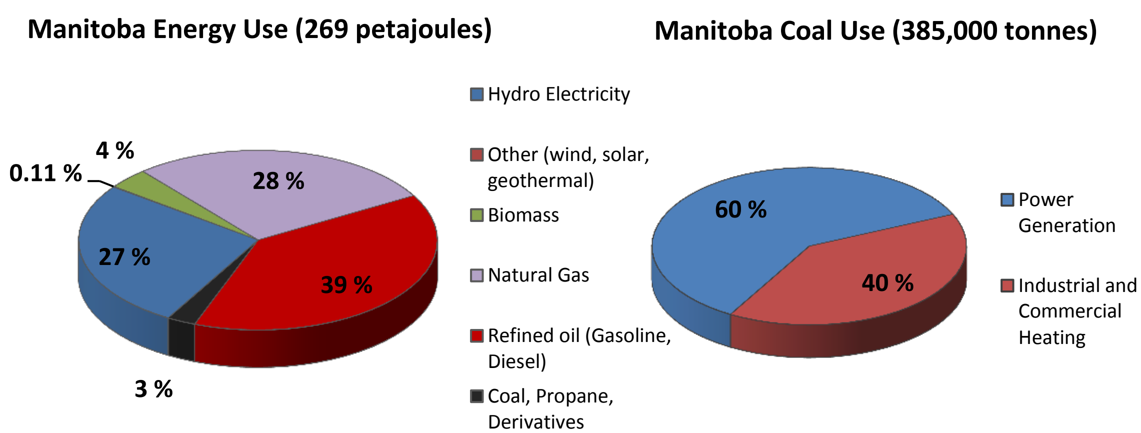


Figure 1.3. (left) Manitoba energy usage and (right) coal use of 385,000 metric tonnes – 40% used for heating (*source: http://www.50by30.org/current-realities/*)

Greenhouse gas (GHG) emission credits created by displacing high-carbon emitting fossil fuels with low-carbon emitting biomass greatly enhance the value of harvesting a novel biomass like cattail (Cicek et al. 2006). Carbon offset equivalents are determined from the direct displacement of fossil fuels with biomass. Additionally, methane avoidance could be considered, which is associated with harvesting of biomass that could naturally decompose anaerobically to produce methane – a greenhouse gas 21 times more potent than CO_2 (Government of Alberta 2007). Although the cost-benefit analysis will strongly depend on the economic and environmental circumstances for each application, the proposed concept of cattail biomass harvesting holds great promise for combining the benefits of bioenergy/emissions credits with the difficult challenge of nutrient control and watershed management.

1.4 Primary PhD Research Focus

This research study identifies three major components:

1. Seasonal plant biomass accumulation, plant nutrient uptake, nutrient accumulation in the litter and sediment layers, and plant-sediment nutrient interactions of the cattail communities in Netley-Libau Marsh, Manitoba.
2. Sustainable harvest of cattail biomass to remove stored nutrients to reduce nutrient loading - evaluating timing of harvest and harvest impacts
3. Use of harvested cattail as a biomass feedstock for bioenergy production - evaluating value of cattail biomass, densified forms, heat production, economics, and recovery of phosphorus from ash post-combustion.

1.5 Objectives and Hypothesis

The objective of this study is to evaluate an innovative solution to address phosphorus loading to Lake Winnipeg, while producing biomass for industry. Harvesting cattail for bioenergy and biomaterials could be a viable mechanism for intercepting phosphorus before it enters Lake Winnipeg.

The Hypothesis is removal of plant material and their stored nutrients will reduce nutrient loading to aquatic systems. Harvesting of accumulated deadfall will also improve marsh habitat by opening the site to sunlight and new plant growth, and controlling dominant plant growth.

This study evaluates the harvesting of cattail to capture nutrients and reduce phosphorus loading to Lake Winnipeg, and use of harvested cattail as a novel renewable and sustainable biomass feedstock for bioenergy production. Explored is the generation of carbon offset credits and reduction of greenhouse gas (GHG) emissions using cattail as a feedstock in place of carbon emitting fossil fuels such as coal for heat production. Also evaluated is the recovery of high-value phosphorus from ash following combustion for greater environmental and economic benefits. The goal is to demonstrate that using biomass more strategically we can address multiple environmental issues profitably rather than at a cost, by producing valuable end-products for revenue while maximizing environmental benefits. This study evaluates the economic feasibility of harvesting and using cattail biomass as a feedstock for the biomass industry.

An additional objective is to gain greater knowledge on the importance of wetlands to the health of Lake Winnipeg, and how passive engineering options such as harvesting a novel plant species like cattail can reduce nutrient loading, while enhancing wetland habitat, and creating incentives for wetland restoration.

1.5.1 Objectives

1. **Wetland Biogeochemistry**
    a. Examine cattail growth and productivity, biomass accumulation, nutrient uptake through the growing and winter season, nutrient removal potential, and plant-sediment nutrient interactions.
    b. Measure phosphorus storage in the marsh sediments.

2. **Harvesting for Nutrient Capture and Recovery**
    a. Evaluate harvesting aboveground cattail biomass to remove stored nutrients - comparing both late summer and winter/spring harvests.
    b. Examine short and long-term impacts of harvesting:
        i. Identify ideal timing of harvest seasonally with nutrient content,
        ii. Impacts and sustainability of harvesting.

3. **Conversion of Cattail Biomass to heat energy**

    a. Viability of cattail as a renewable sustainable biomass feedstock for bioenergy production, energy value compared to other feedstocks.

    b. Evaluation of densification for fuel cubes and pellets.

    c. Conversion of Biomass - test burns and evaluation of cattail in suitable bioenergy conversion technologies.

    d. Evaluate cattail as a low-carbon biomass source for mitigation of greenhouse gas emissions and creation of carbon emission offset credits for cost-recovery.

4. **Recovery of Phosphorus**

    a. Evaluate phosphorus recovery from harvested cattail biomass within ash following combustion.

5. **Netley-Libau Marsh proof of concept**

    a. This study will be a valuable proof of concept: harvesting to capture nutrients, reduce loading to Lake Winnipeg, and wetland biomass for bioenergy.

1.6 Thesis organization

Chapter 2 includes a literature review of:

1. Wetlands and water quality: how emergent freshwater marshes naturally remove and retain various nutrients and contaminants, with some comparison to engineered and wastewater treatment wetlands and the role of emergent plants in water quality.
2. Biogeochemistry of wetland plants and sediment and nutrient interactions and seasonal plant nutrient cycling and fate.
3. Harvesting of wetland plants for nutrient removal and biomass for bioenergy production, including successes in the literature for removing stored nutrients, methods for marsh harvesting, wetlands for bioenergy, and value for bioenergy.

Chapter 4 examines biology and biogeochemistry of cattail, results of harvesting, seasonal biomass and nutrient accumulation, plant-sediment nutrient interactions, seasonal timing of harvests and nutrient loss, phosphorus captured and removed by harvesting, and impacts of harvesting on cattail communities and marsh biodiversity.

Chapter 5 focuses on the bioenergy perspective - use of cattail as a renewable feedstock for biomass bioenergy production to displace fossil fuels for heating. It examines biomass properties and densification, combustion for heat production, and recovery of phosphorus from ash following combustion.

Chapter 6 and 7 identify the economics of harvesting this novel bioenergy feedstock with multiple benefits and high sustainability characteristics directly targeted at users seeking viable alternatives to fossil fuels for space heating and air emissions reductions, and the larger significance for nutrient management in the Lake Winnipeg Watershed. Carbon offsets produced from displacing fossil fuel and carbon markets are discussed in chapter 6, and significance in chapter 7.

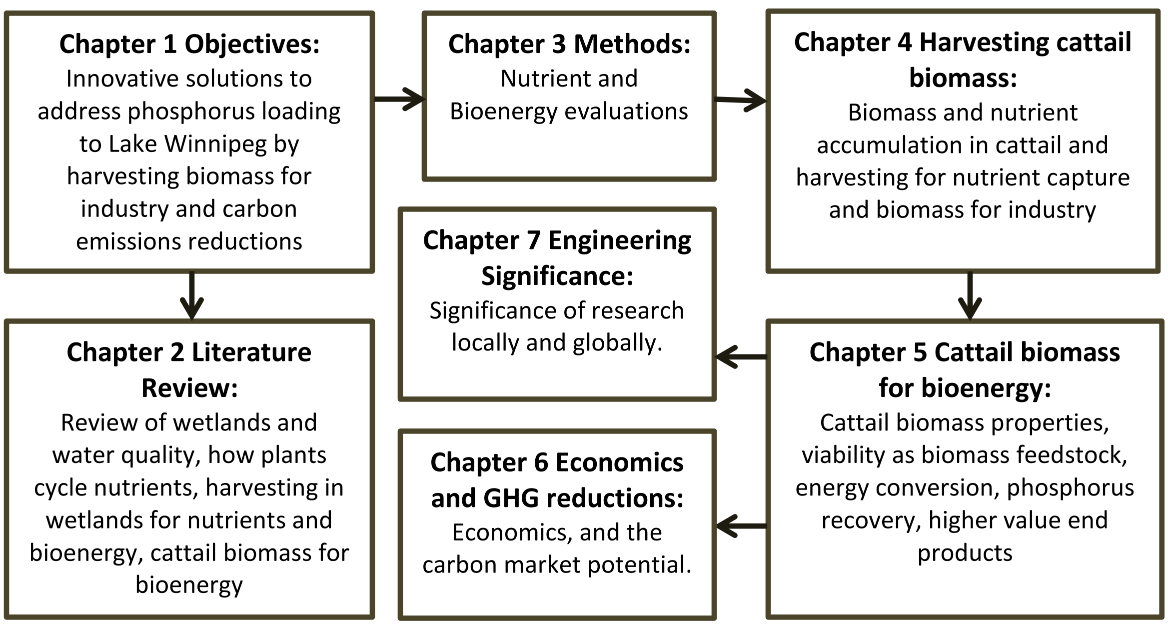


Figure 1.4. Thesis organization – An innovative solution of harvesting cattail (*Typha* spp.) to address nutrient loading (i.e. phosphorus) in the Lake Winnipeg Watershed, while producing biomass for industry and recovering valuable resources.

2.0 Literature Review - Ecological Biomass for Multiple Co-benefits

Nutrient Capture, Bioenergy, Carbon Emission Offsets, Habitat Improvement, and Phosphorus Recovery

This review examines the literature on sustainable wetland biomass harvesting for nutrient capture and biomass bioenergy. Reviewed is nutrient uptake in wetlands in the context of upstream water quality improvement within natural landscapes, and the potential of harvesting wetland plants as an integrated component of watershed management to reduce nutrient loading in aquatic systems. This chapter focuses on the important role and functions of larger rooted emergent plants in wetland ecosystems (i.e. *Typha* spp., *Carex* spp., *Schoenoplectus* spp., and *Phragmites australis*) and their role in nutrient capture and removal. Nutrient removal has been attained harvesting plant species from eutrophic and nutrient loaded wastewater systems, although the degree of success depends on the wetland type, lab vs. field scale, loading rates, and objectives. Harvesting wetland plants is a common practice in Europe simply for biodiversity and nuisance plant control (Wichtmann and Tanneberger 2009), but the nutrient capture benefits of harvesting in natural eutrophic systems could be significant.

Also reviewed is the use of harvested cattail (*Typha* spp.) and wetland biomass as a renewable, sustainable, and economically viable feedstock for bioenergy, biomaterials, and higher value end-products. Harvesting in a wet environment does produce many challenges, particularly harvesting equipment design, logistics, and timing of harvest. Low-impact harvesters that can handle wet and waterlogged wetland conditions are needed beyond traditional farm equipment. Harvesting in wetlands is common in Europe for plant biodiversity management and reed roof thatching, and a range of wet agricultural equipment and harvesters have been developed in Europe over the past several decades with application potential in North America for wetland harvesting.

2.1 Wetlands for Water Quality

2.1.1 Wetlands in the landscape

Wetlands are considered one of the most productive ecosystems on Earth, producing a tremendous amount of biomass within a single season (Kantrud et al. 1989). They provide critical habitat to an abundance of fish and wildlife species, many of which reproduce and spend part or all of their entire life in wetlands. In Canada, more than 200 bird species (including 45 species of waterfowl) and over 50 species of mammals depend on wetlands for food and habitat. Wetlands also provide commercial and recreational opportunities from plant harvesting, fur trapping, fishing, and agriculture. Wetlands provide critical hydrological and water quality functions, often referred to as Nature's Kidney's because of their natural ability to filter and improve the quality of water that moves through them (Gabor et al. 2001).

Wetlands actively remove and process organic and inorganic materials from water and sediments and act as nutrient sinks in watersheds, which helps prevent eutrophication downstream in rivers and lakes (Kadlec and Knight 1996, Mitsch and Wang 2000). They store these elements within the litter, sediment, and plant biomass, where they cycle through the plant and animal communities or are permanently stored in organic litter and sediments (Neely and Baker 1989, Kadlec and Knight 1996, Mitsch and Wang 2000). A significant amount of nutrients from agricultural runoff and wastewater effluents (i.e. nitrogen and phosphorus) can be captured by wetlands preventing it from ending up downstream (Kadlec and Knight 1996, Gabor et al. 2001, Mitsch and Gosselink 2007, Ducks Unlimited Canada 2012). These important transition areas provide critical natural buffers between land and freshwater rivers and lakes. Landscapes with little or no natural buffers provide a direct route for nutrients to enter water bodies causing excessive loading and eutrophication (Gabor et al. 2001). Wetlands managed for habitat or nutrient capture can reduce downstream nutrient exports while producing a lot of plant biomass.

2.1.2 The wetland plant community – an important component

A wetland's ability to trap and filter nutrients and toxins relies in large part with its aquatic plant community (Mitsch and Gosselink 2007). The nutrients retained in a wetland in turn support the productivity and growth of these aquatic plants and microorganisms. The aquatic plant component of a wetland can affect water conditions, function, and mechanisms through nutrient capture (Finlayson and Mitchell 1983), sediment deposition, erosion protection (Foote and Kadlec 1988), shading, transpiration, organic matter buildup, and providing surfaces for algae growth (Campbell and Ogden 1999). Aquatic wetland plants or macrophytes consist of emergent, submersed, and free floating forms, which cycle and obtain nutrients from the wetland in different ways. With their greater biomass, larger rooted perennial emergent plants play an important role in the cycles of carbon, nutrients, and chemicals in wetlands (Sharma et al. 2006). They improve the condition of water entering a wetland by providing large surface areas for growth of algal and microorganism communities that rapidly take up available nutrients and elements from the water column. Nutrients and elements rapidly cycle through microorganism communities, which is eventually stored in the organic litter and sediment layers. Rooted emergent plants almost exclusively take up nutrients from litter and sediment, assimilating nutrients into accumulated root and shoot biomass (Smith et al. 1988, Brix et al. 1992). Submersed and free-floating plants can absorb nutrients directly from the water-column, but produce considerably less biomass (Wetzel 1983a). Emergent plants slow the flow of water increasing retention time, which allows suspended sediments and nutrients to be taken up and broken down by bacteria and algal communities or settle into organic litter and sediments (Reddy and DeLaune 2008). The physical root mass of emergent plants provides a matrix for sedimentation buildup and accumulation or accretion of decaying plant litter, which helps stabilize shores and sediments from large wind and wave effects (Hosper and Meier 1993 Kadlec and Knight 1996, Mitsch and Gosselink 2007). The physical growth of emergent plants effectively reduces sediment stirring and turbidity by reducing wind effects, and open water areas are noticeably more turbid than bordering emergent plant zones.

2.2 Engineered natural wetlands for water quality

The ability of wetlands to reduce eutrophication in downstream waters has not gone unnoticed. The Chinese have almost 3000 years of experience in ecologically engineering wetlands, brought out as a necessity for waste recycling and food and fiber production (Yan et al. 1993). Similarly, Sudanese villages along the Nile long recognized and used wetland plants and clay soils to purify water from the river during the flood season, and use of plants for food and materials (Campbell and Ogden 1999).

Large-scale ecological engineering has been used to restore, rehabilitate, or re-engineer wetlands to harness their natural ability for water quality improvement, which in turn also provides important wetland habitat. The key mechanism for many of these systems are the thriving plant communities partitioned in a series of vegetated wetland cells or flow-ways through which the nutrient-rich water flows, and where sediment and nutrients are effectively trapped. Some of the largest engineered wetlands for water quality are the Everglades storm water treatment areas, STAs in Florida (DeBusk et al. 2001), Lake Apopka, Florida (Coveney et al. 2002), and the Kis-Balaton Wetlands, Lake Balaton, Hungary (Tatrai et al 2000, Dömötörfy et al. 2003). Each wetland system provides some level of filtering of pollutants or nutrients from water as it passes through the wetland before entering the neighbouring lake. Restored emergent plant communities have the added benefit of providing important wildlife habitat. Lake Apopka, Florida marsh flow-way successfully reduced phosphorus and nitrogen loading to the lake and provides restored habitat for hundreds of Everglades species (Coveney et al. 2002). Kis-Balaton wetlands in Hungary act as filters for sediment and nutrients which would otherwise be deposited in the Lake (Dömötörfy et al. 2003), and is a Ramsar site valued for habitat and biodiversity conservation. This type of wetland development and restoration is considered for the Great Lakes in North America, Lake Chao in China, and could be applicable for Netley-Libau Marsh in Manitoba.

2.2.1 Florida Everglades STAs and Lake Apopka

Everglades Storm Water Treatment Areas (STAs) are engineered wetlands north of the Florida Everglades that remove nutrients from storm water runoff before it flows south into protected wetlands. Florida has invested more than $1.8 billion in water quality improvements aimed at lowering phosphorus levels (SFWMD 2013). Currently 57,000 acres south of Lake Okeechobee has been converted to STAs. Wetland plants in these constructed wetlands (cattail, bulrush, southern naiad, algae) take up phosphorus through plant growth and store it through accumulation of dead plant material. Water flowing out of an STA has significantly less phosphorus than storm water flowing in. Long-term sustainability and management of these systems is an issue, particularly as stored phosphorus levels increase. Alum addition is used to reduce phosphorus and management of cattail has been considered (SFWMD pers. comm. 2011).

Lake Apopka was once considered Florida's most polluted large lake after almost a century of wetland drainage, agriculture, and nitrogen and phosphorus loadings from surrounding farmland (St. Johns River Water Management District, 2010). Restoration of this 125 km^2 lake included restoration of wetlands from farmland along the north side of the lake and construction of the Lake Apopka Marsh Flow-Way in 2003, a 3,400-acre wetland treatment system. Water from the lake flows through four treatment cells to settle solids and remove phosphorus and nutrients. This wetland filter has significantly improved the water quality in Lake Apopka with phosphorus levels in the lake down 56 percent and water clarity 54 percent better than earlier conditions, while creating wetland habitat (St. Johns River Water Management District 2010, Coveney et al. 2002). Phosphorus build up is an ongoing concern, and is controlled chemically with addition of alum (Lake Apopka management pers. comm. 2012)

2.2.2 Lake Balaton, Hungary

Lake Balaton is the largest lake in Central Europe with a surface area of 593 km^2 and an average depth of only 3.2 m. The river enters the southwest of Balaton at Keszthely Bay through the Kis-Balaton wetland – an 1800-ha restored wetland that began operation in 1985 (Kadlec and Knight 1996) constructed for water quality protection as a filter for sediment and nutrients that would otherwise be deposited in the Lake (Dömötörfy et al. 2003). There are two artificial lakes, an 18 km^2 upper lake with mainly open water and the 54 km^2 heavily vegetated lower lake. Reeds are mostly responsible for removal of phosphorus and nitrogen as well as stabilizing shoreline. Although it is not clear whether reduction in fertilizer use or wetlands management had the largest effect in reversing eutrophication, but by the late 1990s water quality in Lake Balaton had shown significant improvement (Dömötörfy et al. 2003). Originally designed as a water protection system, it is now also a Ramsar site valued for habitat and biodiversity conservation functions.

2.2.3 Dunnottar, Manitoba, Canada

The village of Dunnottar has operated a series of passive filtration constructed wetlands for the treatment of municipal wastewater and runoff, incorporating a horizontal and vertical flow wetland system. Similar to natural wetlands, nutrients and heavy metals are trapped within the wetland and taken up by plants in their biomass. Operation of the wetland system has consistently resulted in an average 70% phosphorus and 60% nitrogen reduction over the first three years of the pilot study (Dillon Consulting 2012).

2.2.4 Great Lakes, North America

Mitsch and Wang (2000) predicted large scale restoration of 15% of river basin wetlands and along the Great Lakes would result in a reduction of more than half of the phosphorus entering the lake from the watershed (Mitsch and Wang 2000). Only a small percentage of wetlands remain around the Great Lake's shorelines due to development, and most are diked to control water levels. Wetland restoration is primarily for wildlife (i.e. waterfowl) and rarely for water quality improvement, even though this has been recognized as an important function. They recommend large-scale restoration efforts would be a viable management practice for controlling phosphorus and other nonpoint source pollution.

2.2.5 Lake Chao, China

Restoration of wetlands is an important management component for nutrient control in Lake Chao, one of the five largest lakes in China. Five million people live around the lake and it is important for drinking water, irrigation, transportation, fishing, and tourism (Dredging Today 2012). Rapid industry development and population has resulted in eutrophication and silting. Since the 1950s, large areas of riparian wetlands have been drained for agriculture, and a dam built in 1962 for irrigation and water control, also resulting in reduction of fish productions (Xu et al. 1999). In 2012 funding was secured from the Asian Development Bank (ADB) for watershed management, wastewater treatment, and constructed wetlands to reduce nutrient loading (Dredging Today 2012).

2.3 Storm Water Wetlands

2.3.1 North Ottawa retention project

Storm water wetlands constructed for flood control have added benefits of water quality improvement and wildlife habitat. An example of integrated surface water management has been successfully demonstrated by the North Ottawa retention project in the Bois de Sioux Watershed District, USA (BDSWD 2012). A series of constructed impoundments, or cells, constructed to hold back nutrient-rich spring flood water to reduce flood impacts downstream to Fargo, North Dakota, with the added benefit of reducing nutrient runoff. This has shown to reduce flood peaks and impacts with the added benefit of increased production in surrounding agricultural lands. Holding the nutrient rich water also reduces the pulse of nutrients that normally occurs during flood runoff (McCullough 2012). Additionally, these constructed impoundments have become colonized by cattail which adds further nutrient retention capacity and potential biomass production to be integrated into surface water and nutrient management on a larger watershed scale. The Red River Basin Commission headquartered in Moorhead, Minnesota, has supported the North Ottawa project concepts of surface water management within their Natural Resources Planning Framework, an example of River Basin Management (BDSWD 2012).

2.3.2 Geuensee, Switzerland

In Geuensee, Switzerland, a cattail filled storm water retention wetland began operation in 2002 as a cost-efficient alternative to conventional storm water retention systems that require large earthworks and construction, to intercept storm water from sewers and drainage ditches at Geuensee (Wyss 2004). This multifunctional system was found to offer additional services in addition to flood protection particularly water treatment and habitat (Wyss 2004). These simple natural buffers catch the water of heavy rainstorm events, delay release of water, and in turn help improve the quality of the water. The pilot facility in Geuensee gained experience with harvesting and processing of cattail, examined the use of cattail as CO_2-neutral fuel (as pellets or in pyrolysis), and made cattail better known among Swiss clay construction practitioners (Wyss 2004).

2.3.3 Pelly's Lake, Manitoba, Canada

A similar managed storm water wetland is under construction at Pelly's Lake in Manitoba, a large wetland area that has been drained many times in the past in order to achieve better hay production and more pasture. So far, all attempts at this have failed and the land is largely filled with cattails. The LaSalle Redboine Conservation District (2013) is currently developing a backflood system for this area with water control structures to hold back water in the spring and reduce flooding, increase later hay production, recharge for downstream reservoirs, and to improve water quality.

2.4 Engineered artificial constructed wetland systems

Treatment wetlands are artificial wetlands constructed to retain storm water runoff and treat municipal wastewater and agricultural effluents, by trapping and filtering high levels of nutrients and toxins. Often these are constructed to maximize heavy loading with impermeable liners and gravel lined bottoms. Numerous examples around the world prove the effectiveness of these systems to trap and process extreme levels of nutrients, to reduce eutrophication in downstream water (Kadlec and Knight 1996, Karanthanasis 2003, Kadlec 2005a, 2005b, Vymazal 2006). Some issues of overloading and saturation of long-lived systems are an issue, as are high BOD concentrations that lower dissolved oxygen levels to undesirable levels (Kadlec and Knight 1996, Karanthanasis 2003, Kadlec 2005a, 2005b). Current treatment wetland technologies are very efficient and are most effective in treating secondary effluent or at the tertiary "polishing" stage removing phosphorus and nitrogen to very low levels.

Nitrogen and phosphorus are an issue because of their impact on fresh and marine waters in eutrophication, potential toxicity to aquatic species, and the role they play in plant overgrowth of competitive species (Kadlec 2005). Fully vegetated marshes with emergent or submersed plant communities are the most effective for nitrate and nitrogen reduction and phosphorus storage (Weisner et al. 1994, Kadlec 2005a, 2005b). Treatment wetlands typically receive high nitrogen loads and most are designed primarily for nitrogen removal through nitrification/denitrification processes. Phosphorus removal relies on absorption and sedimentation and permanent storage in sediments. Plant communities growing in alternating banded patterns perpendicular to the flow of water improve hydraulic retention and maximizes nutrient uptake by slowing water flow for storage in sediments and plant biomass (Weisner et al. 1994, Kadlec 2005a). Partially vegetated or unvegetated wetlands have had much lower rates of nutrient removal (Kadlec 2005b).

Since phosphorus accumulates in wetlands with no breakdown pathway, physical removal of P-enriched sediments and chemical immobilization of phosphorus in the sediments (i.e. alum additions) is necessary to improve the effectiveness and sustainability of treatment wetlands to remove phosphorus (Kadlec and Knight 1996). Routine harvesting of vegetation to remove nutrient rich plant material could increase the life-span of constructed systems, but the harvesting of wetland plants as a management option to reduce stored nutrients has not been fully explored. Harvesting experiments have been attempted in constructed and semi-engineered wetlands that receive high loadings of nutrients (Toet et al. 2005), and most indicate the success of harvesting would be much more significant in systems without the high nutrient loadings as wastewater treatment wetlands (Toet et al. 2005, Vymazal 2006). A review by Brix and Schierup (1989) concluded constructed wetlands provide valuable cost-effective methods for treating wastewater, and provide valuable plant biomass for animal feed, agricultural fertilizer, or for energy.

2.5 Wetland Plant Adaptations to stress

2.5.1 Oxygen and gas movement

Wetlands are characterized by waterlogged soils and anaerobic (i.e. oxygen-less) conditions resulting in many biochemical transformations unique to wetlands. Rooted emergent wetland plants, such as cattails and reeds (*Phragmites* spp.) have developed remarkable adaptations to deal with stresses imposed by water logged and anaerobic, or low oxygen, conditions (Armstrong et al. 1978, Brix and Sorrell 1996). The ability to maintain effective aeration is a greatly needed adaptation for plants growing in deep water (Tornbjerg et al. 1994, White and Ganf 1998). Continuous uninterrupted tubular air spaces, or aerenchyma tissue, extend from the leaf, through petioles and stems, and down into roots and rhizomes. Cattail and *Phragmites* can move significant levels of gases from the sediment to the atmosphere and oxygen from the atmosphere down to roots and sediments exerting a significant influence on sediment redox potential (Campbell and Ogden 1999, Armstrong et al. 1996, Brix 1993). Redox potential or reduction involves the releasing of oxygen, gaining hydrogen, or gaining an electron. Green living shoots actively move oxygen to roots, while dead plant stems release gases to the atmosphere, i.e. carbon dioxide, methane, nitrous oxide, hydrogen, and carbon monoxide (Brix et al. 1996). Movement of gases through the plant involves pressurized gas flow, pumping air against a pressure gradient, produced by the heat of the sun and not photosynthesis (Cherry 2012). Oxygen oxidizes the soil or rhizosphere around roots creating an oxygenated zone increasing redox potential making it more suitable for root growth (Mitch and Gosselink 2007). Plants also reduce methane emissions oxygenating the root zone in the sediments (Reddy et al. 1989). Pressurized gas flow, creation of oxidized root zones, and anaerobic respiration, allows wetland plants to remain productive under stressful conditions (Cherry 2012).

2.5.2 Rhizomes for survival

Cattail and *Phragmites* are able to withstand the dynamic conditions of wetlands in northern climates, from inundation to complete drying out for long periods of time, making these species extremely competitive and resilient (Li et al. 2004). The large carbohydrate reserves of these thick rhizome plants makes them capable of surviving long periods in flooded or dry conditions (Barclay and Crawford 1982, Studer and Braendle 1987). Cattail responds to changes in water depth by producing thick large rhizome storage to maintain effective aeration during oxygen deficient or anaerobic conditions, or during long dry periods (Sharma et al. 2008). Belowground biomass in cattail often accounts for more than 50% of total annual biomass (McNaughton 1966). They store large quantities of carbohydrates in the large belowground rhizomes, which contribute to the rapid spring growth of shoots (Gustafson 1976).

2.6 Wetland Biogeochemistry - The role of emergent plants

2.6.1 Seasonal resource allocation and translocation

Hydric wetland soils are the primary storage of available nutrients for rooted emergent plants, and the site of reactions that transform stored nutrients. Rooted wetland plants almost exclusively take up nutrients such as nitrogen and phosphorus from the organic litter layer and sediments. Emergent plants absorb carbon from the atmosphere or water, and take up nutrients and other elements from the interstitial pore water within the sediment to produce organic matter or biomass (Reddy and DeLaune 2008). The litter and sediment pool is the main source of dissolved nitrogen and phosphorus to pore waters in sediment replacing nutrients taken up by emergent plants (Barko and Smart 1986, Howard-Williams and Allanson 1981, Carignan 1982, Moeller et al 1988, Smith et al. 1988, Barko et al 1991, Murkin et al. 2000, Noe et al. 2003, Mitsch and Gosselink 2007).

Dense stands of plants act as permanent nutrient sinks in wetlands with storage in belowground rhizomes (Murkin et al. 2000). They allocate photosynthetic products into above- and belowground biomass and store resources (Asaeda et al. 2008). When aboveground tissues die, they slowly re-mineralize during decomposition cycling stored nutrients back into the wetland. The allocation and translocation of resources in emergent plants is highly seasonal and species-specific, and will differ between geographic regions as a result of season and length of growing periods (Smith et al. 1988). Generally, initial shoot growth is based almost entirely on upward translocation of material from rhizomes. The source of resources will gradually be replaced from the rhizome reserves by products of photosynthesis in the aboveground parts during the growing period (Asaeda et al. 2008). Large emergent wetland plants assimilate a significant amount of nutrients into accumulated root and shoot biomass, and are capable of changing growth allocation in response to nutrient limitation (Woo and Zedler 2000).

2.6.2 Plants and nutrient cycling

The high biological activity of wetlands rapidly decomposes waste organic compounds, stores them in sediments, or converts them into gases and harmless by-products. Wetland processes include plant and microbial uptake, volatilization, nitrification, denitrification, nitrogen fixation, mineralization, reduction, anaerobic oxidation, absorption, desorption, burial, and leaching (Kadlec and Knight 1996, Vymazal 2006, Mitsch and Gosselink 2007). The rapid recycling of nutrients and organic carbon in wetlands sustains high productivity (Wetzel 1983).

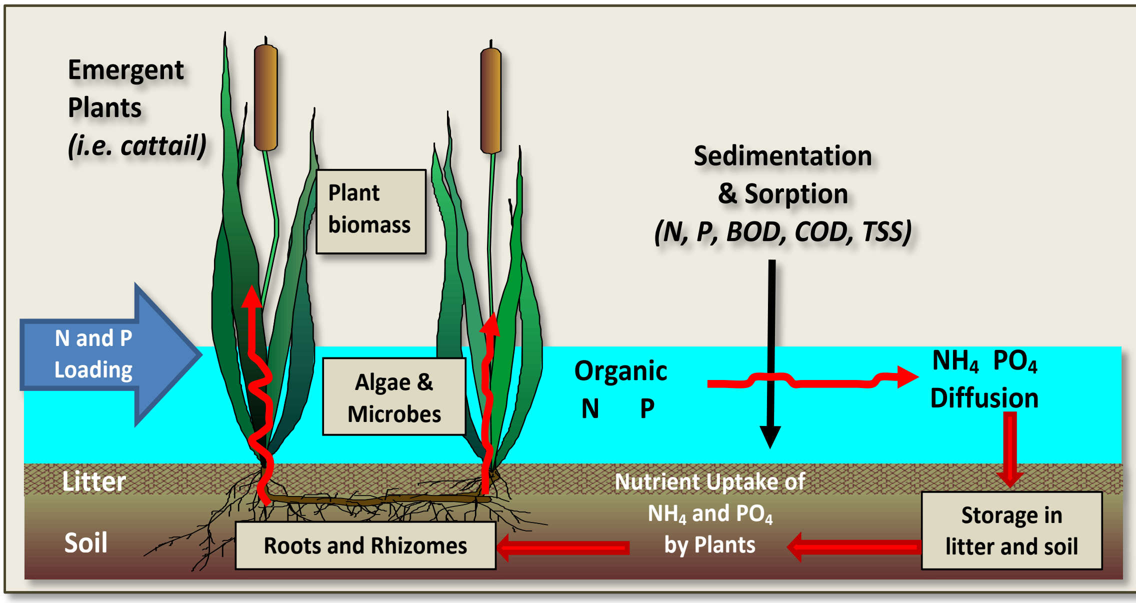


Figure 2.1. Wetland biogeochemistry - uptake by wetland plants. White highlighted areas show regions of nutrient storage in a wetland. (N=nitrogen, P=phosphorus, BOD= biological oxygen demand, TSS=total suspended solids)

The ability of wetland plants and algae to take up nutrients in excess of growth requirements is known as luxury consumption, rapidly depleting nutrient concentrations (Gerloff and Krombholz 1966). Nutrients cycle between water, plants, and sediment through sedimentation and adsorption to sediments, diffusion, re-suspension from sediments, and transferring from plants back to the water (Figure 2.1). Emergent plants depend on inorganic nutrient cycling between the water and sediment nutrient pools, and through invertebrates, fish, submersed plants, and algae (McDougal 2001). Algae and bacteria thrive on the surface area of larger emergent plants and rapidly take up inorganic nutrients from the water column. Transformation of N and P into the sediment allows rooted emergent plants to take up these nutrients (Figure 2.1).

2.6.3 Decomposition and nutrient cycling

Plants and algae release inorganic nutrients back into the wetland through leaching during decomposition. This is an important part of nutrient cycling in wetlands as nutrients are rereleased to the water column and litter and surface sediments, or lost through incomplete mineralization and burial in sediments. Three stages of decomposition have been described – the first short 1-2 day period results in rapid mass loss by physical leaching, the second 90-120 day period is a slower sustained mass loss through microbial decomposition, followed by the third period of indefinite slow mass loss (Davis and van der Valk 1978, Wrubleski et al. 1997b). Neely (1994) found positive interactions between epiphytic algae and heterotrophic bacteria on decomposing *Typha latifolia*, causing cuticular erosion and epidermal pitting. This process increases rate of nutrient release for algae and for surface epiphyton and periphyton (Neely 1994). Anaerobic decay processes in anaerobic zones of wetlands proceeds at a much slower rate than aerobic decay, and generally does not proceed to completion (Schlesinger 1997). These processes enhance the role of wetlands as nutrient and carbon sinks.

2.6.4 Nitrogen (N) and Phosphorus (P)

Nitrogen (N) and phosphorus (P) are often a concern in aquatic systems since the lack of either of these elements limits growth and productivity, while overabundance of either causes eutrophication and accelerated plant growth undesirable in aquatic systems (Willis 1963). Wetlands reduce levels of nitrogen and phosphorus by providing favourable conditions for denitrification and storage of phosphorus. Nitrogen is considered self-regulating within wetlands, cycled and broken down with little being stored permanently, while phosphorus is permanently stored in organic litter and sediments. Gradual accumulation of phosphorus in the sediment challenges effective long term storage, and can accumulate to where wetlands become saturated. This is an issue in treatment wetland systems with higher levels of loading (Noe et al. 2003). Phosphorus removal can be improved by physical removal of P-enriched sediments, chemical immobilization in the sediments with Alum additions, or routine harvesting of plants to remove nutrient-rich plant material (Vymazal 2006, Asaeda et al. 2006). In remote wetlands and northern peatlands phosphorus is a major limiting nutrient, whereas in agricultural and urban wetlands phosphorus from watershed runoff can be quite high. Prairie agricultural wetlands are characterized by higher levels of stored phosphorus, while nitrogen is more likely to limit plant growth.

2.6.5 Wetland plant cycling of Nitrogen (N)

The reducing environment of litter and sediments is the main source of nitrogen for rooted emergent plants, and is most available for plant uptake in the reduced form of ammonium ions NH_4+ (Nichols and Keeney 1976). Nitrogen is somewhat available to plants in an oxidized form as nitrate NO_3-, which is typically the dominant form of inorganic nitrogen in the water column, but is not assimilated immediately by plants. Inorganic nitrogen typically makes up <50% of total soluble in freshwater wetlands. Nitrate is more prevalent in aerobic environments and ammonium in anaerobic. Ammonification occurs as organic matter decomposes and degrades to soluble organic nitrogen, and is mineralized to ammonium ions NH_4+ (Mitsch and Gosselink 2007). In aerobic conditions, nitrification results in nitrite NO_2- then nitrate NO_3-. Under anaerobic soil conditions denitrification reduces nitrate NO_3- to nitrite NO_2-, and ultimately to N_2O or N_2 gas. Wetlands are a significant source of nitrogen release to the atmosphere as N_2 gas (Figure 2.2).

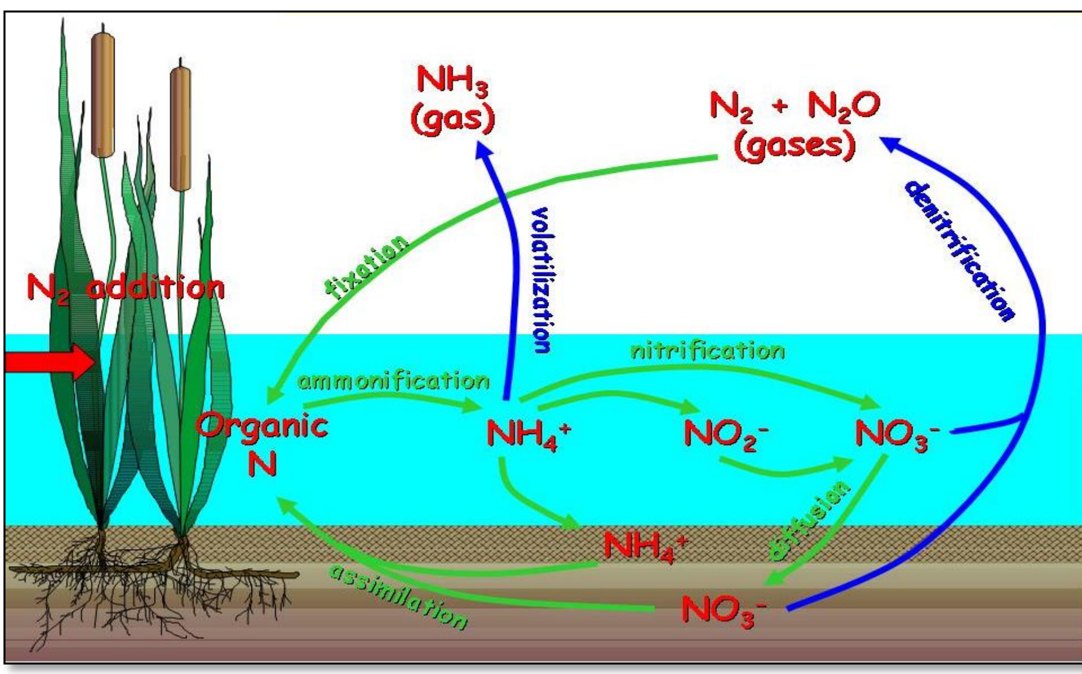


Figure 2.2. The Nitrogen cycle in natural freshwater wetlands.

2.6.6 Wetland plant cycling of Phosphorus (P)

Phosphorus retention is an important attribute of wetlands and can be defined as the capacity of that system to remove water column phosphorus through physical, chemical, and biological processes and retain it in a form that is not easily released under normal environmental conditions (Reddy and Delaune 2008). Phosphorus enters a wetland in either inorganic or organic forms, and as soluble or insoluble. Dissolved inorganic phosphorus is the most readily available to plants and microbes, while particulate inorganic and organic phosphorus must undergo transformation before becoming available (Dunne and Reddy 2005). The concentration of available inorganic forms in the water in a wetland is often quite low because of how rapidly it is assimilated by algae, bacteria, and other microorganisms (Wetzel 1983). Dissolved inorganic phosphorus is produced by natural and anthropogenic processes, i.e. wastewater and fertilizer runoff, while particulate inorganic forms includes phosphorus bound to calcium (Ca), magnesium (Mg), iron (Fe), and aluminum (Al). Organic phosphorus is associated with living organisms and occurs from the breakdown of decaying plant litter (Dunne and Reddy 2005).

In biological systems phosphorus is not found on its own, but exists as part of a phosphate molecule (PO_4), with each compound containing phosphorus in a different chemical formula. Available phosphorus can be found as a free phosphate ion in solution as inorganic phosphate, including the ions PO_4-, HPO_4-, and H_2PO_4-, collectively known as orthophosphates, which are readily available for plant uptake. As a result, orthophosphate (PO_4-) comprises <10% of total phosphorus in the water column in most water bodies (Wetzel 1983). Measurement for biologically available orthophosphates is referred to as soluble reactive phosphorous (SRP).

Phosphorus entering a wetland settles out of the water column and moves into the litter layer quite rapidly (Noe et al. 2003). Using ^{32}P tracer, Noe et al. (2003) showed the periphyton community (metaphyton and epiphyton) rapidly incorporated ^{32}P following addition, which later moved into the litter and soil where long-term storage occurs. They showed uptake of ^{32}P tracer by macrophytes increased over time, identifying the primary source of P to emergent plants is from stored P in litter and soil. Once phosphorus is taken up by the wetland biological community, a significant portion is not readily released under normal conditions. Phosphorus occurs in a sedimentary rather than a gaseous cycle like nitrogen, and at any one point a significant portion in a wetland is bound in sediments by surface adsorption on minerals, in the organic litter, taken up by the microbial community, and stored in wetland plants. When microbes and plants die the phosphorus is recycled in the wetland or buried in sediments (Reddy et al. 1989).

Phosphorus retention is an important attribute of natural and constructed wetlands either through immobilization in microbes and plants or permanent storage in the sediment and litter layers - there is no degradation route for phosphorus in a wetland (Noe et al. 2003, Reddy and Delaune 2008). Storage in sediments can be combined in two distinct pathways: burial (accretion of new sediments) or sorption to wetland substrate (Reddy 2004). Phosphorus sorption is essentially the removal of phosphate from solution to the solid phase, and includes both adsorption and precipitation reactions. (Reddy 2004). Most phosphorus entering a wetland is retained resulting in a gradual accumulation in the sediment.

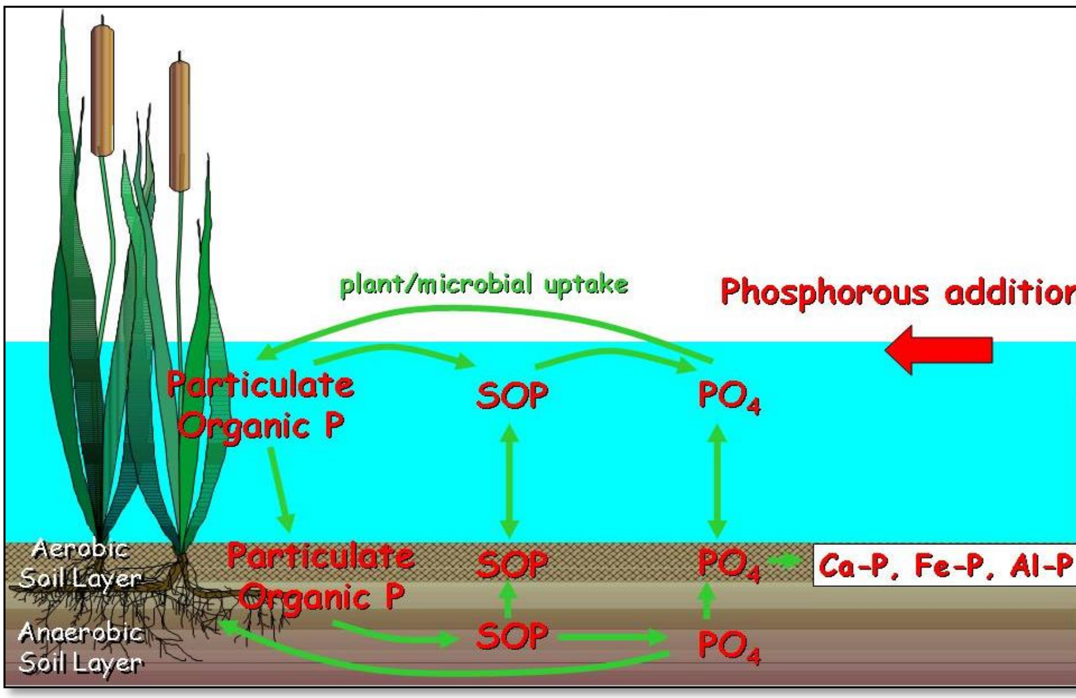


Figure 2.3. The Phosphorous cycle in natural freshwater wetlands.

2.6.7 Wetland sediment cycling of Phosphorus (P)

Since most emergent plants obtain their phosphorus from the organic litter and sediment, decomposing organic matter is a significant source of phosphorus, as is sedimentation of phosphorus sorbed to clay particles when it is released as PO_4- under anaerobic conditions (Mitsch and Gosselink 2007). Phosphorus mobility in a wetland occurs in the presence and absence of oxygen affected by sunlight (Dunne and Reddy 2005). Under sustained anaerobic conditions phosphorus released from surface sediments can be significant. Rooted emergent plants release oxygen into the root zone (Brix 1993, Flessa 1994) causing aerobic conditions, immobilizing phosphorus and reducing the availability of soluble phosphorus. Availability of phosphorus is further complicated by other physiochemical reactions besides redox, including adsorption to clay particles, changes in pH and changes in carbonate equilibrium, which causes co-precipitation with calcium carbonate crystals or the formation of insoluble calcium phosphate salts (Schlesinger 1997). Phosphorus bound to calcium and magnesium are relatively stable and not readily available to wetland plants (Dunne and Reddy 2005).

2.7 Harvesting wetland plants for watershed management and nutrient removal in eutrophic systems

Wetlands plants are a critical component of nutrient capture and water quality improvement in wetlands, providing surface areas for algae and microbes, creating conditions suitable for chemical transformations, and taking up large stores of nutrients into accumulated aboveground biomass. Conceivably, harvesting aboveground plants would remove nutrients bound within the plant tissue, preventing those nutrients from re-entering the ecosystem from decaying plant material. Harvesting is common for bioremediation to treat contaminated soils and water with plants that absorb contaminants without the need to excavate the contaminant material and dispose of it elsewhere (Wani et al. 2012). But harvesting wetland plants as a management option to reduce nutrient loading to downstream eutrophic systems has not been fully explored. Harvesting has shown success in lab-scale systems and in heavily loaded wastewater treatment wetlands (DeBusk et al. 2001, Toet et al. 2005, Vymazal 2006) but the technical and economic feasibility for watershed scale-use to address nutrient loading and eutrophication issues in aquatic systems needs to be explored.

2.8 Harvesting for material and identified secondary benefits

Wetland plants are often cut to control the spread of highly invasive and competitive plant species. The negative effects of excessive aquatic plant growth can be significant both environmentally and economically, impacting important wildlife habitat, and affecting commercial or recreational exploits (Tuchman et al. 2009, Mitchell et al. 2011). Submersed aquatic plants are routinely harvested from lakes and ponds to reduce impacts to fishing and human use in Italy (Giusti et al. 2006) and throughout Turkey where they affect the harvest of fish and crayfish (Bates et al. 1984). Excessive growth causes alteration of hydrology, blocking waterways, interference in fishing and recreation (Bates et al. 1984).

In many developing countries harvesting wetland plants for use as a commercial product, often by manual harvesting techniques, is an important economic resource contributing significantly to the local economy (Bates et al. 1984, Ozesmi 2003, Giusti et al. 2006, Ba et al. 2009). Larger emergent plants, such as bamboo (*Bambusa* spp.), cattail (*Typha* spp.), giant reeds (*Phragmites australis*), and sweet grass are used as building material and for household and commercial products, i.e. mats and baskets. *Phragmites* has been harvested in European countries for roof thatching for centuries and is still an economic practice (Boar and Leeming 1997). Regular harvesting maintains *Phragmites* dominated marshes by controlling its spread and removing accumulated dead material, while increasing growth and quality of future crops. Demand for its use as roof thatching is dependent on the quality of harvested reeds, and reeds of better quality have higher nitrogen content (Boar and Leeming 1997). Since nitrogen is often of concern in wetland and aquatic systems, a secondary benefit of harvesting reeds for roof thatching would be removal of stored nitrogen and reducing downstream loading.

Harvesting sharp-pointed rush (*Juncus acutus*) in the Kizilirmak Delta on the Black Sea Coast of Turkey is an important local economic resource for baskets, cooking utensils, and flower arrangements (Ozesmi 2003). Harvesting was also noticed to maintain biodiversity of the wetland by removing dead material and opening space for new plant growth, and strengthening and thickening the main clumps of shoots improving the quality of harvest the following year (Ozesmi 2003). Because of the agricultural landscape surrounding this wetland, harvesting could have a nutrient benefit as well.

In Portugal, submersed plants have been harvested for fertilizer since the Middle Ages (Calado and Duarte 2000), and recently it was suggested harvesting appears to be reducing eutrophication within the lagoon by removing nutrients and organic matter, improving the lagoon for recreational usage (Calado and Duarte 2000).

Many wetland grasses and sedges are harvested for livestock forage (Freese 1998), and in Manitoba are an important source of protein and nutrient-rich feed for livestock. In Lizard Lake, Manitoba, Canada reed canary grass is harvested annually from a water retention wetland that holds back flood water in the spring. Harvesting this grass improves outgoing water quality benefit by removing high levels of nitrogen and phosphorus preventing its release downstream (Tobacco Creek, pers. comm. 2012)

2.9. Harvesting success for nutrient removal – treatment wetlands

2.9.1 Cattail (*Typha* spp.) harvesting in constructed treatment wetlands

Most wetland harvesting experiments for nutrient removal have been carried out in constructed treatment wetlands and lab-scale experimental settings receiving high nutrient loads from treated or secondary waste water effluent. Toet et al. (2005) harvested cattail and *Phragmites* to increase efficiency of nutrient removal in treatment wetlands used for polishing secondary treatment plant sewage effluent. Nitrogen and phosphorus mass loading rates were 122 to 4190 g N /m^2/yr and 28.3 to 994 g P /m^2/yr. At these high loading rates nutrient removal through harvesting was insignificant compared to the inputs received. At loading rates of 120 g N /m^2/yr and 30 g P /m^2/yr (retention time of 9 days within the treatment wetlands), harvesting reduced mass inputs by 7.0 to 11% for nitrogen and 4.5 to 9.2% for phosphorus (Toet et al. 2005). They consider the net removal of nutrients by harvesting to be minimal, suggesting removal rates of 10% of annual load as insignificant. Others, such as Liu et al. (2003), however, consider 10% removal to be significant and suggest harvesting as an important removal option for nitrogen and phosphorus from constructed wetlands. For constructed wetlands in Lake Dian-chi area, Yunnan Province, China, the nitrogen and phosphorus removed by plant harvesting accounted for 10% and 9% of the input of TN and TP, respectively (Liu et al. 2003). Ancell et al. (1998) also indicates harvesting successful with 15% of total N loaded into experimental constructed wetlands removed when cattail and *Schoenoplectus* spp. was harvested.

Much higher removal efficiencies have been found in experimental treatment wetlands with lower loading rates. Martin and Fernandez (1992) harvested cattail from stands grown in secondary effluent with removal rates of 183 g N/m^2/year and 26.6 g P/m^2/year, and suggest 40-45% of nitrogen and phosphorus could be removed by harvesting aboveground plants following drying out in the fall, the rest remaining in the rhizomes. An earlier harvest before the transfer of nutrients in the fall from shoots to rhizomes could remove 70% of input. Koottatep and Polprasert (1997) harvested cattail from experimental constructed wetlands after 8 weeks yielding nitrogen uptake of 7.1 kg/ha/day (259 g N /m^2/yr) amounting to 66% of total nitrogen input. They suggest occurrence of anoxic and reduced conditions were favourable for nitrogen removal processes by plant uptake (Koottatep and Polprasert 1997). Harvesting the tall grass *Cyperus alternifolius* used in a covered subsurface flow wetland constructed for pig wastewater treatment removed 68.72 g N /m^2 and 18.49 g P /m^2 (Liao et al. 2005).

2.9.2 Harvesting in laboratory scale wastewater treatment

In a laboratory-scale study by Weng et al. (2006) cattail was grown in gravel substrate and fed synthetic wastewater to measure uptake. By the end of the growing season the cattail had removed 40-45% of the phosphorus added to these systems, and it was concluded harvesting would remove it by preventing its release upon decay of the plants. Lakshman (1979) demonstrated cattail and bulrush (*Schoenoplectus* spp.) for nutrient uptake in experimental treatment tanks used to purify untreated raw municipal waste effluent. Upwards of 98% removal rates of TKN and TP were reached in less than 20 days. Rates of nutrient uptake increased with higher levels of loading and after 500 days the cattail continued to absorb nutrients long after control populations reached a saturated state (Lakshman 1979). This was not the case with the sedge *S. mucronatus*., which was not effective at all for removing stored nutrients (Kim and Geary 2001). After nine months the majority of the phosphorus pool applied to experimental mesocosms was stored in the sediment and very little stored in the plant due to its small biomass reserves. Reed canary grass (*Phalaris* spp.) grown in silica sand in small plots had removal rates with harvesting greater than 90% in all treatments (Adler et al. 1996), with ~50% of the N and ~ 80% of the P removed from the effluent

2.10 Harvesting success for nutrient removal - natural wetlands

2.10.1 Larger emergent plants

Not many studies have examined harvesting specifically for nutrient removal in natural systems, but research of nutrient uptake by aquatic plants clearly demonstrates harvesting plants from natural wetlands - wetland systems that do not experience the severe nutrient loadings that wastewater treatment wetlands receive - could be most significant to reduce nutrient loading and eutrophication in downstream waters (Lakshman 1979, Pratt et al. 1984, Pratte et al. 1988, Koottatep and Polprasert 1997, Liu et al. 2003, Karathanasis et al. 2003, Toet et al. 2005, Kadlec 2005a, 2005b, Jiang et al. 2005, Vymazal 2006). Because of their high rates of biomass accumulation and nutrient uptake, larger emergent wetland species, such as cattail, have great potential. These large competitive emergent plants often dominate wetland areas growing in dense homogenous zones. Willows (*Salix spp.*) have the same characteristic of rapid growth and nutrient accumulation, and harvesting has been used for wastewater nutrient removal (Perttu 1993, Adegbidi et al. 2001).

Success in removing stored nutrients from natural wetland systems was achieved by harvesting *Phragmites communis* and *Zizania latifolia* from ditch wetlands in China. Removing the biomass effectively reduced nutrient loadings to lakes in the lower reaches of the Yangtze River (Jiang et al. 2004). Harvesting removed 463-515 kg/ha/year (46.3-51.5 g/m^2/year) of nitrogen and 127-149 kg/ha/year (12.7-14.9 g/m^2/year) of phosphorus from agricultural runoff waters (Jiang et al. 2004). Jiang et al. (2005) report similar phosphorus removal rates from harvesting *Phragmites* in ditch wetlands, with removal rates of 1.9 g/kg (equal to 103.6 kg/ha/year or 10.4 g/m^2/year), but much more nitrogen removal at 15.0 g/kg (equal to 818 kg/ha/year or 81.8 g/m^2/year. *Phragmites communis* showed vertical distribution of total nitrogen and phosphorus, and stored levels increased with plant height. Min and Kim (1983) also found this vertical distribution in coastal salt marshes in Korea. Seasonal changes of nutrient content in biomass per unit land area increased continuously as biomass increased, with vertical distributions of total N, P, and K increasing with plant height. Min and Kim (1983) also found harvesting resulted in significant nutrient removal, and found nutrient return to soil was less than plant uptake. Phosphorus was expected to eventually be exhausted from the soil because of plant harvesting. Papyrus harvesting in the Nakivubo wetland, Kampala, in Uganda removed 7.7% and 15.8% of annual nitrogen and phosphorus loads entering the wetland (Kansiime et al. 2003). They also estimate if distribution of incoming waste water was routed through the entire wetland harvesting could potentially remove 70% and 76% of nitrogen and phosphorus respectively. Sugarcane harvesting removed 55% and 63% of accumulated nitrogen and phosphorus, equivalent to 179% of the phosphorus added in fertilizer (Coale et al 1993).

Cattail was identified as a potential biomass crop from natural and cultivated wetlands for bioenergy use, as a solid fuel and ethanol, with high annual productivity and yields, and was the focus of a primary research study at the University of Minnesota to maximize stand productivity and yields (Pratt et al. 1984, 1988). Cattail contained an average 0.05 to 0.4 % phosphorus content (Pratt et al. 1984) and annual harvesting of cattail produced yields of 6 to 12 tonnes of dry matter per hectare (T DM/ha) and removed 3 to 5 g/m^2 (30 to 50 kg/ha) of nitrogen and 0.5 to 2 g/m^2 (5 to 20 kg/ha) of phosphorus in aboveground cattail plants (Pratt et al. 1988). Annual harvesting over three seasons revealed no short term effects on cattail stands with single harvests per season, but harvesting cultivated stands during peak nutrient uptake in July/August removed significant nutrient reserves requiring fertilization to maintain annual biomass yields (Pratt et al. 1988).

2.10.2 Wetland grasses, submersed, and free-floating

Submersed and floating aquatic species rapidly accumulate biomass and absorb nutrients directly from the water. Removing them before they decompose captures nutrients that would otherwise contribute to eutrophication (Reddy et al. 1989). Harvesting Eurasian milfoil (*Myriophyllum spicatum*) was suggested as a management option to reduce phosphorus loading to Lake Wingra, Wisconsin, USA (Carpenter and Adams 1978). It was estimated annual harvesting could reduce the annual net load of phosphorus to the lake by 37%, representing 100% of available phosphorus. Harvesting submersed pondweed *Potamogeton crispus* which accounts for 20% of the phosphorus budget within the lake in Half Moon Lake in Wisconsin, USA, was also recommended to reduce internal loadings (William et al. 2002). Free-floating water hyacinth (*Eichhornia crassipes*) has been capable of 100% TN and TP removal from the water in wastewater treatment wetlands (Jayaweera et al. 2004). Smartweed (*Polygonum amphibium*) and pondweeds (*Potamogeton crispum* and *P. pectinatus*) were harvested to restore water quality and remove accumulated heavy metals in Lake Nainital in India (Ali et al. (1999). Adey et al. (1993) used managed, attached, algal populations to permanently remove excess phosphorus from agricultural run-off. Total phosphorus removal rates were 104 to 139 mg/m^2/day (380-507 kg P /ha/year). They predict yearly minimum removal rates with algae screens and harvesting, could be 100-250 times that achieved by large-area wetland systems (Adey et al. 1993).

Emergent plants grown on floating wetland islands or bioplatforms would also allow roots to absorb nutrients directly from the water column (Zhang et al. 2006). Floating panels in Lake Tai, China demonstrate nutrient absorbing ability of wetland grasses, sedges, and terrestrial plants grown on floating plastic panels with their roots absorbing nutrients directly from the water column **(**Jing Hua, 2005 pers comm., Zhang et al. 2006,). These plants exhibit high levels of nutrient absorption and harvesting could remove significant quantities of nutrients from these aquatic systems (Zubrycki et al. 2013). The use of floating islands for wetland restoration efforts, shoreline stabilization, and nutrient capture has been demonstrated worldwide with very effective results (Headley and Tanne 2006, Zubrycki et al. 2013).

2.11 The harvesting potential – capture and recovery of nutrients

Research clearly demonstrates harvesting aquatic plants removes stored nutrients in natural wetlands. Periodic harvesting of aboveground plant biomass has been recommended as a management option for nutrient control in many eutrophic and treatment aquatic systems (Karpati et al. 1985, Martin and Fernandez 1992, Adler et al. 1996, Koottatep and Polprasert 1997, Janse et al. 2002, William et al. 2002, Kansiime et al. 2003, Karathanasis et al. 2003, Korner et al. 2003, Liu et al. 2003, Toet et al. 2005, Vymazal 2006). This would be particularly important with respect to the removal of phosphorus and metals which accumulate in the sediment and plant biomass, and less so for nitrogen (Kadlec 2005a, 2005b, Wani et al. 2012). The Florida Everglades storm water treatment areas, for example, could benefit from large scale harvesting to reduce nutrient accumulation in litter and sediments and prolong the life of these treatment wetland systems. Capturing nutrient rich biomass is also a mechanism to recover and recycle valuable nutrients, i.e. phosphorus, for processing or applications, aligning with sustainable phosphorus management policies in the European Union. This additional economic revenue stream increases viability of harvesting and closes the nutrient cycle by recycling captured nutrients back onto agricultural fields for crop growth.

Harvesting and removing dense stands of plants and accumulated deadfall as a management strategy will also maintain open water and plant diversity by controlling dominant plant growth. Selective harvesting has been shown to improve waterfowl habitat by removing deadfall and maintaining a desired balance of open water and plant cover ideal for waterfowl (Kaminski and Prince 1981, Murkin et al. 1982). Wetlands receiving nutrient rich water can be susceptible to overloading and excessive plant growth. If not properly controlled, this can lead to dense monocultures of competitively dominant and undesirable species (i.e. cattail) (Woo and Zedler 2000).

The economic feasibility of harvesting for nutrient removal can be improved by utilizing the harvested biomass as a secondary product of harvesting, simply for animal feed or mulch, or as a biomass feedstock for higher value bioenergy, biomaterials, biofuels and high value end products.

2.12 Wetland Power – Wetland plants for bioenergy

2.12.1 Combined Harvest – greatest feasibility for wetland biomass

Emergent wetland plants produce vast quantities of biomass, and only recently has this potential feedstock been evaluated for high efficiency bioenergy conversion (Cicek et al. 2006). Cattail and *Phragmites*, both extremely prolific wetland plants found throughout North America, have both been evaluated for bioenergy use (Lakshman 1984, Dubbe et al. 1988, Garver et al. 1988, Cheng et al. 2002, Martin et al. 2003, Wyss 2004). *Phragmites* or reeds have been harvested in Europe for habitat management, roof thatching, as well as bioenergy, but has not been fully utilized for commercial energy production (Wichtmann et al 2012). Harvesting biomass from wetlands has received little attention due to difficulties with harvesting in wet environments with traditional equipment, perceived lack of economic feasibility, sustainability as a feedstock, and poorly understood impacts on the wetland environment (Dubbe et al. 1988, Garver et al. 1988, Anderson and Craig 1984, Cheng et al. 2002, Martin et al. 2003).

Greatest economic feasibility of harvesting is gained if carried out for multiple purposes. In Geuensee, Switzerland, a cattail filled storm water retention wetland was built to intercept storm water, and was a cost-efficient alternative to conventional retention systems (Wyss 2004). Cattail was harvested to remove dense overgrowth and the biomass dried and compressed into fuel pellets for bioenergy (Wyss 2004). Floating plants water hyacinth (*Eichhornia crassipes*) and channel grass (*Vallisneria spiralis*) are widely employed for wastewater treatment or harvested for nuisance control, and the harvested waste biomass has been used to produce biogas (Singhal and Rai 2002). Cattails are also widely used for nutrient control and were explored by the US DOE as a potential bioenergy crop (Dubbe et al. 1988, Cheng et al. 2002). Because wetland systems differ and the goals of wetland and nutrient management, and bioenergy production differ, studies of harvesting impacts are needed to optimally merge wetland management, water treatment, and bio-energy production (Martin et al. 2003).

2.12.2 Cattail biomass for bioenergy production

Cattail (*Typha* spp.) is an extremely productive and competitive marsh species found naturally across North America. Cattail was evaluated as a bioenergy feedstock by the

U.S. Department of Energy (DOE) and the Saskatchewan Research Council as early as the 1970s, and concluded annual harvest of cattail biomass stimulated regrowth and that the bioenergy properties of cattail were excellent. But economics of harvesting or cultivation of cattail in wet environments solely for bioenergy was not considered viable (Lakshman 1984, Pratt et al. 1984). They describe difficulties with harvesting in wet environments and the fact cattail consumed too many nutrients and water (Dubbe et al. 1988, Garver et al. 1988). This would not be the case with highly eutrophic systems such as within the Lake Winnipeg watershed and at Netley-Libau Marsh. Managed harvesting in this case could permanently remove nutrients from these systems, while providing plant material for bioenergy production. By considering modern environmental and economic benefits beyond heat production, benefits of harvesting cattail could be significant (Cicek et al. 2006). Specifically, recognizing the benefit of cattail harvesting to water quality and greenhouse gas mitigation warrants a re-evaluation of cattail for bioenergy production.

For a bioenergy plant to be economically feasible, year-around operation would be needed. This would require large volumes of dried and stored cattail biomass, or supplemental feedstocks from other sources. Fluctuations in seasonally available cattail biomass for an industrial-scale bioenergy system would require co-feeding options with agricultural residues such as straw and crop processing residues, forestry waste, and recyclable material. Scalability, efficiency, feedstock supply, and market availability issues are all factors for evaluation (Tampier et al. 2004, Cicek et al. 2006).

2.12.3 Bioenergy conversion technologies

Bioenergy is produced by combustion of plant biomass to generate direct heat, electricity, or combined heat and power (CHP). If the goal is to combine biomass harvesting for nutrient capture and bioenergy production, it is critical to ensure the biomass conversion technology employed is sustainable, efficient, and does not redeposit unwanted elements (i.e. phosphorus) by air dispersion back into the ecosystem. The retaining of nutrients and other heavy metals between the air emissions and residual ash is essential. Phosphorus is the primary element of concern in the eutrophication of Lake Winnipeg and preference needs to be given to conversion technologies that leave higher percentage of phosphorus in the ash, or that reduce flue gas temperature so nutrients can be effectively removed and not redistributed back into the system (Cicek et al 2006). The nitrogen and phosphorus content and emissions released in gases during combustion are crucial in determining viability of wetland biomass as a source of feedstock and nutrient mitigation.

Biomass combustion systems are not a new technology, with hundreds of them in use across Canada (Natural Resources Canada 2001). Stoker boiler biomass burners are solid fuel burners that combust the biomass material to heat water or produce steam, which is used as a distributed heating source or with steam turbines to produce electricity (Blue Flame Stoker 2012). Modern stoker boiler systems build off the concept of traditional coal burners, but are designed to ensure much greater efficient combustion of biomass fuels while maintaining low emissions. Specialized moving grate systems reduce formation of clinkers and fouling and allow for the use of higher ash biomass feedstocks, such as agricultural straw, which tends to have higher levels of silica, calcium, and potassium (Blue Flame Stoker 2012). Multi-cyclone dust collectors remove smallest dust particles or fly-ash, up to 90% generated from solid fuel combustion, with emissions comparable to natural gas (Blue Flame Stoker 2012, Gototalenergy 2011).

Gasification, a form of two-stage combustion where the gas is burned, utilizes the produced gas as an energy source. The resulting syngas can directly fuel an engine or electricity generator. Cicek et al. (2006) examined six small-scale distributed power generation systems with some cogeneration heat applications and gasification produced the most power due to low moisture content of the biomass as analyzed using the method in Tampier et al. (2004). Gasification is a process that converts materials such as plant biomass into a combustible synthetic gas, or syngas by reacting carbon at high temperatures with controlled levels of oxygen (Rezaiyan and Cheremisinoff 2005). The biomass is heated in an oxygen-deficient atmosphere to promote the release of the volatile gases: i.e. carbon dioxide, carbon monoxide, hydrogen and methane. This resulting syngas is much more efficient to burn than direct burning of biomass, and is burned to produce direct heat energy and boil water for steam for heating. The high temperature combustion of the biomass and burning of the syngas instead of the original biomass leaves behind undesirable chemicals in the ash and slag resulting in cleaner emissions and gas production (Rezaiyan and Cheremisinoff 2005). Cicek et al. (2004) demonstrated biomass gasification technology in Manitoba using municipal biosolids as the source feedstock, but there is currently very little industrial scale gasification being utilized in North America (Faaij 2004).

2.12.4 Densification

Biomass is commonly compressed into low-moisture fuel products such as pellets, cubes, or briquettes, which are ideal for storage and transport. The manufacturing process involves reducing and compressing the raw material into cylindrical bars of compressed energy. These compressed fuel products are burned to produce heat in pellet stoves and boilers, or transported for use as fuel in other energy conversion methods, such as coal co-firing plants or to large biomass energy plants (Cicek et al. 2006). Life-cycle analysis shows densified biomass fuel can be transported over significant distances without losing the carbon life cycle benefit it contributes when displacing fossil fuels (Forsberg, 2000). Europe and Asia are major markets for fuel pellets, where demand is increasing exponentially, providing a low-cost and immediate solution to greenhouse gas reduction targets (Vinterbäck 2008**).**

2.12.5 CHP Energy Production

Small scale distributed bioenergy systems similar to those that have been modelled using technologies adapted for the 250 to 5,000 kWe range for forest residues and bugwood applications can also be utilized for cattail biomass (Tampier et al., 2006 and Tampier et al., 2006). Cicek et al. (2006) showed cattail biomass could produce over 3 MWe. Research at the University of Manitoba has focused on two novel bioenergy CHP applications using the Entropic Cycle and the Brayton Hybrid Cycle (Cicek et al. 2006) designed to meet the strident cost constraints for small scale applications. The commercially ready Organic Rankin cycle could also be considered for comparison.

2.13 Wetland harvesting – integrating nutrients capture and bioenergy

Seasonal timing of harvesting wetland plants differs if harvesting to maximize nutrient capture, or for the efficient collection of dry biomass for biomass and bioenergy. Plants, such as cattail and *Phragmites*, transfer nutrients from the aboveground parts to the belowground rhizomes in the fall to survive over the winter until the next growing season (Dubbe et al. 1988, Mitsch and Gosselink 2007), therefore ideal time for harvesting for nutrient removal would be late summer when nutrient levels in aboveground plants are highest. Moisture content would also be highest as would the impacts to wildlife. Bjork and Graneli (1978) and Granelli (1984) recommend a winter harvest when harvesting biomass for bioenergy, for ease of harvesting and to remove cost of drying the harvested biomass. Winter or early spring conditions in the Canadian prairies could provide ideal conditions since the marsh would be frozen allowing machinery into flooded areas, impacts to wildlife would be minimal, and dead plant material would be dry for storage and bioenergy. But whether enough nutrients remain in the plants to remove stored nutrients for combined nutrient capture is not well understood. A winter harvest could also be problematic when there is heavy snow accumulation as is common across the Canadian prairies.

2.13.1 Harvesting Challenges and Early Equipment Design

Harvesting in wet and waterlogged conditions presents some serious logistical challenges, particularly if the goal is to minimize ecological impact and maintain sustainability of the marsh plant community. Because of soft wetland soils rich in organic matter typical heavy machinery intended for harvesting causes compaction and destruction of soil-plant roots, and cannot be used in wetland environments (Rummer et al. 1997). Equipment traction, weight ratio, and flotation are major considerations for wetland harvester design. A range of equipment has been used for harvesting wetlands, including conventional agricultural equipment if soil conditions allow, and wetland harvesters for wet agricultural conditions (Granelli 1984, Wyss 2004, De Vries Cornjum 2013, Piston Bully 2013).

Earlier wetland harvesting is described by Graneli (1984), where winter reed harvesting on lakes in Sweden was done using a chain of three tractors; the first with a cutting bar, next with a swath turner, and the last with a Howard Big Baler. This method worked in easily accessible marsh areas where ground or ice was frozen solid in winter, and would only work with minimal snow cover. Harvest produced 3 t of reed/hour producing rectangular bales ready for transport. Over a 4 day period, 80 t of reeds were harvested. Use of tractors during other times of the year, however, would cause rutting and damage to the marsh structure. A custom built tracked harvester was built for use on Lake Constance, Germany in the 1970s to harvest reeds that cut, chopped, and blew the material into a hopper bin on the harvester (Graneli 1984). Although it was not amphibious, this tracked vehicle had lower ground pressure than tractors and could access various conditions. A six-wheeled balloon-tyre vehicle was tested in Sweden that cut, chopped, and blew the chips onto a wagon pulled behind the harvester, but it was large and unwieldy, particularly in snow conditions (Graneli 1984).

In the late 1990s a specially-designed low impact tracked harvester designed for soft wetland conditions was built for use in the UK to harvest fen vegetation for habitat management in The Broads, Britain's largest protected wetland and third largest inland waterway (Broads Authority 2005). Conservation efforts are working to restore selected fens to the ‘open’ state they were in until the 1920s without trees and bushes (Broads Society 2013), by harvesting and removing grasses, scrub, and bushes. The harvester cuts and chops the plant material into pieces, storing it in an attached hopper, and then blowing the material down a high-pressure air-filled pipeline to a collecting trailer. Alternative markets for the fen product is being explored, including mulch and use as a solid fuel for use in biomass boilers (Broads Society 2013).

Cattail harvesting in Switzerland in 2002 used a small tracked harvester with low weight ratios that cut, chopped, and blew the material into an attached hopper for easy transport to the processing facility, where the material was dried mechanically, and pressed into pellets for bioenergy use Wyss (2004). In this case, the storm water retention wetland was able to be drained to allow greater access for harvesting. Compaction of the marsh area did occur during harvesting, but slight compaction of cattail rhizomes from the tracked harvester was found to actually stimulate growth the following season (Wyss 2004).

In the fall of 2012, IISD successfully demonstrated commercial pilot scale harvesting of cattail using traditional agricultural equipment from ditches along the Trans-Canada highway and at Pelly's Lake, a storm water retention wetland near Holland, Manitoba. Cattails were cut and windrowed at both locations using a MacDon Industries Ltd. Windrower swather and baled with round or square balers depending on site conditions. A total of 250 tonnes of cattail biomass was collected over approximately 5 days of harvesting (Grosshans and Greiger 2013). The growing season during which the cattails were harvested had below normal precipitation, which aided in ease of cutting with commercial grain harvesting equipment. Baling operations were hampered by above normal precipitation later in the year. Challenges encountered during harvesting included stuck equipment, and difficulties with baling due to the volume of swathed cattails in wetland areas (Grosshans and Greiger 2013).

2.13.2 Modern European wetland harvesters

Today, modern harvesting in wet and waterlogged conditions for wetland habitat management to control invasive species and maintain ecological biodiversity is an ongoing economic activity in Europe, as is harvesting of reeds for roof-thatching. European wetland harvesters are a well-established technology for use on ecologically sensitive lands by companies such as De Vries Cornjum (2013), Pisten Bully (2013), LogLogic (2013), Seiga (2013), and Reeda (2013). Designed and built for harvesting in wetland conditions, tracked harvesters, or those fitted with large balloon tires, can negotiate soft terrain without sinking, and have low weight ratios and ground pressure less than 50 grams per square centimetre (Wichtmann and Tanneberger 2009). Several designs exist for collection of harvested material. Some harvesters chop plant material into pieces, blowing it into an attached hopper or collecting trailer similar to an agricultural forage harvester. Others cut and place them in swaths, which are collected and baled in a separate baler (Figure 2.4).

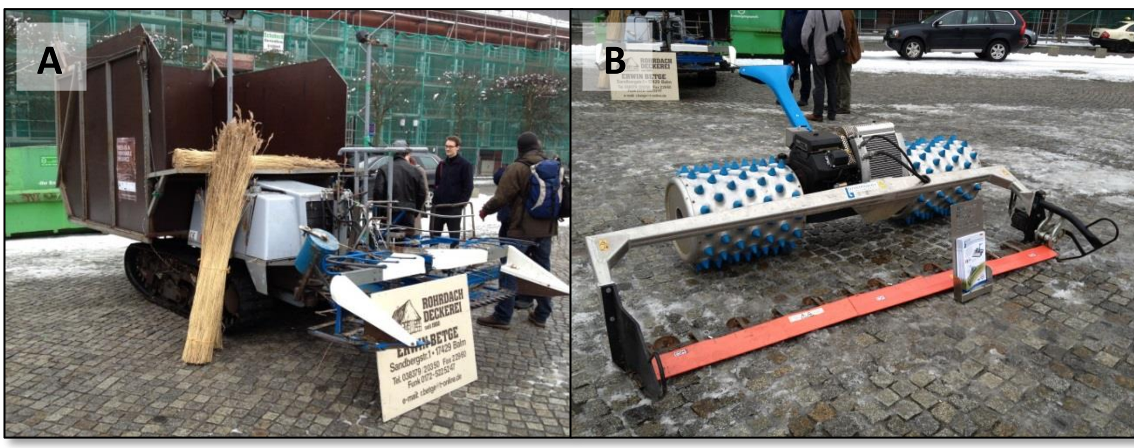


Figure 2.4. Commercial reed harvesters on display in Greifswald, Germany. A) Tracked harvester that cuts and bundles for roof thatching, and B) small-scale walk-behind harvester for habitat management. (*Photo credit: R. Grosshans*)

De Vries Cornjum (2013) in the Netherlands specializes in wetland habitat management, mowing and collecting wetland grasses and reeds to maintain biodiversity on ecologically sensitive lands. Specialized reed harvesters for rood thatching cut and wrap the reeds as bundles, move them up a conveying system, where they are manually loaded onto the back of the vehicle (Figure 2.4). Kässbohrer Geländefahrzeug AP, manufactures the Pisten Bully 300 GreenTech (Figure 2.5), which offers the versatility of 3 point header attachments including mowers, mulchers, and chopped collection units for habitat management, silage, and biomass for bioenergy collection (Pisten Bully 2013). Similarly the LogLogic SoftTrack units are designed for mowing and material collection through chopping and blowing into an attached hopper bin (LogLogic 2013).

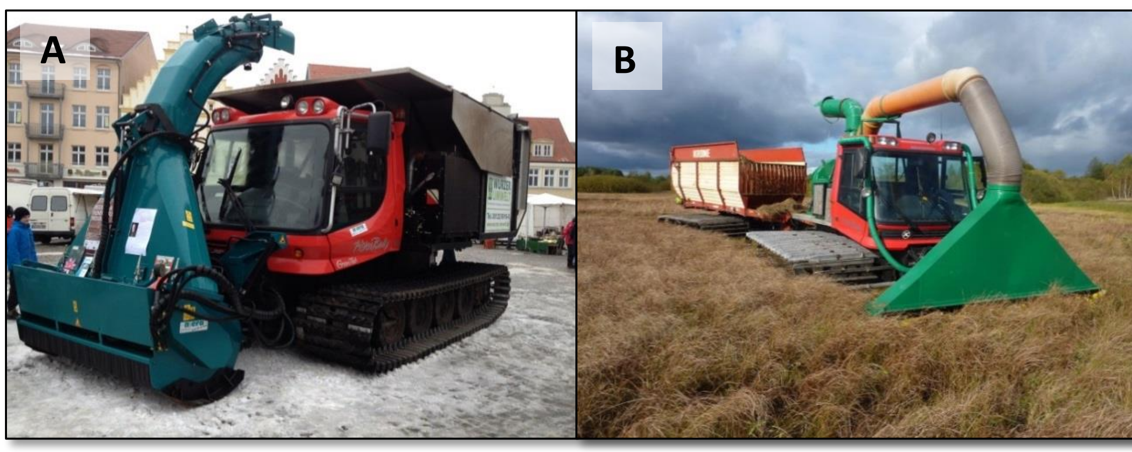


Figure 2.5. A) Pisten Bully 300 GreenTech harvester with chopping collecting system on display in Greifswald, Germany, and B) similar customized harvester in operation in Poland (*Photo credits: (left) R. Grosshans, (right) W. Wichtmann*).

Modern reed cutting is also done with low weight ratio balloon tire vehicles specially built for wet waterlogged conditions. Examples are the Seiga amphibious harvester, Estonia reed harvesters, and the Reed Harvesters in Poland (Reeda 2013). These vehicles have low ground pressure (less than 50g/cm^2), and are amphibious, able to harvest in waterlogged and flooded conditions year round with minimal impact to wetland sediments (Reeda 2013, Estonian water reed cutting and thatching company 2008). Similarly, reeds are cut and bound as bundles, and manually loaded onto the vehicle. The Seiga vehicle was also used to harvest cattail during the bioenergy research trials by the US DOE in Minnesota, USA (Granelli 1984, Dubbe et al. 1988).

2.14 Conclusions

The literature suggests harvesting wetland plant biomass could have great potential to capture, remove, and recover stored nutrients before reaching downstream water bodies. The harvested plant biomass also represents a valuable renewable and sustainable fuel source for bioenergy, biomaterials, and high value end-products that has until now not been fully utilized. Use of harvested plant biomass for production of cleaner low-carbon bioenergy in modern efficient biomass conversion technologies also provides low-carbon energy production useful for mitigation of GHG emissions by displacing carbon-rich, non-renewable energy sources such as petroleum, coal, or natural gas. With continued concern over global warming and reduction in carbon emissions, and as nations move towards reducing emissions, processes that can generate energy with minimal amounts of net-carbon emissions are of great importance. The literature suggests the proposed concept of harvesting cattail biomass for combined purposes of nutrient capture, biomass bioenergy and carbon offsets, and habitat holds great promise at a watershed scale.

Wetland harvesting studies need to address the potential impacts of seasonal harvesting on the wetland and plant communities, and the multi-benefit approach of combining nutrient removal and bioenergy. The value of harvested biomass as a feedstock for production of cleaner bioenergy also needs further research. Winter or early spring ice covered conditions may provide suitable conditions for harvesting plant material from wet environments, but seasonal timing of harvest for various goals and mitigation of impacts needs to be considered. The value of harvested cattail biomass as a feedstock for production of cleaner bioenergy needs to be explored.

3.0 Methods

3.1 Site Background

3.1.1 Lake Winnipeg – an indicator of nutrient stress and prairie sustainability

Lake Winnipeg, at 24,500 km^2, is the tenth largest freshwater lake in the world. It lies within the borders of Manitoba, Canada but its watershed encompasses over 984,000 km^2 receiving drainage water from parts of Alberta, Saskatchewan, Manitoba, northwestern Ontario, Minnesota, and North Dakota, USA (Figure 3.1). Canada's sixth "great lake" is important to the province both economically and recreationally and is part of the livelihood and survival of First Nations communities. The lake supplies water for hydroelectric power generation, provides valuable habitat for fish and wildlife species, supports a large commercial freshwater fishery, maintains a world class recreational sport fishery, provides extensive beaches and recreation areas for residents and tourism.

Evidence has shown the significant degree to which this lake has become one of the most eutrophic large lakes in the world over the past several decades, from overloading of phosphorus from the surrounding watershed (Lake Winnipeg Stewardship Board 2005). Most recently, Lake Winnipeg was awarded the not so prestigious title from Global Nature Fund as the World's Most Threatened Lake of 2013, from the serious phosphorus eutrophication and increased frequency of algae blooms (Global Nature Fund 2013). Scientific evidence reveals significant changes in water transparency, biological species composition, productivity, and sediment chemistry indicating the lake is approaching a state of deterioration that may affect ecosystem sustainability, not unlike that seen in the lower Laurentian Great Lakes during the 1960s (Lake Winnipeg Stewardship Board 2005). Beaches along shores of Lake Winnipeg are more frequently closed to swimming as a result of algal blooms, bacteria and pathogens that make the water unsafe for human use.

Figure 3.1. Lake Winnipeg, Manitoba, Canada and its watershed outlined in yellow.

The phosphorus comes from a complex diversity of sources in the watershed from agricultural fertilizer runoff, livestock, and rural and urban wastewater effluent, storm water, and lawn fertilizer. The largest contributor of phosphorus and nitrogen to Lake Winnipeg is the Red River supplying over 60 % of the phosphorus load from the Red and Assiniboine rivers, even though it has a relatively minor hydrologic input compared to the Winnipeg River and the Saskatchewan River watershed (Bourne et al. 2003). The Red River supports several large urban centres and smaller communities and as a result recieves treated municipal wastewater. Drainage over the past century has modified the landscape across the Red River Valley in Canada and the US, and worsened flooding and nutrient loading to the lake. Spring flooding from snowmelt runoff upstream rapidly moves nutrient-rich flood water from lawns, agricultural fields, and wastewater lagoons downstream to Lake Winnipeg. These spring "pulse" events of nutrient-rich water contribute significantly to the eutrophication of Lake Winnipeg. (McCullough et al. 2012)

3.1.2 Netley-Libau Marsh

At the south end of Lake Winnipeg lies Netley-Libau Marsh, a large freshwater coastal wetland at the mouth of the Red River (Figure 3.2). At 250 km^2 (25,000 ha) in size it is one of the largest freshwater wetlands in Canada. The marsh is comprised of shallow lakes, channels, and wetland areas through which the Red River flows on its way to Lake Winnipeg. The river bisects the marsh into a western (Netley Marsh) and eastern half (Libau Marsh), with nutrient rich Red River water flowing primarily through the western portion out into the lake, and nutrient rich lake water cycling into the eastern marsh via lake currents, wind seiche, and wind setup. It is designated an Important Bird Area by Bird Studies Canada and the Canadian Nature Federation providing important wildlife and fish habitat. Traditional uses of the marsh are agriculture (livestock) and recreation (hunting, trapping, boating, and fishing), but the marsh is an area of historical and cultural significance with evidence of human habitation spanning at least 3,000 years. It provided resources to early aboriginal people and was important to fur traders and early settlers who described the area as rich in waterfowl, wild game, and fish, and providing rich hay lands and sugar maples (Hind 1860). The wetland provides an array of diverse ecological services or EGS benefits, functioning as a filter, sequestering nutrients from the Red River and Lake Winnipeg - an important function that is increasingly understood as a key component of an overall Lake Winnipeg basin nutrient management strategy.

Netley-Libau Marsh was described in 1857 as "a series of reedy marshes that extend in all directions as far as the eye can see" (Hind 1860). Over the past several decades, the structure of the marsh has been significantly altered and critical EGS benefits have been compromised. A study by Grosshans et al. (2004) documented the significant loss of emergent aquatic vegetation and erosion of separating upland habitats within the marsh over a 22 year period. Open water areas within the marsh had increased from 8,880 ha (35%) in 1979 to 13,125 ha (51%) in 2001, while vegetation cover had declined by almost 32% (Figure 3.3). The result has been a gradual loss of plant communities, erosion of channels and islands, amalgamation of water bodies, and subsequent decline in wildlife habitat and populations.

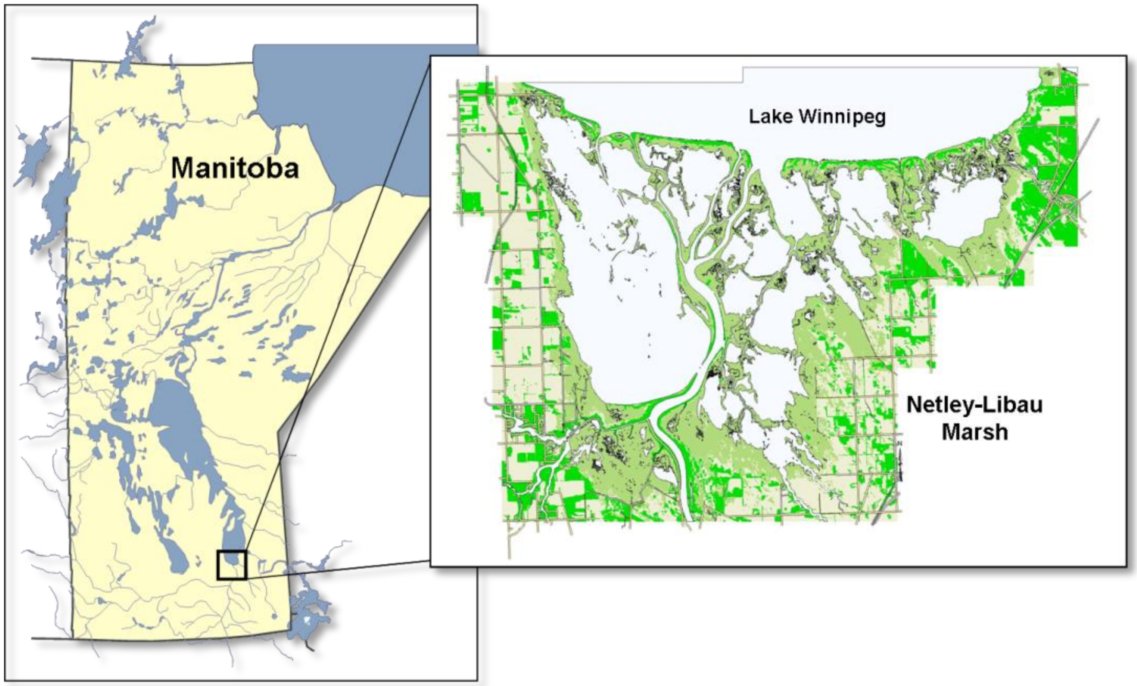


Figure 3.2 Netley-Libau Marsh at the south end of Lake Winnipeg, Manitoba, Canada. (Source: Grosshans et al. 2004)

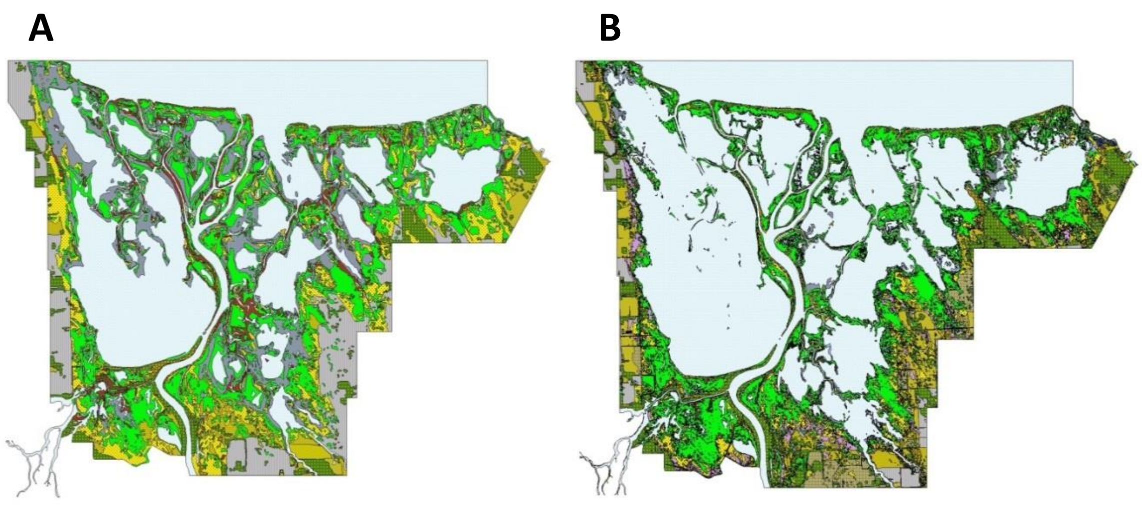


Figure 3.3. Vegetation of Netley-Libau Marsh. A) 1979, and B) 2001. Loss of plant communities and islands is clearly evident (source: Grosshans et al. 2004).

Several factors are contributing to changes in the marsh. Drainage, dredging, and other water management schemes occurring since the early part of the last century have substantially altered the natural flow of the Red River through the marsh. Recent modelling showed a majority of Red River flow is through two main river channels to the lake and an opening in the riverbank into Netley Lake, the “Netley Cut”, on the west side of the marsh. Up to 35% of Red River flow currently passes through the cut into Netley Lake (Haresign 2012). Since the 1970s, Lake Winnipeg water levels have also been managed by Manitoba Hydro for hydroelectric production with some effect on overall hydrology of the lake and marsh (MB Hydro 2012). Other factors include prolonged periods of wet climate over the past decade, flooding, increased nutrient loads, invasive carp, and prolonged periods with no low-water events to allow plants to re-establish from seed (Grosshans et al. 2004). Wetlands do naturally undergo high and low water periods that are essential to the plant community (van der Valk and Davis 1978). Evidence from low water levels in Manitoba experienced in 2003 showed marsh plants can be re-established in Netley-Libau Marsh under proper conditions. Exposed mudflats allowed marsh plants to germinate from the seed bank and re-colonize the marsh (R. Grosshans pers. comm.).

The ability of a wetland to improve water quality by nutrient uptake is dependent on the hydrological condition of the marsh, the aquatic plant community, and retention time of water flow for proper plant/water interactions (Mitsch and Wang 2000). Additionally, by reducing water flow coastal wetlands help regulate flood control and decrease sediment loads. Netley-Libau Marsh is not currently functioning as a healthy coastal wetland. Nevertheless, many of the benefits that have been severely degraded or lost, such as providing habitat and removing and storing nutrients that would otherwise enrich the lake, can be revitalized through restoration and management of this coastal wetland (IISD 2013). Mitsch and Wang (2000) demonstrated restoration of 15% of wetlands along the Quanicassee River in the Lake Erie watershed would effectively reduce significant phosphorus loads to the lake. This suggests a rehabilitated Netley-Libau Marsh could have significant benefits to Lake Winnipeg by removing nutrients from the Red River. Comparatively, the Red River accounts for almost 60% of the phosphorus loads to Lake Winnipeg, while the Quanicassee only 3% to Saginaw Bay (Mitsch and Wang 2000). The potential for water quality improvement from Netley-Libau marsh could be significant.

3.2 Research plots and experimental treatments in Netley-Libau Marsh

Research plots were established in 2006 in the north east portion of Netley-Libau Marsh north of Libau, Manitoba, on private land owned by Dr. Dennis Anderson (Figure 3.4). Sites were accessed over land using an ARGO all-terrain vehicle or over water by canoe. Equipment storage, day facilities, field equipment and repairs, and marsh access was granted by Dr. Anderson. Six open treatment plots 10 m x 10 m (100 m^2) were located in heavily vegetated *Typha* stands, marked with metal fence posts in each corner and GPS referenced (Figure 3.5).

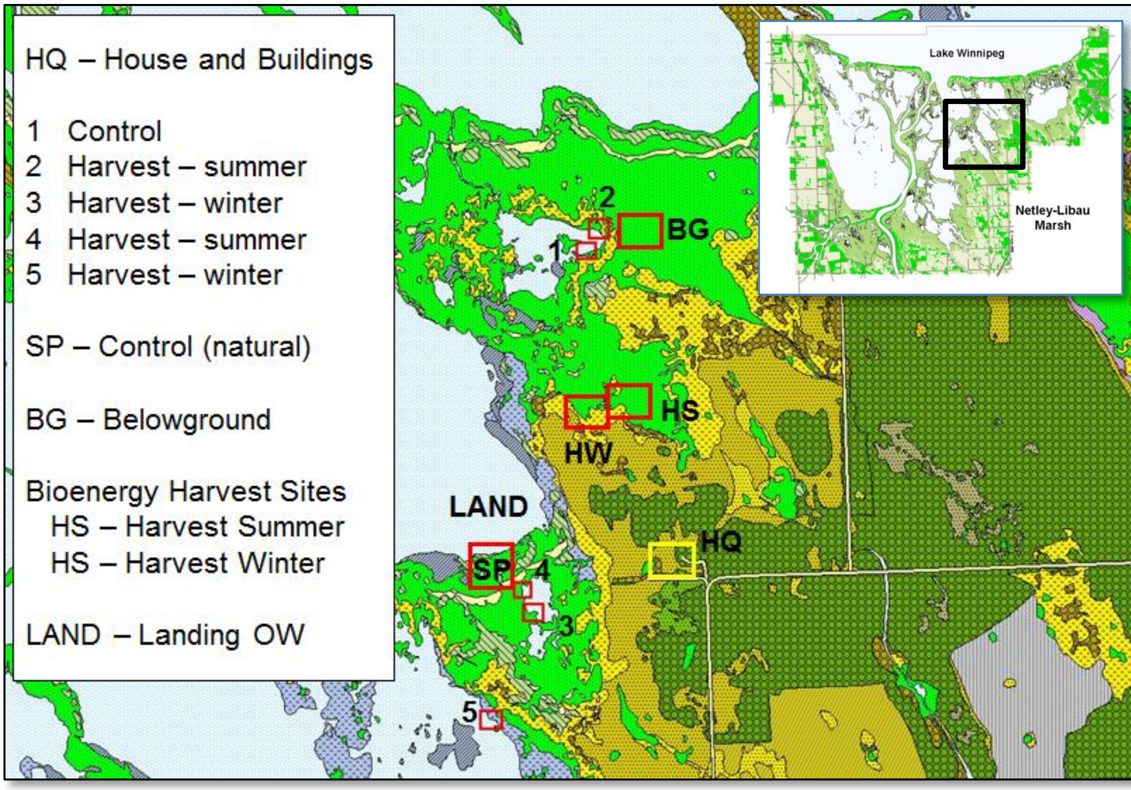


Figure 3.4. Research site in Netley-Libau Marsh north of Libau, Manitoba. Inset map of Netley-Libau Marsh shows location of site in NE corner of the marsh.

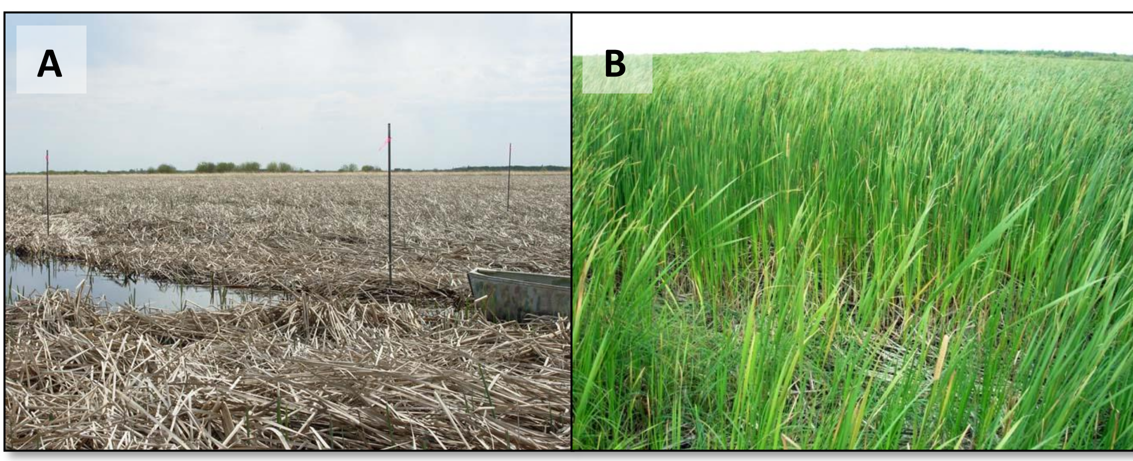


Figure 3.5. Treatment sites in Netley-Libau Marsh. A) Early spring showing metal fence posts marking each site, and B) midsummer overgrown with cattail.

Three experimental treatments were used (Figure 3.6):

1. Two "Control" sites: samples randomly collected to minimize disturbance and monitored for biomass and nutrient uptake - but not harvested;

2. Two "Summer Harvest" sites: samples randomly collected to minimize disturbance and monitored for biomass and nutrient uptake - harvested in late summer – aboveground cattail was harvested in late summer when nutrient content and shoot biomass are maximized for nutrient removal, and analysed for biomass, nutrients, and bioenergy properties; and

3. Two "Spring Harvest" sites: samples randomly collected to minimize disturbance and monitored for biomass and nutrient uptake - harvested in early spring - aboveground *dead* cattail was harvested during early spring and analysed for biomass, nutrients, and bioenergy properties.

Four "Open Water" or unvegetated sites were also monitored for stored sediment, three located near the treatment sites and one at the Landing – one of the large open water bays. Additionally, there were two "Biomass Bioenergy" sites located in dense cattail stands, where larger volumes of cattail was mechanically harvested as a bioenergy feedstock in early spring and late summer/early fall. (Figure 3.4).

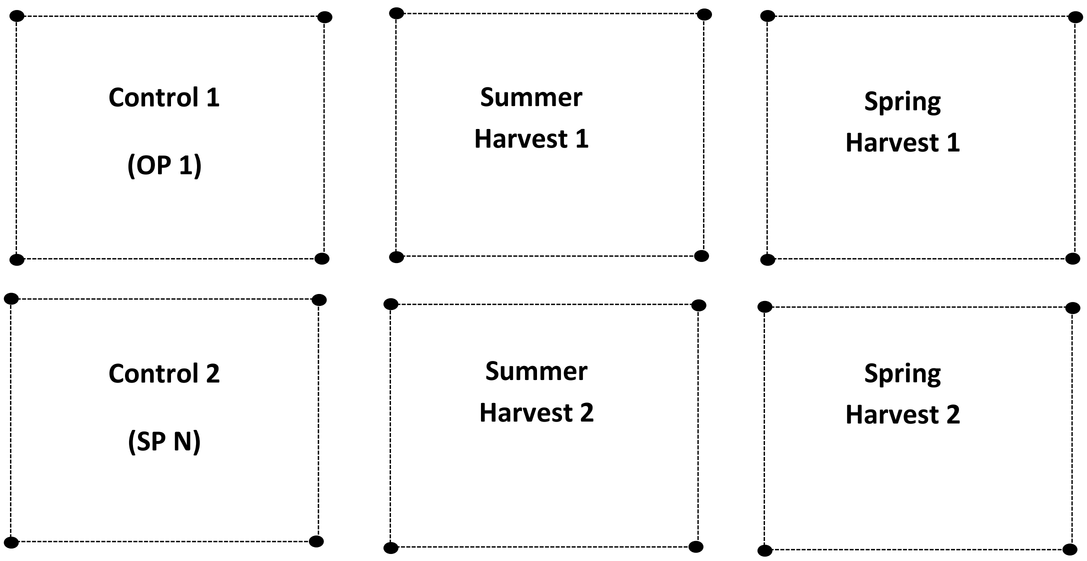


Figure 3.6. Experimental sites, each 10m x 10m in size marked in each corner with a metal post for location.

3.3 Sample collection - nutrient uptake and seasonal biomass

Samples were collected every 2 weeks from the six treatment plots and four open water sites throughout the ice-free and growing seasons from April to October in 2006 and 2007, and in spring (May) and late summer (August) peak growth in 2008 and 2009. During each sample period samples of aboveground plants, roots/rhizomes, litter, and sediment were collected at each of the six treatment plots from four randomly placed 1 m x 1 m square quadrats (as described below) and averaged (for biomass weights) or combined (for nutrients) for a single representative sample from each plot for each period (Figure 3.7). At each quadrat measurements included plant composition, plant density, plant height, water depth, and litter accumulation. At each Open Water site, soil and water samples were collected following procedures as outlined below.

Cattail plants are rooted in the sediment and obtain their nutrients for growth from stored nutrients in the sediment and organic litter layers. Cattail plants and roots - aboveground shoots and belowground roots/rhizomes - were collected to measure seasonal growth rates, seasonal biomass accumulation in above and belowground parts, plant nutrient uptake and seasonal nutrient content, accumulation in plant tissue, and to monitor effects from harvesting (as outlined below) on plant growth, plant density, plant species composition, and average plant height and growth. Other plant species were collected in 2006 to 2009 for comparison and long term monitoring but were not part of this study: the emergents *Schoenoplectus* spp. (bulrush), *Phragmites australis* (giant reed), and *Schoenoplectus fluviatilis* (river bulrush), as well as the submersed plant *Potamogeton* spp. (pondweed) and the floating plant *Lemna* spp. (duckweed). Organic litter and sediment samples were collected to measure sediment nutrient storage and water samples in 2006 and 2007 to measure nutrient inputs. Cattail samples (aboveground shoots) were collected from the control site (OP 1) in December, January, and March to evaluate nutrient loss in aboveground plant material over winter. Methods follow Smith et al. (1988), Bouchard and Mitsch (1999), Mitsch et al. (2005), Goldsborough and Cicek (pers. comm.).

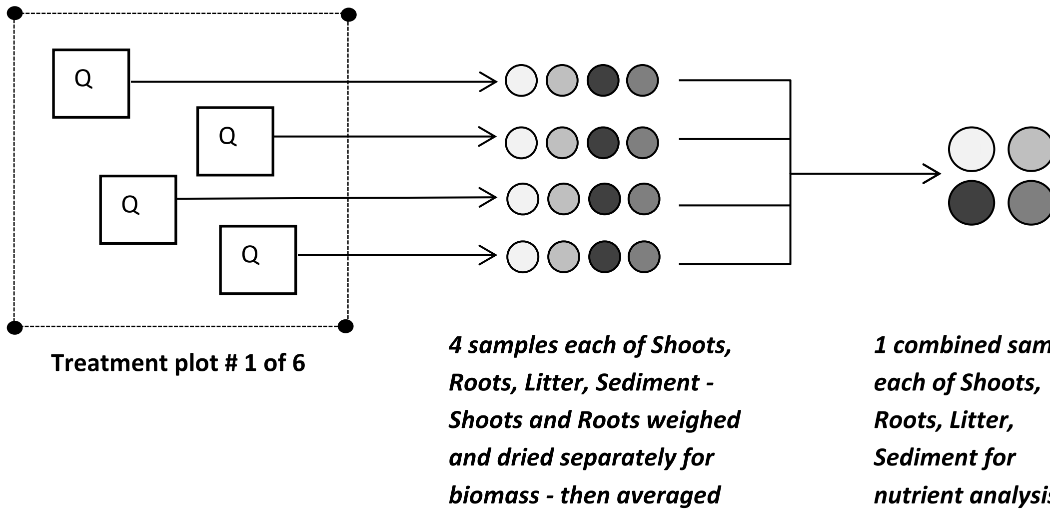


Figure 3.7. Quadrat sample design. Four randomly placed 1m x 1m square quadrats sampled in each research site during each sampling period – cattail shoots, roots, litter, sediment (represented by circles) collected from each quadrat. Shoots and roots weighed then averaged. Samples combined for 1 representative combined sample each for shoots, roots, litter, and sediment for nutrient analysis.

3.3.1 Plant sampling

Samples of cattail were collected for nutrient storage and biomass accumulation in cattail communities of Netley-Libau Marsh. From each quadrat, four individual plants were collected for a total of sixteen plants per site location (Figure 3.8) and four root masses for seasonal biomass and nutrient accumulation. In each quadrat the total number of plants was counted and the average height of plants and average water depth were determined. In 2006, within each quadrat 25% of plants were collected every two weeks to measure seasonal aboveground biomass and nutrient accumulation (Bouchard and Mitsch 1999, Mitsch et al. 2005). Roots were cut from the base of plants, washed to remove soil, bagged separately and washed thoroughly with water in the lab to remove residual soil. Shoot samples were folded, wrapped with rubber bands, and labelled. All shoot and root samples were weighed for wet weight, dried in drying chambers at 65°C for a minimum of 48 hours, and weighed for dry weight to calculate biomass accumulation per square meter and primary productivity. Samples were combined for one representative sample per treatment site per sample period and processed for nutrient analysis (below).

Figure 3.8. Plant sampling in Netley-Libau Marsh. A) Bags of collected samples in early spring, B) 1 m^2 quadrat placed in centre of picture for sampling.

3.3.2 Litter and soil sampling

Four soil cores were collected from each treatment site (one per quadrat) and the four open water (unvegetated) sites with a custom built 2 inch diameter corer (Figure 3.9). Cores were extracted from the corer with a plunger ramrod. The top organic litter layer was removed, combined for all four quadrats, and bagged separately from lower sediment layer. Root pieces were removed from sediment layer cores, and all four quadrat cores combined for one composite sample from each treatment and open water site, bagged in Ziploc storage bags, and stored on ice until delivered to the lab (4 cores from each of 4 quadrats = 1 litter and 1 sediment sample per site per sample period). All litter and sediment samples were weighed for wet weight, dried at 65 °C for minimum 48 hours, and weighed for moisture content and bulk density (dry weight).

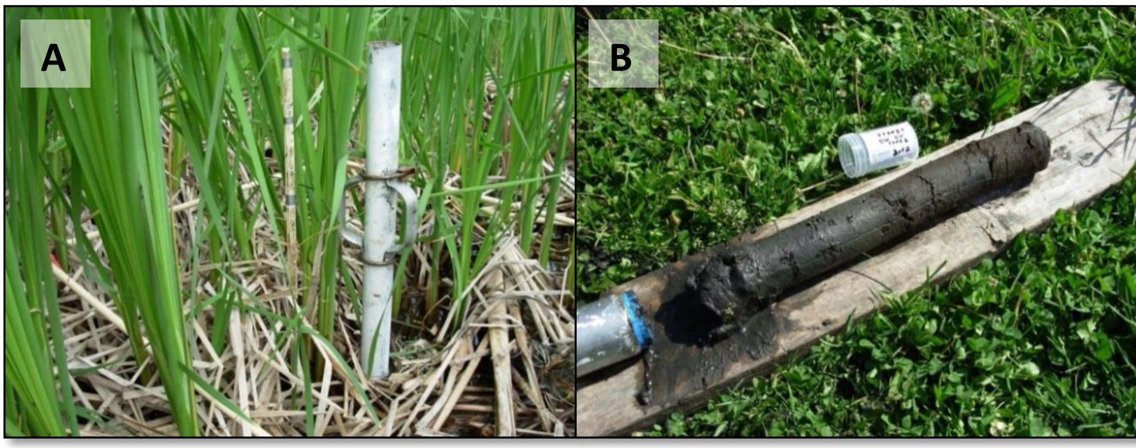


Figure 3.9. A) sediment corer shown in 1m x 1m quadrat; B) 2 inch diameter sediment core removed from corer - litter layer on left, sediment layer to the right.

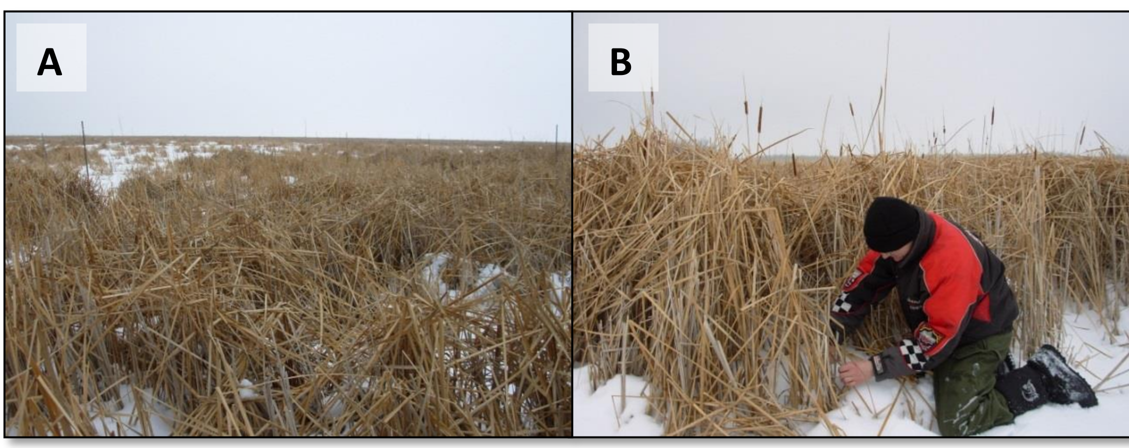


Figure 3.10. A) Dead cattail biomass in control plot in winter. B) Winter sampling for analysis of nutrient loss over winter and spring.

3.3.3 Water sampling

Water samples were collected every two weeks in 2006 from April to October from each research site, open water site, the large open water bay of the main marsh, and several other sites in the marsh for comparison: Devil's creek which drains into the south end of Netley-Libau Marsh, the Red River, Netley Creek before it drains into the Red River, and Netley Lake on the west side of the marsh. In 2007 and 2008 samples were collected in May and August. Water samples were collected from deeper sites (> 30 cm) using a 1 meter long 2 inch wide acrylic tube placed in the water column, stoppered at the top, and the water drained into a 4 L water jug. This effectively collected a mixed sample from the entire water column. In shallower sites (< 30 cm) a 4 L water jug was used to collect a mixed water sample. Each sample was transferred to a 1 L white plastic sample bottle stored on ice and analyzed within 24 hours (outlined below).

3.3.4 Belowground nutrient uptake and biomass accumulation

Belowground cores were randomly collected 2006 to 2009 from each treatment site, a belowground biomass site, and the large "biomass bioenergy" harvest sites for belowground biomass accumulation and nutrients (Figure 3.11). Each spring three 6 inch diameter cores were collected randomly from each treatment site. In 2006 four cores were randomly collected every 2 weeks from May-October from the belowground biomass sample area - a dense stand of cattail near one control (OP 1) and treatment site (OP 2). Every spring and fall from 2006 to 2008 six cores were randomly collected from the biomass bioenergy harvest sites – six within the harvested zone, and six within the neighbouring unharvested zone. Belowground sampling followed Smith et al. (1988), Van der Valk, and Murkin and Murkin (1989).

Figure 3.11. Belowground sampling in Netley-Libau Marsh. A) Coring for belowground plant samples, B) removing core from corer, and C) successful 6 inch diameter belowground core.

The root corer is a six inch diameter metal cylinder attached to a **T** shaped pipe and handle. Inside the pipe and down into the cylinder is a rod with plunger to push the core out of the corer. A bandsaw blade is welded to the bottom of the cylinder for cutting through roots and rhizomes (Figure 3.11). Cores were placed in large Ziploc bags and stored on ice until analyzed. Soil samples were taken from each biomass core, dried, and processed as other soil samples (below). Each core was washed to remove all inorganic soil. Washing consisted of a water bath to loosen soil. The core was broken up in the water bath, and root matter was washed repeatedly in a soil wash sink and sieved with 10 mm sieves until all soil was washed from core. Root/rhizome mass was dried in drying ovens at 65°C for a minimum of 48 hours and weighed for dry weight to calculate biomass accumulation. Samples from each site were combined for each sample period. Dead litter and fine root mass was removed from rhizomes. Rhizomes were ground in Wiley Mill grinders, and stored in Ziploc bags for digestion and nutrient analysis (as described below).

3.4 Sample processing and nutrient analysis

3.4.1 Plant samples

Dried plant samples were combined for one composite sample of shoots and roots from each treatment site per sample period (4 quadrat samples = 1 averaged sample of shoots and roots per site). Dried samples were ground to 1/16" screen size using Wiley Mill grinders in the Department of Soil Science at the University of Manitoba (Figure 3.12) and stored in Ziploc bags until digested and analyzed for nitrogen and phosphorus content (outlined below). Select samples of ground cattail were sent to Agvise Laboratories in North Dakota and analysed for complete nutrient analysis (total Phosphorus (TP), total Nitrogen (TN), Potassium, Calcium, Magnesium, Sodium, Zinc, Iron, Manganese, Copper, Sulphur, and Boron) and to Central Labs in Winnipeg for metals analysis. TP and TN sample results from Agvise were compared to samples analysed in the lab for confirmation of results.

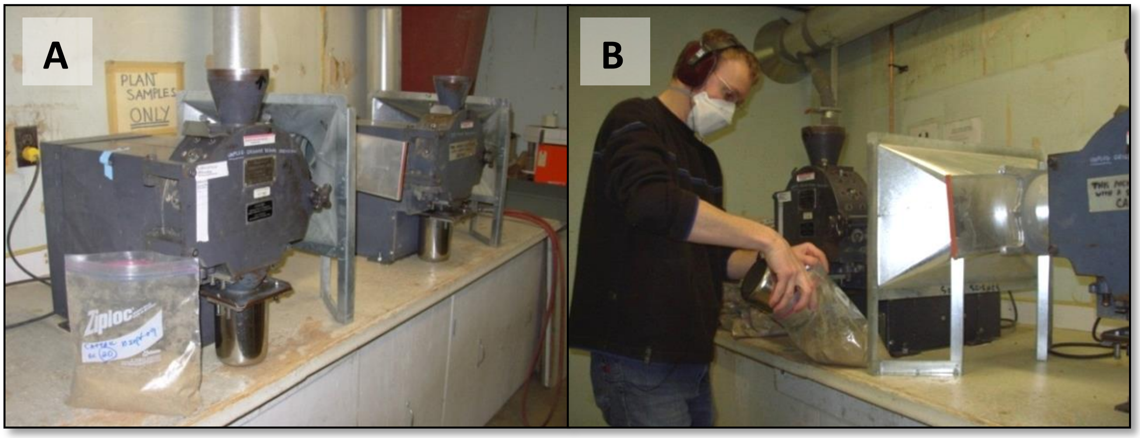


Figure 3.12. A) Wiley Mills grinders at the University of Manitoba, Department of Soil Science. B) Grinding plant material to dust for nutrient analysis.

All ground plant samples (shoots and rhizomes) were analysed for TP and TN following digestion using a HACH Digesdahl by concentrated sulphuric acid and 50% hydrogen peroxide digestion following HACH digestion procedures (HACH 2009). Ground plant sample (0.4 g) was weighed and transferred to a 100 mL HACH digestion flask (Figure 3.13). Concentrated sulphuric acid (18%) was added to the flask (4 mL) and heated on the Digesdahl at 440 C for 4 minutes until sample was digested to char. Hydrogen peroxide (50%) was added (10 mL) to the charred sample in the flask via the funnel on the fractionating column. Once addition of peroxide was complete excess was boiled off for 1 minute until presence of white acid fumes was gone and liquid fraction was clear. If digest did not turn colourless peroxide was added in 5 mL increments until digest became clear or did not change colour. Hot flasks were removed and allowed to air cool.

Samples were diluted to 100 mL with deionized water and stored in 50 mL plastic centrifuge tubes for analysis.

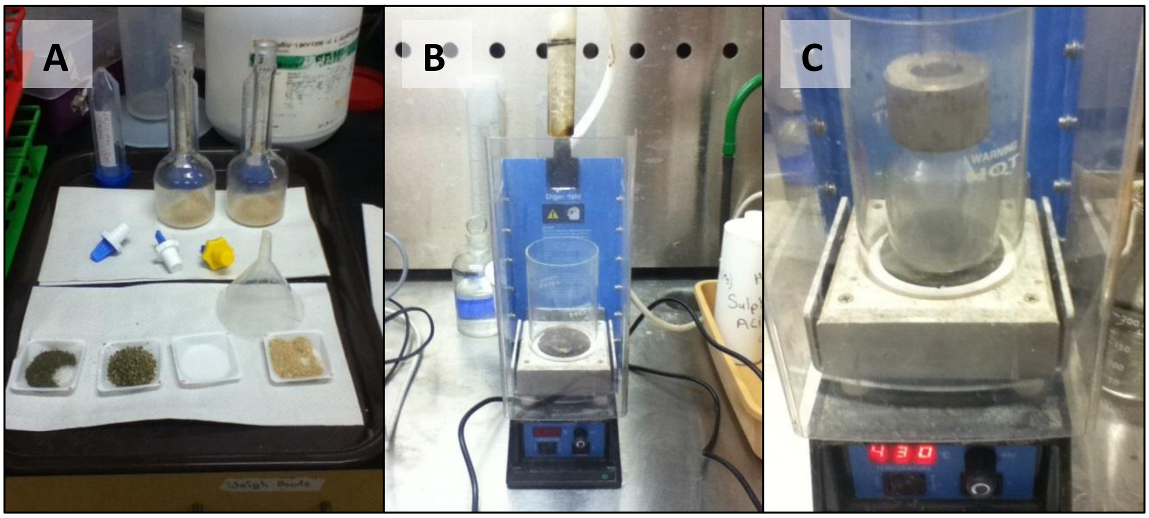


Figure 3.13. Digestion of plant material. A) Ground and weighed samples for digestion, B) HACH Digesdahl apparatus showing heating element, safety shields, condenser and aspirator tube setup attached to water tap, C) digestion flask on heating element after peroxide addition.

Digested samples were analyzed for TP (as PO_4) and TN (as NH_4) using a flow injection Lachat xyz autosampler, QuickChem 8500, in the department of Biosystems Engineering at the University of Manitoba. Ammonia-N was measured by hypochlorite method and phosphorus employed ascorbic acid and molybdate colour reagent method (Stainton et al. 1977). Acidic digested liquid samples (pH 1.5) were diluted for analysis using 1 mL sample and 6 mL of deionized water. Nitrogen and phosphorus concentrations were calculated as mg/L.

3.4.2 Sediment and litter samples

All dried sediment samples were finely ground in soil grinders in the department of Soil Science at the University of Manitoba (Figure 3.14), bagged in AgVise soil bags, and sent to AgVise in North Dakota where they were analyzed for elements.

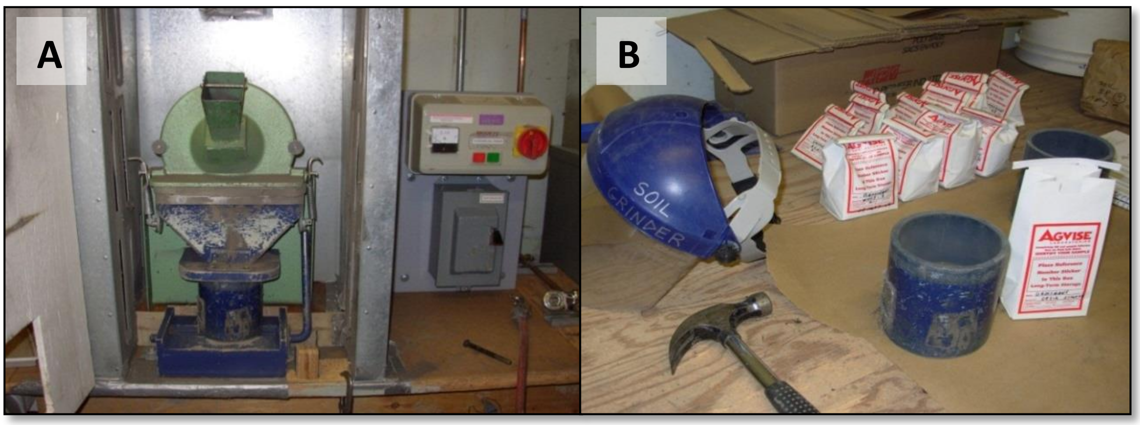


Figure 3.14. Soil sample processing. A) Soil pulveriser at University of Manitoba, Department of Soil Science. B) Pulverized soil samples packed and shipped to Agvise Laboratories for analysis.

3.4.3 Water analysis

All water samples were analyzed at the Environmental Engineering lab, in the Department of Biosystems Engineering (Dr. Nazim Cicek), at the University of Manitoba following “Standard Methods for the Examination of Water and Wastewater, 18th Edition” (APHA, 1998), and “The Chemical Analysis of fresh water, 2nd edition” (Stainton et al. 1977).

Total reactive phosphorus (TRP) and Ammonia (NH_3)

Total reactive phosphorus (TRP) methods employed the ascorbic acid and a molybdate color reagent method and Ammonia-N was measured following the hypochlorite method, both determined using colorimetric analysis using a UV/visible light spectrophotometer. Water samples were not filtered to remove particulate matter so TRP included soluble reactive phosphorus (SRP) plus phytoplankton particulate P that reacted to acid molybdate analysis.

Total phosphorus (TP)

Total phosphorus was measured using HACH reagents and protocol by the PosVer 3 with acid persulfate digestion method (HACH 2009), followed by colorimetric analysis using a HACH visible light spectrophotometer.

Total suspended solids (TSS)

Total suspended solids (TSS) were measured by filtering 200 ml of sample through a 1.2 µm pore size glass microfiber filter (grade GF-C Watman International Ltd.). Filters with TSS were dried at 105°C for 24 hours and weighed, heated in a muffle furnace at 550°C for 1 hour to remove organic matter, and final dried samples weighed to calculate total inorganic suspended material.

Algal biomass (Chlorophyll a)

Phytoplankton and metaphyton biomass (chlorophyll a concentration) were measured by filtering 200 ml of sample onto a 1.2 µm pore size glass microfiber filter (grade GF/C, Whatman International Ltd.). Filters were frozen for a minimum 24 hours to lyse cell membranes prior to analysis. Algal pigments were extracted from thawed filters by placing in 90% methanol for 24 hours in the dark to extract chlorophyll pigments. Spectrophotometric absorbance readings were made at 665 and 750 nm before and after acidification with 10 N HCL to facilitate correction of pheophytin. Calculation of chlorophyll followed the formulae of Marker et al. (1980).

Alkalinity, pH, conductivity and temperature

Alkalinity was performed by titration using 0.02 N hydrochloric acid to a clear end point (bromocresol green-methyl red indicator solution), pH determined using a pH meter, turbidity (NTU) determined using a HACH turbidimeter (model 2100A), and conductivity, salinity, and water temperature measured in the field with a conductivity/salinity probe.

3.5 Harvesting for nutrient removal

Cattail was harvested in four of the 100m^2 treatment sites while two were left unharvested as controls from 2006-2009. Experimental harvests were carried out in either spring or summer to evaluate the harvesting of aboveground cattail to capture and remove stored nutrients. Harvesting of dead aboveground plant material took place during early spring (April to May) in the two "spring harvest" permanent sites when the snow was gone, the ground is still frozen, and there is minimal ecological impact from harvesting. Summer harvests of live cattail plants was carried out in the two "summer harvest" sites in mid to late August, when aboveground plant biomass and nutrient content can be expected to be highest (Smith et al. 1988). Only a certain portion of the plant above water or ice surface is removed to ensure sustainable harvesting and not kill the emergent plant community (Figure 3.15).

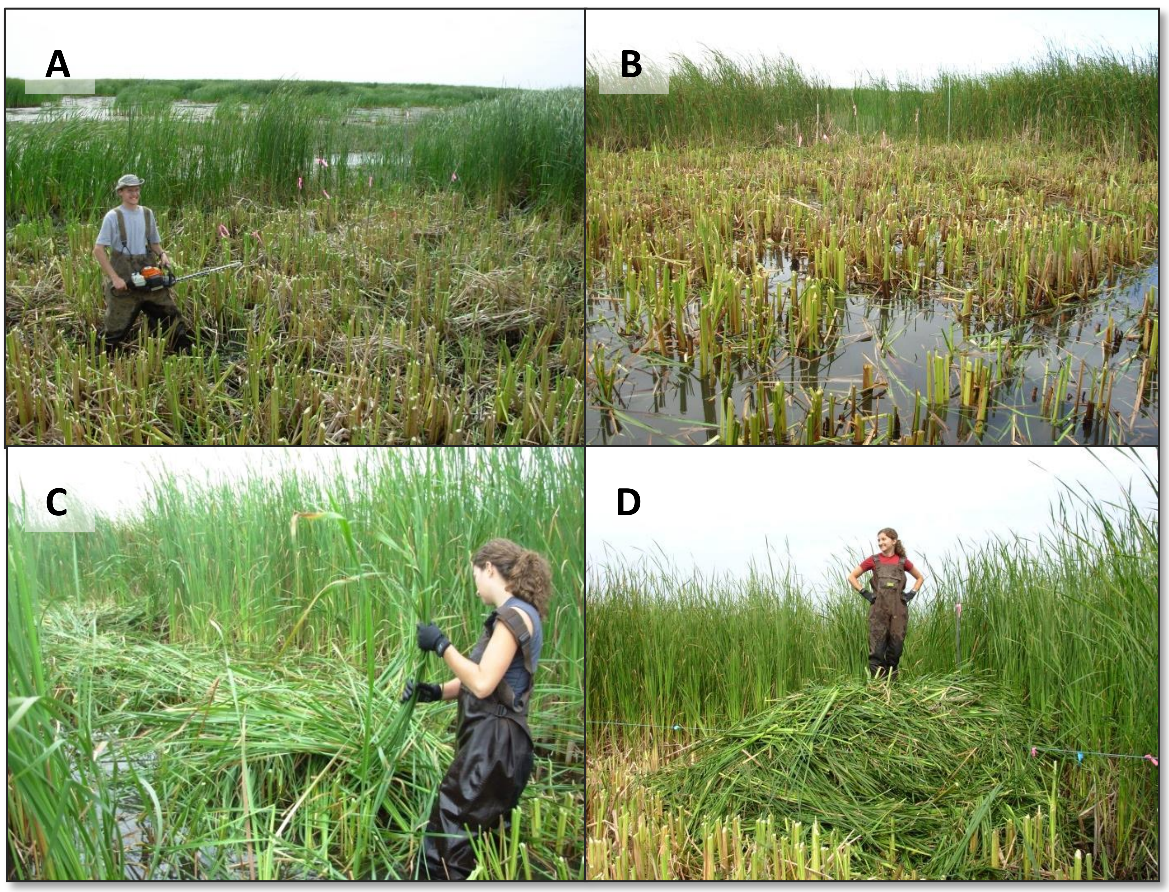


Figure 3.15. Summer (mid-August) harvest of live green cattail (2007). A) and B) 10 m x 10 m summer harvest site, C) and D) collecting and piling cut cattail to be hauled out of the site to prevent nutrient re-introduction into harvested area.

Being monitored was the benefits and effects of seasonal harvesting on plant growth and biodiversity over the four years by measuring regrowth of plant communities, biomass accumulation, nutrient uptake, and nutrient storage in litter and sediments.

3.6 Harvesting for Biomass Bioenergy Production

As part of this research study, a low-impact wetland harvester was designed and constructed in 2007 and its ability to cut cattail tested in various marsh conditions. It was used to harvest several metric tonnes at two different times of the year to evaluate cattail as a feedstock for bioenergy. Early spring harvests of dead dry standing material was conducted in April 2007, 2008, and summer harvests of live green cattail in August 2006, 2007, and 2008. Four randomly placed quadrats (pseudo replicates) in harvested and neighbouring unharvested sites compared plant composition, plant cover, height, and regrowth. Plant and sediment samples were collected and analyzed for nutrients and bioenergy properties. Biomass yield was calculated from total dry weight per square meter (kg/m^2) also expressed as tonnes per hectare (T DM/ha), averaged from collected samples and multiplied by total number of plants per square meter.

3.7 Cattail Biomass Densification and Biomass Properties

3.7.1 Biomass Densification

Densification of cattail biomass was examined for bulk storage and handling, uniformity for bioenergy thermal conversion, creation of a standardized densified fuel that can be easily integrated with commercially available forms, transportation, and optimization for small-scale bioenergy systems. Two different sizes were compared for commercial comparisons:

1) Standard fuel pellet size of ¼ inch similar to commercially available wood pellets was chosen because of their existing market value and use in commercially available pellet stoves for space heating – these were manufactured and tested by Alberta Innovates Technology Futures (formerly Alberta Research Council, ARC)

2) Larger fuel cubes 1 inch x 1 inch square requiring less energy to produce, manufactured by Prairie BioEnergy (now Biovalco) in Manitoba - utilized in larger biomass burners in use around the province for heat production or CHP systems

While there are many advantages to using densified biomass as a source of energy, combustion of biological matter has several issues or characteristics that influence the suitability of densified biomass as an alternative energy. Characteristics such as bulk density, ash content, inorganic content, and moisture were examined.

3.7.2 Bulk Density

Average bulk density of pellets and cubes were calculated by determining air-dry weight of several randomly selected pellets or cubes. Pellets were coated in a thin film of wax and submerged in a graduated cylinder containing de-ionized water. The change in water level before and after submersion was recorded - considered the volume of the pellet. Weight of the pellet over the change in volume in the graduated cylinder gave a measurement of bulk density.

$$\textit{Bulk Density (g)} = \frac{\text{[weight of pellet (g)]}}{[\,V_1 - V_2\,]\ \text{(mL)}}$$

3.7.3 Mass of Ash Produced

Two methods were used to calculate the amount of ash produced by combustion of cattail biomass: 1) field method - rough approximation based on the on-site combustion of the cubes during the Blue Flame Stoker burn trial measuring biomass weight before and ash post-combustion, and 2) theoretical method - conducted in the lab at the University of Manitoba, and by Alberta Tech Futures.

Field Method for Determining Mass of Ash Produced

Fuel cubes were combusted in a Blue Flame Stoker located on the Sturgeon Creek Hutterite Colony in Headingly, Manitoba. Since the burner is run continuously and cannot be shut down except for maintenance, calculating ash content during a burn trial is not possible. Ash was collected from the ash disposal system for nutrient analysis. The weight of ash was calculated in a separate stove by measuring ash produced and relating back to the initial cubes burned to determine percent of ash generated.

Theoretical Method for Determining Mass of Ash Produced

Cubes and pellets were placed in ceramic dishes and put into a muffle furnace at 550°C for one hour, which resulted in complete combustion. The residue left in the ceramic dishes was a very fine light ash. The weight of the empty ceramic dish, and the ceramic dish with the ash was recorded and the difference related to the original weight of the samples at room temperature to determine % of ash generated.

$$\textit{Ash content (\%)} = \frac{\textit{[weight of ash (g)]}}{\textit{[weight of biomass (g)]}} \times 100$$

3.7.4 Energy Value (Calorific value)

The calorific value of cattail was measured several times from various samples by the University of Manitoba Department of Animal Science, Norwest labs, and Alberta Tech Futures, determined by using an oxygen bomb calorimeter. The calorimeter is sealed and injected with oxygen. A heat source initiates combustion of the sample; the change in temperature within the calorimeter is measured as the sample combusts and is related back to the initial weight of the sample being analysed expressed as megajoules per kg (MJ/kg) and British Thermal Units (BTU).

3.8 Bioenergy technologies

Several bioenergy technologies were examined for combustion of densified products. Major burn trials were conducted in different forms in three different biomass bioenergy systems in commercial use in Manitoba: 1) round bales and loose form burned in an industrial scale gasification system to produce steam heat at Vidir Machines in Arborg, Manitoba (now BiomassBest), 2) densified cubes burned in a Blue-Flame Stoker biomass/coal boiler system to produce hot water for space heating on the Sturgeon Creek Hutterite colony, and 3) densified pellets burned in a pellet stove for space heating conducted by Alberta Tech Futures. Emissions were recorded during burn trials and final fate of phosphorus calculated by nutrient analysis of biomass pre-combustion and ash post-combustion. Approximate/ultimate analysis of cattail biomass and ash was carried out by NorWest Labs and Alberta Tech Futures.

3.9 Statistical Analyses

Statistical analyses were performed using the Data Analysis add-in application for Windows Microsoft Excel software (v. 2010), XLStat software add-in (XLStat 2012), and SAS for Windows (v.9.3, SAS Institute Inc, 2013). All tests were evaluated at 0.05 level of probability. Student T- Tests and analysis of variance (ANOVA) were used to determine the effect of harvesting treatment on cattail biomass accumulation and nutrient content. T-Tests and analysis of variance ANOVA compared significant differences between or among sample means, whether there was a significant difference between treatment and control samples and for treatments between years, testing a null hypothesis that the groups represented random samples from populations with the same means (Harris 1995). The null hypothesis would be rejected when $p < 0.05$ and the conclusion was drawn that the means of the harvesting treatment sites or years differed significantly.

Repeated measures two-factor analysis of variance (ANOVA) was used to evaluate the effect of harvesting treatments and determine significant temporal trends or differences over the years of the study (v.9.3, SAS Institute Inc, 2013). The use of two-factor step-wise ANOVA allowed evaluation of treatment effects (harvesting) on biomass and nutrients and interactions between these treatment effects over time, since samples were collected on a biweekly basis.

4.0 Harvesting cattail (*Typha* spp.): Nutrient cycling and seasonal biomass accumulation

4.1 Introduction

4.1.1 Harvesting cattail for nutrient capture

Phosphorus removal in wetlands is through permanent storage in the sediment and litter layers (Noe et al. 2003). Unlike nitrogen, phosphorus storage involves buildup of new sediments, sorption to wetland substrate, and bound in organic matter and litter – there is no degradation route. Gradually, phosphorus accumulation in the sediment occurs and can affect biogeochemical phosphorus removal pathways and limit the long-term removal effectiveness of wetland systems (DeBusk et al. 2001, Noe et al. 2003). Phosphorus can accumulate in wetland sediments to the point where these wetlands can become saturated and actually become sources of phosphorus (Mitsch et al. 2012).

Emergent plants almost exclusively take up nutrients from the organic litter layer and sediments (Smith et al. 1988, Noe et al. 2003, Mitsch and Gosselink 2007). Dense stands of emergent wetland plants act as permanent nutrient sinks with storage in the belowground plant material and in decaying plant litter (Kadlec and Knight 1996, Mitsch and Gosselink 2007). Mitsch and Wang (2000) found 74% of the phosphorus inflow into a series of constructed wetlands was effectively taken up by wetland plants, most of which cycled through the plants in the summer and was incorporated back into the organic layer and sediments during fall die-off. Decaying plant material releases considerable quantities of phosphorus to the water (Mitsch and Gosselink 2007). Phosphorus entering a wetland is rapidly taken up out of the water column by algae and periphyton and moves into the litter layer quite rapidly. It is the litter and sediment pool that is the main source of dissolved nitrogen and phosphorus to surface and pore water, replacing nutrients taken up by aquatic plants (Noe et al. (2003).

A plants ability to absorb nutrients from the litter and sediment makes them potential tools to capture and remove stored elements from aquatic systems, such as phosphorus and nitrogen, which often are the focus of eutrophication issues (Vymazal 1984, Jiang et al. 2005, Mitsch and Gosselink 2007,). If the aboveground emergent plants are harvested and removed at a time when they still retain enough phosphorus and nitrogen, this could effectively capture and remove these stored nutrients and ultimately reduce loading to downstream rivers and lakes (Martin and Fernandez 1992, Vymazal 2006). Harvesting the plant biomass prevents nutrient rich material from re-releasing the phosphorus and nitrogen back into the aquatic system as occurs during decomposition (Toet et al. 2005, Morris et al. 1986). Harvesting wetland plants from natural and eutrophic systems as a nutrient management strategy could be an essential component of integrated watershed management to reduce eutrophication.

4.1.2 Purpose and Objectives

Cattail (*Typha* spp.) is a large emergent plant characteristic of wetland environments that produces large amounts of biomass each growing season while taking up nutrients from the litter and sediment (Dubbe et al., Pratt et al, Lakshman 1984, Tuchman et al. 2009, Angeloni et al. 2006, Larkin et al. 2011). It is highly prized for its nutrient cycling properties and is a primary emergent plant for use in constructed wetland and wastewater treatment applications (Kadlec and Knight 1996, Vymazal 2006). The purpose of this chapter was to examine seasonal biomass and nutrient accumulation in cattail to evaluate harvesting and removal of cattail as an environmental engineering approach to capture and remove stored nutrients from wetlands and marginal land areas, and reduce nutrient loading in aquatic systems. The hypothesis is removing nutrient-rich (i.e. phosphorus) aboveground plant material prevents re-release of nutrients into the wetland, which naturally occurs during decomposition.

Cattails (*Typha* spp.) were harvested from 2006 to 2008 in an area of Netley-Libau Marsh. Spring and summer harvests were compared for phosphorus and nitrogen capture, seasonal nutrient loss, as well as regrowth following harvests. Phosphorus and nitrogen content was examined in plants, rhizomes, litter, sediment, and water. Impacts of harvesting on plant community, regrowth, biodiversity, and nutrients were examined and short term harvesting impacts on the wetland community.

4.2 Methods

4.2.1 Sampling

Methods follow those as outlined in Chapter 2. Plants (aboveground plants, roots, and rhizomes), litter and sediments were collected on a biweekly basis throughout the ice-free and growing seasons (May to October) in 2006 and 2007, and during August peak growth in 2008 and 2009 from control and experimental sites (10 m x 10 m in size). Plant samples were collected in mid-December and March to evaluate seasonal nutrient loss in above ground plant material. Water samples were analyzed for water chemistry in 2006 and 2007 for background nutrient inputs and comparison to the rest of Netley-Libau Marsh. Soil and litter samples determined soil storage.

4.2.2 Harvesting

Cattails were harvested in four of the 100 m^2 permanent research sites, while two were left unharvested as controls, from 2006-2009. Dead aboveground cattail was harvested in early spring (April to May) in two “spring harvest” sites when snow was gone, the ground still frozen, and there is minimal ecological impact from harvesting. Live green cattail plants were harvested from two “summer harvest” sites in August, when aboveground plant biomass and nutrient content can be expected to be highest. Only a certain portion of the plant above the water or ice surface (30 cm stubble) is removed to ensure sustainable harvesting and not kill emergent plant communities. Monitored was the benefits and effects of seasonal harvesting on plant growth and biodiversity.

4.2.3 Analysis

Complete litter and soil nutrient analysis as performed by Agvise labs (Agvise 2012).

Table 4.1. Complete litter and soil nutrient analysis (Agvise 2013).

Symbol	Element	Importance
NH_4	Ammonical nitrogen	Cause of eutrophication in water
P	Phosphorus (P-Olsen)	Available P form - eutrophication in water
		Essential nutrient - readily exchangeable
K	Potassium	Fouling element in bioenergy systems
		Readily exchangeable - P retention capacity
Ca	Calcium	Fouling element in bioenergy systems
		Readily exchangeable - P retention capacity
Mg	Magnesium	Fouling element in bioenergy systems
S	Sulphur	Essential macronutrient
Fe	Iron	Trace metal – very reactive with P
Zn	Zinc	Trace metal
Mn	Manganese	Trace metal
Cu	Copper	Trace metal
Cl	Chlorine	Fouling element in bioenergy systems
Na	Sodium	Readily exchangeable
% O	% organic matter	Source of nutrient storage and release
pH	pH	Plant growth and nutrient storage
salts	Soluble salts	salinity
CEC	Cation Exchange Capacity	Ability of soil to hold onto nutrients

4.3 Results

4.3.1 General Meteorology

Average monthly temperatures and monthly precipitation during the research study 2006 to 2009 (Table 4.2) was compared to Canadian Climate Normals (1971-2000) as recorded by Environment Canada (2012).

Table 4.2. Comparison of Average monthly air temperature (°C) and precipitation (mm) during growing season from Canadian Climate Normals (1971-2000) to 2006-2009 climatic conditions as recorded at Gimli harbour (Environment Canada 2012).

	Average monthly temp (°C)	**Average Monthly Precip. (mm)**	**Mean Temp (°C)**				**Total Precipitation (mm)**			
	1971-2000	**1971-2000**	**2006**	**2007**	**2008**	**2009**	**2006**	**2007**	**2008**	**2009**
April	2.7	30	8	3	1	2	24	27	17	16
May	10.6	49.8	12	11	7	7	57	78	39	73
June	16.1	94.1	18	16	15	15	42	109	126	102
July	19.2	69.7	20	20	18	16	21	57	142	63
Aug	17.5	64.2	19	16	18	17	43	26	76	114
Sept	11.6	66.7	13	12	12	17	63	57	102	14
Oct	4.8	38.3	4	6	6	4	49	59	38	19
Nov	-5.2	27.6		-5	-5	1	0	13	32	4

4.3.1.1 Air temperature and precipitation

The first year of the study in 2006 experienced fairly warm and dry conditions with above average air temperature (Figure 4.1) and below average precipitation (Figure 4.2) according to Canadian Climate Normals from 1971-2000 as recorded from Environment Canada (2012). Low precipitation in 2006 caused a drop in water levels in the marsh and some treatment sites to have no standing water. The second year 2007 experienced average temperatures and precipitation, and appeared to provide ideal growing conditions and productivity in the marsh. Low precipitation in 2007 in August again caused water levels to drop and some sites to go dry. In 2008 and 2009 temperatures were well below average during the growing period and precipitation was well above average, and this was noticed with significant ground saturation in the fall and spring flooding in 2009.

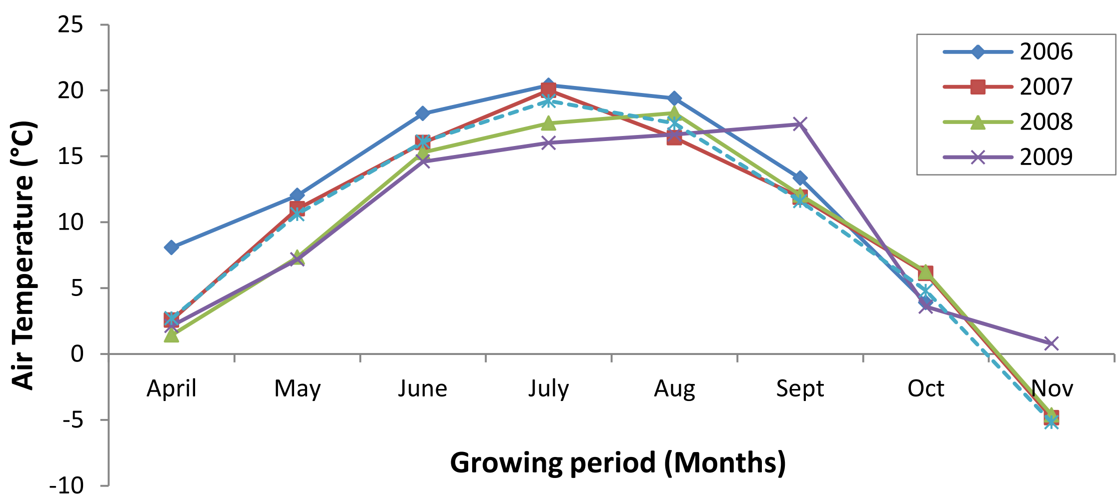


Figure 4.1. Mean air temperature 2006 to 2009 compared to Canadian Climate Normals (1971-2000) (Environment Canada 2012).

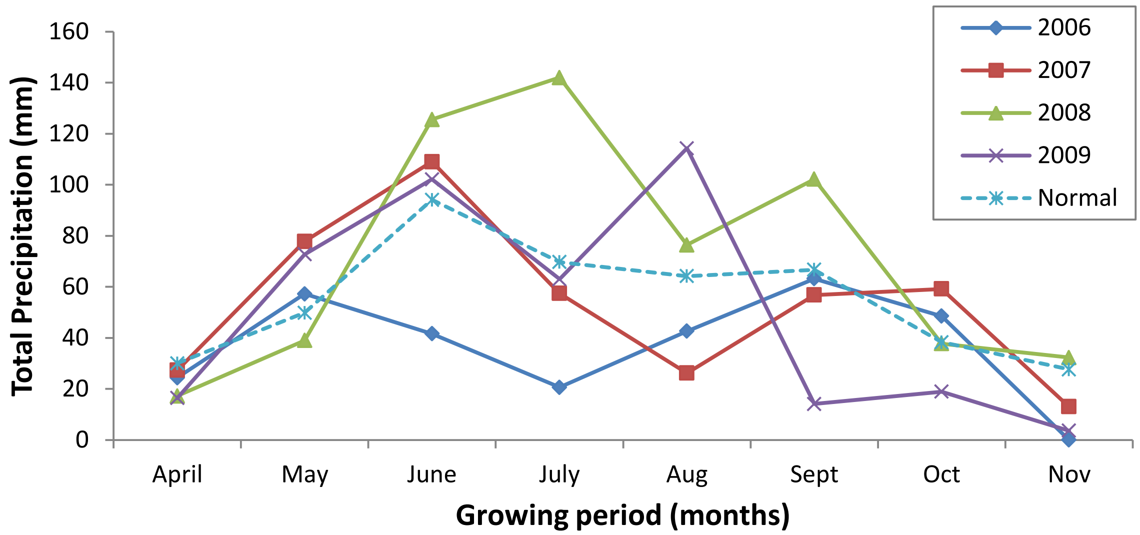


Figure 4.2. Average monthly precipitation 2006 to 2009 compared to Canadian Climate Normals (1971-2000) (Environment Canada 2012).

4.3.1.2 Growing degree days

Growing degree-days (GDD) are frequently used as a weather-based indicator for assessing crop development (Environment Canada 2012). As an equation:

$$GDD = \frac{T_{max} + T_{min}}{2} - T_{base}$$

Temperature based GDD's provide a reliable indication of the development of many crops throughout the growing season (Gordon and Bootsma 1993). Crop growth refers to an increase in crop weight, height, volume or area over a certain time scale, and the potential biomass yield is dependent on how quickly the crop moves through its stages of development and also the rate at which it accumulates dry matter. GDD are calculated by taking the average of the daily maximum and minimum temperatures compared to a base temperature, Tbase. A base of 10 °C is often used for corn and soybeans and was used in this case for cattail.

Growing degree days were highest in 2006 (total annual GDD = 949) and 2007 (total annual GDD = 949 and 774) and lowest in 2008 and 2009 (total annual GDD = 707 and 738) (Figure 4.3). This was evident with cooler wet summers and growing seasons, and spring flooding in 2009, which would impact productivity of cattail communities in the marsh. Higher number of GDD in 2007 with average temperatures and precipitation could have aided productivity.

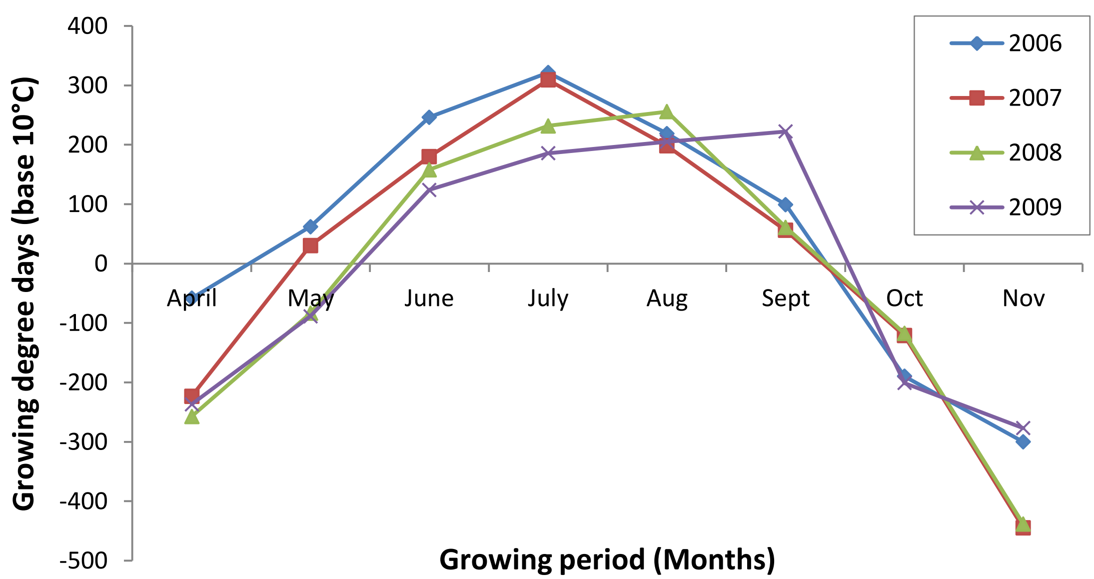


Figure 4.3. Growing degree days (GDD) 2006-2009 based on maximum and minimum temperature ranges and a base temperature of 10 °C (Environment Canada 2012).

4.3.1.3 Lake Winnipeg and research site Water levels

Water levels on Lake Winnipeg as recorded at the Gimli Harbour were the lowest in 2006 during the growing season April to November (Figure 4.4), and coincide with the 3 Ecotone water level recorders set up at the research site calibrated to match Lake Winnipeg levels at feet above sea level (ft. asl) (Figure 4.5). The water level recorders recorded water levels every 4 hours and captured the dynamic nature of the water levels in the marsh with the dramatic high and low levels. Visible are the dramatic “weather bomb” event resulting in high water levels in October 2006 (Environment Canada 2006) and sustained higher levels in 2008 and 2009 as a result of above average precipitation.

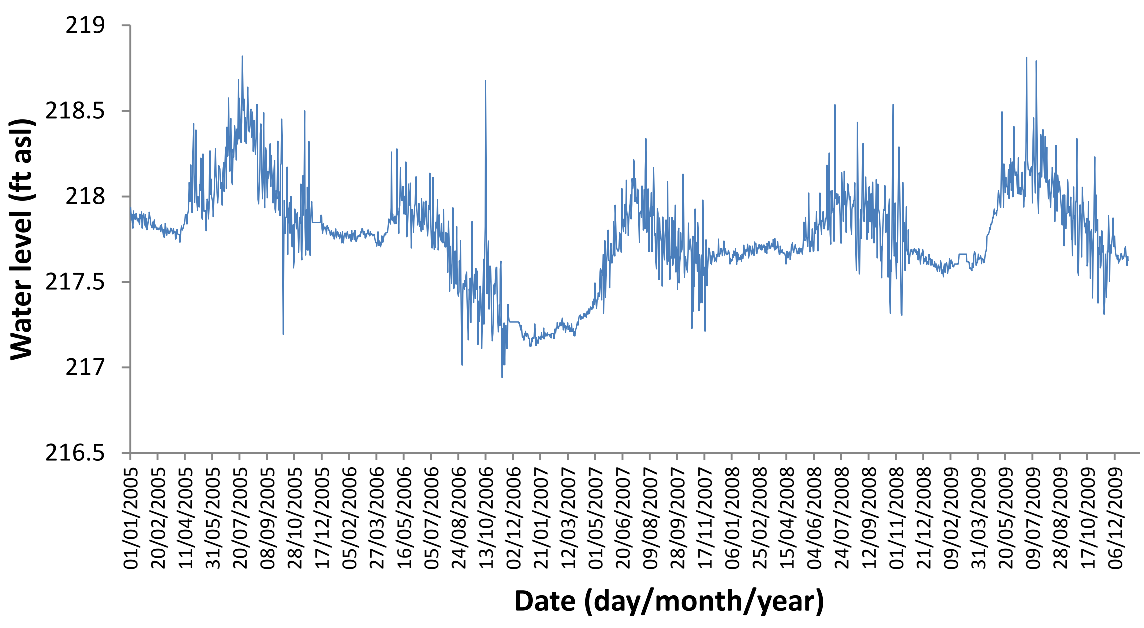


Figure 4.4. Average daily Lake Winnipeg Water levels (feet above sea level) January 1, 2005 to December 31, 2009 compiled from water level data recorded at Gimli, Manitoba (data source: Environment Canada 2012).

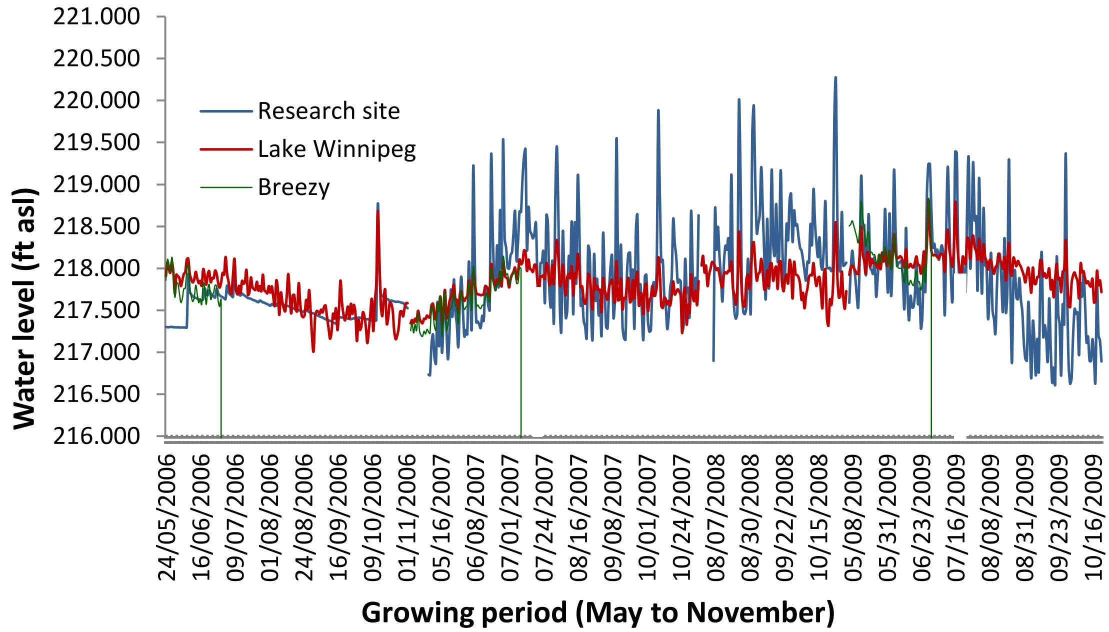


Figure 4.5. Average daily water levels (ft. asl) at Netley-Libau Marsh research site recorded on Ecotone water level gauges, compared to Breezy Point on Red River and Lake Winnipeg during growing season 2006-2009. Lake Winnipeg levels compiled from water level data at Gimli, Manitoba (data source: Environment Canada 2012).

Water depth was recorded at each treatment site during sampling throughout the growing season (Figure 4.6). Low precipitation and water levels during July and August 2006 caused several treatment sites to not have standing water for several weeks during the growing season. Ground water was present near the surface, but no standing water would have changed the chemical interactions with the litter and soil surface.

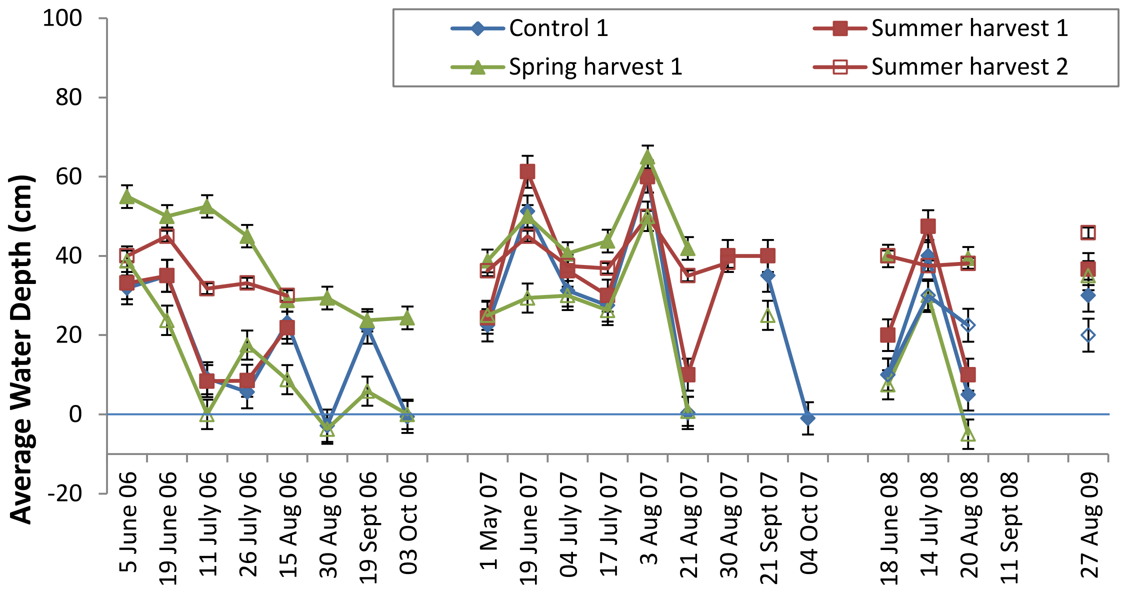


Figure 4.6. Average water depth (cm) in each research plot measured during sample collection through the growing seasons 2006-2009. Line at 0 cm represents the sediment/litter layer and measurements below this are below the organic litter layer.

4.3.2 Water Chemistry

4.3.2.1 Total Phosphorus and TRP

Total phosphorus (TP) is the total amount of inorganic and organic P that is found in the water including particulate and dissolved. Total phosphorus levels above 0.03 can cause eutrophication and algae blooms, and above 0.1 mg/L in Manitoba waters is considered hypereutrophic (USEPA 2012). Manitoba Water Quality Guidelines (Manitoba Conservation 2002) state TP should not exceed 0.025 mg/L, in any reservoir, lake, or pond, or in a tributary at the point where it enters such bodies of water. In other streams, total phosphorus should not exceed 0.05 mg/L, although the level of phosphorus in many water bodies of southern Manitoba is expected to be higher due to naturally higher nutrient levels in the surrounding soil. TP concentrations in the treatment sites and Netley-Libau Marsh were significantly above the guideline with the lowest levels sampled of 0.51 mg/L (Figure 4.7). Samples ranged between an average of 0.51 and 1.93 for all sites in 2007 and 2008, with significant spikes in May 2008 with some treatment sites between 4.60 and 7.83 mg/L, This coincides with a wildfire in 2008 that burned a large portion of Libau Marsh, including two of the treatment sites. In 2009 spring flooding and inputs of phosphorus from the watershed caused high levels in August 2009 in treatment sites and Netley-Libau Marsh (Figure 4.7).

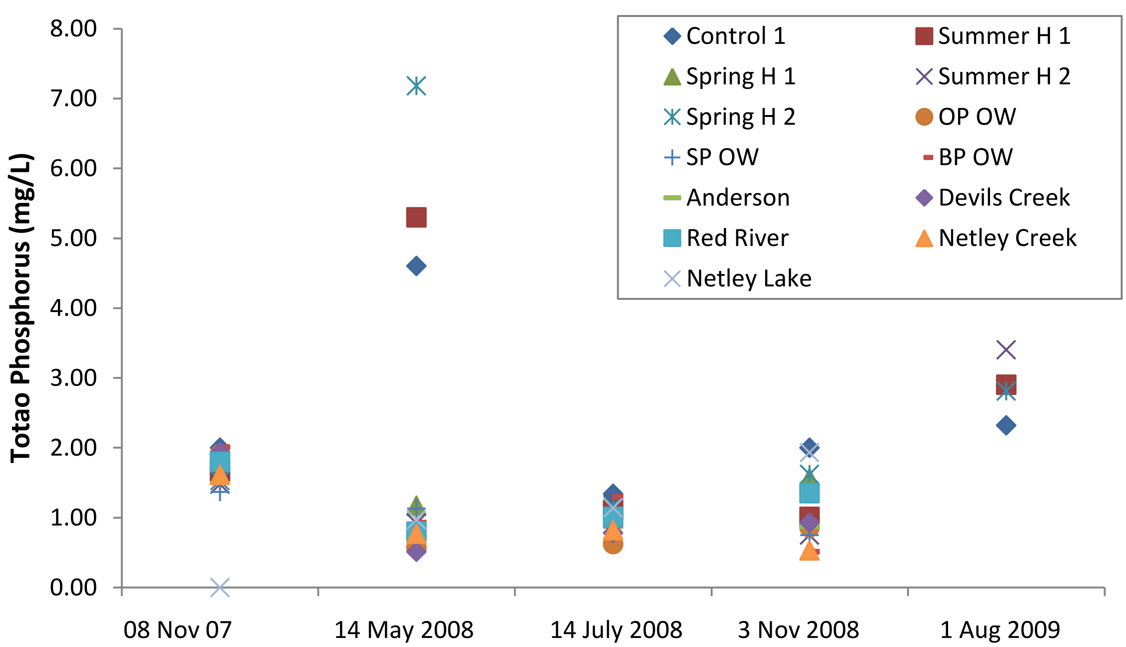


Figure 4.7. Total phosphorus (mg/L) in the water column within sample sites and open water bays and creeks of Netley Marsh (Netley Lake, Netley Creek, and Red River at Breezy Point) and Libau Marsh (Anderson Lake, Devils Lake).

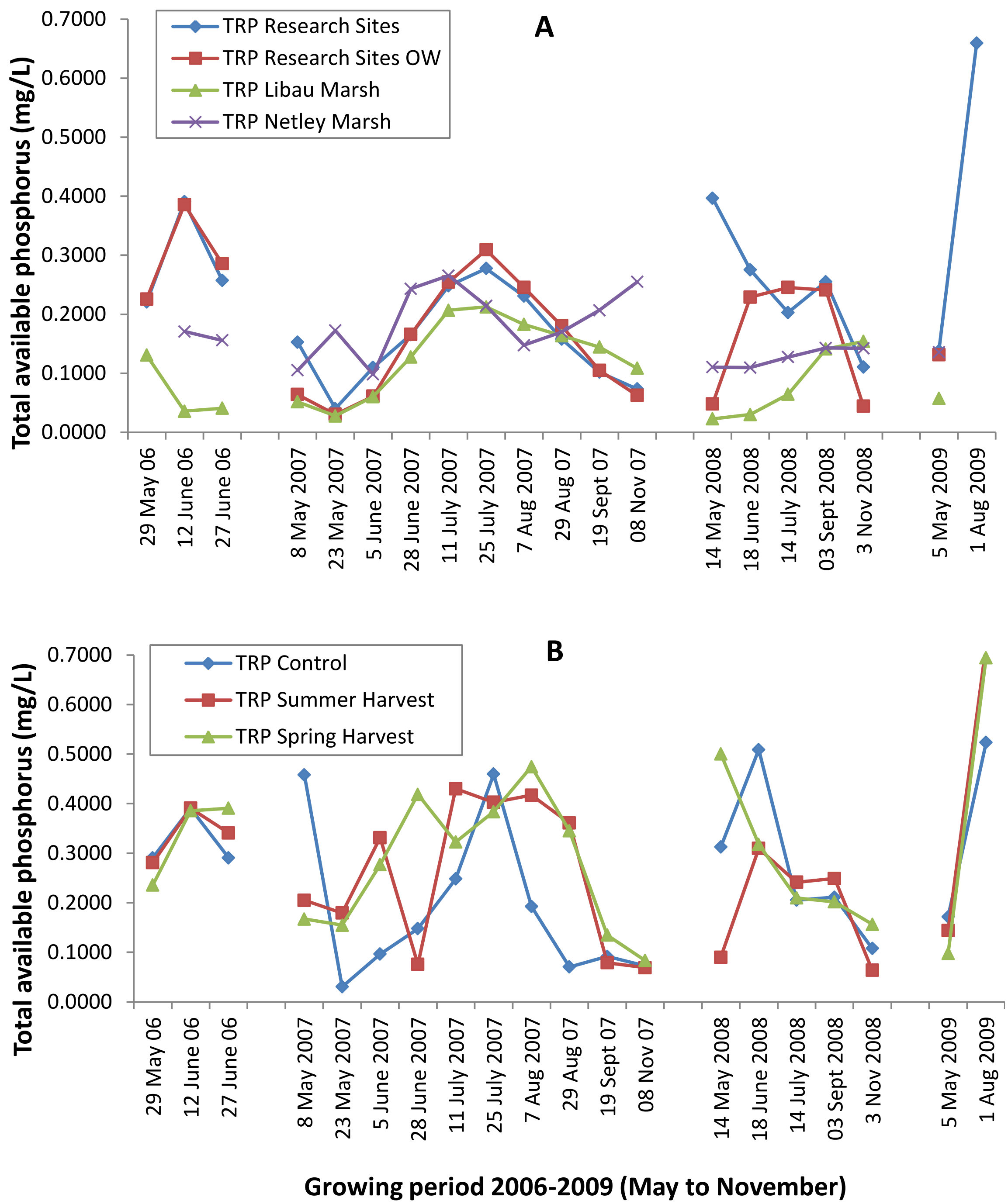


Figure 4.8. Total available phosphorus (PO_4) in water column within cattail research plots compared to nearby open water areas, open water of Netley Marsh west of Red River and Libau Marsh East of Red River (Top A) and (Bottom B) within cattail research plots comparing control sites to summer and spring harvest sites.

Total reactive phosphorus (TRP), or available phosphorus, is the amount of phosphorus in the water that is readily available for biological uptake, and represents the phosphorus that can be immediately taken up by algae, plants, and microorganisms. TRP for the cattail treatment sites in 2007 followed the same general trend as samples collected from the open water bays and creeks of Netley Marsh west of the Red River (Netley Lake, Netley Creek, and Red River at Breezy Point) and Libau Marsh east of the Red River (Anderson Lake, Devils Lake) East of the Red River (Figure 4.8). TRP levels ranged between 0.03 mg/L to 0.15 mg/L in spring and up to 0.2 to 0.3 mg/L in August 2007. Research sites did have on average slightly higher levels of TRP compared to the other sites, which were collected from open water sites. The Netley Marsh side had on average higher TRP levels than the Libau Marsh side. Similarly, August 2008 was 0.06 to 0.2 mg/L. A spike is noticed in spring 2008 which coincides with spikes seen in TP, as well as 2009 spring flood inputs of phosphorus in August 2009 (Figure 4.8).

4.3.2.2 Ammonia-N

Ammonia-N is a measure of the concentration of nitrogen found in the water column as ammonia NH_3. This form of nitrogen is a waste product of organisms and toxic to aquatic organisms in high concentration. Toxicity of ammonia varies depending on pH and temperature. At a temperature of 20°C and pH of 9 a level of ammonia < 0.3 mg/L is desirable (Manitoba Conservation, 2002). The ammonia levels were mostly undetectable in the cattail research sites and nearby open water areas for most of the summer each year at < 0.01 mg/L, with slightly higher levels in the spring each year up to 0.04 mg/L with a higher spike in the spring of 2008 in the cattail sites compared to the nearby open water sites, suggesting ammonia released from decaying plant material. Libau Marsh was similar with fairly low levels < 0.04 mg/L. Netley Marsh, however, had comparably much higher spikes in ammonia levels up to 0.12 to 0.16 mg/L at certain times of the year, which suggests there was some waste input downstream from the Red River, which were still all tolerable levels at 20 °C and a pH of around 8 (MB water quality guideline is < 2.6 mg/L of ammonia at pH 7.6 and 20 °C).

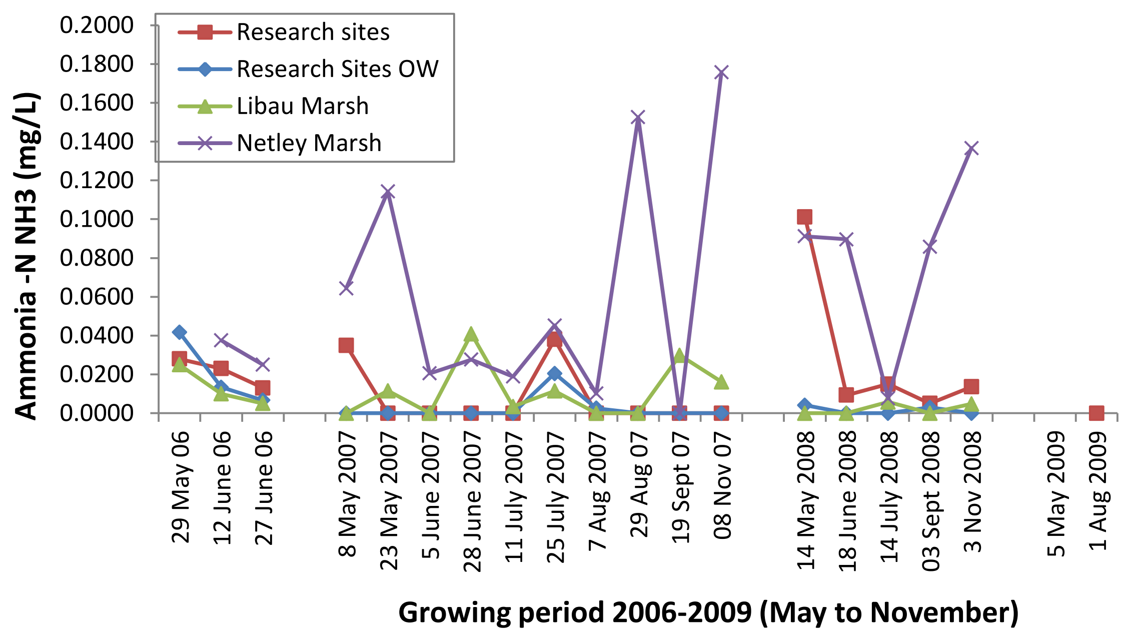


Figure 4.9. Total Ammonia -N NH_3 (mg/L) in the water column within cattail research plots compared to nearby open water areas, open water areas of Netley Marsh west of the Red River (Netley Lake, Netley Creek, and Red River at Breezy Point) and Libau Marsh East of the Red River (Anderson Lake, Devils Lake).

4.3.2.3 Alkalinity

Alkalinity is the measure of the buffering capacity of water, referring to the concentration of dissolved chemicals (solutes) in water that neutralize acids without pH being changed. Bicarbonate and carbonate are the most common buffering solutes in natural environments (Wetzel, 2001). Average alkalinity of the cattail research sites was 200 to 320 mg/L, which was similar to the Netley Marsh area west of the Red River, and the Libau Marsh east of the Red River, and consistent with regional values of the Assiniboine and Red River at 241 mg/L (Kolochuk 2005). Average alkalinity range of the research sites and nearby open water was between 200 to 600 mg/L.

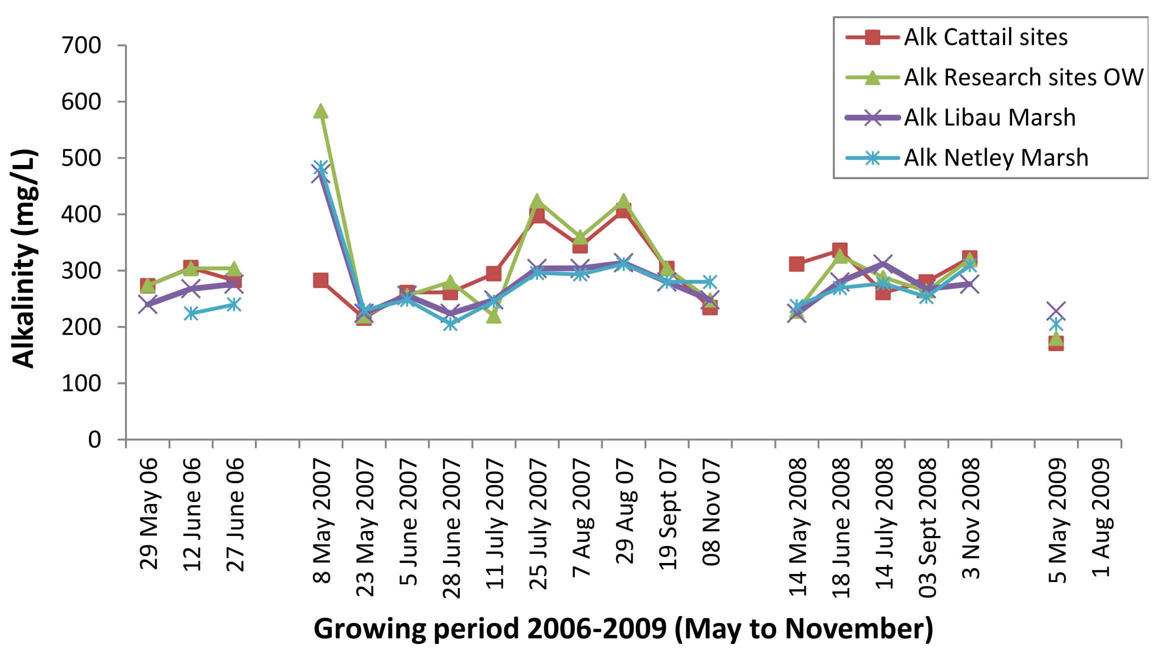


Figure 4.10. Average alkalinity (mg/L) in the water column within cattail research plots compared to nearby open water areas, open water areas of Netley Marsh west of the Red River and Libau Marsh East of the Red River (Anderson Lake, Devils Lake).

4.3.2.4 pH

The concentration of hydrogen ions (H+) found in solution is the measure of pH, which is important for many chemical reactions. NH4+, for example, is not a very toxic substance but in a pH > 7 (basic) environment the extra H+ on NH4+ is taken by a H+ accepting basic chemical (i.e., OH-, HCO3-) and converts NH_4+ to ammonia (NH_3), which is much more toxic to aquatic organisms. Preferred pH range for aquatic life is 6.5 to 9.0 (Manitoba Conservation 2002). The pH in the cattail research sites and nearby open water areas were in the range of 7 to 8, and were slightly more acidic than the Netley and Libau Marsh areas in the range of 7.5 to 8.5 (Figure 4.11).

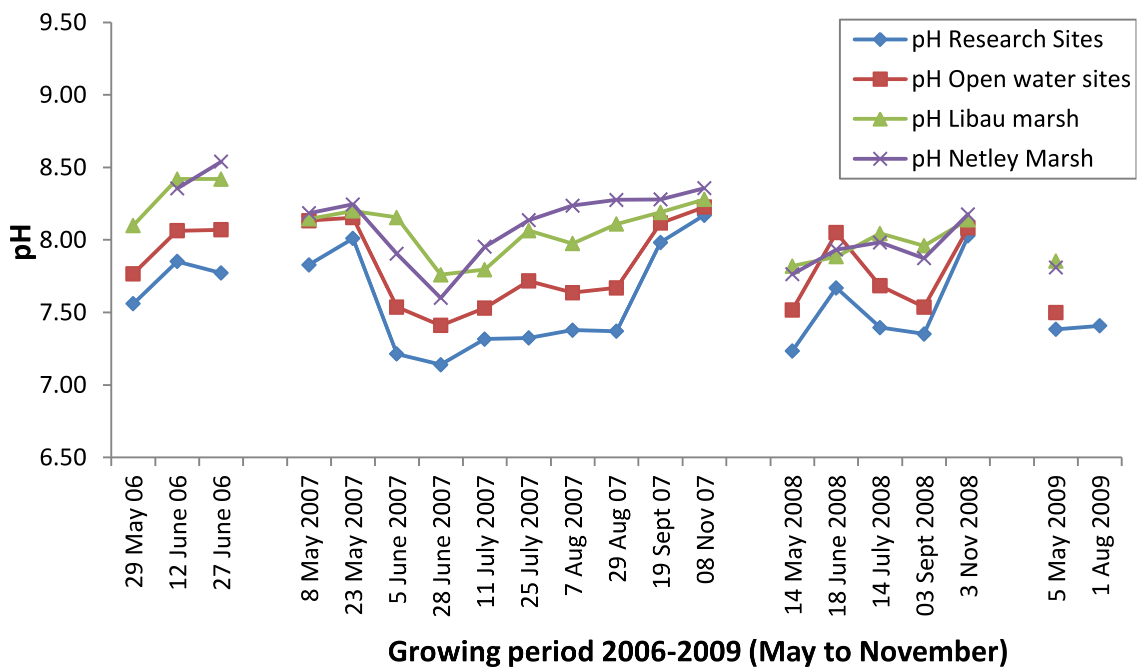


Figure 4.11. pH in the water column within cattail research plots compared to nearby open water areas, open water of Netley Marsh west of the Red River and Libau Marsh East of the Red River.

4.3.2.5 Chlorophyll a

Chlorophyll *a* is a green pigment found in all plants and is a measure of algae production in water. High algae levels cause undesirable aesthetics and odor, and foul taste in drinking water and can release dangerous toxins. Large algae die-offs can reduce oxygen concentrations in the water, which can be lethal to fish. The desirable limit of chlorophyll *a* is variable depending on the natural levels in a particular area. Total chlorophyll includes chlorophyll *a* pigments from both living and dead plant cells (Appendix A). Average total chlorophyll *a* values in the research sites was 17.0 µg/L in the range of 2 to 32 µg/L. Chlorophyll *a* levels in the Netley and Libau Marsh areas were 30.8 µg/L and 48.3 µg/L respectively in the range of 5.0 to 80.3 µg/L and 13.0 to 98.9 µg/L (Figure 4.12). Water bodies with chlorophyll *a* concentrations between 56 to155 µg/L are considered eutrophic (i.e., high in nutrients) and characterized by dense algae and macrophytic growth. The summer of 2007 had the highest chlorophyll values, which could be attributed to the above average temperatures and higher number of growing degree days.

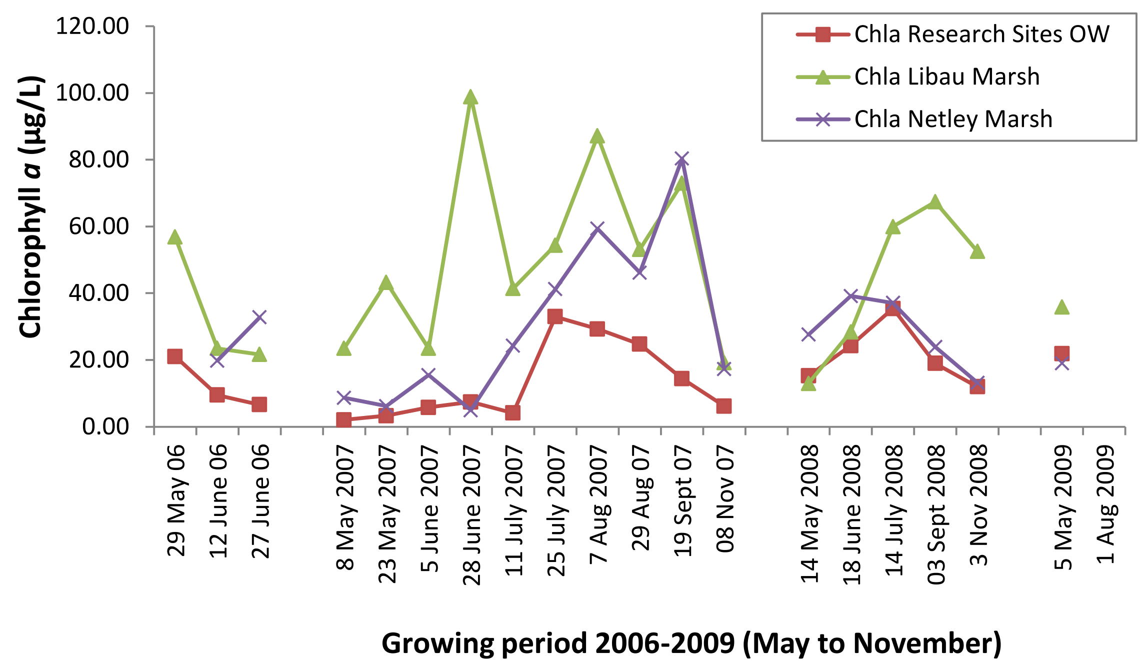


Figure 4.12. Chlorophyll *a* (µg/L) in water column within research plots compared to open water areas of Netley Marsh west of the Red River and Libau Marsh East of the Red River.

4.3.3 Cattail (*Typha* spp.) growth and resource allocation

4.3.3.1 Emergence and biomass accumulation

In Netley-Libau Marsh, cattails were found to emerge between the middle of May to early June, depending on weather conditions and spring thaw, with cattails typically fully emerging in early June (Figure 4.13). Peak growth and biomass accumulation in cattails occurred during middle to late August, when cattail communities contained the highest biomass (dry matter) per square meter. Cattail transferred material to the belowground rhizomes in early fall replenishing essential biomass reserves for winter survival.

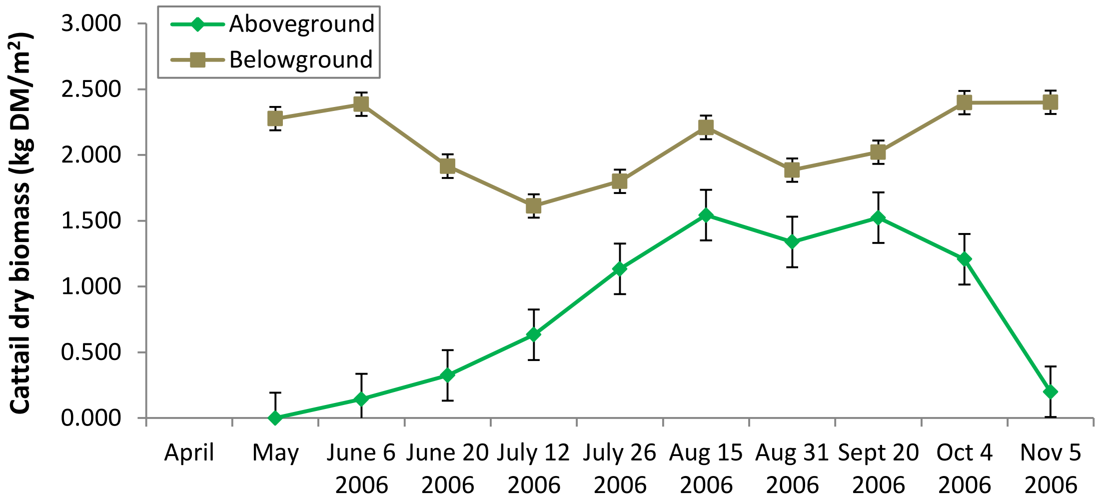


Figure 4.13. Seasonal average above and belowground biomass (kg DM/m^2) of cattail (*Typha* spp.) within the research sites over the 2006 growing season.

4.3.3.2 Cattail Nutrient Uptake - phosphorus and nitrogen

Peak nutrient content coincided with peak biomass accumulation in early to mid-August (Figure 4.14). During the growing season, nutrients such as phosphorus and nitrogen are taken up by cattail roots and rhizomes from litter and sediment layers and incorporated within aboveground and belowground biomass. Figure 4.14 shows significant phosphorus and nitrogen reserves within belowground rhizomes, which are used during peak growing season from summer to fall to produce aboveground plant growth, and slowly replenished during summer and into fall from nutrient uptake from surrounding soil and later translocation from aboveground plants down to rhizomes (Figure 4.14).

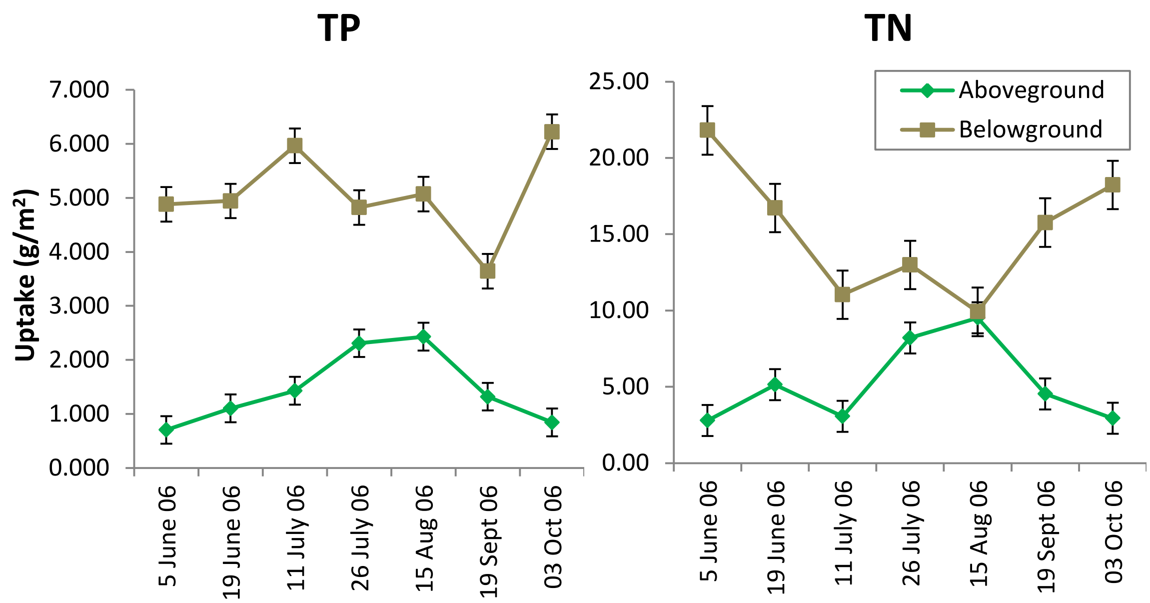


Figure 4.14. (Left) Phosphorus and (Right) nitrogen content (g/m^2) in aboveground plants and belowground rhizomes of cattail during the growing season in 2006.

4.3.3.3 Cattail Nutrient Partitioning – phosphorus and nitrogen

Long term sustainability of cattail harvesting is essential to allow the plants to survive until the next growing season. This required leaving a 20-30 cm high stubble to allow cattail plants this snorkel to provide oxygen and gas exchange to belowground rhizomes to survive flooded conditions in fall and into next spring. Allocation or partitioning of phosphorus and nitrogen in the aboveground cattail plants was measured to determine where the highest concentrations of nutrients are contained within the aboveground plants. Cattail plants (n=50) were sectioned into 25 cm sections (except topmost portion which was 55 cm due to amount of material). Phosphorus and nitrogen concentrations per unit of biomass (%P and %N) was highest in the upper parts of the plants, which would be harvested, but the bottom 25 cm stubble left behind with harvesting has greater total biomass and the most phosphorus and nitrogen per square meter (Figure 4.15). From a larger scale harvest perspective at kilograms per hectare (kg/Ha), the bottom 25 cm portion contains 25 and 16 percent of the total phosphorus and nitrogen within the aboveground cattail plants respectively (Figure 4.16).

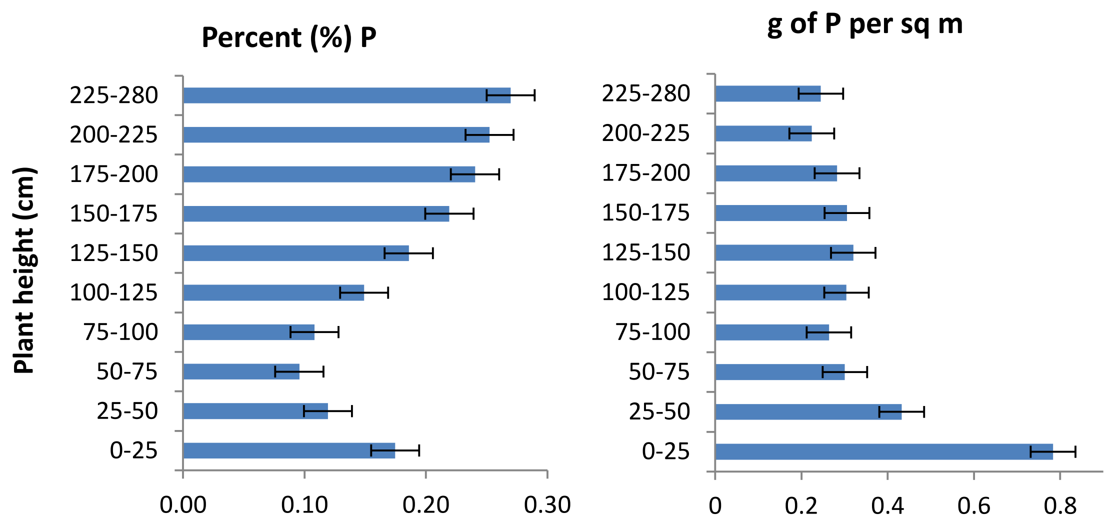


Figure 4.15a. Cattail phosphorus allocation and partitioning in aboveground plants (n=50) from collected samples in 2007.

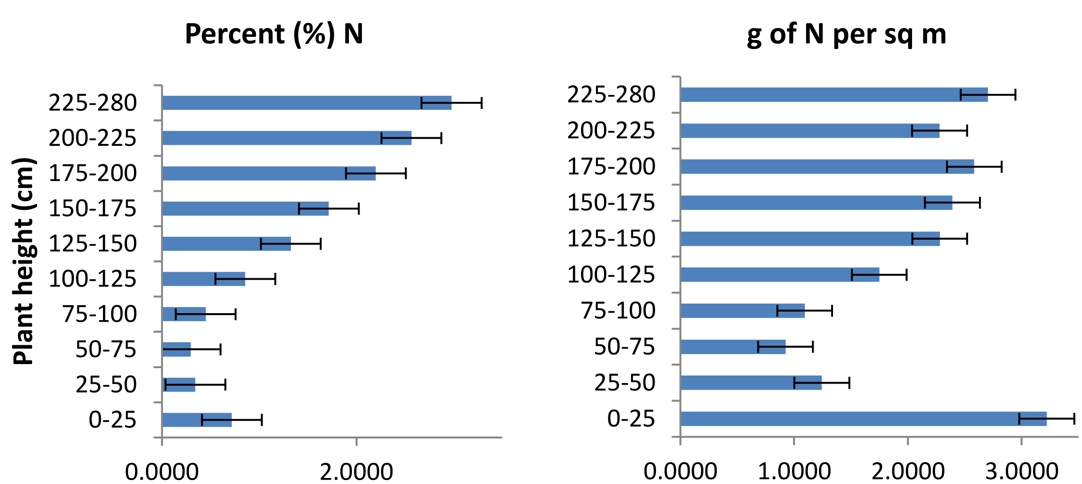


Figure 4.15b. Cattail nitrogen allocation and partitioning in aboveground plants (n=50) from collected samples in 2007.

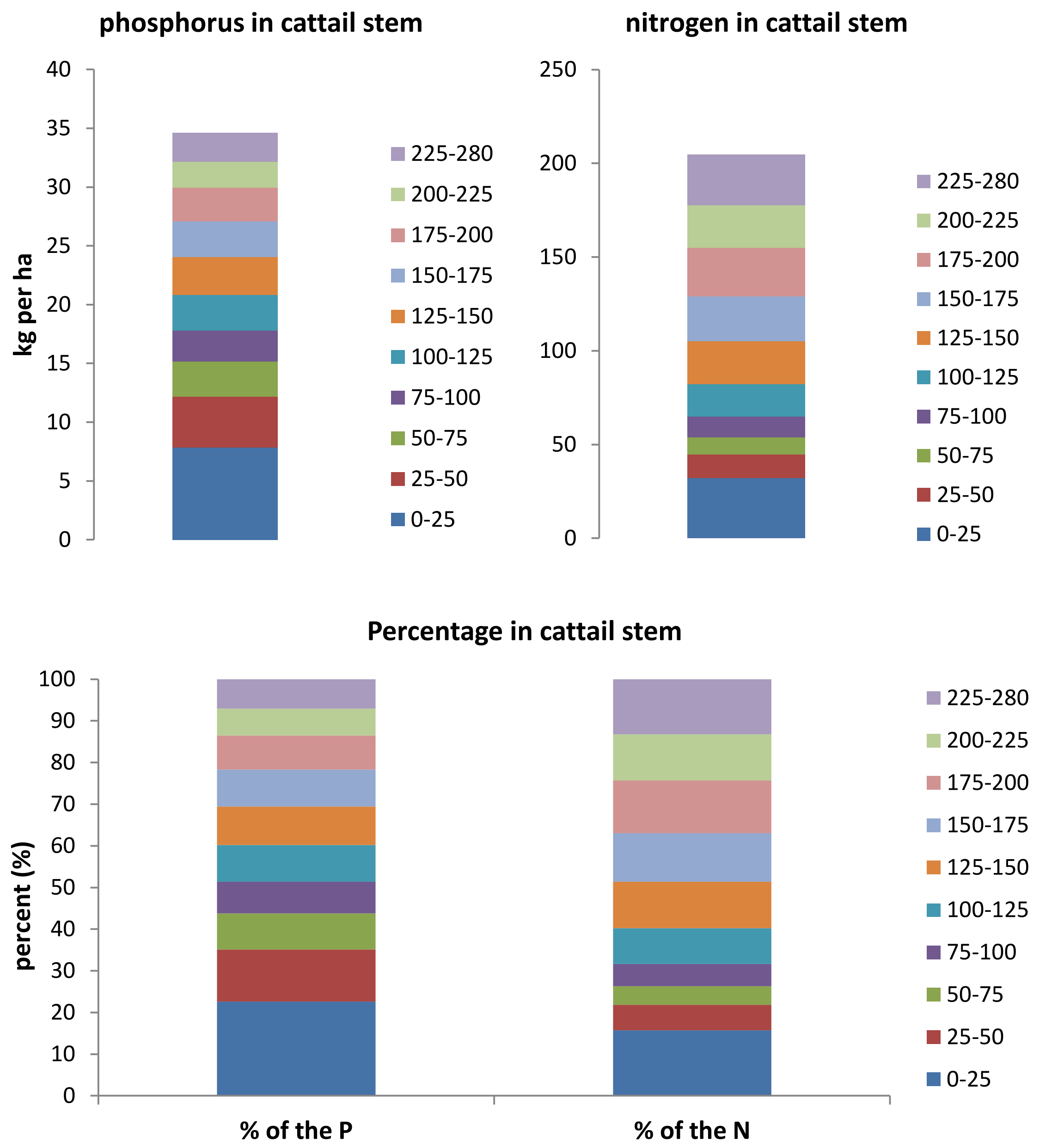


Figure 4.16. Cattail nutrient allocation and partitioning in aboveground plants (n=50) from collected samples in 2007, showing (Top) total phosphorus and nitrogen and (bottom) percent of phosphorus and nitrogen captured by harvesting with 25 cm stubble left behind. Height sections (cm) are identified on left.

4.3.4 Effects of harvesting on cattail

4.3.4.1 Cattail height, density, and biomass accumulation

Cattails were harvested from 2006-2009 during spring and summer to evaluate harvesting for the removal of stored nutrients. Effects of harvesting aboveground cattail on regrowth in years following harvesting was evaluated by measuring height, density, and total dry biomass accumulation of aboveground shoots and belowground rhizomes. Harvesting of cattail and removal of accumulated deadfall stimulated plant regrowth the following spring and resulted in earlier emergence of cattail in harvested sites and greater density of cattail per square meter (Figure 4.17). Following harvests in 2006 and spring 2007 aboveground plants emerged nearly 2 weeks earlier than unharvested areas (Figure 4.18).

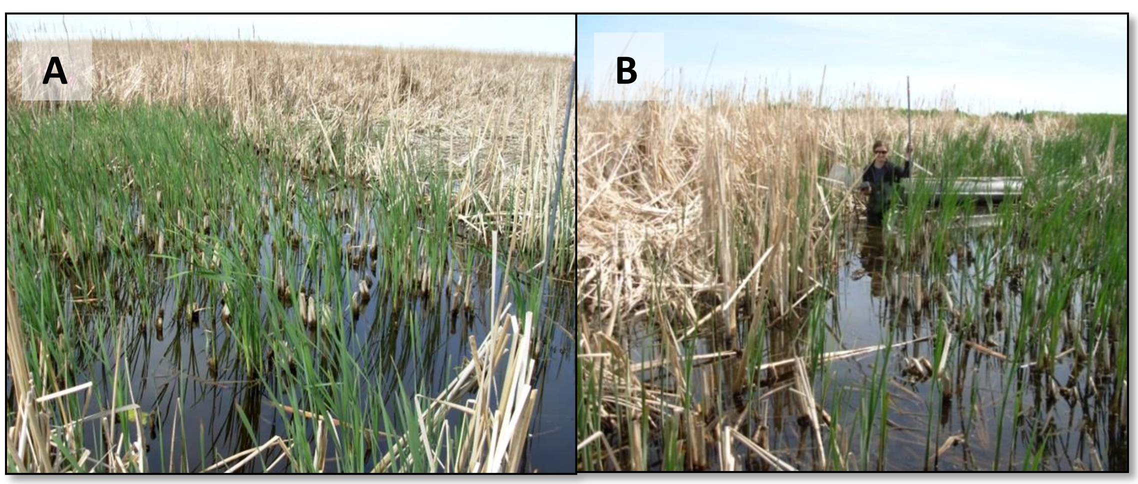


Figure 4.17. A) and B) Early spring harvest plot with new green cattail growth 1 m high, unharvested areas are covered in deadfall with little emerging new growth.

From May emergence until attaining full height in early August 2007, cattail plants in both the spring and summer harvested sites were 30 to 50 cm taller than cattail in unharvested control sites. There was a significant difference between control and treatments (control vs. spring, P = 0.006, control vs. summer, P = 0.020), but not between treatments (summer vs. spring, P = 0.265). Full height of cattail was average 250 to 310 cm tall from plant base at sediment to tip. Removal of overlying dead cattail from harvesting in summer 2006 or spring 2007 opened the marsh area reducing shading and competition for light, allowing the ground to thaw earlier in spring. Soil coring was not possible late May 2007 or May 2008 in unharvested areas because the ground was still frozen solid, while harvested plots were ice free. Removal of cattail and opening the area also resulted in greater numbers of plants emerging and higher density per square meter in years following harvest, at 53, 30, and 5 for summer harvest, spring harvest, and unharvested respectively (Figure 4.18). By August peak growth in 2007 densities in unharvested plots were similar to spring harvest sites but less than summer harvested sites. Greater plant densities in 2007 in harvested sites was attributed to greater numbers of smaller, shorter and less robust cattail plants, which responded quite well to the opened sites. This could be attributed to a competitive response from the cattail to the disturbance and opening up of the sight (Tuchman et al. 2009). This resulted in greater numbers of cattails and greater amounts of total biomass, but not greater biomass per plant (Figure 4.18). By August peak growth total dry biomass of harvested and unharvested sites was similar and not statistically different, and harvesting did not appear to have a negative effect on cattail regrowth.

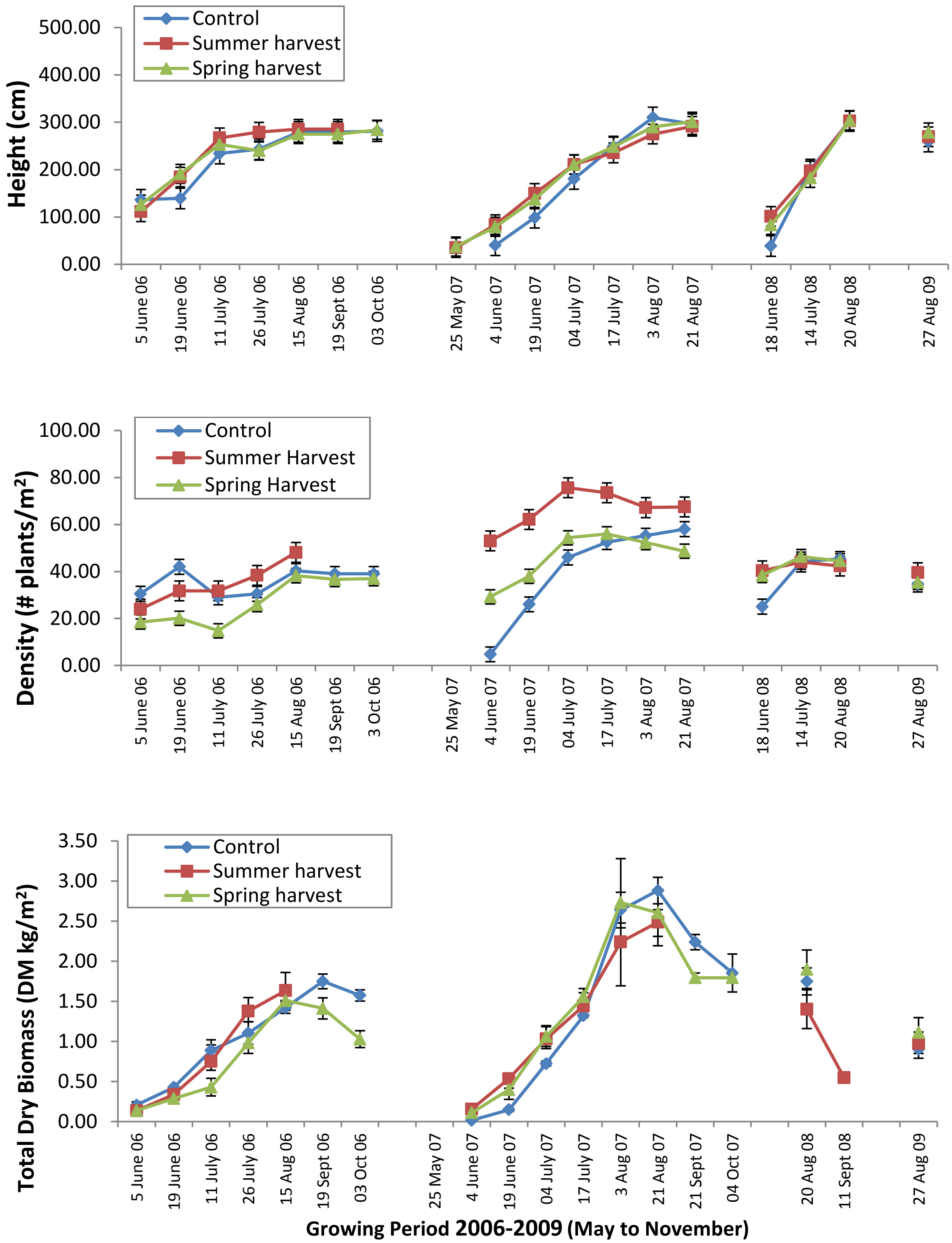


Figure 4.18. Cattail height (cm), density (# plants/m^2), and total dry biomass accumulation (Kg DM/m^2) within unharvested (control) and harvested treatment plots (summer, spring harvested) during the growing season in 2006-2009.

4.3.4.2 Cattail peak biomass accumulation

Peak biomass accumulation typically occurs between mid to late August. Following this cattails transfer nutrients, sugars, starches, etc. in the fall to belowground plant parts for winter. Figure 4.19 shows average August peak biomass accumulation (dry weight per m^2) in aboveground cattails over several growing seasons. Annual differences are noticed n 2007 compared to other years (Figure 4.19), which can be attributed to good growing conditions with above average temperatures, GDD, and average rainfall and water depth. There was a significant difference between years for control and treatments ($P = 0.0002$), but not between control and treatment each year for August peak growth ($P = 0.437$). No significant difference in peak biomass accumulation occured between harvested and unharvested sites, regardless of harvesting treatment from 2006 to 2009 (Figure 4.19). Aboveground cattail biomass accumulation in 2006 and 2008 was 1.5 to 1.75 kg/m^2 or 15 to 18 T/Ha in harvested and unharvested sites. In 2007 biomass accumulations reached 2.60 to 2.88 kg/m^2 (26 to 29 T/Ha). In 2009 the poorer growing conditions, lower than normal temperatures, and prolonged spring flooding resulted in a much lower yield of 1.0 to 1.10 kg/m^2 (10 to 11 T/Ha) in all treatments.

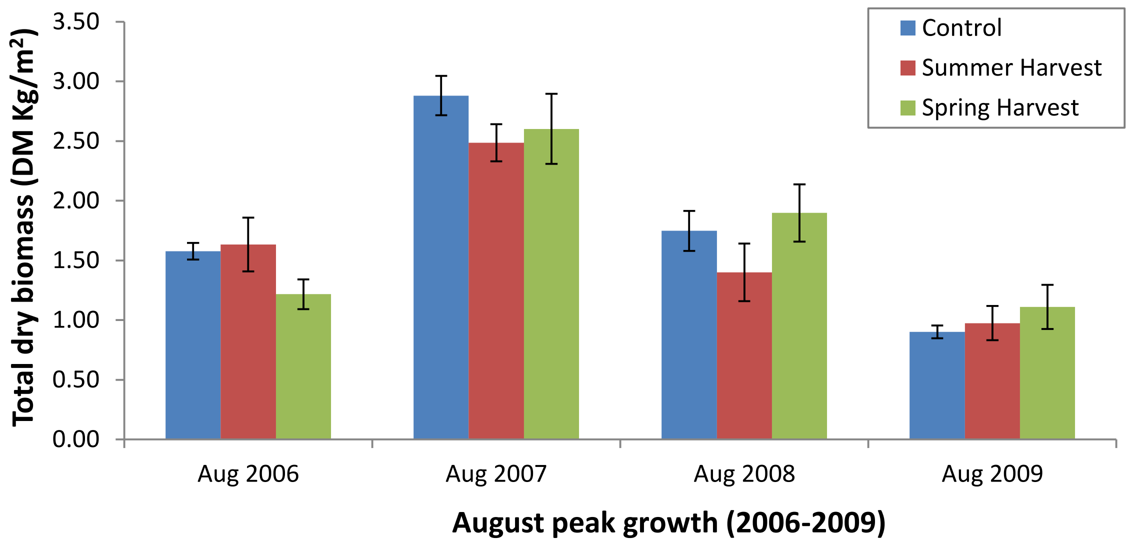


Figure 4.19. Cattail peak August biomass accumulations (dry matter kg per square meter) over four growing seasons (2006-2009). Research plots are identified: unharvested (control), Summer Harvest, Spring Harvest.

4.3.4.3 Cattail rhizome (belowground) peak biomass storage

Peak belowground storage in rhizomes can be measured in early spring (June) before growth and emergence of aboveground plants occurs. Belowground biomass in all sites between years showed some variation, although not significant. There was no significant difference between harvested and unharvested sites from 2006 to 2008, regardless of harvesting treatment (Figure 4.20). In spring 2009 there was a significant difference between harvested and unharvested (P = 0.002), which could be attributed as an effect after several years of harvesting, but there was no significant difference between spring and summer treatments. It may also be attributed to below average growing conditions in 2008 and 2009 with high water in 2009, reducing the amount of belowground accumulation. Prolonged high water in spring 2009 caused a partial die-off of cattails in harvested sites, which would have negatively impacted the cattail community and belowground biomass.

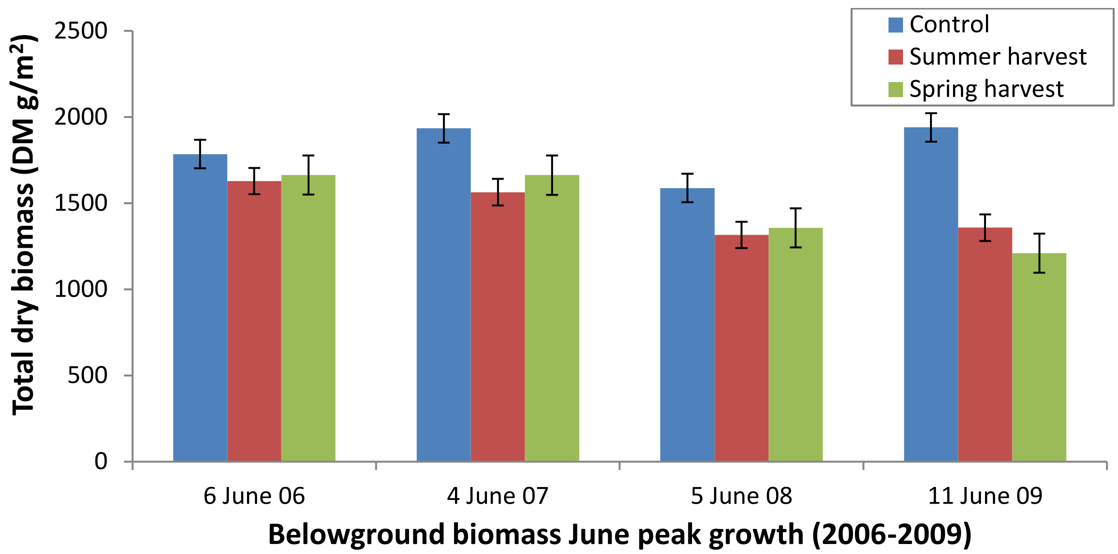


Figure 4.20 Cattail belowground peak June biomass storage (dry matter kg per square meter) over four growing seasons (2006-2009). Research plots are identified: unharvested (control), Summer Harvest, Spring Harvest.

4.3.4.4 Cattail nutrient uptake – phosphorus and nitrogen

During the growing season, nutrients such as phosphorus and nitrogen are taken up by cattail roots and rhizomes from the litter and sediment layers and incorporated within the aboveground and belowground biomass. Average nutrient content in Table 4.3 is from samples collected in a separate study at 28 sites throughout Netley-Libau Marsh in August 2009 (Grosshans et al. 2010), plus the 6 treatment sites, and analysed for Complete Nutrient Analysis (a suite of elements important for plant growth) by Agvise

Labs (AgVise 2013). Cattail biomass contained highest amounts of potassium (K), followed by nitrogen (N), calcium (Ca), sodium (Na), magnesium (Mg), phosphorus (P), and sulphur (S) – elements often associated with fouling and slagging in biomass burners and which influence the amount of ash (Chapter 5).

Table 4.3. Cattail average nutrients, 34 sites in Netley-Libau Marsh, August 2009.

	Cattail shoots		**Rhizomes**	
	%	**Kg/ha**	**%**	**Kg/ha**
NUTRIENTS	**dry matter**	**(± std dev.)**	**dry matter**	**(± std dev.)**
Nitrogen	1.2443	234.80 ± 36.53	0.8293	149.27 ± 29.13
Phosphorus	0.2596	35.79 ± 7.01	0.3289	59.21 ± 11.30
Potassium	1.7625	332.59 ± 85.53	1.3750	247.50 ± 53.99
Sulphur	0.1436	27.09 ± 6.02	0.1564	28.16 ± 11.39
Calcium	0.9093	171.59 ± 26.04	0.7089	127.61 ± 39.80
Magnesium	0.3036	57.29 ± 9.75	0.3971	71.49 ± 26.33
Sodium	0.4186	78.99 ± 28.41	0.4043	72.77 ± 30.42
Zinc	0.0013	0.24 ± 0.06	0.0040	0.73 ± 0.58
Iron	0.0285	5.39 ± 5.34	0.1416	25.49 ± 15.90
Manganese	0.0519	9.79 ± 3.23	0.0268	4.82 ± 1.63
Copper	0.0003	0.06 ± 0.03	0.0006	0.11 ± 0.08
Boron	0.0012	0.23 ± 0.02	0.0012	0.22 ± 0.09

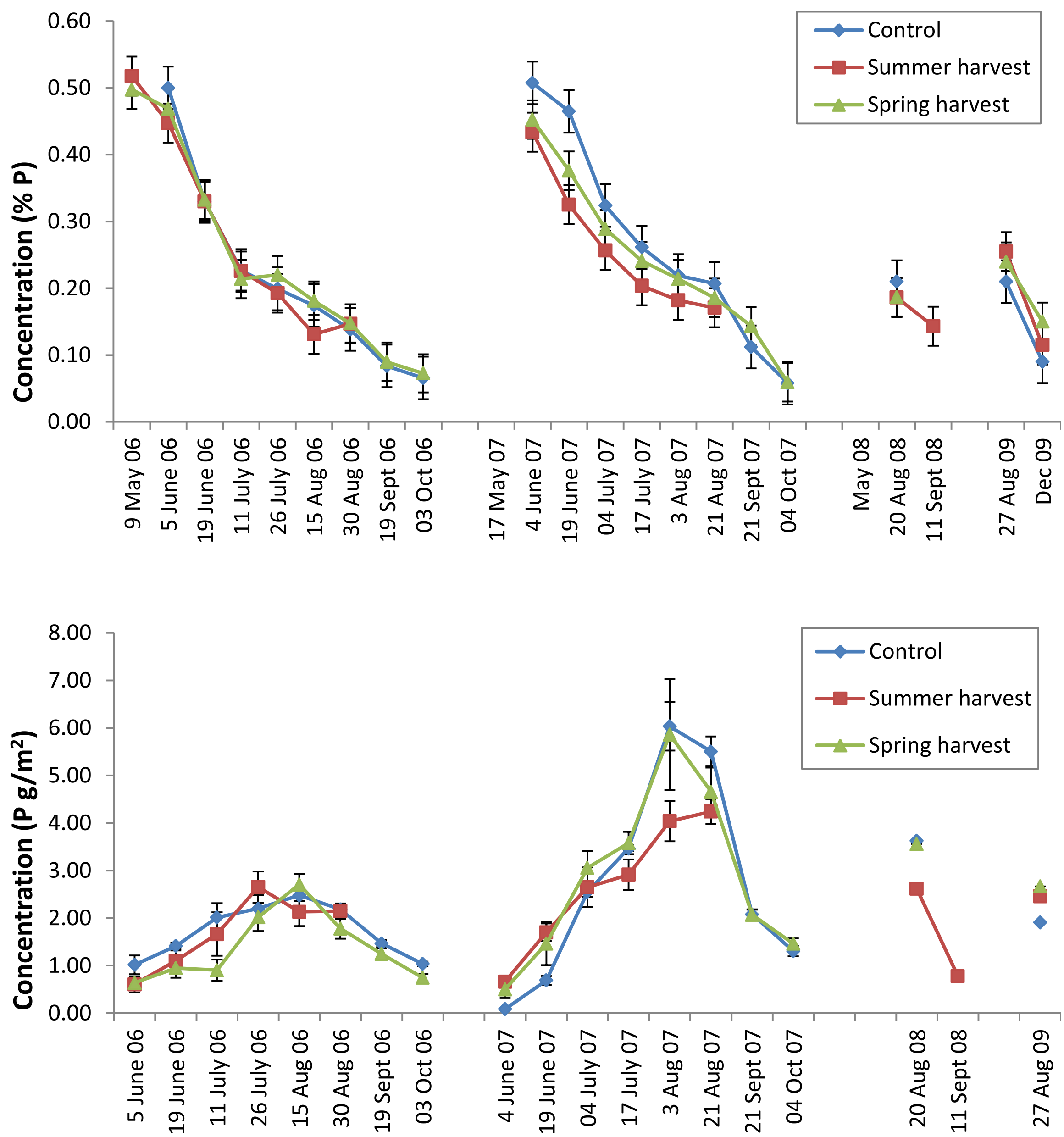
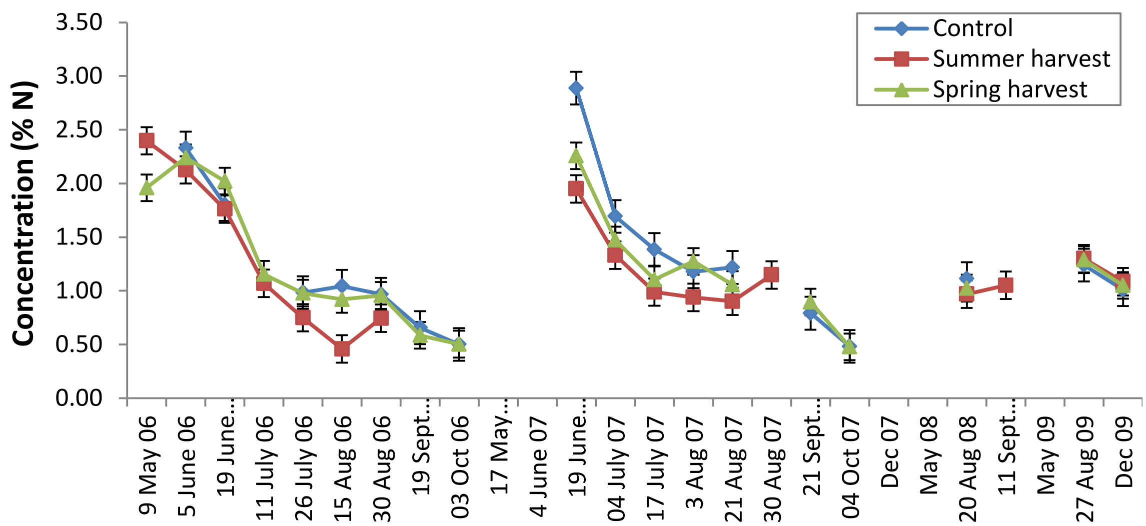


Figure 4.21 Cattail phosphorus uptake in aboveground plants (Top) as a percentage of total biomass (%) and (Bottom) in grams per square meter (g/m^2) from 2006-2009. Research plots are: unharvested (control), Summer Harvest, Spring Harvest.

Phosphorus and nitrogen concentrations in aboveground cattail shoots is highest as a percentage of total dry biomass (% P and % N) in the early spring as small cattail shoots are actively growing (Figure 4.21, 4.22) and reach peak nutrient content as a percentage of dry biomass by mid-August with 2.13 to 2.71 grams per square meter (g P/m^2) in 2006 and up to 5.86 g P/m^2 in 2007. Amount of phosphorus and nitrogen in aboveground cattail plants as a percentage of total biomass (% DM) was similar between unharvested and harvested sites in 2006 with no significant difference between treatments. Percentage of phosphorus and nitrogen was higher in 2007 than 2006 (P = 0.006) (Figure 4.21, 4.22), and percent and total amount of phosphorus and nitrogen in cattail from summer harvest sites in 2007 was significantly lower than unharvested sites (phosphorus, P = 0.007, Nitrogen P = 0.023) and spring harvested sites (phosphorus, P = 0.009, Nitrogen P = 0.010). This could be associated with greater number of smaller cattail shoots emerging in summer harvest sites as a response to harvesting, all competing for available nutrients, resulting in less % P and % N per plant.

As biomass accumulates the percentage of total phosphorus and nitrogen decreases. Cattails stop actively taking up nutrients by mid-August when Peak nutrient accumulation is reached corresponding to peak biomass accumulation (Figure 4.23), and decreases slowly during translocation to rhizomes and fall drying out and senescence. Based on phosphorus content in treatment sites large scale harvests of cattail biomass could capture and remove an average 26, 53, 33, and 24 Kg of P per hectare (Kg P/ha) of cattail in 2006 to 2009 respectively (Figure 4.23). Phosphorus content of belowground rhizomes remained relatively the same over the four year period and harvesting did not appear to reduce belowground reserves, suggesting an active pool of available phosphorus in the sediment and litter. Nitrogen did decrease in all treatments, quite dramatically for summer harvest sites, but there was no statistical difference between unharvested and harvested sites suggesting another effect.



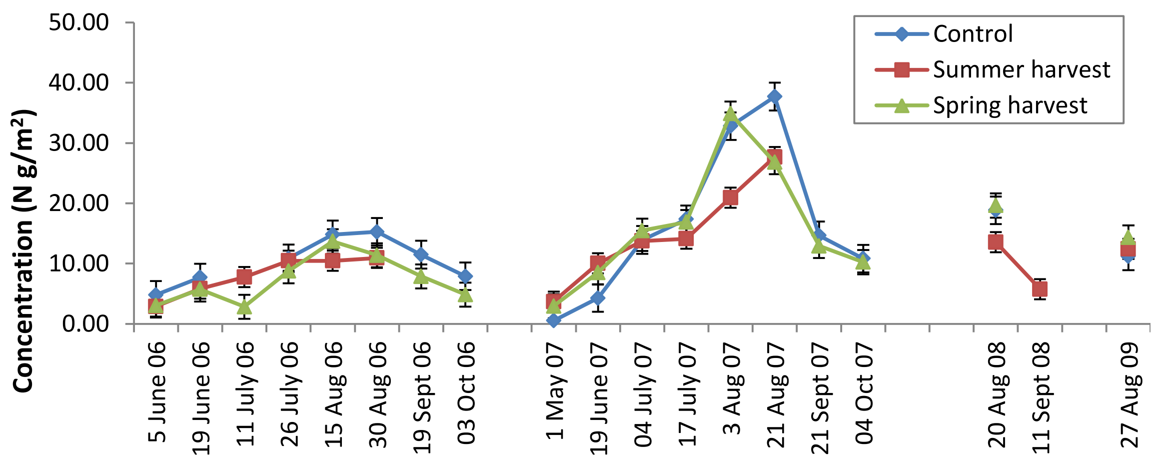


Figure 4.22 Cattail nitrogen uptake in aboveground plants (Top) as a percentage of total biomass (%) and (Bottom) in grams per square meter (g/m^2) from 2006-2009. Research plots are: unharvested (control), Summer Harvest, Spring Harvest.

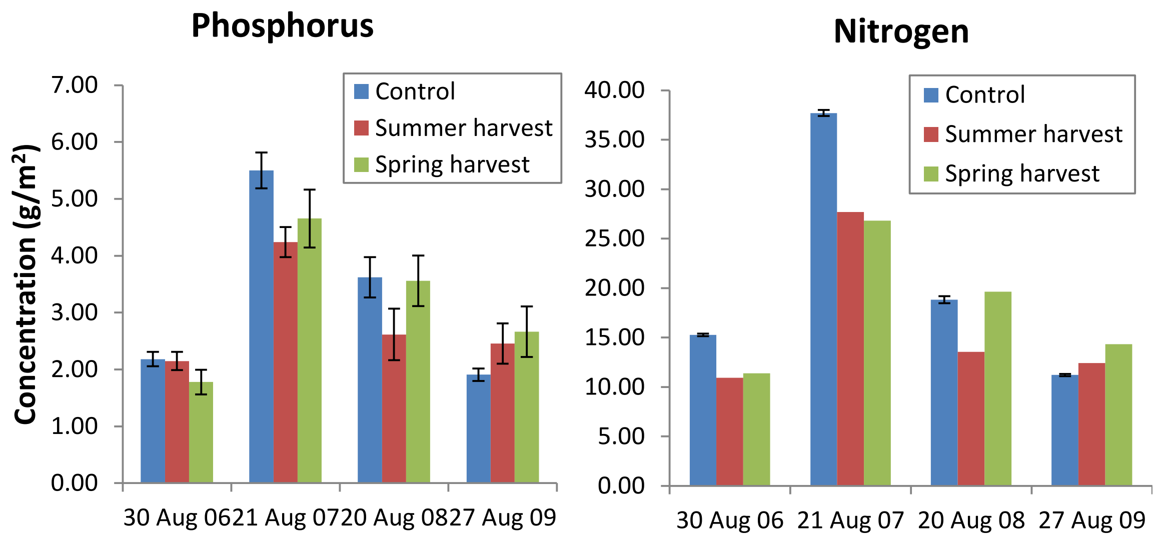


Figure 4.23 Cattail aboveground plant August peak phosphorus (left) and nitrogen (right) uptake as grams per square meter (g/m^2) 2006-2009. Unharvested (control), Summer Harvest, Spring Harvest.

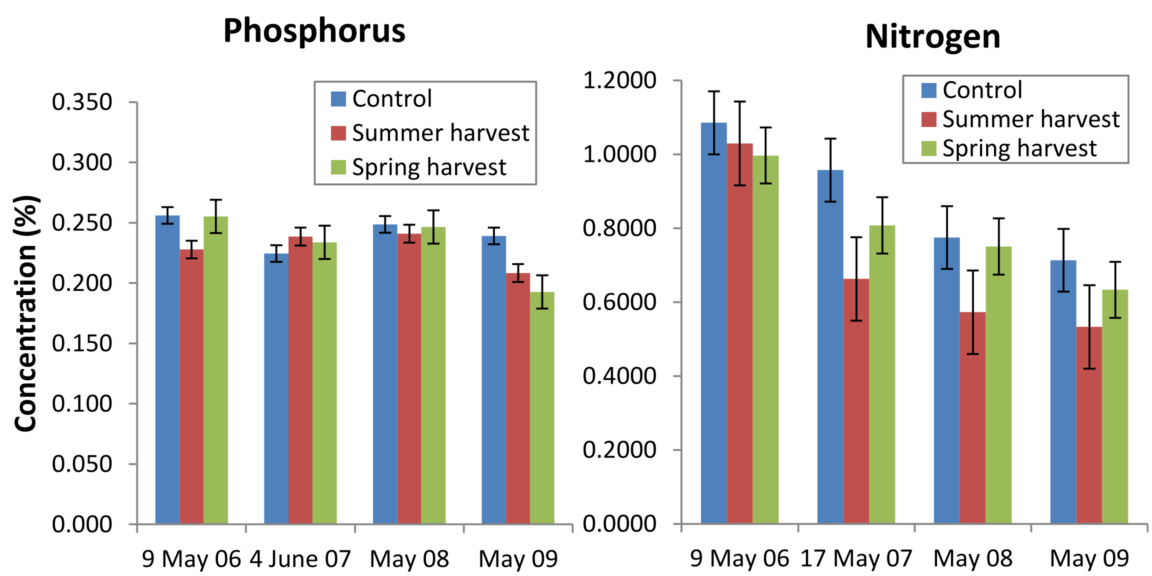


Figure 4.24 Cattail belowground rhizome June storage of phosphorus (left) and nitrogen (right) as percent of total biomass (%) 2006-2009. Unharvested (control), Summer Harvest, Spring Harvest.

4.3.5 Soil phosphorus

Average litter (top 10 cm of organic layer) and sediment (lower 30 cm in soil core) content in Table 4.4 is from samples collected in a separate study at 28 sites throughout Netley-Libau Marsh in August 2009 (Grosshans et al. 2010), plus the 6 treatment sites, and analysed for elements important for plant growth by Agvise Labs (AgVise 2013).

Table 4.4. Soil & litter nutrient data averaged, from 34 sites (28 sites plus 6 research sites) in Netley-Libau Marsh, August 2009.

	Litter		**Sediment**	
NUTRIENTS	**% dry matter**	**kg per ha (± std dev)**	**% dry matter**	**kg per ha (± std dev)**
Available Phosphorus (Olsen-P)	0.0038	9.85 ± 6.25	0.0018	45.77 ± 21.01
Potassium	0.0209	54.11 ± 17.86	0.0247	635.35 ± 290.58
Calcium	0.4011	1038.11 ± 325.62	0.5043	12961.59 ± 1919.56
Magnesium	0.0931	241.02 ± 72.34	0.1366	3510.20 ± 1741.82
Sodium	0.0164	42.50 ± 19.61	0.0150	385.05 ± 141.62
Sulfur	0.0134	34.80 ± 9.91	0.0108	276.60 ± 115.43
Zinc	0.0004	1.10 ± 0.45	0.0004	10.41 ± 4.07
Iron	0.0144	37.32 ± 12.98	0.0143	366.31 ± 154.36

Manganese	0.0072	18.71 ± 10.78	0.0060	153.57 ± 99.89
Copper	0.0007	1.80 ± 0.84	0.0009	21.92 ± 6.22
Chloride	0.0126	32.69 ± 3.96	0.0027	69.94 ± 41.67
Ammonia (NH4)	0.0034	8.87 ± 2.51	0.0024	60.73 ± 19.31
CEC (meq)	29.06	-	37.88	-
Salts (mmhos/cm)	1.23	-	1.03	-

Phosphorus exists in the soil largely as P adsorbed on iron and aluminum oxides at low pH or in association with calcium at higher pH, consequently, movement of phosphorus in soils is very low and is in equilibrium with phosphorus in solution (Reddy and DeLaune 2008). Phosphorus also occurs in organic forms and may be released by microbial activity. To be effective, an extractant must remove a constant proportion of the phosphorus that is available to plants from different soils. Soil pH and the presence of $CaC0_3$ (lime) in the soil have a major influence on this relationship. The Olsen-P $NaHC0_3$ extraction developed by Olsen (Olsen et al. 1954) was found to account for 89% of the variability in P absorption and was superior to all other extractants tested at all pH ranges in regions where soils are neutral or calcareous (OMAFRA 2012).

Soil and litter (L) phosphorus (Olsen-P) were calculated as a percentage of total soil bulk density (%) from 2006-2009. Litter is the topmost 10 cm of organic matter and debris, while soil is the next 30 cm. Litter samples were collected starting in mid-July of 2007, when it was determined organic matter and litter phosphorus pool could be contributing significant available phosphorus. Phosphorus in the litter interacts with surface water and can be released as litter decomposes and is disturbed by fish (i.e. carp) and wind and wave action. Over time, harvesting cattail biomass will reduce the amount of new litter being added.

Soil phosphorus levels within the control, treatment sites, and open water areas were not significantly different between 2006 and 2007 with little seasonal variation between 0.001% to 0.002% throughout the growing season from when the ground thawed in early June until early October (Figure 4.25). Similarly litter phosphorus levels were not significantly different over the growing season in the range of 0.002% to 0.003%. The spring harvest sites had relatively higher soil and litter phosphorus levels in 2006 and 2007 compared to the summer harvested and unharvested sites, as well as compared to the open water sites next to the cattail treatment sites (Figure 4.25), suggesting phosphorus storage within the cattail above and belowground parts. Harvesting the cattail did not result in a statistically significant difference in available soil and litter phosphorus levels between 2006 and 2007.

A large spike in litter available phosphorus levels was observed in spring 2008 with litter phosphorus levels up to 0.007% and 0.008% for harvest sites and unharvested respectively following the wildfire. Burning is known to release nitrogen, phosphorus, sulfate, and other biochemicals locked in plants, wood, and soils, making them available (Fisher 2012). Another spike was observed in spring 2009 during the spring flooding and high water, which brought new phosphorus from upstream. In both years phosphorus levels decreased by August, which could be attributed to adsorption in the soil and plant uptake. The variability of the Netley-Libau Marsh research sites with water level and phosphorus inputs as an open connected marsh system to Lake Winnipeg made it impossible to determine reductions in soil phosphorus levels as a result of harvesting cattail.

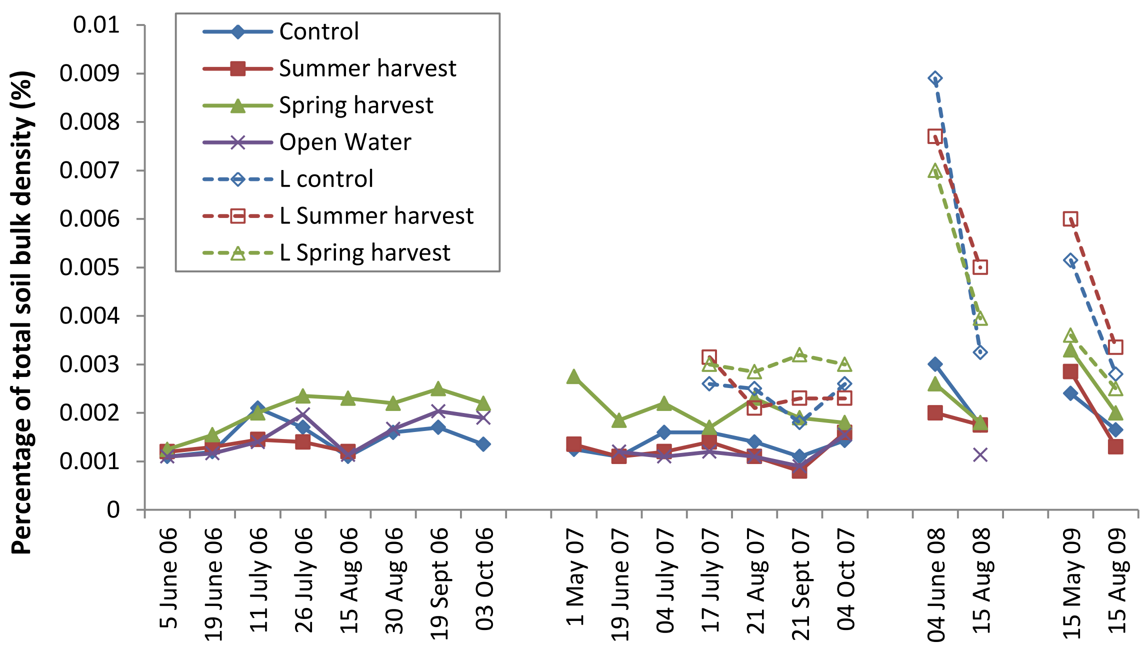


Figure 4.25 Soil and litter (L) phosphorus (Olsen-P) as a percentage of total soil bulk density (%) from 2006-2009. Litter is the topmost 10 cm of organic matter and debris, while soil is the next 30 cm. Research plots are: unharvested (control), Summer Harvest, Spring Harvest compared to open water sites next to cattail research sites.

4.4 Discussion

4.4.1 Environmental discussions

The first two years of the research study, 2006 and 2007, had the highest number of growing degree days (GDD), but low precipitation in 2006 and subsequent drop in water levels in the marsh resulted in some treatment sites to go dry, which appears to have lowered overall cattail productivity and biomass accumulation. Average temperatures and precipitation in 2007 appeared to provide ideal growing conditions for productivity, and could have contributed to the high overall productivity of cattail and associated biomass and nutrient accumulation. Lower number of GDD and below average temperatures in 2008 and 2009, with well above average precipitation appears to have reduced cattail productivity.

Total phosphorus levels in the water was between 0.5 to 3 mg/L, well above provincial guidelines where total phosphorus should not exceed 0.05 mg/L (Manitoba Conservation 2002), while total available phosphorus levels averaged between 0.03 and 0.3 mg/L. Ammonia levels in the water were typically undetectable, with occasional spikes at various times of the year suggesting inputs from upstream in the Red River and from rain events. This does not, however, account for the levels of phosphorus (20 to 60 kg/ha) and nitrogen (200 to 400 kg/ha) taken up by cattail each year, and indicates the majority of phosphorus and nitrogen taken up by cattail was obtained from previously stored reserves in the soil (Ackerman 2008).

Average total chlorophyll *a* values in the research sites was 17.0 µg/L, and levels in the Netley and Libau Marsh areas 30.8 µg/L and 48.3 µg/L respectively. Water bodies with chlorophyll *a* concentrations between 56 to155 µg/L are considered eutrophic (i.e., high in nutrients) and characterized by dense algae and macrophytic growth. The summer of 2007 had the highest chlorophyll values, which could be attributed to the above average temperatures and higher number of growing degree days as is also evident in the productivity of cattail stands in these years. This difference in chlorophyll *a* concentrations between years is not uncommon for prairie wetlands, and may be due to a number of environmental and human induced factors (McDougal 2001, Hartwig 2008). Chlorophyll *a* concentrations may have been affected by the lack of precipitation in 2006, and an associated shortage of dissolved nutrients in the water column that would otherwise be introduced via leaching or surface runoff (Hartwig 2008). Chlorophyll *a* concentrations in 2007 to 2009 peaked in the spring and summer, and gradually decreased, which would coincide with an influx of dissolved nutrients in the spring, and a reduction later in the season as nutrients are taken up by algae, submersed and emergent macrophytes, and microorganisms. This is evident in the increase in soil phosphorus levels later in the season, as phosphorus makes its way into the organic and sediment layers from dying algae and microorganism and become unavailable bound in the sediment. Also evident in cattail nutrient reserves, as they translocate nutrients to belowground rhizomes in late summer to early fall. Spikes in the rest of Netley and Libau marshes could be a result of nutrient influxes upstream and decomposition of plant material, which would have increased dissolved organic matter as well as provided nutrients for algal growth and (Jackson and Hecky 1980).

4.4.2 Phosphorus capture: Cattail harvesting success

Impacts of harvesting on plant community, cattail regrowth, biodiversity, and nutrients for short term harvesting impacts were minimal. Harvesting did not appear to have a negative effect on cattail regrowth, but rather harvesting and clearing the site the previous year opened the site to sunlight allowing for earlier emergence of new spring cattail shoots. Earlier emergence and faster growth in harvested sites could be a competitive advantage during spring flooding and high water as occurred in 2009, allowing plants to emerged faster. Harvesting aboveground cattail biomass proved to be successful in removing a significant amount of stored phosphorus and nitrogen in the harvested plant material. Highest phosphorus removal was during summer harvests with an average 2.5 to 3.5 grams per square meter (g/m^2) or 25 to 30 kg of phosphorus per hectare (kg P/ha) per year averaged over the four years of harvesting and cattail sampling and up to 60 kg P/ha in 2007. Spring harvesting was much less effective with regards to capturing and removing nutrients with average 5 kg P/ha of cattail remaining in dead spring harvested biomass, compared to over 25 kg P/ ha for summer harvested.

Harvesting standing cattail biomass removes nutrients taken up by plants during the growing season preventing those nutrients from being re-released back into the aquatic system during decomposition (Wrubleski et al 1997a, b, Ruppel et al. 2004). Similarly found with fire suppression in forests where accumulated dense litter layers retain high levels of phosphorus and nitrogen, which slowly wash away through litter interflow water (Fisher 2012). Mitchell et al. (2011) found dense hybrid cattail communities caused increased litter accumulation, as did Angeloni et al. (2006) where sediments showed higher nutrient levels as a result of cattail and its litter accumulation impacting nutrient removal. The literature demonstrates wetland plants can take up and capture a significant amount of nutrients in heavily loaded systems, from 3 up to 27 g of P/m^2 (Martin and Fernandez 1992, Jiang et al. 2005, Liao et al. 2005, Toet et al. 2005) suggesting harvesting as a nutrient management strategy could reduce nutrient loading in aquatic systems (Lakshman 1979, Martin and Fernandez 1992, Koottatep and Polprasert 1997, Liu Hosoi et al. 1998, Liu et al. 2003, Toet et al. 2005, , Sharma et al. 2006, Weng et al. 2006, Vymazal 2006). Although harvesting emergent wetland plants such as cattail for nutrient capture in eutrophic systems has not been fully explored in the literature (Dubbe et al. 1988 Garver et al. 1988, Martin et al. 2003) it has been suggested periodic harvesting of aboveground cattail biomass could remove elements from the water in the long term (Martin and Fernandez 1992).

This study indicates harvesting cattail in natural eutrophic aquatic systems with removal rates of 20 to 60 kg of P/ha (2 to 6 g of P/m^2) of cattail is significant compared to annual loading rates from watershed runoff. This is in comparison to harvesting studies from heavily loaded wastewater treatment wetland systems where an average 14 g P/m^2 was removed annually, representing only 10% of annual phosphorus loading, and considered insignificant in heavily loaded systems (Martin and Fernandez 1992, Toet et al. 2005). Other studies have achieved much higher than 10% removal rates, with up to 70% of annual loading present in emergent plant tissues, and recommend harvesting as an important removal option for nitrogen and phosphorus (Liu et al. 2003, Jiang et al. 2005, Liao et al. 2005, Menon and Holland 2013). Pratt et. al. (1988) explored the cultivation of cattail with treatment of wastewater from sugar beet plants, and harvested cattail removed 3 to 5 g/m^2 (30 to 50 kg/ha) of nitrogen and 0.5 to 2 g/m^2 (5 to 20 kg/ha) of phosphorus in aboveground cattail plants (Pratt et al. 1988), which was suggested would prolong the life of the treatment wetland (W. Johnson pers. com 2012). Results from harvesting in the current study indicates harvesting for nutrient control would be an effective nutrient management tool in natural and storm water wetlands used to control eutrophication (Vymazal 2006).

Percent of phosphorus as a function of dry cattail biomass was high from Netley-Libau Marsh, with August averages 0.1 to 0.3 %. Concentrations in cattail tissue will vary depending on location and available phosphorus in the system (Grosshans and Grieger 2013). Lakshman (1979) found phosphorus levels in cattail up to 0.5% of dry matter with excessive nutrient loading, as did Pratt et. al (1988) who reported up to 1.5% in some cultivated stands, much higher content compared to the natural eutrophic environment of Netley-Libau Marsh. Average phosphorus levels reported in the literature are comparable to the current study at 0.21% (Table 4.5) (Mitch 1994, Reddy & Smith 1987).

Table 4.5. Comparison of cattail properties from current study (mid-August) to samples collected in Netley-Libau Marsh during 2009 (August), and from the literature.

Plant species	**Study**	**Season**	**TP % dry matter**	**TN % dry matter**
Cattail	Current Study	Summer	0.17 – 0.21 (20 - 60 kg/ha)	1.0 – 1.27 (260 - 370 kg/ha)
Cattail	Grosshans et al. 2010	Summer	0.20	1.21
Cattail	Cicek et al. 2006	Winter	0.32	1.72
Phragmites	Cicek et al. 2006	Winter	0.08	0.64
Cattail	Reddy and Smith 1987	Summer	0.21	1.37
Phragmites	Reddy and Smith	Summer	0.18	2.57
Cattail	Lakshman 1984	Lab	0.5 to 0.7	-
Cattail	Woo and Zedler	Nutrient addition	0.24	2.2
Cattail	Woo and Zedler	Natural	0.18	1.8
Cattail	Maddison et al. 2009	Summer/ Fall	0.16 – 0.44	1.27 – 2.74
Cattail	Sharma et al. 2006	Summer	0.2 – 0.25	1.0 – 1.8
Cattail	Pratt et al. 1984	Summer	0.05 – 0.41 (10 to 20 kg/ha)	0.75 to 1.6
Cattail	Pratt et al. 1988	Summer	0.18 (8 kg/ha)	0.78 (35 kg/ha)
Cattail	Weng et al. 2006	Lab	0.2 – 0.3	-
Cattail	Miao and Sklar 1998	Summer	0.058 - 0.12	-

4.4.3 Cattail seasonal phosphorus loss: where does the P go?

Winter or early spring conditions in the Canadian prairies provide suitable conditions for harvesting in wet environments, since the ground is still frozen minimizing impacts from harvesting equipment, and harvested biomass is dry. A winter or early spring harvest of dead plant biomass has the least impact and effect on wildlife, minimal disturbance to human recreation, and cattails have transferred nutrients to the belowground parts in late summer ensuring their survival and sustainability. Harvesting in winter to early spring is a common practice in Europe for reed harvesting for roof thatching (Wichtmann et al. 2010) and biomass harvesting for bioenergy (Ukraine pers comm. 2012) as it allows elements that cause fouling in bioenergy systems to be reduced in standing biomass (Granelli 1984). Whether enough nutrients remain in dead aboveground biomass to still effectively capture and remove phosphorus and nitrogen from the watershed is not well studied. In North America, winter harvests could be difficult with heavy snow accumulation and in spring with runoff flooding, as is common on the Canadian prairies (Environment Canada 2012).

Plants transfer nutrients to the belowground parts in late summer (i.e. translocation) ensuring their survival until the following spring (Grace and Wetzel 1981, Mitsch and Gosselink 2007). Over the four growing seasons dead cattail plants lost considerable biomass and nutrients over the winter months from fall until spring, particularly during freeze/thaw cycle (Figure 4.26). Senescing cattail still contained an average 0.12 % P in early fall following nutrient translocation, but lost nearly half of its stored P to .04% by early spring (Figure 4.26). An early spring harvest may have the least impact and dry biomass for additional uses of the material such as a solid fuel for burning, but from a nutrient management perspective the amount of phosphorus removed by harvesting cattail is quite low (Figure 4.26). This is consistent with Asaeda et al. (2006) who also found nutrient levels in *Phragmites* were lowest in dead spring material. Cicek et al. (2006) also show dead aboveground cattail biomass harvested in earlier winter (December) retained higher amounts of N and P, comparable to aboveground yield estimates reported in the literature (Cicek et al. 2006).

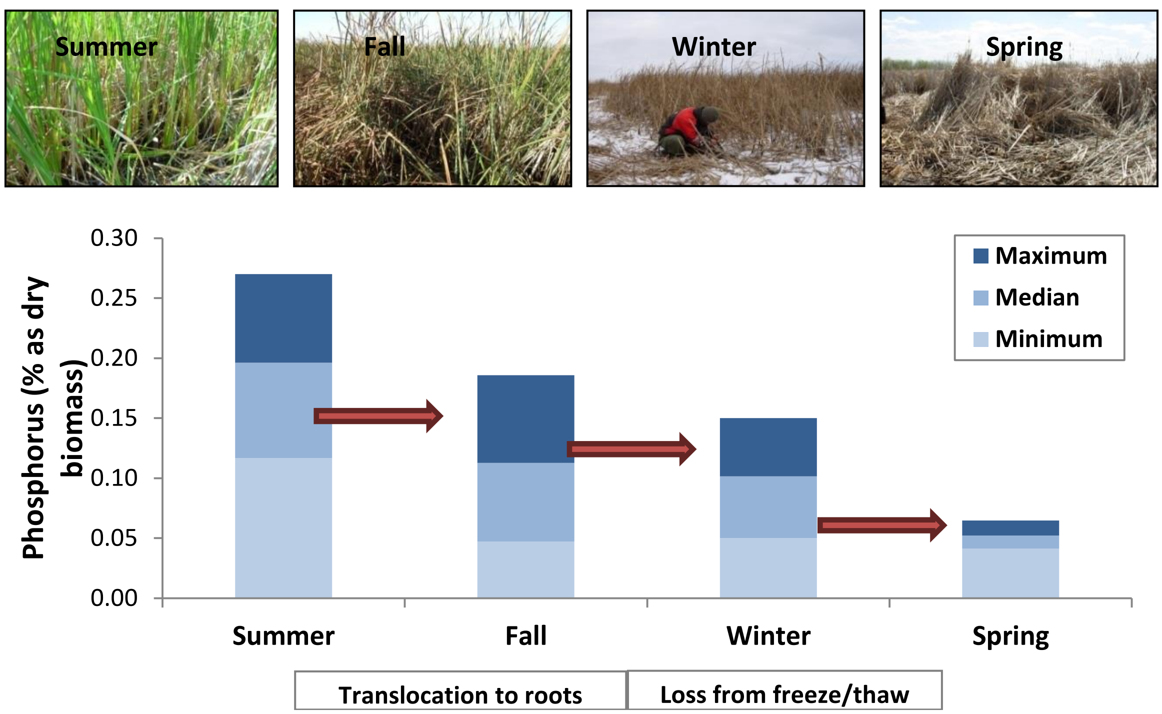


Figure 4.26. Cattail harvesting for nutrient removal - Seasonal phosphorus loss in cattail in emergent biomass: peak biomass content in Summer (August), nutrient translocation to roots in Fall (October), loss of biomass and nutrients during death of plant, drying, and freeze thaw over Winter (December) to Spring thaw (May).

4.4.4 Impacts of wetland harvesting to cattail survival

Seasonal timing of harvest differs if the goal is to maximize nutrient capture or drying of biomass for bioenergy and biomaterials. Bjork and Graneli (1978) and Graneli (1984) recommend a winter harvest when harvesting biomass for bioenergy, for ease of harvesting and to remove cost of drying. Results from this study indicates a spring harvest captures less than 20% of phosphorus compared to summer harvested cattail, which is very low for nutrient management (< 5 kg of P per hectare). Maximum nutrient capture and removal would be late summer when nutrient levels in aboveground plants are highest (Kadlec and Knight 1996, Mitsch and Gosselink 2007, Smith et al. 1988). Although, continual summer harvests when rhizome reserves are lowest before plants transfer nutrients to belowground rhizomes could negatively affect long term sustainability of wetland plants. Impacts to wildlife would also be highest during summer when waterfowl and other wildlife are utilizing the marsh (Murkin et al. 1997).

Asaeda et al. (2006) compared rhizome biomass accumulation in *Phragmites* stands harvested in June and July and found timing of harvesting aboveground biomass greatly affected annual rhizome resource allocation and aboveground plant growth (Asaeda et al. 2006). Early harvests decreased long-term productivity of reed beds, while later harvest maintained stand productivity and sustainability. Aboveground and rhizome biomass accumulation showed significant decline when harvested during peak growth when belowground resources were depleted, but did not show a significant decline when harvested later in the season following translocation. There was a reduction in stored resources in the following season as a direct result of harvesting earlier during the previous growing season (Asaeda et al. 2006). This is also supported by Karunaratne et al. (2004a, 2004b), who indicate rhizome reserves would be replenished by an August harvest date. They do acknowledge earlier harvests would remove larger bound nutrient stocks while still preserving a healthy *Phragmites* stand long-term. Nutrient depletion impact was not demonstrated in the current study in the short term over four years of harvesting. In order to ensure long-term sustainability, harvesting must also leave stubble above the water to provide oxygen and gas exchange for belowground rhizomes so they don't drown causing a loss of the entire stand. Flooding and cutting cattail below the water is an effective management technique to drown out and control invasive dense cattail stands (Murkin et al. 2000, USDA 2006), and was observed in 2009 with prolonged high water levels from spring flooding and a partial die-off of sections of harvest sites. The following year (2010) the cattails had fully recovered.

This study indicates a fall harvest provides a compromise for the combined purposes of nutrient capture, biomass for bioenergy, and sustainability of the cattail community. Cattail plants in the fall have 1) lost considerable moisture during fall senescence; 2) replenished nutrient reserves to belowground rhizomes lost during the growing season, and 3) senescing aboveground plant material has not yet fully lost accumulated biomass and stored nutrients. A fall harvest date would remove a larger bound nutrient stock than a spring harvest of dead biomass, while still preserving a healthy cattail plant community (Smith et al. 1988, Karunaratne et al. 2004, Asaeda et al. 2006).

In this study, peak growth, biomass, and nutrient content occurred during August, when cattail communities contained highest biomass and phosphorus and nitrogen per square meter. Similar profiles were measured in cattails in the mid-US, but emergence was much earlier in early May and April, two months earlier than emergence in Netley-Libau Marsh (Figure 4.27). Resource accumulation varies depending on geographic location and climate, so understanding local seasonal growth profiles is essential to incorporate harvesting as a nutrient management strategy (Smith et al. 1988, Dubbe et al. 1988). Measuring over the growing season will determine peak biomass and nutrient accumulation, thereby ideal time for harvest and nutrient removal.

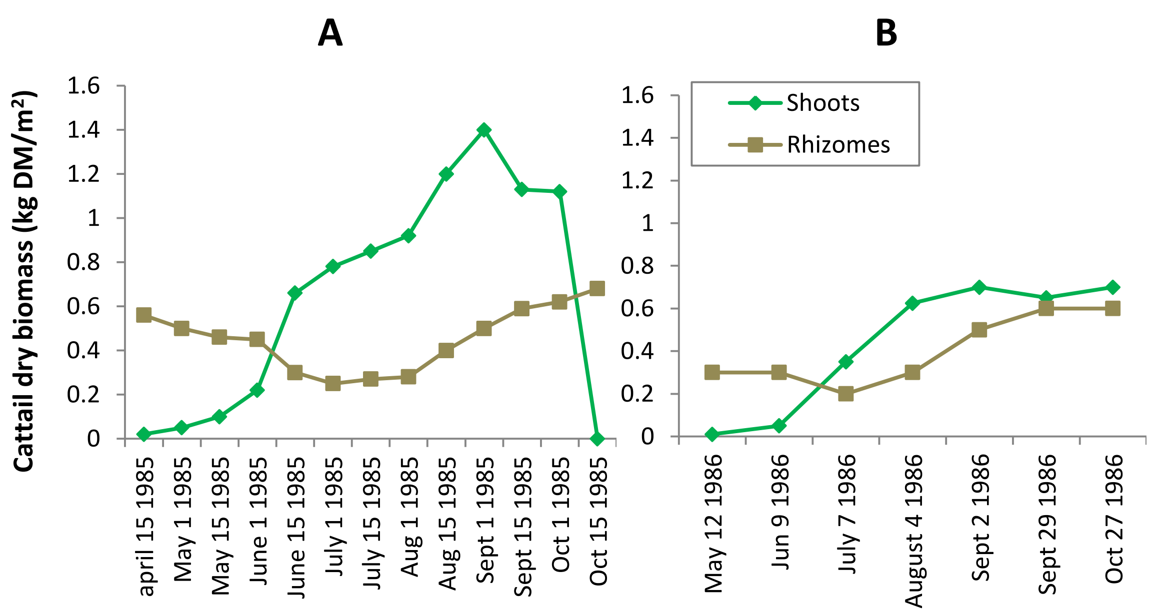


Figure 4.27. Seasonal profile of above and belowground biomass in cattail (*Typha* spp.) over two growing seasons in the mid-US region (A) from Smith et al. (1988) and (B) from Dubbe et al. (1988).

4.4.5 Impacts of wetland harvesting to biodiversity and wildlife habitat

Impacts of harvesting for wildlife biodiversity can be associated with the change in plant diversity and reduction of overlying deadfall, creating healthier stands of plants. Wetlands thrive with occasional disturbances to maintain healthy diverse plant communities, and more preferable wildlife habitat than dense monocultures of invasive plants and stands of deadfall (van der Valk and Davis 1978, Kantrud et al. 1989). Emergent plants provide protective nesting and loafing habitat for waterfowl and marsh birds, and feeding areas abundant with food prey (i.e. invertebrates) and submersed plants (Swanson and Duebbert 1989). The value of this habitat is highly dependent on diversity and structure of plant cover. A dense thick cattail marsh does not provide suitable habitat for most marsh wildlife, which instead prefer a more diverse open habitat with suitable open water areas (Swanson and Duebbert 1989, Murkin et al. 1997). Waterfowl and marsh birds prefer partially opened areas and a mix of vegetation and open water areas for nesting and loafing, where there is an equal mix 50:50 of vegetation and open water habitats (Kaminski and Prince 1981, Murkin et al. 1997, Balcombe et al. 2005). Harvesting and removal of dense cattail growth improves wetland habitat and creates more open and desirable habitat conditions reducing dead plant density and exposing more open water (Murkin et al. 1982).

Harvested and cleared cattail plots at Netley-Libau Marsh were often used by waterfowl in the fall as loafing sites, these harvested and cleared plots provided open pockets within the larger cattail communities. Redwinged blackbirds nested on fringes of the harvested sites, and the occasional muskrat mound appeared in the middle of harvested plots in the final year. These opened areas also provided frog habitat, as one of the summer harvested sites was full of mating frogs in 2008 while none were singing in the surrounding cattail and open water areas. Mitchell et al (2011), Tuchman et al. (2009), Larkin et al. (2011), and Angeloni et al. (2006) have been studying benefits of removing invasive cattail in the southern Great Lakes and have found improved wetland habitat with greater diversity of plant species when dense cattail stands are removed.

4.4.6 Harvesting Challenges

Harvesting in wetlands and waterlogged conditions presents serious logistical challenges to harvest sustainably with minimal ecological impact. While commercial-scale harvesting of wetland biomass has been demonstrated in many parts of the world, it has not been widely demonstrated in North America. Soft organic wetland soils are easily compacted and destroyed from heavy equipment; therefore, low-impact wetland harvesters are needed beyond typical farm equipment. In Europe tracked harvesters and those fitted with balloon tires are a well-established technology for use in wetlands and waterlogged conditions, on ecologically sensitive lands and can be considered for cattail harvesting in North America (De Vries Cornjum 2013, Pisten Bully 2103, LogLogic 2103, and Reeda 2013). Harvesting logistics and evaluation of seasonal timing of harvest is needed to maximize nutrient capture, reduce moisture content, and improve efficiencies for biomass use and bioenergy.

4.5 Conclusions

This chapter demonstrates harvesting cattail successfully captures and permanently removes significant levels of stored phosphorus and nitrogen in the harvested biomass, taken up by roots and rhizomes from stored litter and sediment. This removal of phosphorus directly addresses goals of the Manitoba Government, Environment Canada, and recommendations by the Lake Winnipeg Stewardship Board to reduce phosphorus loading to Lake Winnipeg – all while providing a biomass feedstock for industry and recovering a valuable strategic resource (Chapter 5). Harvesting cattail for nutrient management will have its greatest success and economic feasibility if combined with biomass for high value end-products, economic valuations of carbon offset (Gass 2012) and potential water quality trading markets (Selman et al. 2009).

Removing overlying deadfall opened harvested sites to sunlight allowing plants to emerge nearly two weeks earlier than unharvested sites. This study indicates an early fall cattail harvest prior to onset of winter maximizes nutrient capture, sustainability of the cattail community, and reduces impacts to wildlife.

Harvesting in fall ensures:

- It is past period of peak growth of cattail in summer and plants have replenished nutrient reserves to belowground rhizomes lost during the growing season ensuring sustainability of the cattail,
- Allows cattail to have lost moisture during fall senescence (approx. 25%), requiring less energy required for drying and cost of transportation,

- Ensures greater percentage of nutrients are contained in aboveground material in late fall compared to spring, maximizing removal of stored nutrients,
- Ensures higher overall recovery of biomass than spring harvesting when material is often matted and brittle,
- Avoids spring flooding and agricultural demand for available equipment.

This study also provides considerable data for Netley-Libau Marsh, to better understand a coastal marsh system we know very little about and yet is a key component of an integrated nutrient management strategy for the Red River and Lake Winnipeg watershed. It also adds knowledge to how rehabilitation of plant communities in natural wetlands can effectively improve nutrient capture by removing greater phosphorus and nitrogen. The economic feasibility of bioenergy production and carbon emissions credits from harvested cattail biomass is explored in the following chapters.

5.0 Cattail (*Typha* spp.) Biomass: Bioenergy, offsets, and phosphorus recovery

5.1 Introduction and objectives

In Manitoba, Canada, a key driver for a regional bioeconomy is the fact plants like Cattail (*Typha* spp.) soak up nutrients that would otherwise flow into waterways and cause eutrophication and large-scale algal blooms (Chapter 4). Harvesting novel forms of biomass that also effectively absorbs nutrients (i.e. phosphorus) from the watershed, improves the economic viability of harvesting raw materials for the biomass industry (Grosshans et al. 2012). Cattail is a large emergent aquatic plant characteristic of wet environments in North America, prized for its bioremediation and water quality benefits, which is a significant competitive advantage as a novel ecological biomass feedstock (Lakshman 1984, Kadlec and Knight 1996, Vymazal 2006). This plant is an under-utilized source of biomass to be integrated into solid and cellulosic bioenergy systems to help meet increasing sustainable energy demands.

5.1.1 Expanding the portfolio of biomass bioenergy

Biomass bioenergy - the production of energy and fuels from biological material – is a sustainable renewable energy source to reduce dependence on fossil fuels and reduce global carbon emissions (Paine et al 1996). In Europe primary energy output from solid biomass combustion continues to increase as countries strive to meet alternative energy policies and reductions in carbon emissions (Schaps 2013). Solid biomass leads the alternative energy sector by incineration of municipal solid waste and combustion of wood fuel pellets and agricultural straw residues (European Commission 2012, State of Green 2012). Approximately 70 per cent of renewable-energy consumption in Denmark currently stems from biomass (State of Green 2012). Availability of biomass derived solid fuels in clean and convenient forms (i.e. chips, pellets, cubes, briquettes) and modern combustion technologies (i.e. stoker boilers, gasifiers, pellet stoves) allows for full commercial and industrial scale or domestic use for heat and combined heat and electrical power generation (CHP) (US EPA 2007, Blue Flame Stoker 2012). In addition to a solid fuel, there is potential to convert this biomass into much higher value energy products, including biogas, biochar, and third-generation biofuels, as well as high value biomaterials and biochemicals (Titan Energy 2012, CENNATEK 2013, Fraunhofer 2012) as part of a broader innovation agenda for the bioeconomy.

The use of biomass in Canada is growing and it is anticipated this growth will continue with federal and provincial renewable energy policies and regulations to reduce the use of coal (Government of Manitoba 2012a). Combined heat and power systems (CHP) for large scale applications are a well-developed technology in Europe (European Commission 2012). Conversely, smaller scale applications are not well defined in Canada in terms of technological approach, cost and payback period for distributed power generation (Cicek et al. 2006). Developing biomass into a sustainable renewable energy source will require the flexibility to use a variety of biomass feedstocks and energy conversion technologies. A lack of feedstock sustainability and economic viability is a significant risk to the biomass industry (Biomass Research and Development Board 2008). The business case for the development of biofuels is highly dependent on availability and sustainability of feedstock, logistics of harvesting and transportation, and economics of the biomass end-product. There is a need to characterize and expand the portfolio of sustainable and renewable feedstock sources, particularly those that can improve the economic viability of biomass (Grotheim 2011). Novel sustainable and renewable ecological feedstocks, such as cattail (*Typha* spp.), willows (*Salix* spp.), and reeds (*Phragmites* spp.) can provide greater environmental co-benefits beyond typical biomass sources to significantly improve economic viability. Harvesting cattail as a biomass feedstock will have its greatest economic advantage when harvested for multiple combined benefits.

5.1.2 Cattail (*Typha* spp.) a novel ecological biomass feedstock

Cattail (*Typha* spp.) is a novel ecological biomass feedstock for use in the biomass industry that delivers valuable ecological services through nutrient capture and reduction of nutrient loading (i.e. phosphorus) to downstream water bodies (Chapter 4). It is extremely resilient, fast growing, and competitive, growing wherever standing water persists and produces a lot of biomass in a single growing season. As they grow they sequester carbon from the atmosphere and take up nutrients from the sediment, incorporating them into plant biomass (Chapter 4). Cattail grows on wet and marginal agricultural land, which provides landowners with additional revenue from otherwise unproductive land. It is a biomass feedstock that does not compete with prime agricultural land and food crops (Evans 2008).

5.1.3 Chapter objectives

This chapter evaluates cattail as a sustainable renewable low-carbon solid fuel for biomass bioenergy production to displace coal and natural gas heating, and produce carbon offset credits to be sold on voluntary markets (Gass 2012). Additionally, to recover high-value phosphorus for fertilizer from ash following combustion (Hermann 2011). Use of the nutrient-rich harvested biomass adds value to harvesting cattails for nutrient capture, and provides a “Lake Friendly” feedstock for bioenergy production (Lake Friendly 2013). This study will diversify the portfolio of sustainable renewable biomass feedstocks and introduce a new commercial feedstock for cellulosic ethanol production to help meet demands created by Canada’s Renewable Fuel Standard (Government of Canada 2010). This research will also demonstrate environmental benefits of biomass bioenergy to restore sensitive ecosystems, while improving water quality and recycling nutrients for agricultural fertilizer.

This chapter examines biomass and energy characteristics, densification, and subsequent combustion for heat production to displace the use of coal and fossil fuels for space heating and air emissions reductions.

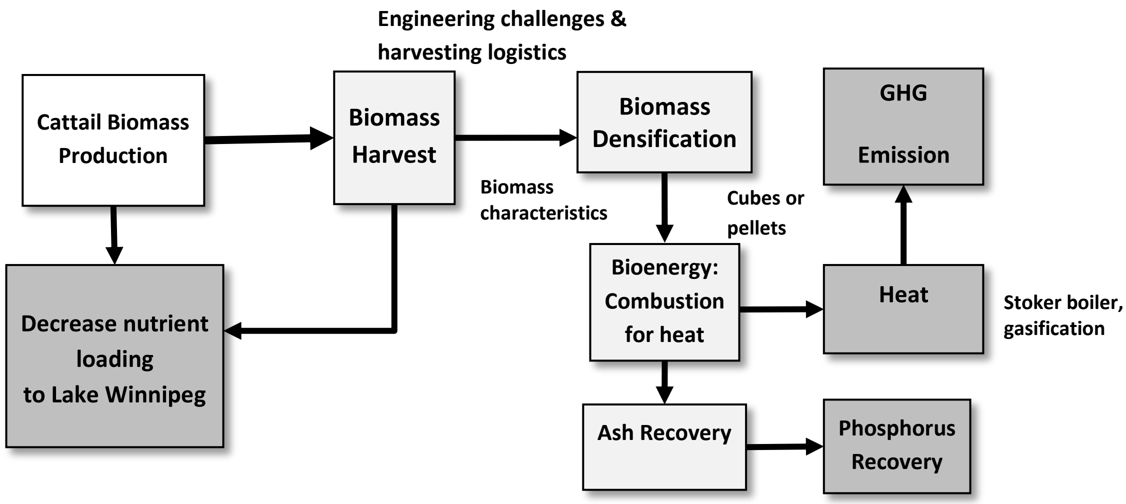


Figure 5.1. Cattail biomass harvesting – closing the nutrient cycle by intercepting and removing nutrients in harvested biomass, utilizing biomass for bioenergy production, GHG credits from displacement of fossil fuel use, and phosphorus recovery from ash.

5.2 Methods

Methods follow those described in Chapter 2 to analyze cattail biomass and energy properties. Densification into fuel pellets and cubes was evaluated for reduction of volume, storage, and transportation as a standard fuel source in distributed biomass bioenergy systems. Methods were developed to produce ¼" diameter pellets and 1" fuel cubes. Pellets included testing of steam processing and a binding agent for agglomeration of cattail particles. Average pellet durability was compared to typical wood pellets. Pellets were ignited in a combustion chamber simulating conditions of a typical wood pellet stove, and cubes and bales were combusted in commercial scale bioenergy systems. Cattail biomass was analyzed for calorific value and ash. Ash remaining after combustion was analyzed for phosphorus and nitrogen by digestion using the HACH (2009) digesdahl sulphuric acid method for both lab and field trial produced ash, to determine potential phosphorus recovery. Greenhouse gas mitigation and carbon offset potential was determined on the basis of coal displacement using cattail as a solid fuel for heating, and carbon emissions calculations (IPCC emission factor 2010).

5.3 Results

5.3.1. Cattail biomass accumulation

Above and belowground biomass accumulation of cattail was measured over four growing seasons 2006-2009 (Chapter 4). Measuring biomass dry weight (DM) determines periods of peak growth and can assess impacts of seasonal harvesting on regrowth and long-term survival (Figure 5.2). Peak biomass accumulation occurred between mid to late August with average biomass yields in 2006 of 12 to 16 dry metric tonnes per hectare (T DM/ha), and up to 25 to 29 T DM/ha in 2007. As a potential biomass feedstock, average yield over four years with varying growing conditions (Chapter 4) was 16.9 ± 1.7 T DM/ha (N=96). Moisture content is highest during initial growth at 80 to 90% reducing to 75% near peak biomass accumulation in mid-August harvest period (Figure 5.3).

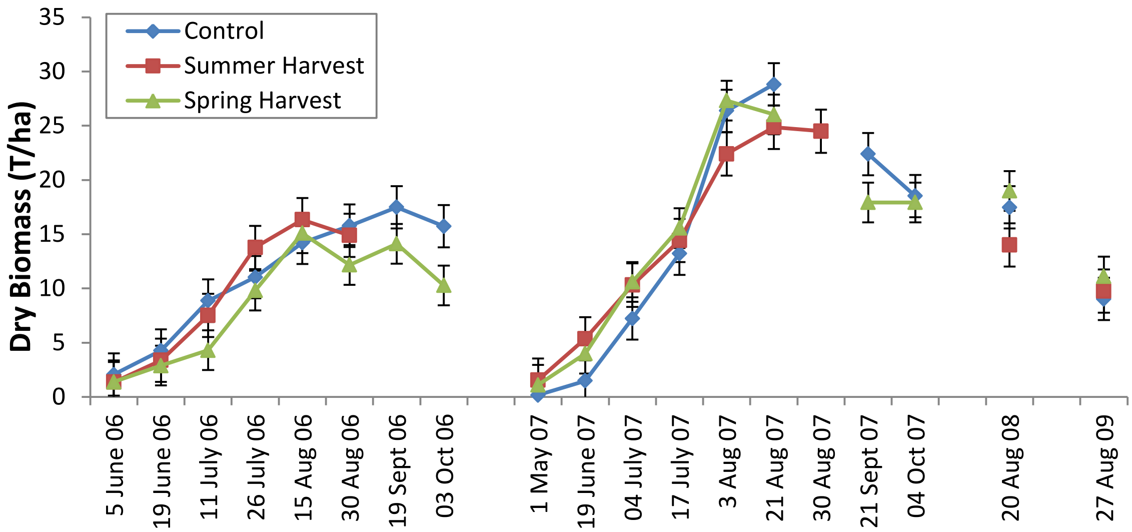


Figure 5.2 Cattail biomass accumulations (T DM/ha) over four growing seasons (2006-2009). Research plots are identified: Control, Summer Harvest, Spring Harvest.

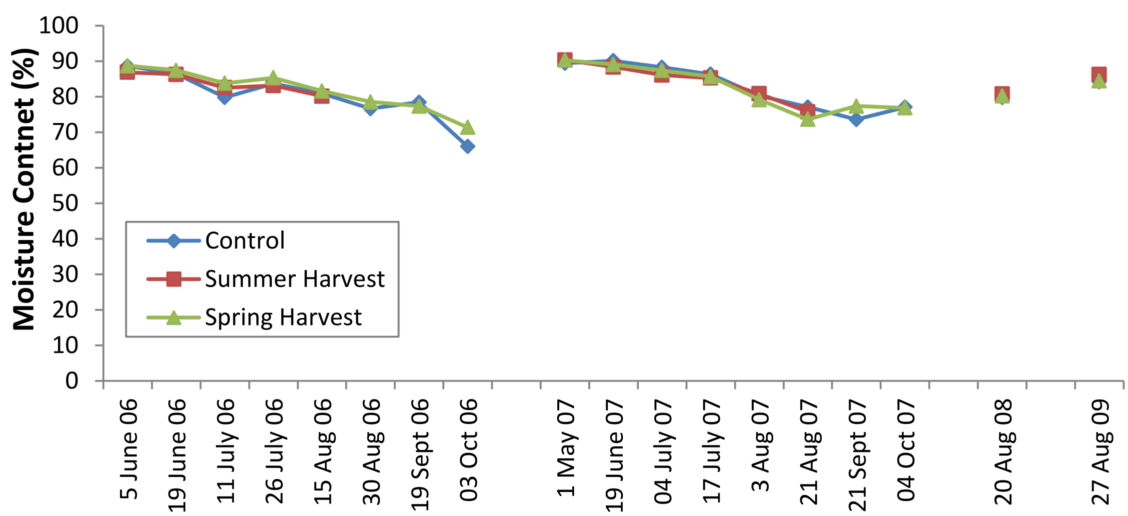


Figure 5.3 Moisture content (%) over four growing seasons (2006-2009). Research plots are identified: Control, Summer Harvest, Spring Harvest.

5.3.2 Cattail biomass harvesting – research scale

As part of this research study a low-impact wetland harvester was designed and constructed in 2007 and its ability to cut cattail tested in various marsh conditions. The purpose was to demonstrate harvesting on soft wetland soils with minimal impact. It was used to harvest several metric tonnes at two different times of the year (spring and summer) to evaluate seasonal harvesting conditions. The harvester was built as an independent cutting unit on a small trailer that could be pulled behind an ATV such as an Argo (Figure 5.4). The harvester consisted of a 2 m Enoagricola Rossi BF-180 double blade sickle bar mower with hydraulic lift. It was modified to remove all PTO attachments and excess weight. It was powered by a Honda 20 hp V-twin engine, which ran a custom built hydraulic power unit used to lower and raise the sickle bar, power the cutting blade, and raise and lower the back tires to adjust cutting height of the trailer. The harvester worked well cutting dense cattail stands in any seasonal conditions and moisture content of the cattail plants – spring dead or summer green - with no loss of power and only occasional jamming of the cutting blades with dense litter. Cutting speed and efficiency was high, laying down a 2 m wide 60 m long swath of cattail in about 5 minutes.

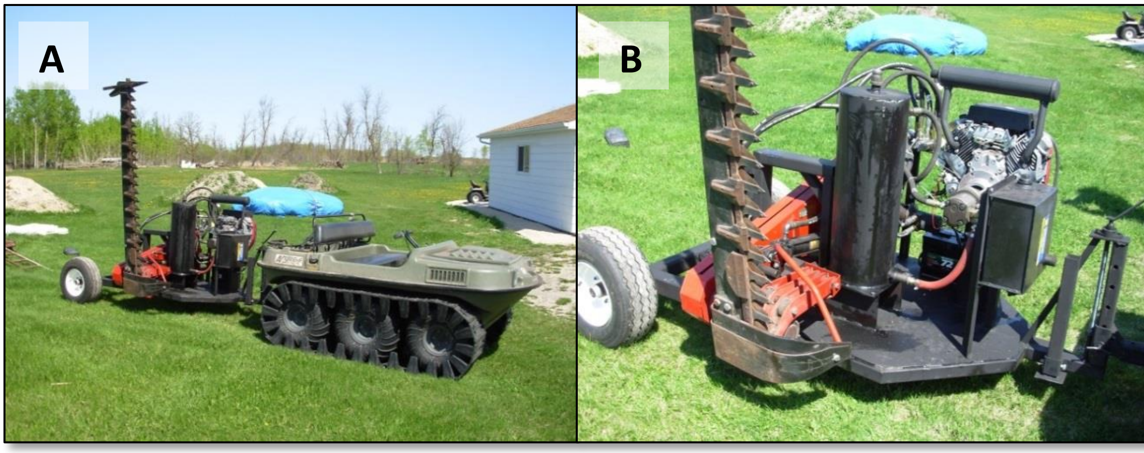


Figure 5.4 A) Wetland harvester pulled behind an Argo tracked all-terrain vehicle. B) Hydraulic power unit on trailer.

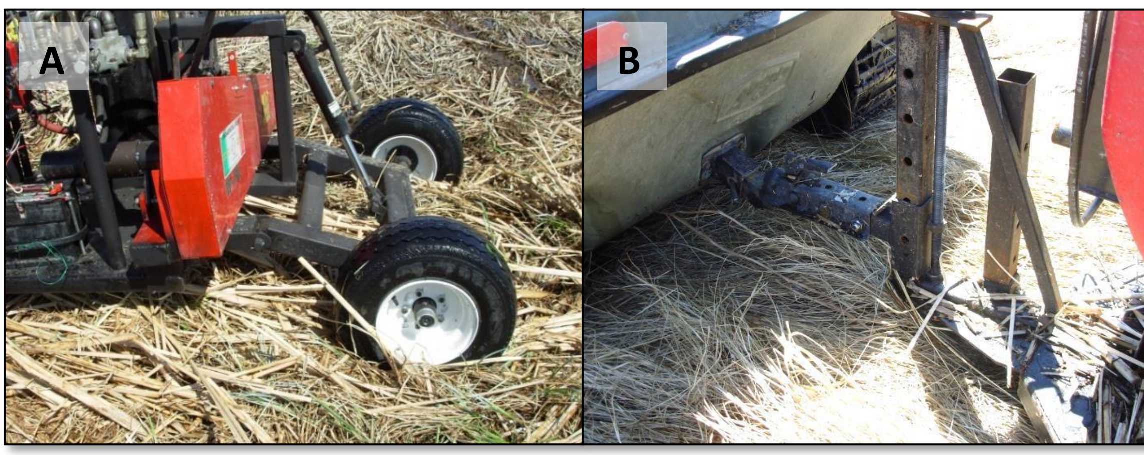


Figure 5.5 A) Harvester and tracked Argo caused only slight compaction of the litter and debris, but it rebounded quickly and left no permanent ruts. B) The front heavy design of the harvester weighed down the back of the Argo causing the adjustable hitch on the trailer to collect debris.

The weight of the harvester trailer was of some concern at over 200 kg, and was greater than originally designed. The design with wheels at the rear of the harvester put excess strain on the hitch of the Argo. It also weighed down the back of the Argo pressing it into the soft wetland surface. The adjustable hitch on the trailer often dug into the litter catching and collected debris which needed to be cleared. Impact on the wetland surface was very minimal with slight compaction to the cattail and organic litter, but no permanent ruts were left (Figure 5.5). The harvester could not traverse flooded conditions. During summer 2007 the 2006 harvest site was almost 2 feet deeper than 2006. A harvest at this site was attempted but the harvester sunk in the soft ground and tipped sideways, so a new summer harvest site was selected nearby.

5.3.3 Cattail biomass yield

Cattail was harvested from these sites over three growing seasons (2006-2008). Early spring harvests of dead dry standing cattail in April 2007, 2008 were manually collected in large 1m x 1m x 1m tote bags for transport (Figure 5.6). Total average cattail harvested in spring from an area of 674 m^2 was 1255 kg or 18.2 T DM/Ha in 2007 and 2008 (Table 5.1). Seven bags were collected in 2007 and nine in 2008 with an average total weight of 135 kg (300 lbs) at 22% moisture content, for a total of 945 kg (737 kg DM) in 2007 and 1200 kg (936 kg DM) in 2008. The cattail could have been baled but because of wet spring conditions it would have had to be moved to higher ground. A crew of 3 people could harvest, collect, and pack 1 tote bag full of cattail per hour. Tote bags were transported to Prairie Bioenergy in La Broquerie, Manitoba (now Biovalco) for processing.

Table 5.1. Cattail biomass characteristics from spring and summer harvests

	Average swath length (m)	Total area harvest (m^2)	Total cattail harvest (kg DM)	Wet weight (kg @ 25%)	Dry weight (kg DM)	Yield (T DM /Ha)	P removal (kg)	(Kg/ha)
Spring (April/May)								
2007	54	648	1237	945	737	19.1	0.61	9.55
2008	54	700	1234	1200	936	18.3	0.62	9.15
Average	**54**	**674**	**1255**	**1080**	**842**	**18.6**	**0.61**	**9.3**
Summer (August)								
2006	n/a	n/a	n/a	500	390	16.3		
2007	50	700	728	820	640	16.3	1.82	41
2008	50	700	770	n/a	n/a	10.4	1.92	26
Average	**50**	**700**	**875**	**820**	**640**	**12.5**		

Summer harvest of live green cattail in August 2006 harvested approximately 900 kg (2100 lbs) wet weight, and average 500 kg @ 25% moisture after drying (Table 5.1). The weather in 2006 was hot and sunny and cattail dried within 4 days, whereas wet conditions in 2007 required 3 weeks for drying. Due to flooded conditions the 2006 site could not be accessed in 2007, and a new site was selected 60m east. Cattail at this site was harvested August 2007 and 2008. Average 1184 kg (2610 lbs) wet weight was harvested from summer harvests, an area of approximately 700 m^2, a total of 875 kg DM at 12.5 T DM/Ha. Green cut cattail was manually loaded on trailers after harvest, moved to higher ground and spread in swaths to dry to moisture content of 22 to 25%. Swaths were baled by a local farmer using a round baler (Figure 5.6) for two bales each year with an estimated weight of 410 kg (903 lbs) at 22 to 25% moisture. Based on nutrient content from Chapter 4 (average P content of 0.1% to 0.3% total cattail biomass) average 0.5 kg (1 lb.) of phosphorus was removed in each bale of cattail.

Figure 5.6. Spring harvest of dry cattail. A) Harvester, B) manually collected using custom cattail rakes, and C), D), and E) manually stuffed into large tote bags.

Figure 5.7. A) Summer harvest of live green cattail. B) Cattail was manually moved on trailers to higher ground and raked into swaths for drying. C) Swaths were baled using a round baler and stored ready for transport for processing.

5.3.4 Impacts to cattail community

Regrowth in large spring harvest plots indicates denser populations of cattail in years following harvest and removal of deadfall, compared to unharvested plots (Figure 5.8) (P = 0.0005). This is attributed to removal of deadfall, which delays appearance of new cattail shoots in the spring, and decreases available light and space for new growth (Chapter 4). As in the experimental plots, harvesting opened areas to new plant growth. In the large harvest plots, average cattail biomass yields for summer site was 12.5 T/ha, and spring site 18.6 T/ha (Table 5.1). On average biomass yield decreased per square meter than the previous year's growth for unharvested sites. Spring and summer harvest sites also showed some signs of decreased biomass yields, but was not statistically significant. Removal of dead material resulted in more plants per m^2, but not a lot of increase in biomass (Figure 5.9). This could be attributed to the harvested sites had greater number of thinner, less robust cattails responding to the opened conditions and not greater numbers of large plants with high biomass. This was particularly evident in the spring harvest sites where water levels were lower.

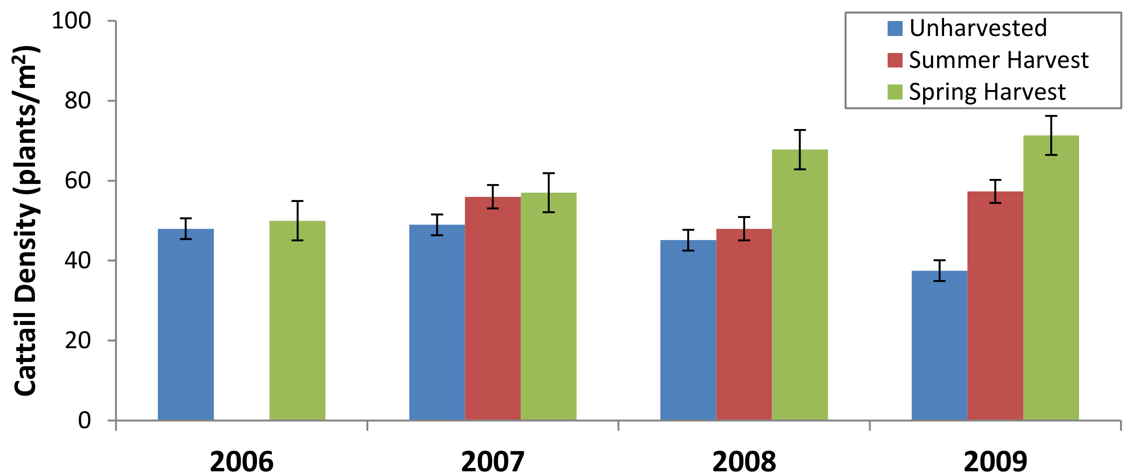


Figure 5.8. Cattail density in number of plants per square meter (plants/m^2) in harvested and unharvested sites (N = 6 per treatment each year)

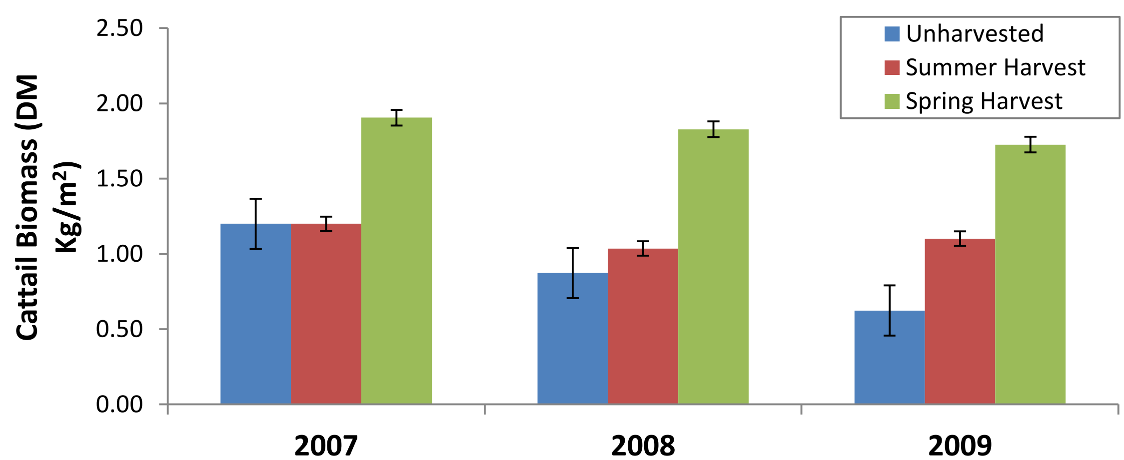


Figure 5.9. Cattail biomass dry weight (DM) in kilograms per square meter (Kg DM/m^2) in harvested and unharvested sites (N = 6 each treatment each year).

5.3.5 Biomass characteristics and comparisons

Cattail biomass had high yields and high growth rate reaching maturity in less than 90 days (Table 5.2). Cattail biomass yields averaged from the experimental study sites (Chapter 4) and the large harvest sites over four years shows an average cattail yield from Netley-Libau Marsh of 12 to 20 T DM/ha within a single growing season (n=192). Typical moisture left in biomass after drying was 6 to 15 % DM. Average ash content was 6 % of dry matter, from lab results and samples sent for analysis.

Table 5.2. Cattail biomass general characteristics.

Characteristic	Average
Biomass yield (dry metric tonnes)	14 - 20 T DM/ha
Moisture content green (%)	75 %
Moisture (% of dry matter)	6 - 15 %
Carbon (% of dry matter)	38.8 - 43 %
Calorific Value	17.1 – 19.2
Ash content (% of dry matter)	5.5 - 7.5 %
Ash fusion temperature (F)	2513 F
Phosphorus capture (kg/ha)	20 – 60 kg/ha

Similar to other biomass crops, cattail has lower carbon content (38.8 to 43.6 %) than higher value coal such as anthracite or bituminous but similar carbon content to lignite coal (40.1 %). Sulphur content in cattail is significantly lower in comparison to coal

(Table 5.3). Using biomass in place of coal reduces not only carbon but sulphur emissions. Inorganic elements such as silica (Si), potassium (K), sodium (Na), sulphur (S), chlorine (Cl), phosphorus (P), calcium (Ca), magnesium (Mg), and iron (Fe) are often associated with fouling and slagging. Elements such as Si, Ca, K, P, and Mg also directly influence the amount of ash produced, therefore higher concentrations in the biomass feedstock result in greater ash content (Table 5.4). With comparison to wheat straw as an agricultural residue, phosphorus content is much higher in cattail, while other fouling elements such as chlorine, magnesium, iron, and silica are lower on average in the cattail samples compared to wheat straw samples (Table 5.4).

Table 5.3. Elemental analysis (ultimate analysis) of cattail biomass with comparison to wood, straw, and coal presented as a % of total biomass (DM) (source: CBT 1998)

Biomass	**Carbon (%)**	**Hydrogen (%)**	**Nitrogen (%)**	**Sulphur (%)**	**Oxygen (%)**
Cattail	38.8 - 43.6	5.61 – 5.96	0.71 - 0.98	0.14 - 0.30	35 - 43.3
Wood	47.6 - 52.6	4.91 – 6.1	0 - 0.35	0 - 0.1	31 - 43
Straw	39 - 42	4.48 - 5.1	0.38 - 1.08	0.12 - 0.14	33.0 - 37.5
Coal (*Anthracite*)	80		0.90	0.70	
Coal (*Bituminous*)	52.5 - 81.7		1 - 1.5	1 - 1.5	
Coal (*Lignite*)	40.1		0.70	1	
Natural Gas	75	24	0.9	0	0.9

Straw has much higher silica content, which contributes to lower ash fusion temperature (Table 5.4). When ash fuses at a lower temperature, it will cause clinker formations or build-up within the biomass combustion system. Straw contains up to twice the amount of chlorides which will cause corrosion within the systems. Cattails have on average lower concentrations of metals than wheat straw (Table 5.5)

Table 5.4. Cattail biomass – inorganics associated with fouling and slagging in bioenergy systems (% dry matter).

Inorganics (% dry matter)	**Cattail (%)**	**Wheat straw (%)**
Phosphorus	0.05 - 0.33	0.018 – 0.025
Phosphorus in ash (post combustion)	2.0 – 3.0	-
Nitrogen	0.7 - 0.98	0.38 – 1.08
Potassium	0.7 - 1.7	0.7
Sodium	0.52	
Chlorine	0.18	0.25
Calcium	0.63 - 1.67	2.6
Magnesium	0.38 - 0.74	0.87
Manganese	0.033 - 0.11	0.033
Iron	1.56	1.93
Silica	0.11	4 - 8
Aluminum	0.90	1.16

Table 5.5 Metals strong acid digestion of cattail biomass compared to wheat straw biomass presented as an average % of dry matter (DM) as reported by Bodycote Labs/Central Testing from samples collected in 2007 to 2008.

Metals Strong Acid Digestion	Cattail (% of DM)	Wheat Straw (% of DM)
Antimony	0.00002	0.00002
Arsenic	0.00063	0.00092
Barium	0.0214	0.0292
Beryllium	0.00005	0.00006
Bismuth	0.00005	0.00005
Cadmium	0.000024	0.000022
Chromium	0.00144	0.00184
Cobalt	0.00075	0.00087
Copper	0.0012	0.0016
Lead	0.0008	0.00099
Molybdenum	0.0001	0.0001
Nickel	0.00191	0.00212
Selenium	0.00007	0.00006
Silver	0.00001	0.00001
Strontium	0.0048	0.0097
Thallium	0.00002	0.000025
Tin	0.0001	0.0001
Titanium	0.0222	0.0259
Vanadium	0.00284	0.00361
Zinc	0.0051	0.007

5.3.6 Cattail biomass densification – Fuel Pellets

Cattail biomass was successfully densified into ¼" fuel pellets, similar in size and property to wood fuel pellets found in local hardware stores for pellet stoves (Figure 5.10). Cattail pellets were produced and tested by Alberta Tech Futures and compared to traditional industry standard wood pellets (Table 5.6). This size was chosen because of their existing market value internationally for power-generation, and locally in domestic pellet stoves for space heating. Multiple pelletization trials were evaluated to determine appropriate conditioning of ground cattail and methods that produced the best results. Pellets were monitored for visual defects and amount of fines produced.

Pelletization trials consisted of blending water with the ground cattail to create batches of material with various moisture contents. These batches (approximately 500 grams per batch) were run through the pellet press separately and pellets produced from batches compared qualitatively. Moisture content of approximately 17% (w.b.) was ideal. The addition of steam supplied at a pressure of 15 psi and 105º C to the feedstock was used on some trials. Steam is normally used in commercial scale operations to assist with pelletization by loosening feedstock's fibres and softening of the lignin and will increase moisture content of the feedstock. The addition of steam did not improve the quality of cattail pellets. Once suitable moisture content was determined a corn starch binding agent was tested for its potential to increase durability and crush strength of the pellets. The binder used was: National 1215, Unmodified Corn Starch, National Starch and Chemical Co. Bridgewater N.J. USA. Corn starch binder was added at a rate of 1%

based on dry mass of the feedstock. Quantitative testing was conducted on pellets with best qualitative results. Standard wood pellets used for comparison were: ¼” spruce wood produced by Vanderwell Contractors Ltd. in Slave Lake, AB.

Figure 5.10. A) Pellet press used for pellet creation and analysis B) one of many batches of densified cattail pellets manufactured by Alberta Tech Futures.

Densification and durability properties of pellets were excellent with no additional binding agent needed, and heating value requirements exceeded those of major wood pellet standards associations (Table 5.6). Cattail pellet durability was high at > 95%, but lower than durability of typical wood pellets due to scale of lab equipment. Commercial scale pellet mills will have much greater compression and produce a denser more durable pellet. Crush strength resistance of cattail pellets was significantly higher than that of wood pellets which may be an indicator that cattail pellets can exceed wood pellets in durability if made in a commercial scale pellet mill (Table 5.6).

Table 5.6 Cattail pellet crush strength and durability comparison to wood pellets.

Average	Cattail Pellets (no Binder)	Cattail Pellets (Starch Binder)	Wood Pellet Standard
Crush Strength (Radial)	46.3 ft-lb (205.8 N)	62.9 ft-lb (279.7 N)	28.3 ft-lb (125.7 N)
Crush Strength (Axial)	56.6 ft-lb (251.7 N)	43.3 ft-lb (192.6 N)	33.1 ft-lb (147.1 N)
Durability (%)	95.2	96.27	98.53
Bulk density	40 lb-ft3	40 lb-ft3	40 lb-ft3

Proximate analysis of cattail pellets and biomass determined heating value (calorific value), moisture content, fixed carbon, volatiles content, and ash (Table 5.7). Pellets produced with 1% starch had lower heating value than pellets with no binder added (Table 5.8). This suggests starch binder, which contains higher sugar content than cattail biomass, lowered overall heat value. Table 5.8 shows both gross and net heating values. Net is typically used as attainable heating value when combusted in a standard furnace. Gross heating value accounts for water in exhaust leaving as vapour, and includes liquid water in fuel prior to combustion. This value is important for wood or coal, which will usually contain some amount of water prior to burning. Average cattail heating value exceeded the requirements of major wood pellet standards associations (Table 5.8).

Table 5.7. Proximate analysis (% dry basis) of cattail prior to densification and of produced fuel pellets.

Biomass	**Moisture content (%)**	**Volatile Components (%)**	**Fixed Carbon (%)**	**Ash Content (%)**
Cattail biomass	6.44	65.79 ± 1.1	22.71 ± 6.2	5.8 ± 0.9
Cattail pellet (no binder)	n/a	64.52 ± 0.11	28.94 ± 0.14	6.54 ± 0.03
Cattail pellet (starch binder)	n/a	68.54 ± 0.69	25.25 ± 0.74	6.21 ± 0.05

Table 5.8. Average heating value of cattail pellets, comparing no binder and addition of starch binding agent (± std error) and ash content to pellet standards.

Average	**Heating Value (dry basis) Gross**		**Heating Value (dry basis) Net**		**Ash Content**
	MJ/kg	BTU/lb	MJ/kg	BTU/lb	%
Cattail Pellets (no binder)	21.18 ± 0.14	9108 ± 59	19.89 ± 0.15	8552 ± 66	6.54 ± 0.03
Cattail Pellets (starch binder)	18.10 ± 0.03	7779 ± 12	16.80 ± 0.03	7224 ± 12	6.21 ± 0.05

Wood pellet (Austria standard) [a]	-	-	> 18.0 MJ/kg	> 7738.2	< 0.5
Wood pellet (Sweden standard) [a]	-	-	> 16.9 MJ/kg	> 7265.31	< 0.7
Wood Pellet (Fuel Institute standard) [a]	-	-	> 17.2 MJ/kg	> 7394.28	< 3

5.3.7 Cattail biomass densification – Fuel Cubes

Prairie Bio Energy (now BioValco) provided the technical assistance and pilot-scale capacity for densification of dry cattail biomass into fuel cubes in June 2009. Mixed cattail/marsh grass cubes in a 1:1 ratio were created to simulate a typical wetland edge, storm water retention, or ditch wetland harvest, and to supply sufficient biomass material for a complete commercial scale simulation run. Average bulk density for the compressed cattail/mixed marsh grass cubes was 25 lbs per cubic ft. (400 kg per cubic m), comparable to compressed straw cubes of 28 lbs per cubic ft. Pre-processing and shredding of cattail had minor issues with regards to the dense and fibrous nature of cattail, but a standard bale shredder reduced the material to 2 cm to 6 cm long pieces. This material flowed well through the feed system and modified hammermill to produce over 2200 kg of 1” cattail fuel cubes within a 3 to 4 hour processing time (Figure 5.11). Cattail biomass flowed and densified into 1” cubes similar to agricultural straw cubes manufactured at that time. No binding agent or steam was added to the process, only heat and pressure. Moisture content of raw shredded biomass was approximately 22%.

Figure 5.11. Cattail fuel cube production. A) Shredded cattail using bale shredder, B) modified hammermill, C) cattail/mixed marsh grass 1 inch x 1 inch fuel cubes being produced, D) cubes after packaging step ready for use in stoker boiler burners.

5.3.8 Cattail Bioenergy - Commercial-Scale Burn Trials

Two bioenergy technologies were examined for combustion, which are in commercial use in Manitoba. Cattail biomass was burned as 1) densified fuel cubes in a stoker boiler typically used to burn coal for distributed hot water heat on a Hutterite Colony (Blue Flame Stoker 2012) and 2) round bales in a two-stage gasification system used for distributed hot water heat for industrial use (Innovaat 2012).

5.3.8.1 Thermal Conversion (Stoker Boiler) - Cattail Fuel Cube Burn Trials

Densified cattail cubes were burned in a Blue Flame Stoker biomass stoker boiler (Blue Flame Stoker 2012) November 2009, at the Sturgeon Creek Hutterite Colony north of Headingly, Manitoba (Figure 5.12), which is in continual operation for the heating of pig barns and the colony kitchen unit. Prior to cattail cube combustion the burner was run at capacity with coal and steady-state conditions were firmly established. Approximately 255 kg of cattail cubes were fed through the screw auger feed system and burned over a 1 ½ to 2 hour period, producing 4750 MJ (4.5 million BTUs) of heat energy, compared to 5 million BTUs of heat energy normally produced by coal (Table 5.9). Emissions were recorded with a handheld tester and were similar to those recorded for wheat straw with CO 50 to 125 ppm and CO_2 12 to 20 %, with no visible particulates or dark smoke. The Blue Flame Stoker boiler systems produce little smoke, and emit very low levels of particulate matter emissions, which remained the same with the cattail biomass combustion.

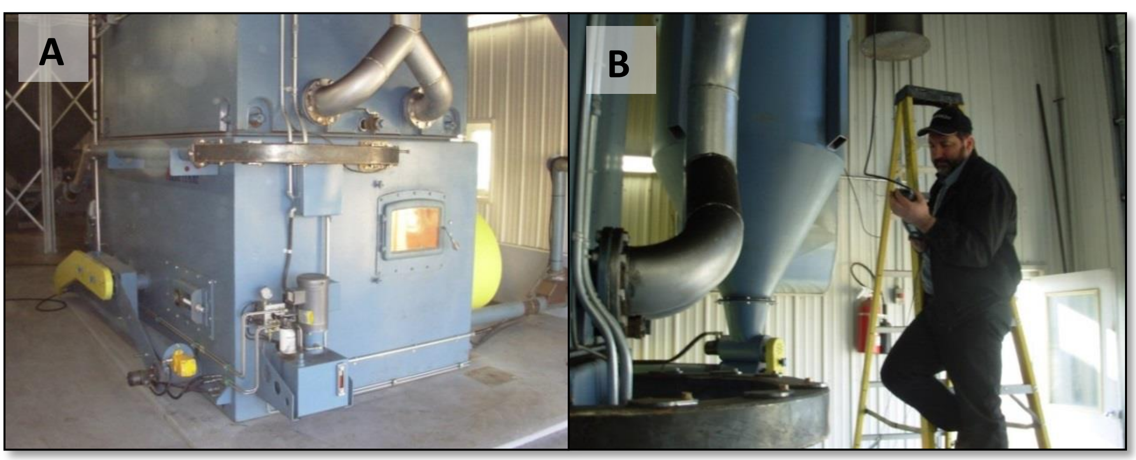


Figure 5.12. A) Blue Flame Stoker burner at the Sturgeon Creek Hutterite Colony burning densified cattail cubes; B) emission testing during cattail cube burn.

Table 5.9. Cattail/mixed marsh grass fuel cube burn trial in Blue Flame Stoker (2012), November 2009, on the Sturgeon Creek Hutterite Colony.

Stoker burn trial	**Average**
Cattail/grass cubes burned	255 kg
Phosphorous content (calculated)	434 g
Calorific value (average)	17.5 MJ per kg
Heat produced	4,463 MJ (4,230,120 BTUs)
Burn time	1.5 to 2 hours
CO emissions	125 ppm
CO_2 emissions	12 %
Ash content (average)	10 %
Ash produced (calculated)	25 kg
Total phosphorus recovered in ash	382 g (88%)

5.3.8.2 Thermochemical conversion (Gasification) - Cattail Bale Burn Trials

Cattail bales were burned in the Biomass Energy System Technologies Inc. (BEST) two-stage combustion updraft, atmospheric pressure gasification system to evaluate use of baled cattail as a solid fuel and for GHG emission reductions (Innovaat 2013). Baled cattail was transported to Vidir Machines in Arborg, Manitoba, with a commercially installed BEST system which combusts straw or corn stover bales to provide heat in their manufacturing facility (Innovaat 2013). During burn trials in 2006 and 2007 cattail biomass was fed manually because the auto bale feeder and shredder was not fully installed until 2008 (Figure 5.13). To ensure sustained operation of the two-stage combustor, wheat straw was burned for several hours to allow for stabilization before feeding the cattail. Summer harvested cattail bales with 30% moisture did not perform well in the gasifier until a constant temperature of 1900 C was maintained with straw bales for an hour prior to adding cattail biomass. Winter harvested cattail from 2005 of 100 kg with 14% moisture content performed very well on a separate burn trial in the BEST unit. In 2006, approximately 550 kg of cattail was combusted to produce 3165 MJ (3 million BTUs) of heat energy, producing approximately 30 kg of ash (Table 5.10).

Figure 5.13. Gasification of cattails (2006). A) Bale shredding and B) feeding cattail biomass feedstock into gasifier unit for heat production.

The BEST system has three areas where ash was collected during gasification: primary chamber, secondary chamber, and cyclone collector. Final fate of phosphorus during gasification of cattail was determined by analyzing ash. Exhaust gases leave through a cooling tower before they are exhausted into the atmosphere. The cooling tower is equipped with two sample ports located near the top of the tower, and are used to extract gas samples and collect airborne ash and particulate matter. Emissions were measured as part of separate studies to model the gasifier performance (Balcha 2010). Ash samples taken from the primary chamber differed in appearance from samples from the secondary chamber. Pieces of burned or charred feed could still be seen in ash from the primary chamber. Ash in the secondary chamber was found in hard clumps. Ash collected by the cyclone differed greatly in appearance from residual ash in the other two chambers. It was fine and powdery in appearance and weighed significantly less. Phosphorus was found in all three chambers suggesting the cyclone is removing fly ash particles and phosphorus (Table 5.11).

Table 5.10. Cattail bale burn trial in BiomassBest gasification system 2006.

Stoker burn trial	**Average**
Cattail bales burned	550 kg
Calorific value (average)	18.2 MJ per kg
Heat produced	3165 MJ (3,000,000 BTUs)
Burn time	3 to 4 hours
Ash content (average)	5.47 %
Ash produced (calculated)	30 kg

Table 5.11. Cattail ash analysis from BiomassBest gasification system burn trial.

Biomass	Location	% SiO2	% P2O5
Wheat Straw	Primary	22.14	0.65
	Secondary	58.54	2.27
	Tertiary (cyclone)	42.6	1.05
Cattail	Primary	57.96	1.85
	Secondary	62.26	1.62
	Tertiary (cyclone)	42.08	0.95

5.3.9 Phosphorus Recovery following combustion

Results from ash from burn trials in the lab of pellets and cubes (burned at 550 C for 1 hour), and ash collected from commercial burn trials in the Blue Flame Stoker boiler and BiomassBest gasification system, indicates cattail ash had phosphorus contents from 1.64 to 2.28 percent of total biomass (%), while mixed cattail/grass cube ash had much lower phosphorus 0.52 to 0.73 % (Table 5.13). Up to 89 % of the phosphorus contained in the biomass was retained in the ash. The remaining amount could be lost in emissions, or bound to residuals left following digestion since samples contained black residue following digestion. The lower % of phosphorus content in the fuel cubes is likely due to mixing of cattail with mixed marsh grasses (i.e. sedges), which have lower phosphorus content. Ash content of the cubes at 10% was also much higher than cattail which is 6 %, likely due to higher ash content of marsh grasses. Ash content of 6-10% is considered high for use in pellet stoves when compared to standard wood pellets, but is lower on average in comparison to agricultural residues, and much lower than coal - typical fuel for use in biomass burners. Most modern biomass burners are designed to handle high ash feedstocks better than typical pellet stoves. Recovery of the phosphorus closes the loop – from harvesting and nutrient capture of watershed nutrients, to bioenergy and recovery of phosphorus for fertilizer.

Table 5.12. Phosphorus recovery in ash following combustion of cattail biomass.

Biomass samples	P contained in Biomass (%)	P contained in Ash (%)	P Recovered in Ash (%)
cattail pellet lab analysis Ash	0.18	2.28	89.2 ± 0.2
cattail cube lab analysis Ash	0.059	0.73	85.7 ± 2.8
cattail cube burn trial Ash sample #1 (Sturgeon creek Blue Flame Stoker)	0.059	0.52	86.5 ± 1.0
cattail cube burn trial Ash sample # 2 (Sturgeon creek Blue Flame Stoker)	0.059	0.58	88.0 ± 1.1
Cattail bale burn trial (BiomassBest gasification system)	0.18	1.64	70.3 ± 13.6

5.4 Discussion

5.4.1 Cattail (*Typha* spp.) for Bioenergy and Carbon displacement

Cattail (*Typha* spp.) was found to be a viable biomass feedstock for bioenergy and biomaterials, with exceptional energy, densification, and biomaterial properties. Cattail fuel cubes successfully displaced coal as a solid fuel to produce heat energy in a farm-scale application, generating CO_2 offsets from reduced carbon emissions. Average cattail biomass yields in all the Neltey-Libau Marsh research sites over the four year period was 12 to 20 T DM/ha within a single growing season from multiple experimental and harvest sites (N = 192). Densification tests show cattail biomass can be compressed into pellets and cubes for use in a variety of biomass burners. Calorific heat value was comparable to commercial wood pellets at 17 to 20 MJ/Kg, and comparable to typical agricultural feedstocks and lignite coal (Table 5.13). Cattail had excellent densification and combustion properties, and although ash content is higher than typical wood pellets at over 6%, it is similar to corn stover and lower than other agricultural straw (Table 5.13). For use in pellet stoves, mixing or co-feeding of cattail pellets is recommended because of the ash content, but would not be an issue in energy conversion technologies (i.e. stoker boilers or gasifiers) designed to handle higher ash (Blue Flame Stoker 2012, Innovaat 2013). Combustion trials indicate cattails are a suitable low-carbon low-emission feedstock for use in a variety of bioenergy technologies to replace carbon emitting fossil fuels. No major concerns were identified regarding combustion emissions and analysed ash.

Table 5.13. Energy value of cattail biomass and densified cattail fuel pellets, with comparison to standard wood pellets and other common biomass feedstocks and fuel sources (sources: [a]Pami 1995, [c]Blue Flame Stoker 2012, [d]Cicek et al. 2006)

Biomass	Calorific Value		Ash Content
	MJ/kg	BTU /lb	(%)
Cattail	17.12 to 19.5	7360	5.8 to 6.5
Cattail [d]	18.23	7837	
Cattail pellet (no binder)	19.89	8551	6.54
Cattail pellet (starch binder)	16.80	7223	6.21
Wood pellet (standards) [a]	16.9 - 18.0	7266 - 7739	< 0.5 - 3
Wood (15 % mc) [b]	15.0 to 22.3	7309	0.65 to 1.52
Wood chips	10.4	4471	0.6 to 1.5
Wheat Straw (dry) [b]	17.86	7678	3.5
Wheat Straw (20 % mc) [b]	13.74	5907	4
Flax Straw (dry) [b]	19.97	8586	-
Flax Straw (20 % mc) [b]	15.43	6634	-
Corn stover [c]	17.6	7567	5.58
Miscanthus	19	8169	2 - 3
Switchgrass	18	7739	3 - 5
Sunflower hulls [c]	19.7	8469	2.86
Propane [b]	46.37	19936	0
Natural Gas	48	20636	0
Fuel Oil [b]	37	15907	-
Coal - anthracite	30 to 35	12898 to 15047	10.5
- Bituminous	20.9 to 33.4	8985 to 14360	6 to 12
- lignite [b]	10 to 20	4300 to 6800	6 to 19

Cattail fuel cubes were successfully used on a commercial scale burn trial to displace coal in a Blue Flame Stoker solid fuel stoker boiler (Blue Flame Stoker 2012) used for heating on the Sturgeon Creek Hutterite Colony, in Manitoba. Ash was recovered post-combustion, and up to 88% of the original phosphorus captured in the harvested biomass was recovered in the ash as calculated from analysis in the lab. This reduces carbon emissions replacing a carbon emitting fuel source (coal) and closes the nutrient cycle in this process by removing phosphorus from the Lake Winnipeg watershed, where it can be recovered and reused for fertilizer (Figure 5.14).

By combining alternative biopower production with nutrient capture and removal, with additional GHG mitigation potential, multiple environmental and economic benefits can be realized. Harvesting this novel ecological biomass feedstock is capturing nutrients and reducing nutrient loads on Lake Winnipeg. The potential to refine cattail biomass into high-value end products such as biochemicals, bio plastics and third-generation biofuels deserves further research and evaluation.

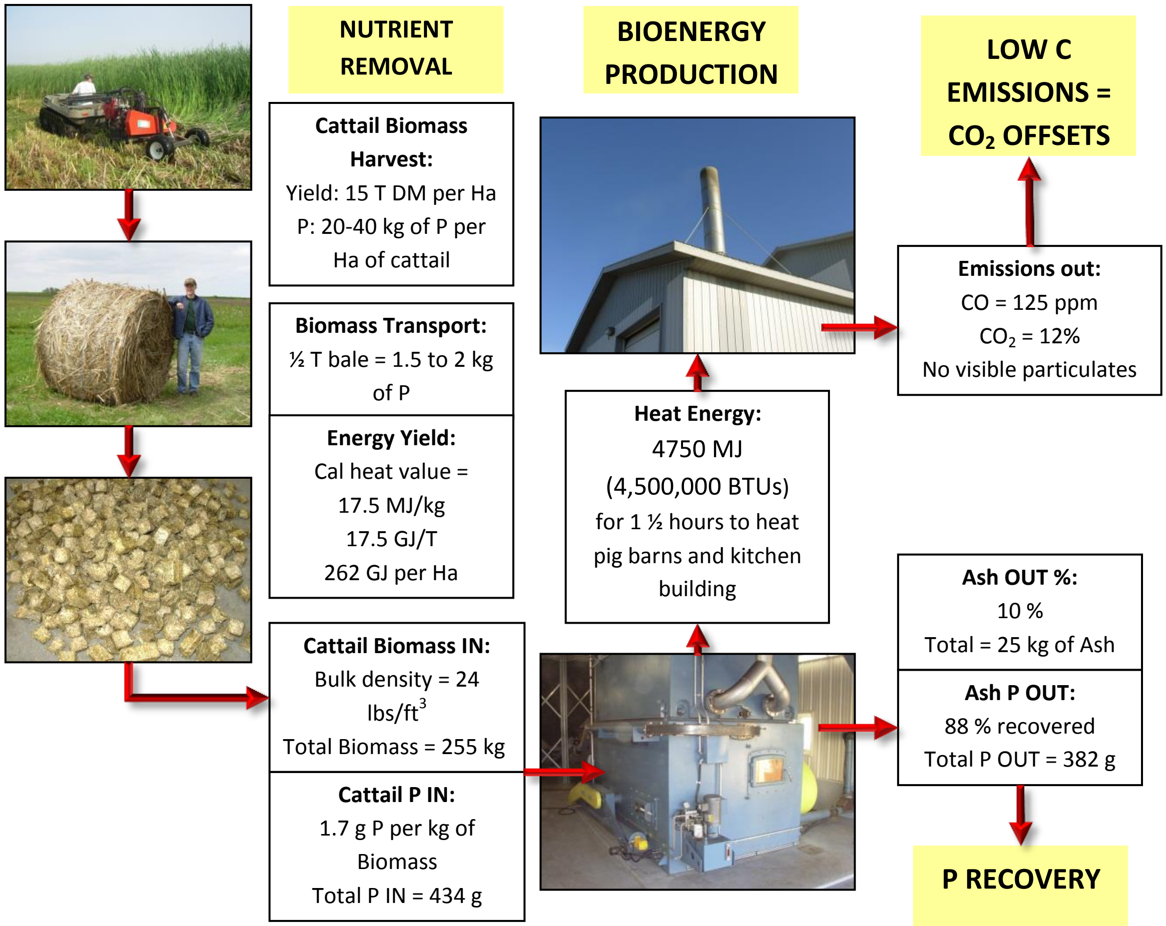


Figure 5.14. Life cycle of cattail biomass from harvesting for phosphorus capture, transport, densification, displacing coal for heat, phosphorus recovery in ash.

5.4.2 Cattail seasonal growth and nutrient accumulation

In Netley-Libau Marsh, cattail peak growth and biomass accumulation occurred during middle to late August when cattail communities contained the highest biomass (dry matter), similar for cattails in the mid-US (Dubbe et al. 1988, Smith et al. 1988). Understanding seasonal growth profiles is essential if harvesting for multiple uses, such as nutrient capture (Chapter 4) or biomaterials. Research on fibre and building structure properties of cattail, for example, indicates a late winter or spring harvest of naturally dried material improves anti-fungal and fibre properties (Fraunhofer 2012). In Europe, *Phragmites* reeds are harvested as late as possible in the winter to allow for freeze-thawing and breakdown and loss of fouling elements (Bakker and Elberson 2005, Fraunhofer 2012). Similarly reeds are harvested in Japan for water quality improvement, and are harvested at maximum nutrient content regardless of moisture or long term impacts to plant community (Asaeda et al. 2006). In Manitoba, biomass is a mechanism for capturing nutrients and reducing nutrient loading to Lake Winnipeg, therefore a compromise is necessary for nutrient capture, wildlife use, and bioenergy.

Cattails are a highly valued plant species for bioremediation and nutrient capture (Lakshman, 1979; Kadlec & Knight, 1996), which is a significant additional benefit and revenue as a novel ecological biomass, as opposed to only harvesting for bioenergy or biomaterials. Evidently, cattails growing in nutrient rich water also lead to greater growth and higher biomass yields, so combining nutrient capture with harvesting for biomass may in fact increase biomass yields (Woo and Zedler 2000, Wyss 2004). Its ability to grow in flooded areas and on marginal agricultural land is a significant advantage compared to other biomass feedstocks, and provides a harvestable product and revenue for a landowner from otherwise unproductive land without competing for crops as a food product (Evans 2008). Cattail is common in storm water drainage ditches and water retention ponds (VanRaes 2012), which are often required by municipalities to be maintained and mowed for drainage (Grosshans and Grieger 2013).

5.4.3 Cattail biomass and energy yields

Cattail biomass is comparable to other grass type biomass sources with high yields and high growth rate, and reaches maturity in less than 90 days (Figure 5.15). Yields are much higher than traditional biomass feedstocks, which aids in increasing harvesting efficiency and reducing harvesting time and transportation. Yields up to 30 T/ha were possible, particularly when cattail communities were dominated by more of the larger robust cattails and less of the shorter narrow cattail. This could be due to cattail species or varieties of the hybrid (*Typha glauca*), which can produce considerably more biomass (Tuchman et al. 2009, Angeloni et al. 2006).

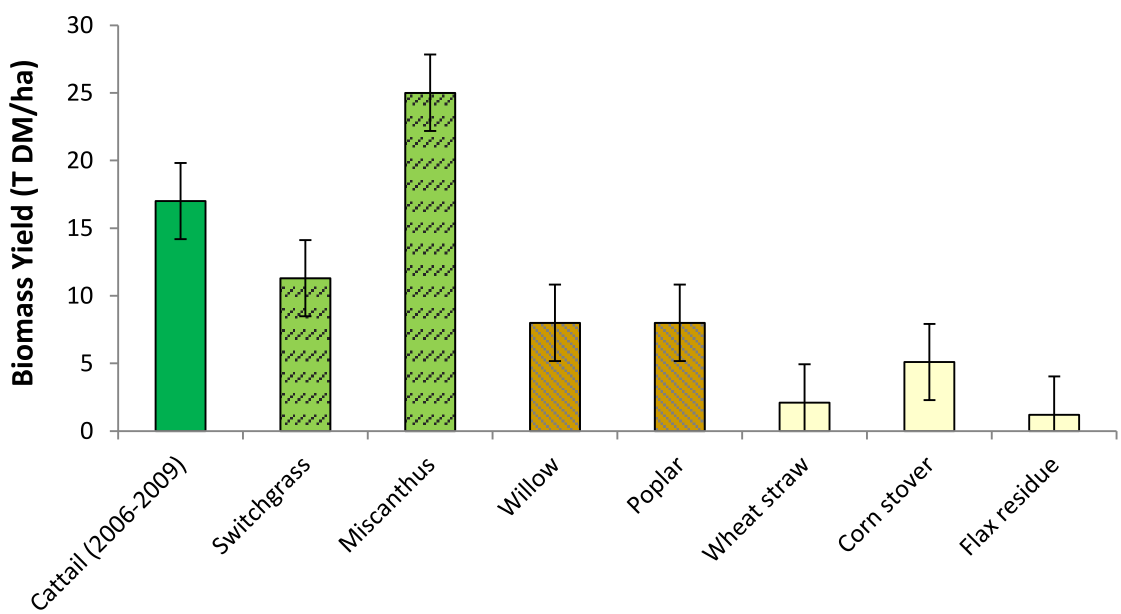


Figure 5.15. Cattail biomass characteristics - Average biomass yield (T DM/ha) of cattail compared to other biomass feedstocks.

Switchgrass and miscanthus as energy crops have attracted attention with lower ash content, good growth characteristics, and can be baled and densified (Levelton Engineering 2000, Pyter et al. 2008, Garland 2008). Unlike cattail, switchgrass and miscanthus take 3 to 5 years to reach yield maturity, while cattail does in 90 days each growing season. Switchgrass was evaluated in Manitoba by Manitoba Agriculture, Food and Rural Initiatives with yields of 1.6 to 8.7 T/ha (Government of Manitoba 2013). Agricultural residues (i.e. wheat straw, corn stover) reach maturity in less than 90 days, but as residues their yields are lower per area (Stewart and Brown 2001). Agricultural residues have high volumes, ease of availability, and ease of collection as part of an established agricultural industry. They have excellent energy properties (Larson 1997, Blue Flame Stoker 2012), but they do not have the nutrient capture and water quality characteristic as cattail (Heard and Hay 2006). Woody species (i.e. poplars and willows) have much lower ash content than crop residues, grasses, and cattail, and consistent high yields, but require much longer times to reach maturity although they can be harvested much sooner sacrificing overall yields (Samson and Chen 1995). Willows and poplars also share the same nutrient absorbing trait as cattail, used for waste water treatment and remediation of contaminated soils (Kadlec and Knight 1996, Vymazal 2006, Perttu 1993), and can considered as ecological biomass feedstocks.

Research by the International Institute for Sustainable Development (IISD) has revealed up to 14 million tonnes (mT) of potential biomass is available annually from the southern agricultural regions of Manitoba, which includes provisions for maintaining soil quality by leaving a proportion of agricultural residue in the field. Up to half of this biomass is from wetlands and waterlogged areas - not including additional biomass from restored wetlands and water retention projects. This could assist to completely displace coal for space heating in Manitoba, Canada (IISD unpublished).

Using heating values from Table 5.13 and assuming average yields from Figure 5.15, average potential energy yield of cattail (GJ/ha) is significantly higher than many other biomass feedstocks at under 300 GJ per ha (Figure 5.16). Miscanthus has been reported with very high yields per given area, but does not grow well in northern climates (Zub and Brancourt-Hulmel (2010).

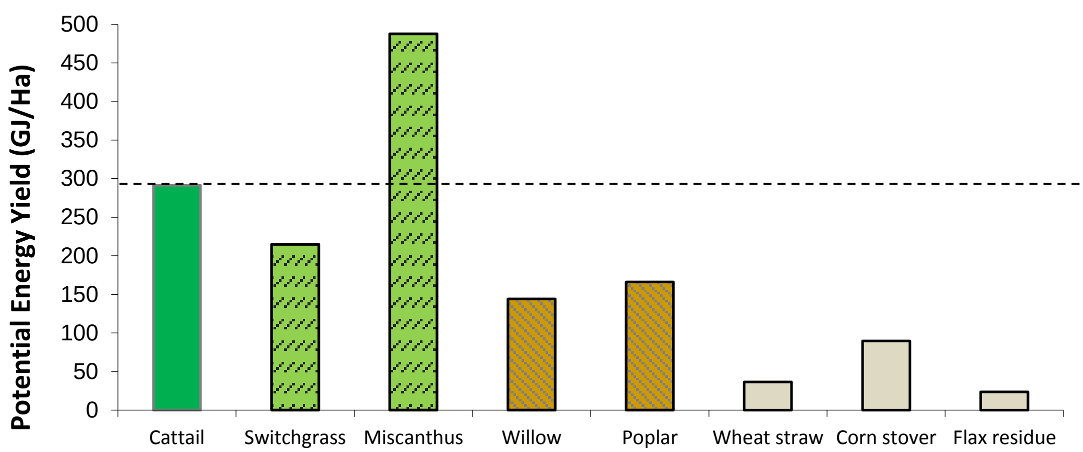


Figure 5.16. Average Potential energy yields of cattail biomass compared to traditional biomass sources – assuming average biomass yields per hectare (Figure 5.15), and average calorific values (Table 5.13).

5.4.4 Cattail Biomass Processing and Densification

5.4.4.1 Baling cattail biomass

Cattail was easily baled utilizing traditional round baling agricultural equipment. The operator indicated he simply had to reduce his speed for baling to allow the denser material to be picked up (Greening pers. comm. 2007). Bales produced were very densely packed, with good long-term storage longevity stored over multiple seasons until processing. Additional mixed bales of cattail/grass stored outside at the cubing plant since 2009 are still in fairly good shape with less breakdown of cattail compared to grass (S. Gauthier pers comm. 2013). A recent study by IISD and PAMI evaluated the commercial scale harvesting of cattail with traditional agricultural equipment, utilizing a MacDon Industries windrower. (Grosshans and Greiger 2013). Round balers worked well to collect material from 5 foot wide swaths, while large square balers worked better in areas with less material. Dense round bales were much more difficult to transport while square bales were recommended for transport (Grosshans and Greiger 2013).

5.4.4.2 Cattail biomass densification

Densification of cattail biomass into fuel pellets produced an economically viable standard solid fuel that can be integrated into available markets in North America and Europe. Pellets are easily stored and transported, and are a universal solid fuel with a well-established market for fuel pellets in Europe (Schaps 2013). Based on current market conditions, biomass is traded in European markets in the form of ¼” pellets for use in large scale energy production and distributed heating plants (Dong Energy 2013).

Dong Energy burns approx. 600,000 t/yr of wood pellets and 500,000 t/yr of straw in its Danish power plants (Dong Energy 2013). The multi-fuel Avedøre Power Station on the outskirts of Copenhagen ranks among the best in the world with a total capacity of the two units approximately 810 MW electricity and 915 MJ/s heat to supply 200,000 households. Domestically within Manitoba, Canada, a large part of buyers prefer loose biomass material or in the form of larger fuel cubes for use in smaller scale stoker boiler systems for distributed steam or hot water heating. Demand is primarily for industrial, localized residential, or academic institutions (B. Duggan pers. comm. 2012).

5.4.5 Cattail Biomass Properties

5.4.5.1 Bulk Density

Coal bulk density is 600 kg/m^3 for brown coal to 900 kg/m^3 for bituminous coals (Statistics Canada 2008), while loose agricultural residues have much lower densities from 50-122 kg/m^3. Densification to pellets and cubes provides a uniform combustion and reduction in particulate emissions. Higher bulk densities decrease transportation and storage costs associated with biomass feedstock and increases rate of combustion (Tampier et al. 2004). Cattail fuel bulk density was comparable for compressed straw pellets and cubes and slightly lower as pellets than standard wood pellets (Figure 5.17), but exceeded minimum acceptable bulk densities of 250 kg/m^3 or 16 lbs/ft^3 (PAMI 1995).

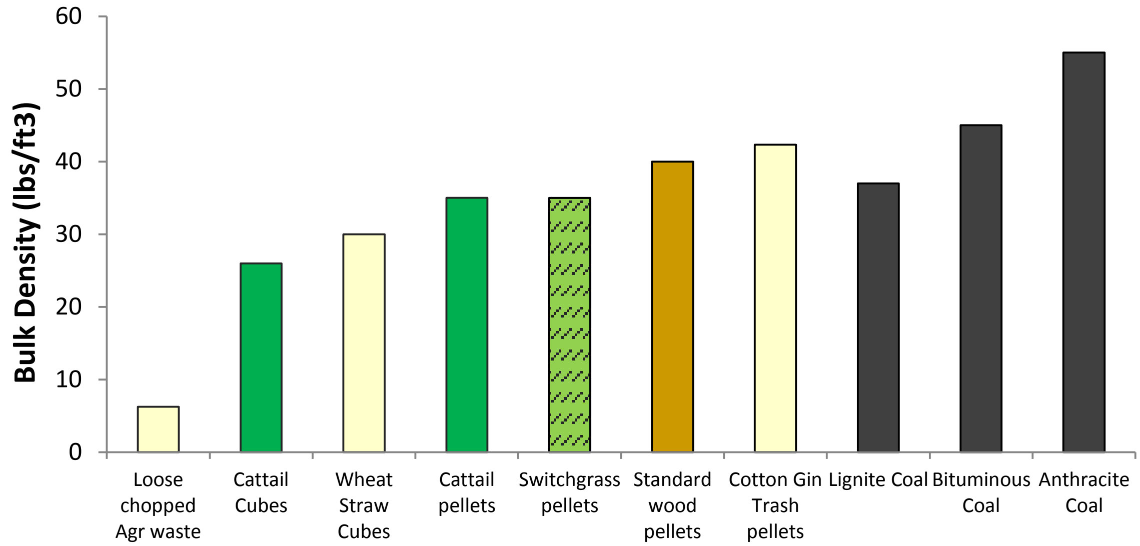


Figure 5.17 Bulk density comparisons of cattail biomass and densified fuel products with other biomass fuel products and coal.

5.4.5.2 Ash Content

Ash content in any biomass fuel can affect feedstock performance as a solid fuel, and is highly dependent on the bioenergy technology (MAFRI 2012). Cattail has higher ash than wood (5 to 6% compared to 0.5 to 3%), but less than agricultural residues (7 to 10 %) (Figure 5.18). Higher ash could cause issues in pellet stoves designed for low ash wood pellets. Higher ash lowers the efficiency of the combustion system, increases maintenance, cost and amount of ash disposal required, and will result in clinkers (fused ash) forming in combustion. Co-firing cattail pellets with lower ash pellets, or mixed pellets with lower ash feedstocks is best (Ba et al. 2009, Bakker and Elbersen 2005). Bioenergy technologies designed to handle higher ash feedstocks such as agricultural waste and coal will handle cattail with fewer issues. Blue Flame Stoker boilers are designed to handle loose raw biomass and reduce formation of large clinkers and fouling so higher ash cattail would not be as significant an issue (Blue Flame Stoker 2012). Biomass Best gasification units are also designed to handle higher ash trapping silica and allowing for removal in collection chambers (Innovaat 2013). Since biomass with higher ash can also create higher particulate emissions upon combustion, emission control is essential, particularly if the goal is to capture and remove nutrients.

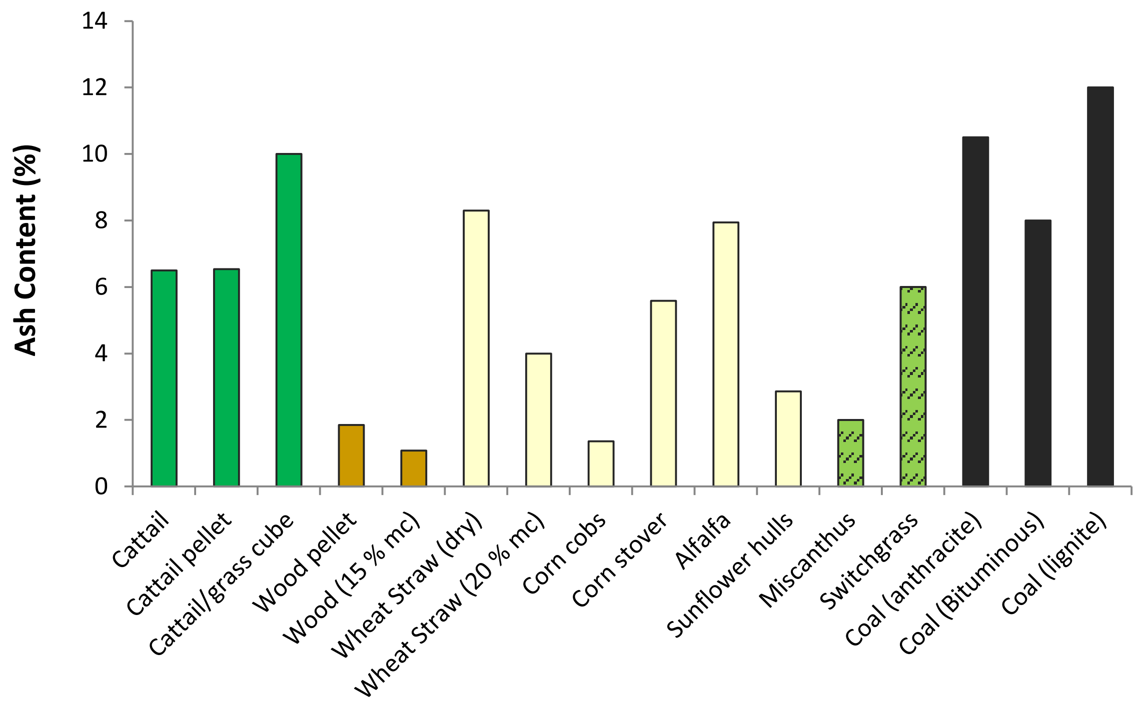


Figure 5.18. Cattail biomass characteristics - Average cattail ash content compared to other biomass feedstocks and fuel products (sources: CBT 1998, Pami 1995, Blue Flame Stoker 2012)

5.4.5.3 Inorganic Content

Inorganic content of ash influences melting point and subsequently the combustion process. They also influence the nature of particulate and gaseous emissions and are important factors for determining how ash is disposed (Bakker and Elbersen 2005). Inorganics affect combustion by forming deposits on furnace surfaces (slagging) and in heat-recovery sections of combustors (fouling) and can reduce heat transfer rates. Ash with higher concentrations in potassium oxide (K_2O) and silica will have lower melting points, leading to problems such as bed agglomeration, fouling, scaling, and corrosion of surfaces. Cattail has moderate levels of these inorganics, with higher levels of phosphorus, potassium, and silica. Agricultural residues as biomass fuels cause inefficiencies in biomass combustion systems (Blue Flame Stoker 2012), predominantly in systems with a fixed grate (e.g., Decker), typically fusion of ash causing clinker formations or build-up within the biomass combustion system. Cattail has much lower silica than straw (Table 5.4), and less than half the amount of chlorides, which causes corrosion within systems. Cattails could reduce average silica and chlorides in agricultural biomass for a cleaner fuel source. Previous studies investigating the path of heavy metals have shown most remain in ash following combustion and not released in emissions (Hasselriis 1992, Hermann 2011). This was found for phosphorus in cattail ash following combustion. Fuel based NO_X is released in emissions when a fuel with high concentrations of nitrogen, such as cattail, is combusted with high concentrations of oxygen, therefore combustion technologies that minimize formation are needed.

5.4.5.4 Moisture Content

Moisture content in biomass feedstocks can affect densification as well as combustion, depending on bioenergy technology. Moisture content in oven dried ground cattail material was found to be too dry for pelleting at 6% moisture, and water and steam up to 17% needed to be added to produce fuel pellets. Cattail fuel cubes were produced with air dried shredded material, with moisture content near 25%, and was suitable for cubing. High moisture content delays ignition and increases retention time of volatile matter within combustion systems. Moisture also reduces furnace temperature and decreases efficiency of the combustion system creating higher particulates and emissions (Tampier et al. 2004). Cattail green moisture content is quite high at over 70%, but rapidly dried to less than 25% when laid in swaths. Sufficient drying time or pre-drying is necessary following harvest. Although modern bioenergy technologies can handle feedstocks up to 25% moisture content or higher (Blue Flame Stoker 2012) (dry basis), efficiencies and heat production are reduced. This occurred in the BiomassBest unit with higher moisture cattail from 2007, requiring pre-burning with dry straw to reach a steady state high temperature before adding cattail. Recommended moisture content of biomass fuels is less than 15 - 20% (dry basis) (Tampier et al. 2004).

5.4.6 Cattail Bioenergy

As early as the 1970s, the U.S. Department of Energy (Pratt et al., 1984) and the Saskatchewan Research Council (Lakshman, 1984) evaluated cattails as a biomass feedstock for alternative bioenergy, and it was concluded cattail was an excellent biomass feedstock suitable for bioenergy production. Calorific heating values were similar to this study (17.1 to 19.5 MJ/kg), with Pratt et al. (1988) reporting 17.6 to 18.9 MJ/kg, and yields up to 10 T DM/ha. Similarly Lakshman (1984) reported energy values of lab cultivated and natural cattail as 19.1 MJ/kg. Pratt et al. (1984, 1988) and Dubbe et al. (1988) evaluated the harvesting of cattail from natural and planted and fertilized stands for use as a bioenergy feedstock, and also planted and harvested cattail for treatment of wastewater from sugar beet production. But the economics of harvesting or cultivating cattails solely for bioenergy was not considered viable at that time (Pratt et al. 1984, 1988 Dubbe et al. 1988), nor was the economics of traditional agricultural equipment (W. Johnson per com 2012). As the oil crisis in the 1970s ended, the interest in alternative biomass energy from cattail ended, as well as the funding to pursue further research (W. Johnson pers. comm. 2012). The difficulties encountered with harvesting in a wet environment were deemed too costly to use cattail as a planted energy crop, and in addition it was determined cattail used very high amounts of water and nutrients for a cultivated bioenergy crop and had to be fertilized to maintain productivity (Pratt et al. 1984, 1988, Dubbe et al. 1988, Garver et al. 1988).

In this current study, by considering modern bioenergy technologies, advancements in agricultural equipment, and current policies to reduce global carbon emissions and reduce nutrient loading in aquatic systems, harvesting cattail biomass today is significantly more economically viable (W. Johnson pers. com 2012). By also considering environmental and economic co-benefits beyond heat production, and accounting for additional value of nutrient capture, wildlife habitat (Tuchman et al. 2009, Swedarsky et al. 2012), carbon emission offsets (Gass 2012), and potential water quality trading (Selman et al. 2009) the benefits of harvesting cattails are significant (Figure 5.19) (Cicek, et al. 2006; Grosshans et al., 2011). The multifunctional wetland system in Switzerland was a cost-efficient alternative to conventional stormwater retention systems built to intercept storm water, which also provides important environmental services (Wyss 2004). In addition to flood protection and stormwater retention, it provides water treatment and wildlife habitat, and harvesting provided a low CO_2 fuel (as pellets or in pyrolysis), and product for clay construction practitioners (Wyss 2004).

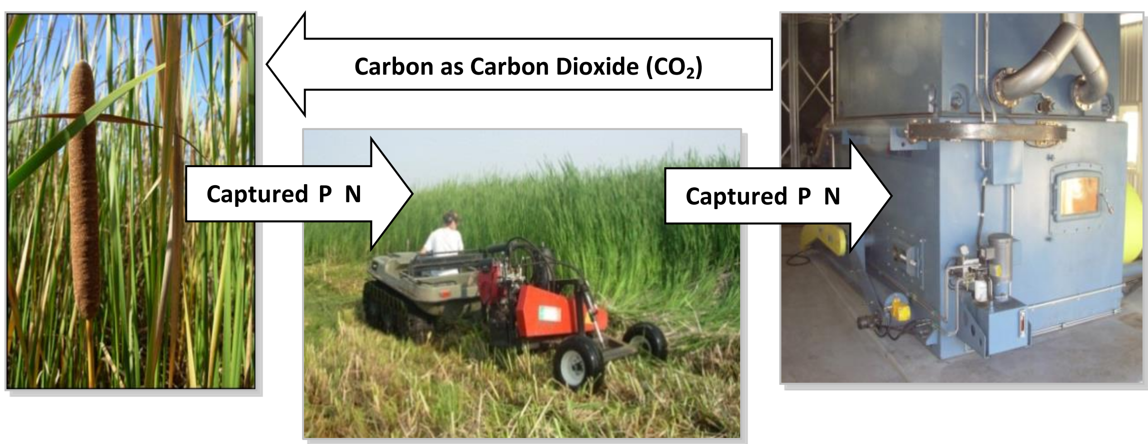


Figure 5.19. Utilizing cattail as a novel low-carbon biomass feedstock for bioenergy has its greatest economic feasibility if evaluated for its multiple co-benefits.

5.4.7 Cattail Biomass Conversion – Low and High Value End-Uses

This study demonstrated thermal and biochemical conversion of cattail biomass for simple heat energy production, to address current markets and demands. Nevertheless, there are much higher value end uses of the harvested cattail biomass including biochar and third-generation biofuels (Figure 5.19). In the case of Manitoba, phosphorus is the primary element of concern in the eutrophication of Lake Winnipeg and is also a potential higher value secondary by-product if recovered. Technologies that leave higher percentage of phosphorus in the ash, or reduce flue gas temperature so it can be effectively removed and not redistributed back into the system are important (Cicek et al 2006).

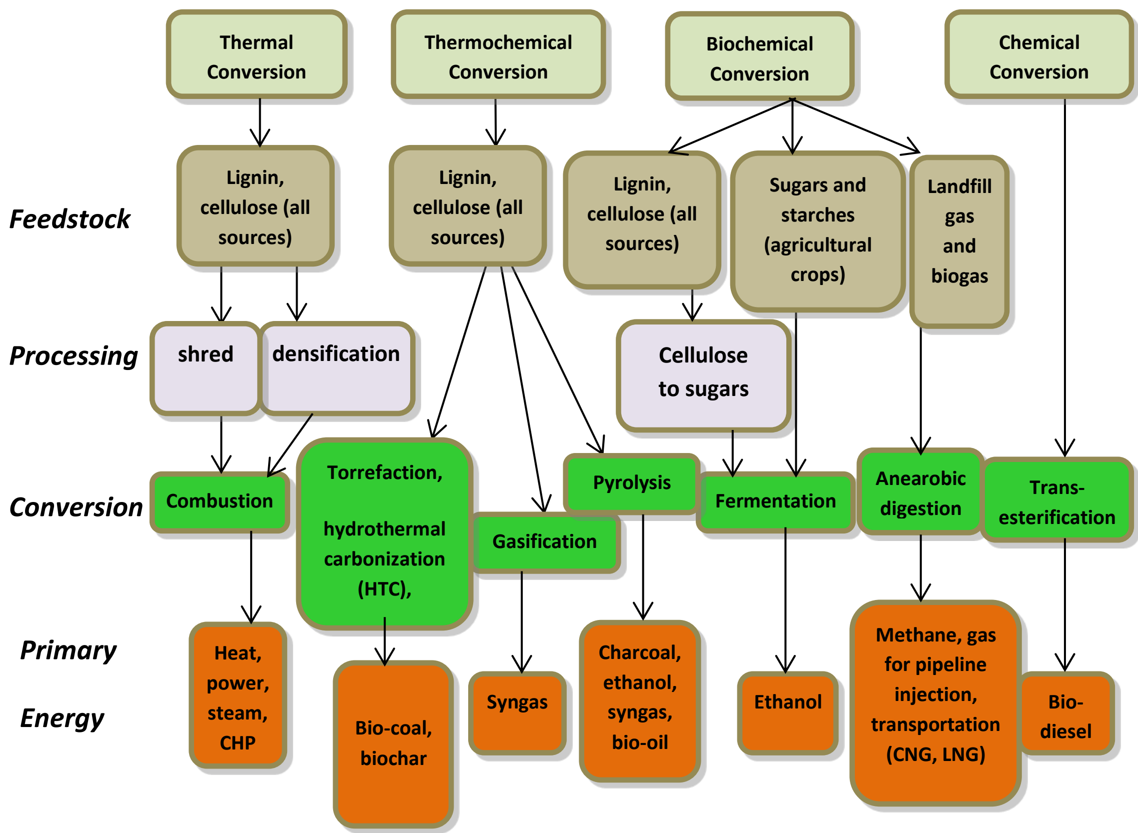


Figure 5.20. Several conversion pathways and end-uses of cattail biomass can be identified (combined heat and power [CHP], compressed natural gas [CNG], liquefied natural gas [LNG])

5.4.7.1 Combustion for space heating - Thermal Conversion

The Blue Flame Stoker used in this study is an example of a thermal conversion or solid fuel stoker boiler system that is suitable for cattail biomass, designed for efficient combustion of a wide variety of loose and densified feedstocks while maintaining low emissions (Blue Flame Stoker 2012). Operating temperature is around 400 °C, which minimizes clinker formation in ash and formation of glass. The chain grate system is designed for efficient burning of higher ash feedstocks such as agricultural residues and cattail and the multi-cyclone dust collector removes smallest dust particles or fly-ash, up to 90% generated from solid fuel combustion, with emissions comparable to natural gas (Blue Flame Stoker 2012, Gototalenergy 2011). Several industrial applications in Manitoba have converted from coal or natural gas to burn biomass to meet their primary energy needs for heating, at Vanderveens Greenhouses in Carman, Pineland Nurseries near Hadashville, Providence College south of Winnipeg, and several Hutterite colonies with considerable heat demands (Sturgeon Creek Colony 2009), all of which could consider cattail as a co-fed or primary biomass.

5.4.7.2 Gasification - Biochemical Conversion and Combined Heat and Power (CHP)

Gasification converts organic plant biomass into a combustible synthetic gas, or syngas that is much more efficient to burn than direct burning of the original biomass (Rezaiyan and Cheremisinoff 2005). At temperatures above 1000 °C biomass is heated in an oxygen-deficient atmosphere to promote the release of volatile gases: i.e. carbon dioxide, carbon monoxide, hydrogen and methane. Hot gases produced in the primary chamber are transported to the secondary chamber and oxygen or air is injected to ignite produced gases. The heated flue gas from the secondary chamber transfers heat to water surrounding tubes and the hot water is used for space heating. High temperature combustion of the biomass and burning of syngas instead of the original biomass leaves behind chemicals and nutrients in the ash and slag resulting in cleaner emissions and gas production (Rezaiyan and Cheremisinoff 2005), and potential for recovery of nutrients from the ash. Agricultural biomass and cattail can cause issues from silica and ash with formation of glass. The BiomassBest gasification system used in this study collects silica and potassium debris in a removable tray at the bottom of the secondary combustion chamber as fused chunks, and requires periodic cleaning (Innovaat 2013). In Europe gasification is a reliable and common industrial scale bioenergy technology (Faaij 2004).

Small scale distributed bioenergy systems can be used on-site to convert low moisture biomass feedstock not only into heat but energy or combined heat and power (CHP) Tampier et al. (2004). The syngas produced in gasification for example can be used to run an internal combustion engine to produce electricity in CHP systems (Rezaiyan and Cheremisinoff 2005). Cicek et al. (2006) investigated six small-scale distributed power generation systems with some cogeneration heat applications using cattail biomass based on Tampier et al. (2004). The systems vary in complexity (highest for gasification and organic Rankine cycle), capital cost (highest for organic Rankine cycle and small steam with cogeneration), and operating cost (highest for small steam because of operator requirements) (Table 5.14). For each bioenergy system the conversion efficiencies were calculated assuming that the biomass was sized appropriately by the harvester and did not absorb moisture following harvest. The power and cogeneration heat produced is shown in Table 5.14. Gasification, small steam, and indirect air Brayton cycle do not produce heat in a form that is appropriate for use: no cogeneration heat is credited to these systems. Power produced varies from 1.75 to 4.71 MW and cogeneration heat is produced in the form of steam (115 degrees C) and liquid glycol (80–90 degrees C). Gasification produces the most power followed by the Entropic cycle. Nevertheless, using producer gas from gasification directly in an engine has several technical challenges that have yet to be overcome (i.e. cleaning of producer gas). Cogeneration economics were best for the Entropic and organic Rankine cycles.

Table 5.14. Results of energy conversion technologies (*Source: Cicek et al. 2006*).

	Small condensing steam	**Small steam with cogeneration**	**Organic Rankine cycle**	**Air Brayton cycle**	**Entropic cycle**	**Gasification ***
Heat recovery loss (MW)	8.0	8.0	7.8	12.3	5.3	11.0
Cycle loss (MW)	15.2	16.5	15.3	12.1	7.2	10.5
Power generated (MWe)	3.03	1.75	3.13	1.83	3.68	4.71
Cogeneration heat (MWth)	0.0	15	14.5	0.0	16.4	0.0

** assumes producer gas has heat value of 5.5 MJ/Nm^3 and cooled down to room temperature*

Using assumptions from Cicek et al. (2006), they estimated an average harvest of 51,000 tonnes of cattail biomass collected at 16.6 % moisture content and an average heating value of 18.02 MJ/kg could result in a total estimated heat content of 26.22 MW for dry cattail fuel. Based on yields and energy values from the current study, a large scale harvest of cattail would require 3400 hectares.

5.4.7.3 Biochar - Thermochemical Conversion

Beyond the application as an alternative to fossil coal for energy production, biochar has excellent potential to improve fertility and offer carbon sequestration and storage in agricultural soils (Laird et al. 2010). IISD in partnership with MB Hydro and PAMI is currently evaluating cattail biochar for improving soil conditions for farming, as well as use as a coal replacement (Grosshans and Grieger 2013). The potential to evaluate alternate biomass sources such as cattails and crop residues could offer a means to lower cost for producing biochar from its current high cost of production (Titan Energy 2012). These enhancements are anticipated to more clearly define the options for producing biocarbon in a cost effective manner and identify markets for non-energy grade biocarbon (Laird et al. 2010).

5.4.7.4 Advanced Biofuels Lignin and cellulose - ethanol

The potential to produce ethanol from cattail was investigated previously by the Saskatchewan research council in the late 1970s and early 1980s but was determined to be not economically viable (Lakshman 1984). The rhizomes of the cattail function as the carbohydrate reserves for the plant for wintering and for producing new shoots. Most of the sugars produced in the leaves by photosynthesis are translocated to the rhizomes for starch synthesis. During growth some of the photosynthate is converted into structural carbohydrates in the shoots (Lakshman 1984). Shoots typically contain 30-35% cellulose, similar hemicellulose, and 15% lignin by dry weight (Table 5.15). Rhizomes contain mostly starch and reducing sugars, with varying fractions of cellulose and hemicellulose depending on time of harvest. Cattail also contains comparable fibre and digestible organic matter to alfalfa and straw (Lakshman 1984).

Table 5.15: Starch and Sugars in Cattail (% of dry biomass).

	Starch	**Reducing Sugars (glucose)**	**Glucose & Fructose**	**Total sugars***	**Fermentable Material**
Cattail shoots					
Current study	0.51 to 0.59				
Minnesota	0.1 to 29	-	7 to 12	4 to 16	11 to 37
Cattail Rhizomes					
Saskatchewan	12 to 27	9 to 25	-	-	-
Minnesota	5 to 30	-	4 to 10	6 to 10	25 to 41

** Total sugars is glucose, fructose, and sucrose Source: Pratt et al. 1981, Lakshman 1984*

Starch and sugars from research in the late 1970s shows the sugar and fermentable material in cattail for first-generation biofuels (Table 5.15). More recently cattail has been used to produce ethanol; with harvested cattail biomass yields up to 40 T DM/ha (Suda et al. 2009). With new third generation ethanol technologies there is opportunity to produce ethanol from cellulose and hemi-cellulose (Suda et al. 2009). Research at the University of Manitoba is currently investigating the potential of cattail biomass for the production of advanced biofuels and third generation biofuels i.e. ethanol (Bisong 2012 unpublished data). Cattail samples from the current study yielded lignin of 8.14 to 12.46 % of total dry biomass, appearing to increase from summer content as cattail shoots dried naturally over winter (Table 5.16). Cellulose and hemicellulose content of cattail was 37.46 to 40.00 % and 18.42 to 20.94 % (Bisong 2012 unpub. data).

Table 5.16: Cellulose, hemi-cellulose, lignin, and protein, content of cattail (% of dry biomass August to September).

Biomass	Cellulose	Hemicellulose	Lignin	Crude Protein
Cattail Shoots				
Current study (August)	37.46	20.94	8.14	7.23
Current study (Dec)	40.00	18.42	12.46	5.36
Current study (March)	38.63	20.88	11.76	5.61
Saskatchewan (1979)	20 to 29	24 to 36	15	
Minnesota (1980)	31 to 33	19 to 20	-	
North Carolina (2009)	28.7	23.4	10.1	

Cattail Rhizomes				
Saskatchewan (1979)	10 to 21	-	-	
Minnesota (1980)	22 to 40	-	-	
Wheat straw (2012)	47.60	16.42	15.45	2.44

* Total sugars is glucose, fructose, and sucrose *Source: Lakshman 1984*

5.4.7.5 Phosphorus recovery

Phosphorus is critical for agricultural fertilizer and food production, and recovery of this resource could be a valuable economic revenue addition to the value of the biomass as a raw feedstock (Ulrich et al. 2009). Following combustion, the majority of phosphorus remains in the ash, which can be used as a fertilizer and for soil amendment (Hermann 2011). This is also shown in the literature, which also indicates the majority of phosphorus is retained in ash following burning of biomass to produce bioenergy (Pike 1930). One would then expect the majority of captured phosphorus removed in harvested cattail should remain in the ash. Following combustion ash is typically land applied to crop fields for use as a slow release fertilizer and soil conditioner, but ash can also be processed through thermal (Hermann 2011) or chemical (Petzel 2011) processes to extract valuable phosphorus and other elements. Recovery of phosphorus from the biomass prior to combustion is also possible by nutrient extraction, resulting in a high value liquid fertilizer. The resulting residual biomass product has higher heating values, is cleaner burning, and has much lower ash content with reduced fouling and clinker issues since elements associated with fouling have been extracted (CENNATEK 2013).

The extracted multi-nutrient fertilizer is an additional revenue stream in addition to bioenergy products, and the residual biomass compressed into fuel pellets, torrefied, or used for cellulosic ethanol (CENNATEK 2013).

5.4.8 Harvesting equipment challenges for commercial scale

Harvesting in wetlands presents some serious logistical challenges, particularly if the goal is to minimize ecological impact and maintain sustainability of the marsh plant community. Because of soft wetland soils rich in organic matter typical heavy machinery causes rutting and damage to soil-plant roots. Low-impact wetland harvesters are needed beyond typical modified farm equipment, such as those used in wet-agriculture applications in Europe (De Vries Cornjum 2013, Pisten Bully 2013, LogLogic 2013, Reeda 2013). Tracked harvesters and those with balloon tires developed in Europe for reed harvesting and land management can negotiate soft terrain without sinking with low weight ratios and ground pressure less than 50g/cm^2 (Wichtmann and Tanneberger 2009). Several designs exist for collection of harvested material. Some harvesters chop the plant material into pieces blowing it into an attached hopper or collecting trailer similar to an agricultural forage harvester. Others cut and place them in swaths, which are collected and baled in an attached baler. An essential component of future research will need to demonstrate commercial-scale agricultural equipment for harvesting cattails from wet environments (Wichtmann et al. 2010). Commercial scale harvesting of cattail biomass is currently being explored in Manitoba for nutrient capture and biomass for energy and higher value end products (Grosshans et al. 2012).

6.0 Cattail Economics: Bioenergy and GHG Offsets

6.1 Economics associated with harvesting cattail biomass

6.1.1 Production costs of cattail biomass harvesting

The associated costs of cattail harvesting and bioenergy are identified in this chapter, but further economic and environmental cost-benefit analysis is needed to fully capture the complexity of direct and indirect benefits and costs associated with harvesting for nutrient capture and biomass opportunities.

Production costs associated with the harvest of cattails (i.e. harvest, baling, processing) were estimated based on 2012 custom contracting rates in Manitoba (MAFRI 2013. *Farm Machinery Custom and Rental Rate Guide*) and costs associated with wheat straw production off current production costs guidelines (*MAFRI 2012, Wheat straw biomass production costs*) (Table 6.1). Fertilizer costs for cattail are essentially zero, since no planting or additional fertilizer is required in an already eutrophic environment; therefore fertilizer costs are not included for wheat in comparisons. Estimated Nutrient Value for wheat straw is included, which represents the estimated value of the wheat straw if left on the field reducing necessary fertilizer additions by the producer for the next cropping season, so additional cost incurred for fertilizer application is included (Table 6.1). Cubing and pelleting costs are based on current costs.

Production costs associated with cattail biomass harvesting, utilizing rates from current Manitoba Agricultural Food and Rural Initiatives rates (MAFRI 2012, 2013):

Custom Baling of Cattail

$/tonnes = 0.41 tonnes (900 lbs)/bale x $7.84 per bale

$/hectare = $/tonne x 15 tonnes/hectare cattail

Custom Field moving of Cattail bales

15 tonnes of cattail per hectare / 900 lbs (0.41 tonnes) bale x 2.75 per bale

Average wheat yield is 2.37 tonnes per hectare = cost of $13.44 per hectare

Average cattail yield is 15 tonnes per hectare = cost of $13.44 / 15 T

$/tonnes = 0.41 tonnes (900 lbs)/bale x $2.75 per bale

Custom Hauling

$25 per load, 34 bales per load x 0.41 tonnes = 13.94 tonnes/load, $1.79 per tonne

Based on a 5 mile distance haul and contract cost of $5 per loaded mile

Table 6.1. Production costs associated with cattail harvesting, baling, densification compared to wheat straw, based off MAFRI (2012, 2013). Estimates based on straw yield of 1.4 tons per acre, and cattail yield of 6.70 tons (6.07 tonnes) per acre.

Operating and Fixed Costs	Straw Cost per unit	Wheat straw $/acre	Wheat straw $/tonne	Cattail $/tonne	Cattail $/hectare	Cattail $/acre
Est. Nutrient Value*	N,P,K,S	19.19	19.92	0.00	0.00	0.00
Est. Harvest cost				1.32	19.79	8.01
Custom baling	7.84	18.47	19.16	19.16	287.40	116.31
Custom field moving	2.75/bale	6.48	6.72	6.72	100.80	40.79
Custom Hauling	$5/mile	1.73	1.79	1.79	26.90	10.88
Repairs and maint.	$.30/acre	0.3	0.23	0.23	3.47	1.40
Misc. costs	$2.50/acre	2.5	1.97	1.97	29.54	11.95
Interest	5.30%	1.34	1.40	1.40	20.96	8.48
Fixed Costs	$1.05/acre	1.05	0.83	0.83	12.38	5.01
Total Cost of Production		**51.06**	**52.02**	**33.41**	**501.22**	**202.84**
Handling and shredding (cubes)			10.00	19.50	292.50	118.37
Cube production and finishing			30.00	30.00	450.00	182.11

Total cost of Fuel cubes	**92.02**	**82.91**	**1243.72**	**503.32**
Pellet production and finishing	100.00	100.00	1500.00	607.03
Total cost of Fuel pellets	**152.02**	**133.41**	**2001.22**	**809.87**

** nutrient value is the value of the straw remaining on the field*

6.1.2 Energy costs and comparisons of cattail biomass

Based off production cost guidelines from MAFRI (2012) and energy system calculations comparing biomass to coal and natural gas (MAFRI 2012), energy costs of cattail biomass and densified cubes and pellets was compared to other biomass sources (Table 6.2). Calculation spread sheets are provided in Appendix 10.4 from MAFRI (2012). Cost of wheat straw biomass includes cost of production + 15% producer mark-up. Cost of cattail biomass per energy unit is much lower than typical biomass feedstocks (Table 6.2). Depending on the costs associated with densification, the cost per million Btu or KWh increases (Figure 6.1). Current electricity (Manitoba Government 2013b) and natural gas rates (MB Hydro 2013) in Manitoba remain relatively low (Figure 6.2), and although electricity rates have increased slightly since earlier comparisons in 2009 and 2010 (Figure 6.2), natural gas rates have decreased significantly. Cattail biomass products currently compete only with the heat market in Manitoba (i.e. coal and natural gas); therefore comparisons by million BTUs are more relevant.

Table 6.2. Energy cost comparisons cattail biomass to traditional biomass (see Appendix B). Estimates based off production costs guidelines (MAFRI 2012) and current electricity and natural gas rates from Manitoba Hydro (*MB Hydro 2013*).

Biomass	**Cost***	**Net BTU/T**	**$ Per Million BTUs**	**KWh per T**	**$ Per KWh**
Cattail bales	$38.42/T	9,024,600	$4.31	2,644	$0.015
Cattail cubes	$95.35/T	9,024,600	$10.68	2,644	$0.036
Cattail pellets	$153.42/T	9,024,600	$17.19	2,644	$0.058
Wheat straw	$ 60/T/T	8,923,941	$6.72	2,615	$0.023
Wheat straw cubes	$ 100/T	8,923,941	$11.21	2,615	$0.038
Wheat straw pellets	$ 175/T	8,923,941	$19.59	2,615	$0.067
Coal lignite	$ 100/T	7,893,600	$12.67	2,312	$0.043
Wood pellets	$ 150/T	10,127,000	$14.81	2,967	$0.051
Oats -grain	$ 3.40/bu	9,375,275	$21.33	2,747	$0.073
MB Hydro	$0.071/KWh	-	$20.80	-	$0.071
Natural gas highE	$0.0967/m3	30216/m3	$3.20	8.85/m^3	$0.011
Natural gas lowE	$0.0967/m3	24,633/m3	$3.93	7.22/m^3	$0.013

**Straw and cattail cost of production includes 15% producer markup (risk, management, and profit margin)*

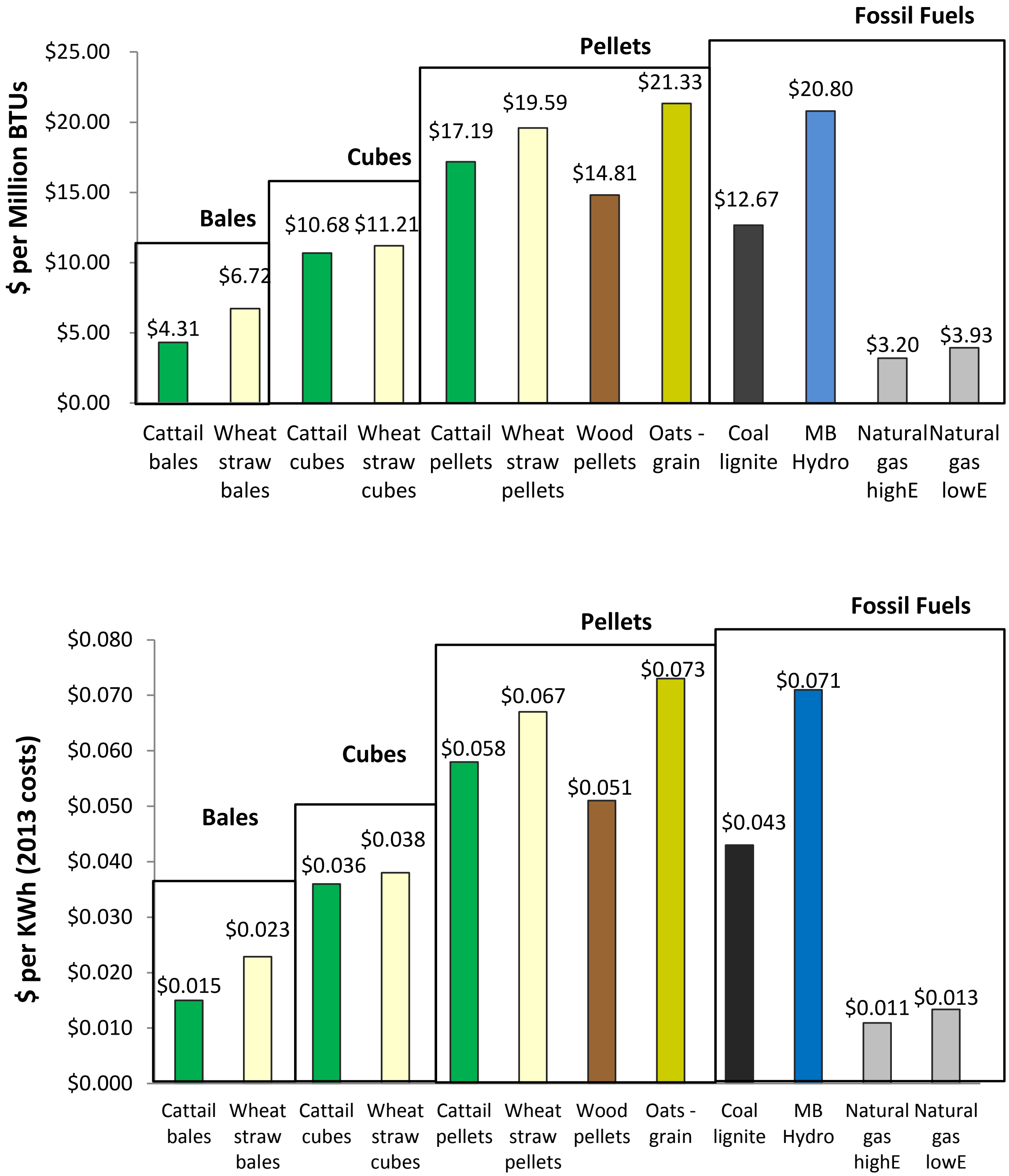


Figure 6.1. Energy cost comparisons (top) $ per million BTUs, and (bottom) $ per KWh for 2013. Estimates based off production costs guidelines (Source: MAFRI 2012), and electricity and natural gas rates from Manitoba Hydro (Source: MB Hydro 2013).

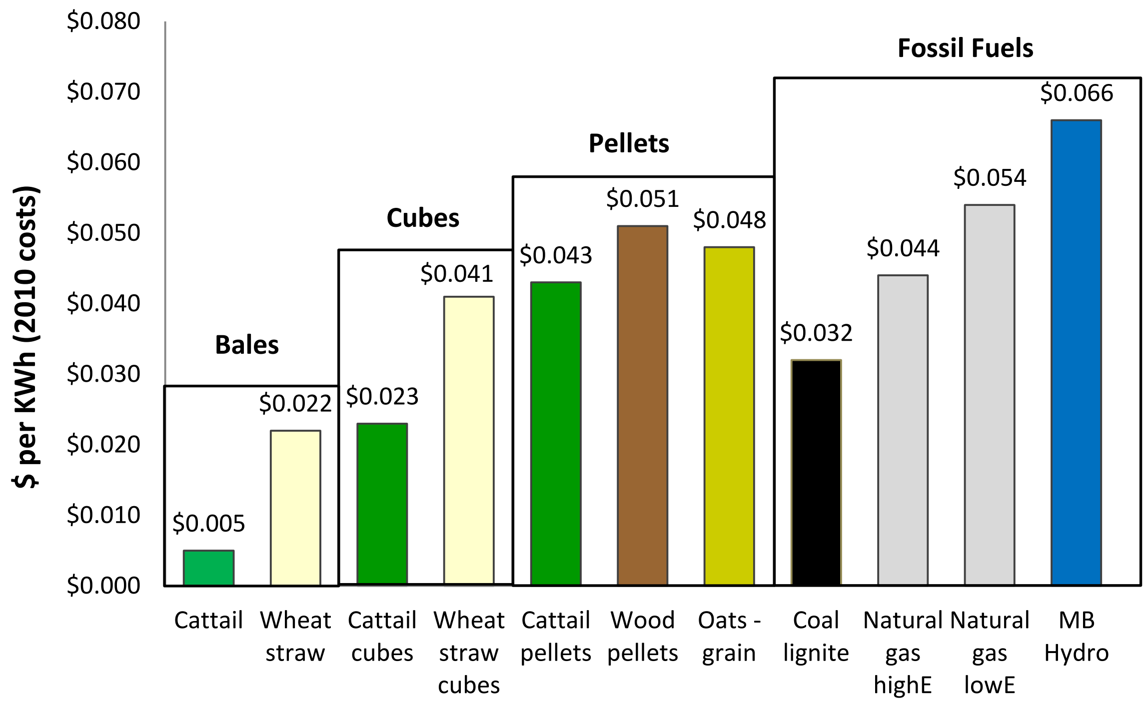


Figure 6.2. Energy cost comparisons ($ per KWh) for 2010 of cattail biomass to traditional biomass and fossil fuels. Estimates based off production costs guidelines (Source: MAFRI 2012), and electricity and natural gas rates (Source: MB Hydro 2013).

6.2 GHG emission offsets and mitigation

6.2.1 Fossil fuel displacement and carbon off-set potential

Further economic and environmental benefits are gained when cattail biomass is used as a low-carbon feedstock to displace the use of coal or natural gas, through the use of carbon markets and GHG emission offsets. This greatly enhances the value of harvesting cattail biomass by mitigation of carbon emitting sources (Cicek et al. 2006). Based on coal emission data obtained from the literature (IPCC emission factor 2010) it is estimated the displacement of coal by one tonne of cattail biomass used as a feedstock for bioenergy production, would generate 1.05 tonnes of CO_2 offsets (Table 6.3). These calculations assume the coal replaced is Alberta bituminous, and substituting with other types of coal would yield different results.

Table 6.3. Cattail carbon offsets and potential GHG emission credits displacing coal (Alberta bituminous). (IPCC emission factor 2010)

Biomass	Yield (T DM /ha)	Energy Content (MJ/t)	Energy Content (MJ/t) at 80% efficiency	Emissions (t CO_2/t biomass)	Emissions per unit energy	P Content (kg/t)	CO_2 offset per t
cattail	15	17500	14000	0.5	0.0357	3.5	1.05
coal	-	25800	-	2.44	0.0945	0.5	-

At a conservative average harvest rate of 15 T DM/ha, 350 hectares of harvestable cattail biomass could produce an estimated 5250 tonnes of biomass and displace 2835 tonnes of coal. Potential GHG emission offsets estimate this could displace 5513 tonnes of CO_2 emissions, without considering methane reductions. With current volunteer carbon offset market values of $10 to $25 per tonne of offsets (*see below section on Markets*), this could potentially produce $55,130 to $131,250 in carbon offset credits to be sold for cost recovery. This carbon price is given for illustrative purposes and fair market value should be considered.

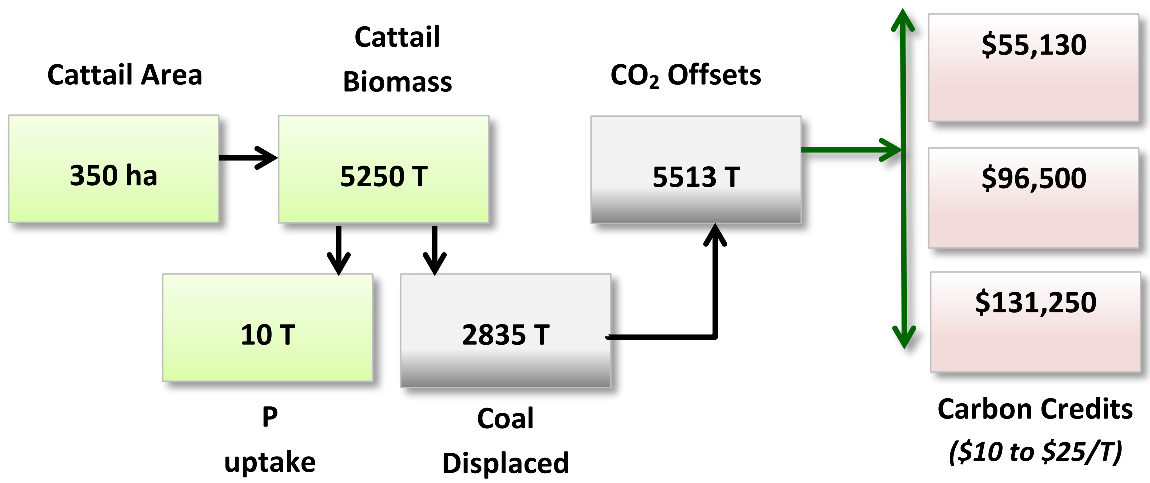


Figure 6.3. Coal and CO_2 offsets generated from displacing coal with harvested cattail biomass for energy production.

Coal displacement and CO_2 emission offsets

Coal displacement = (energy content of cattail /energy content of coal)

CO_2 offsets = Coal displacement x (coal CO_2 emissions – cattail CO_2 emissions)

Further research is needed to confirm and quantify potential carbon sequestration associated with wetland restoration and methane reduction credits associated with harvesting plant material that could otherwise decompose anaerobically. Often cattail and other plant material removed from municipal and city ditches is piled, landfilled, or composted, which can release methane during decomposition (Government of Alberta 2007). Decomposition of biomass and compost in an anaerobic environment produces methane (CH_4) with 21 times the GHG potential and carbon dioxide equivalents than CO_2. Preventing anaerobic decomposition represents a significant reduction in carbon dioxide equivalents and an environmental benefit to harvest and combust the biomass rather than leave it to decompose (Tampier et al. 2004).

Also to be explored is the additional reduction in SO_2 emissions by utilizing a biomass feedstock like cattail in place of coal, which has much lower sulphur content in comparison to coal (Tampier et al. 2004). Research into scalability and feasibility of larger scale cattail harvests in Manitoba is currently being investigated (IISD 2013). With continued concern over global warming and reduction in carbon emissions, processes that can generate energy with minimal net-carbon emissions are of importance.

6.2.2 Carbon Tax and Biomass Policy Context

The Federal and Provincial governments of Canada are taking action to reduce GHG emissions, and expect to reduce GHG emissions by 2020 to 607 Megatonnes (Mt) (Government of Manitoba 2012a). Manitoba's recently announced annual coal tax of $10 per tonne of CO_2 equivalents, and a mandate to eliminate coal for heat production by 2014 (Government of Manitoba 2012a), requires an immediate need for alternative energy sources for industries, communities, and small coal users in MB to reduce their reliance on coal. Biomass provides an alternative fuel source for direct replacement of coal. The emerging Manitoba Bioeconomy is evidenced by the release of provincial policies such as *The Manitoba Bioproducts Strategy* (Government of Manitoba 2011b), and *The Emissions Tax on Coal Act* (Government of Manitoba 2012a), which provides an enabling environment to the development of renewable energy including biomass. In addition, recent changes to *The Retail Sales Tax Act* to expand retail sales tax exemption for straw pellets and other biomass materials used for heating.

6.2.3 Carbon Offset Market Opportunities for cattail biomass and Certification

6.2.3.1 Federal and Provincial Carbon Markets

IISD conducted a preliminary study of the potential for offsets to help Canada meet its 2020 emissions reduction target, showing offsets can be a significant contributor to emissions reduction. Domestic offsets alone have the ability to contribute 26 Mt of reductions annually in 2020 at a price of $25 per tonne in the sectors of agriculture, waste, buildings and transport (Sawyer 2011). This represents as much as 12% of the reductions needed to meet the Canadian Government's 2020 target of 17% below 2005 levels. While these numbers are only an initial modelling, they illustrate how offsets could contribute to emissions reductions targets. Efforts have been made to propose the development of an offset system for greenhouse gases in Canada, the last of these in 2009 (Environment Canada 2009), but there is currently no national strategy or market for offsets for GHG mitigation at the federal level in Canada, and GHG mitigation is based on a patchwork of approaches without a clear guiding strategy (Grosshans et al. 2012).

In the absence of a federal system, provinces have developed offset regimes with varying levels of coverage, standards and pricing. Current potential markets for Manitoba-based cattail harvesting credits could come from Manitoba-based offset purchasers. Currently in Manitoba, domestic offsets were piloted through the Manitoba Sustainable Agriculture Practices Program (MSAPP), currently under review for renewal (MAFRI 2012). The MSAPP operates as a single-purchaser of offsets to help the province achieve its climate change objectives to reduce GHG emissions in the agriculture sector. The BMP program enabled farmers to adopt practices that would achieve GHG reductions which could be used for cattail harvesting. MSAPP market for agricultural offsets of $24 per tonne resulted in 82,000 tonnes of emissions reductions the province (as purchaser) claimed towards provincial targets (Government of Manitoba 2010).

Alberta has the most mature offsets regime in Canada, due in part to the strength of its GHG mitigation strategies. The structure of Alberta's climate change plan including The *Climate Change and Emissions Management Amendment Act* and the Specified Gas Emitters Regulations developed three methods through which covered entities can meet compliance requirements: 1) Improve efficiency of operations; 2) Purchase offset credits through in-province offset system; or 3) Make payments into a provincially managed fund (*Climate Change and Emissions Management Fund [CCEM]*) designated for technology improvements at $15 per tonne of CO_2e. The presence of the CCEM and the offset system serve as flexibility mechanisms to enable compliance at reasonable cost. By end of 2011 more than $250 million was collected through CCEM fund payments accounting for over 16 million tCO_2e in emissions reductions (Government of Alberta 2013). Alberta also developed a protocol for biomass combustion related to avoided GHGs from switching to biomass from fossil fuels as well as avoided GHGs by combusting biomass vs. undergoing anaerobic decomposition. This protocol, with some amendment, could be used as a basis on which to build an offset protocol for cattail harvesting (Carbon Offset Solutions 2012).

6.2.3.2 Voluntary Carbon Markets

Without established markets many purchasers rely on voluntary markets for offsets. Much of this market relies on targets imposed internally, not by government regulations, but by shareholding management or ownership groups imposing internal reduction targets. For cattail harvesting projects, like other projects in stages of development that have GHG mitigation opportunities, the presence of a voluntary market serves as an outlet to gain a crediting benefit while they wait for a regional compliance market to come into form. In the case of fuel switching from coal to cattail biomass for heat generation where the biomass is more expensive, it becomes economically competitive with this offset credit.

There are a series of regionally and globally accepted standards that operate in place of jurisdictional standards (i.e. Alberta or WCI's system) in the voluntary market. The Verified Carbon Standard (VCS) is one of the most commonly used standards around the world (Verified Carbon Standard 2012), with the largest market share (Peters-Stanley et al 2011) and involves a step-by-step process to get accredited and issue credits in the form of Verified Carbon Units (VCUs) (Verified Carbon Standard 2012). It is a viable option for cattail harvesting projects to bring offsets to the voluntary carbon market and is currently being evaluated to enhance the economic viability of cattail biomass harvesting projects (Grosshans et al. 2012).

7.0 Engineering Significance: Viability of Cattail (*Typha* spp.) Biomass for Nutrient Capture and Bioenergy

7.1 Project Significance

7.1.1 A novel renewable and sustainable feedstock

This study proved five main benefits from the harvesting of cattail (*Typha* spp.):

1. Nutrient capture and recovery (i.e. phosphorus),
2. Improved habitat conditions from removal of dead plant material,
3. Biomass for bioenergy production,
4. Fossil fuel displacement and GHG mitigation, and
5. Phosphorus concentration and recovery in ash following bioenergy production.

This study evaluating harvesting cattail for multiple environmental and economic co-benefits is an important proof-of-concept for an innovation-focused bioeconomy. The research emphasizes how Lake Winnipeg nutrient management combined with surface water control and novel biomass feedstocks creates new revenue and economic opportunities. One of the fundamental insights underlying this research is that phosphorus, the pollutant causing eutrophication in Lake Winnipeg and other aquatic ecosystems, is also a valuable resource critical to global food security (Ulrich et al. 2009). This phosphorus can be intercepted, removed from the watershed, and recycled by harvesting ecological biomass such as cattail, and an input to the bioeconomy. In the Lake Winnipeg, Manitoba context, harvesting nutrient-rich cattail provides a sustainable renewable “Lake Friendly” feedstock (Lake Friendly 2013) for small-scale distributed heat, while directly addressing goals to reduce phosphorus loading to Lake Winnipeg (Government of Manitoba 2011a). This study addresses objectives outlined by the Government of Manitoba to reduce nutrient loading to Lake Winnipeg (Government of Manitoba 2011a), and recommendations by the Lake Winnipeg Stewardship Board (Lake Winnipeg Stewardship Board 2004). This innovative solution to recapture and recycle phosphorus also aligns with sustainable phosphorus management policies of the European Union, who have identified phosphorus recycleing as a food security priority. Additionally, it applies to Manitoba Hydro to expand the portfolio of sustainable biomass feedstocks for distributed heat opportunities in Manitoba (MB Hydro 2013).

Using biomass as a solid fuel for heat production is a current market in Manitoba, but research continues to develop new production methods for higher value uses beyond combustion in the form of biocoal, composites, ethanol, plastics, and chemicals from biological material. Additionally, utilizing “low carbon” biomass feedstock to replace the use of fossil fuels (i.e. coal and natural gas) for heat production reduces global carbon emissions, and provides valuable GHG carbon offsets that meet the basic requirements of most international markets which can be sold on global carbon markets.

7.1.2 Multiple co-benefits from harvesting cattail biomass

The multiple environmental and economic co-benefits of harvesting cattail biomass in Manitoba and associated direct environmental and economic costs and benefits of harvesting cattail for nutrient capture and as a biomass feedstock are outlined in Figure 7.1. Included are the costs and benefits of wetland restoration and construction, as well as the compounding costs both economic and environmental of ongoing nutrient loading to Lake Winnipeg from its surrounding watershed without harvesting of cattail.

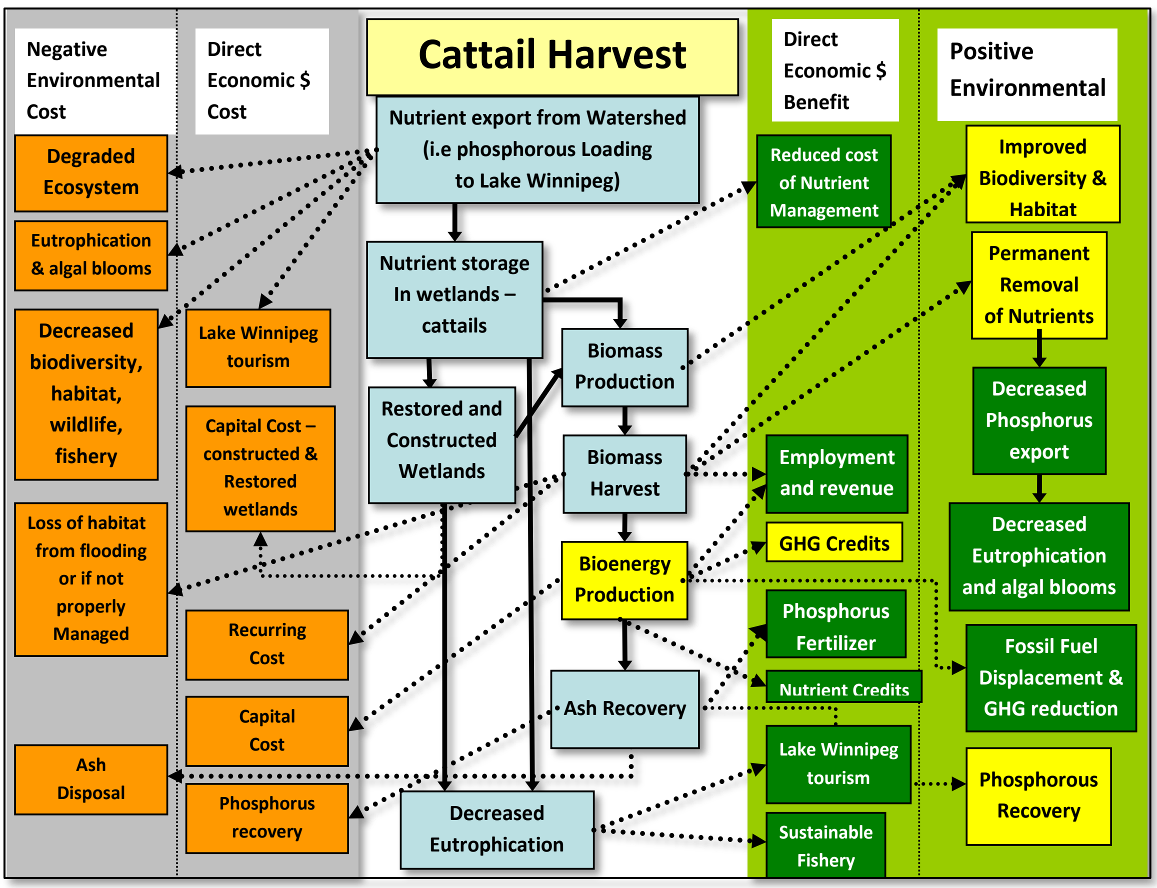


Figure 7.1. Multiple environmental and economic co-benefits and cost of harvesting cattail biomass in Manitoba, including wetland restoration and construction. Included are compounding costs (economic and environmental) of ongoing nutrient loading.

7.1.3 Opportunity for integrated surface and nutrient management

Manitoba faces increasing concerns around the health of Lake Winnipeg and its watershed, and a struggling rural economy. Flooding, drought, surface water management, nutrient overloading, habitat and wetland loss are some of the sustainable development challenges facing this region, and there are opportunities to address these interrelated issues as an integrated approach. Phosphorus loading to Lake Winnipeg is linked to spring flood pulses in Manitoba, with a direct relation of volume of flooding or discharge to levels of phosphorus input (McCullough 2012). Retention projects that hold runoff water on the land to reduce flood impacts (BDSWD 2012), also have the added benefit of retaining and capturing dissolved and suspended nutrients (i.e. phosphorus) within this runoff water. Integrating cattail biomass production and harvesting would create both greater ecosystem co-benefits, through wetland habitat and water for irrigation, and valuable economic revenues through production of biomass and phosphorus recovery. The addition of emergent plants and organic litter to flooded agricultural basins allows plants and microbes to take up and store these nutrients, increasing retention and adsorption capacity within sediments and organic litter (Reddy and Smith 1987, Reddy 2004, Reddy and Delaune 2008).

The Lizard Lake (Morden Times 2011) water retention project in Manitoba, Canada, holds back runoff and flood waters to reduce flood impacts downstream, and provides reed canary grass (*Phalaris arundinacea*) for high value livestock forage. The Pelly's Lake (VanRaes 2012) project in Manitoba, once completed, will provide water for irrigation later in the season, and is currently a major source of cattail biomass for nutrient capture and biomass feedstock (Zubrycki et al. 2012). The North Ottawa water retention project in the Boise de Sioux watershed in Minnesota, USA is one of many retention projects in that region, and an example of much larger integrated water management to reduce flooding to the city of Fargo, ND. A series of integrated dyked and managed cells retain flood water in the spring to effectively reduce damage to downstream homes, farmland, and infrastructure such as washed out culverts and roads. (BDSWD 2012). Although the original objective was to reduce flooding to the city of Fargo, these water retention cells also retain nutrients and reduce loading to Lake Winnipeg. As a secondary benefit the North Ottawa cells have since become colonized by cattail, providing a valuable biomass feedstock to be harvested for nutrient capture and revenue (H. Venema pers. Comm.). Harvested biomass represents a source of revenue for landowners from otherwise unproductive agricultural land, also creating economic incentives for wetland restoration. As governments move towards tighter regulations on nutrient release, investing in ecosystem services upfront can reduce nutrient loading and future impacts of flooding (Government of Manitoba 2013). Capture and storage of phosphorus within water retention sites and recovery through cattail and other ecological biomass harvesting provides a mechanism towards nutrient offsets through water quality trading on voluntary markets, similar to carbon offset credits for reducing carbon impacts (Selman et al. 2009, Government of Ontario 2012, Perez et al. 2013).

7.1.4 European demand - Growing the Manitoba biomass industry

The growth of Manitoba's biomass industry could find opportunities through the rising European demand for biomass fuel pellets, which could see over 60% of necessary biomass fuel pellets to be imported from other countries. European demand for biomass fuel pellets to produce electricity will rise more than three-fold by 2020, estimated to reach 29 million tonnes up from 8 million tonnes in 2010 (Schaps 2013). This demand is driven by the need to reach legally-binding targets to cut carbon emissions as part of their environmental policies and as governments offer subsidies for greener energy sources to replace dirtier coal in electricity generation - notably Britain, Sweden, Denmark, and the Netherlands (Schaps 2013). Comparatively, the current biomass demand in Manitoba is small with low hydroelectric rates and low natural gas prices in the energy and heat sectors (Government of MB 2013a, b). The wood pellet exports from North America to Europe were up 70% in the third quarter of 2012, and reached a new record of 860,000 tonnes from the two-primary pellet-producing regions in North America - the US South and British Columbia (Ekstrom 2013).

Additionally, biofuel mandates and growth in the biochemicals industry are also expected to triple demand for biomass by 2030, placing pressure on available feedstocks (Lux Research 2012). Demand from the biofuel and biochemical industry could grow to more than a billion metric tons of biomass material each year to replace 3% of total petroleum products, and grow to 3.7 billion by 2030. This includes cellulosic based biofuels, as the US EPA is proposing a 62 percent increase in cellulosic biofuels that must be blended into gasoline and diesel, despite a US federal court decision to strike down its 2012 standard for the fuel (Lux Research 2012).

The demand for biomass fuel pellets in Europe is an opportunity to build the biomass industry in North America, to meet this demand through exported biomass fuel pellets. Taking advantage of the European export markets to bring in foreign dollars will help build necessary biomass industry and infrastructure, and to establish much needed local biomass markets for energy, higher value bioproducts, and to meet the anticipated demand for cellulosic based biofuels. These demands will also establish necessary markets for renewable sustainable forms of novel biomass, such as cattail, that provide much greater additional environmental and economic co-benefits.

7.2 Project Recognition

This research has been featured in local media sources, trade magazines, and awarded a Manitoba Excellence in Sustainability Award in 2012.

1. **Cattail farming could help save troubled lake.** Robert Arnason, the Western Producer, June 3, 2010. http://www.iisd.org/pdf/2011/producer_cattails.pdf

2. **Manitoba researchers convert cattails into pellets.** Anna Austin, Biomass Power & Thermal, March 8, 2011. http://www.iisd.org/pdf/2011/biomass_cattails.pdf

3. **An Unconventional Feedstock**. Biomass Power and Thermal's Pellet Mill Magazine, Spring 2011, pages 36-41. http://issuu.com/bbiinternational/docs/spring11_pmm?mode=embed&layout=http%3A%2F%2Fskin.issuu.com%2Fv%2Flight%2Flayout.xml&showFlipBtn=true

4. **Creating fuel out of cattails.** University of Manitoba Research, March 2011. http://www.youtube.com/watch?v=7bhMrH4LCCg

5. **Manitoba Excellence in Sustainability Award for Innovation and Research for Sustainability, 2012.**

   http://news.gov.mb.ca/news/index.html?archive=&item=13613

6. **Nature of Things: Save My Lake**

   http://www.cbc.ca/documentaries/natureofthings/2011/savemylake/index.html

8.0 Overall Conclusions

8.1 Objectives and Hypothesis revisited

This research study was successful in evaluating the harvesting of cattail (*Typha* spp.) for multiple combined benefits: 1) to capture and remove nutrients in harvested biomass thereby reducing nutrient loading (i.e. phosphorus) to aquatic systems, 2) use of the harvested cattail biomass as a renewable and sustainable biomass feedstock for energy production and reduction in global carbon (GHG) emissions, and 3) recovery of phosphorus – a valuable strategic resource critical for global food security.

The Hypothesis that harvesting and removal of cattail (*Typha* spp.) biomass and its stored nutrients would reduce nutrient loading to aquatic systems was validated. Cattail reaches maturity in less than 90 days, and late summer/early fall harvests of cattail yields an average 15 to 20 tonnes per hectare (T DM/ha/year), and harvesting this biomass captures up to an average 30 kg of phosphorus per hectare per year (kg P/ha/year). Once harvested, nutrients locked in plant tissue are prevented from being re-released into the environment as would occur during natural decomposition. Biomass accumulation in cattail reached its peak around mid-August, coinciding with peak phosphorus and nitrogen accumulation, with decrease in biomass and nutrients as senescence occurred in late fall and the translocation of nutrients to belowground rhizomes. This project identified that an early fall cattail harvest prior to the onset of winter removes a larger bound nutrient stock than a spring harvest of dead biomass, eliminated summer harvesting concerns, and provides suitable biomass feedstock while still preserving a healthy plant community. Spring harvested cattail biomass contains very low levels of nutrients compared to summer and early fall as a result of translocation, senescence, and biomass breakdown and loss of nutrients during winter freeze-thaw. Harvesting impacts over the short-term (3 to 4 years) was minimal.

It was demonstrated utilizing harvested biomass as a bioenergy feedstock provides a further benefit by displacing fossil fuels used for heating or electricity, and thereby generating valuable carbon offsets to be sold on voluntary carbon markets. Cattail biomass was shown to be a viable renewable and sustainable feedstock, or "ecological biomass", for bioenergy production. Cattail was successfully compressed into densified fuel pellets and cubes without additional binders as a standard product for storage and transport costs. Combustion trials show an average calorific heat value of 17 MJ/kg to 20 MJ/kg, comparable to commercial wood pellets and average ash content of 5 to 6%, and no major concerns identified regarding combustion emissions and ash. This concurs with earlier research, which also determined cattail had excellent bioenergy properties.

Cattail was successfully used as a feedstock in place of carbon emitting coal for heat production. Greenhouse gas mitigation potential for small-scale distributed heat was estimated at 1 tonne of cattail biomass used to displace coal for heat production could generate 1.05 tonnes of CO_2 offsets. As an additional co-benefit, elements were recovered in the ash following combustion, with up to 88 % of total phosphorus recovered in ash following combustion in solid fuel burners. Phosphorus, the noxious pollutant fouling Lake Winnipeg, is also an important natural resource for plant growth, and critical for agriculture and global food security.

Harvesting and use of cattail biomass as a feedstock was shown to be economically feasible, by addressing biomass more strategically to address multiple environmental issues profitably rather than at a cost, and by producing valuable end-products and revenue stream markets while maximizing environmental benefits. By applying modern economic and environmental valuations this study demonstrated cattail as an alternative bioenergy feedstock with major environmental and economic co-benefits.

Harvesting of cattail and accumulated deadfall showed an improvement in marsh habitat by opening the site to sunlight and new plant growth, and controlling dominant plant growth. Plant response was quite vigorous the following spring with two weeks earlier emergence in harvested sites from elimination of shading and insulating deadfall. Harvested patches and openness of sites with removal of deadfall provided healthier marsh conditions for wildlife as demonstrated in the literature and by the use of wildlife within harvested sites.

An additional objective gained was greater knowledge on the importance of wetlands to the health of Lake Winnipeg, particularly collecting extensive new data on Netley-Libau

Marsh, a coastal wetland we know very little about and yet is an important component of Lake Winnipeg. The research demonstrates how passive engineering options such as harvesting a novel plant species like cattail can reduce nutrient loading, while enhancing wetland habitat, and creating incentives for wetland restoration.

8.2 Cattail biomass for nutrient capture and bioenergy

Harvesting cattail for nutrient management or bioenergy has its greatest economic advantage when harvested for multiple combined benefits (Figure 8.1). Five major co-benefits were identified with harvesting of cattails from nutrient rich environments:

1) Permanent removal of nutrients - from aquatic systems and reduction of nutrient loading to Lake Winnipeg (i.e. phosphorus) by harvesting nutrient rich cattail,
2) Improved habitat conditions in wetland areas - by removing dead plant material and opening areas to sunlight,
3) Biomass bioenergy production - for renewable and sustainable distributed heat or CHP to displace fossil fuels (i.e. coal),
4) Mitigation of GHG emissions - and revenue from carbon offset credits,
5) Recovery of phosphorus - retained in the ash following combustion - a valuable agricultural commodity critical for global food security

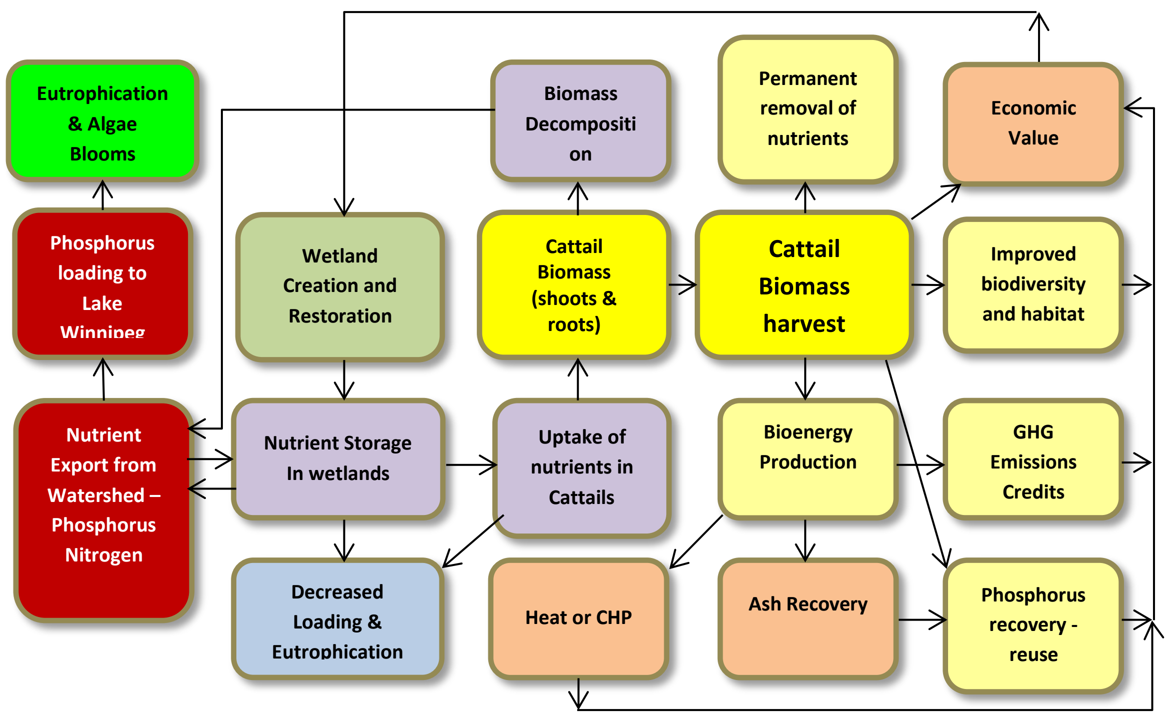


Figure 8.1. The multiple co-benefit pillars of cattail biomass harvesting – permanent nutrient removal (i.e. phosphorous) from the aquatic ecosystem, biomass for bioenergy production, wetland habitat improvement, GHG credits from displacement of fossil fuel use, and phosphorous recovery from ash.

While commercial-scale harvesting of wetland biomass and has been demonstrated in many parts of the world, and technologies for wet-agriculture is available, it has not been widely demonstrated in North America. European wetland harvesters are a well-established technology for use on ecologically sensitive lands and can be considered for cattail harvesting in Canada.

8.3 A Proof of Concept: Ecological Biomass for Watershed Management

This research study is an important proof of concept that demonstrates harvesting plants or ecological biomass like cattail, which soak up nutrients that would otherwise flow into waterways and cause eutrophication, is a key driver for a regional bioeconomy. The research shows how Lake Winnipeg nutrient management and novel biomass feedstocks can be combined with surface water management for greater economic gains. Water deliberately stored on land reduces flooding downstream and provides conditions for biomass production and harvesting. It is a mechanism to capture and recover phosphorus to reduce loading within watersheds profitably, rather than at cost both environmentally and economically. Creating value for cattail biomass creates incentives for conservation and restoration of wetlands in an agricultural setting. Harvesting cattail could be part of a larger nutrient management plan within the Lake Winnipeg Watershed and applied to engineered wetlands, storm water retention wetlands, and vegetated ditches. Sustainable renewable biomass can also be refined into higher value biofuels, chemicals, and biomaterials. These higher value bioproducts are made from low value inputs, which are often considered a waste or by-product for disposal. The fundamental concept is we are turning a waste stream into an input for sustainable biomaterial production, a key building block of the bioeconomy, and simultaneously closing the resource loop through nutrient reclamation.

This study addresses objectives outlined by the Province of Manitoba to reduce nutrient loading within the Lake Winnipeg watershed outlined in the Nutrient Management Strategy of Manitoba, the Lake Winnipeg Action Plan, and recommendations by the Lake Winnipeg Stewardship Board. It aligns with conservation efforts of groups including Ducks Unlimited Canada and Delta Waterfowl for wetland restoration and enhancement. It targets clean energy and GHG emission reduction efforts of the Province of Manitoba and Federal Government and goals of Manitoba Hydro to explore distributed heat and CHP opportunities in Manitoba, while enhancing their on-going water stewardship efforts. It also supports actions of Manitoba Agriculture, Food and Rural Initiatives, to explore additional revenues for agriculture and landowners from marginal agricultural land that would otherwise be unproductive.

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10.0 Appendix

10.1 Netley-Libau Marsh flow

Recent hydrological modelling of the marsh has shown that the majority of the Red River flow does not flow through vegetated areas of the marsh at all, but rather drains into the lake through two main river channels and into Netley Lake, a large open water basin on the west side of the marsh. Up to 35% of the Red River flow currently passes through the Netley Cut into Netley Lake (Haresign 2012), and can be observed in thermal imaging (Figure 10.1).

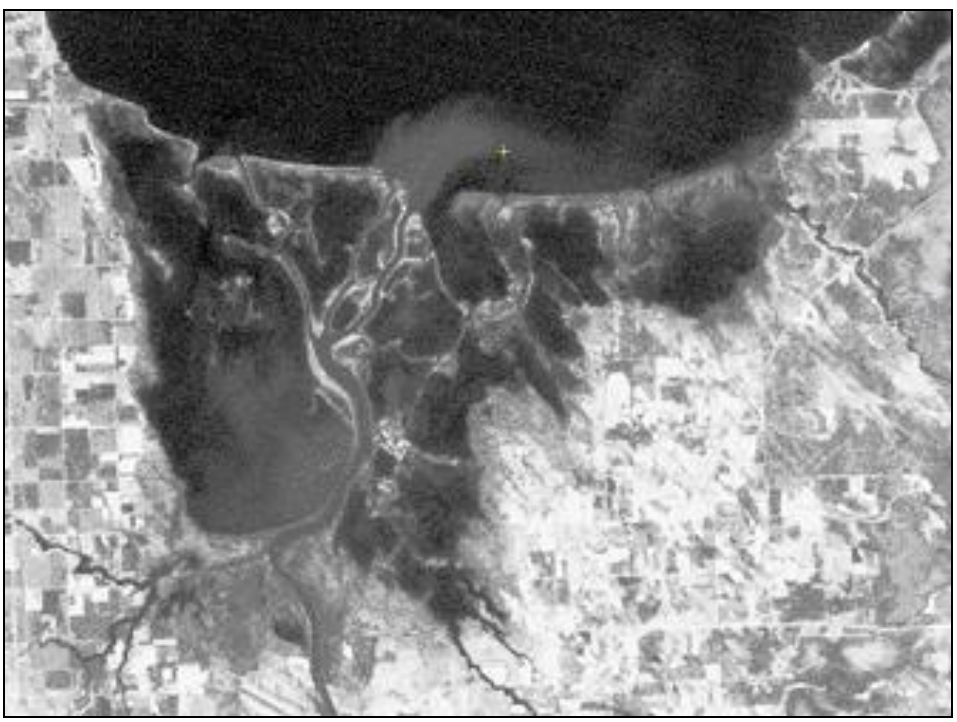

Figure 10.1 Thermal imaging of Netley-Libau Marsh. Flow from the Red River is shown entering Lake Winnipeg to the north and Netley Lake (a large open water bay of the marsh) to the west *(source: Manitoba Land Initiative).*

10.2 Water chemistry

10.2.1 Total available phosphorus in Netley-Libau Marsh open water

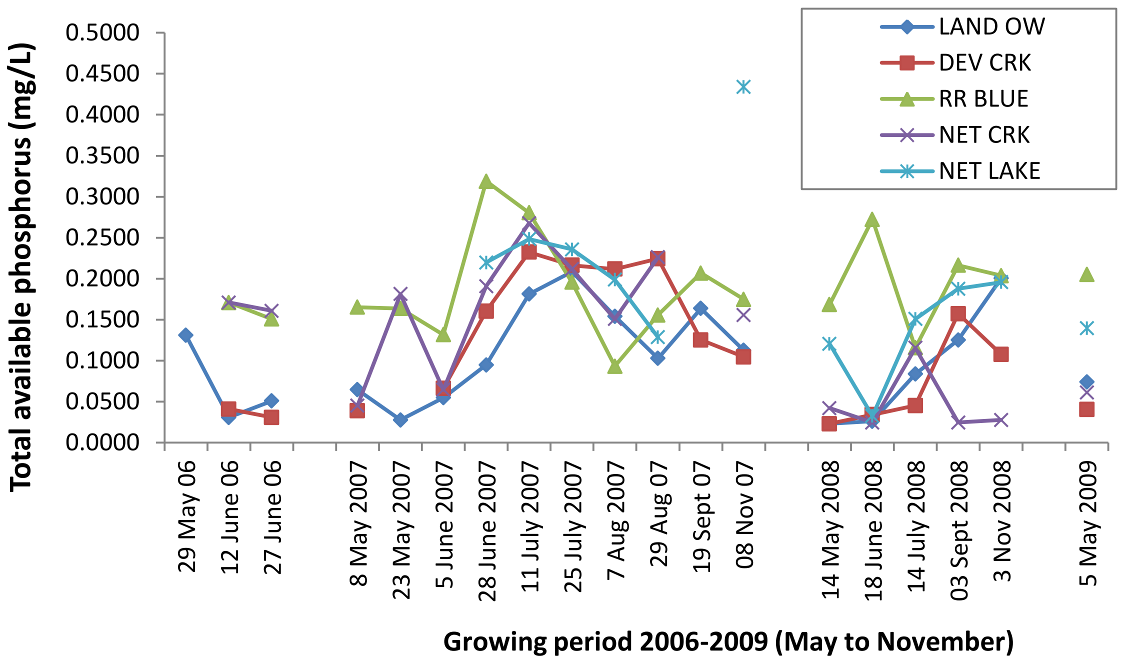

Figure 10.2. Total available phosphorus (PO_4) in the water column in open water areas of Libau Marsh East of the Red River in Anderson Lake (Land) and Devils Lake (DEV CRK), and Netley Marsh west of the Red River in Red River at Breezy Point (RR BLUE), Netley Creek (NET CRK), and Netley Lake (NET LAKE).

10.2.2 Total available phosphorus in Netley-Libau Marsh open water

The effects of carp on levels of available phosphorus can be observed in an open water site near the treatment sites that was invaded by carp in 2007 during high water levels, which allowed carp into this area. Winter conditions would have removed carp for the following year in 2008 and none were present in 2009 (Figure 10.3).

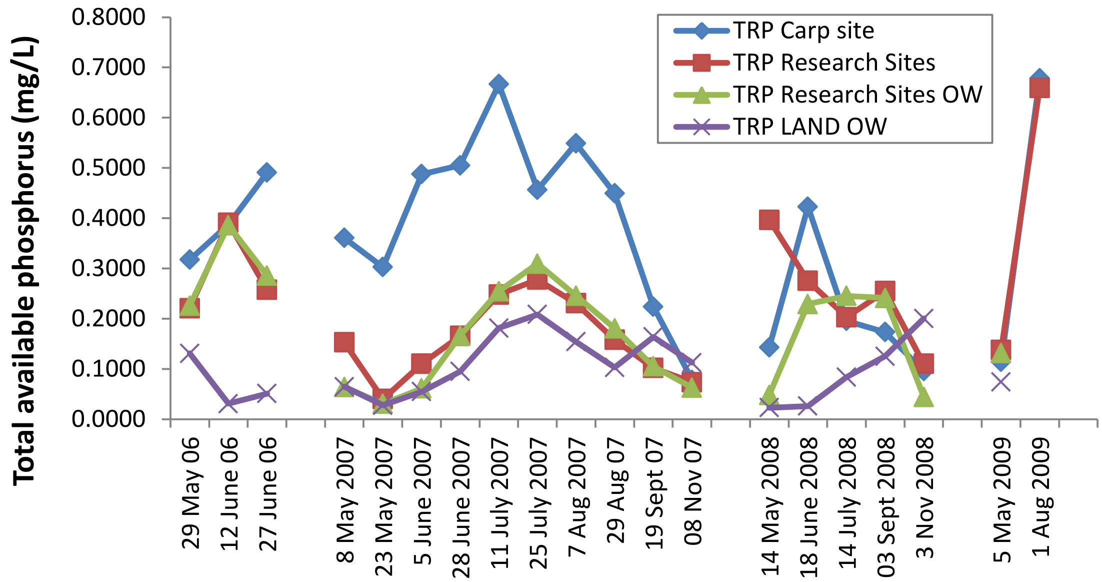

Figure 10.3. Total available phosphorus (PO_4) in the water column within cattail research plots comparing research sites, open water areas next to research sites, Anderson Lake (LAND), an open water area near research site, and an open water area full of carp.

10.2.3 Total available phosphorus - Netley vs. Libau Marsh

Total available phosphorus levels on the west side of the Red River in sampled open water areas of Netley Marsh, were on average higher than the east side of the Red River in sampled Libau Marsh open water areas (Figure 10.4).

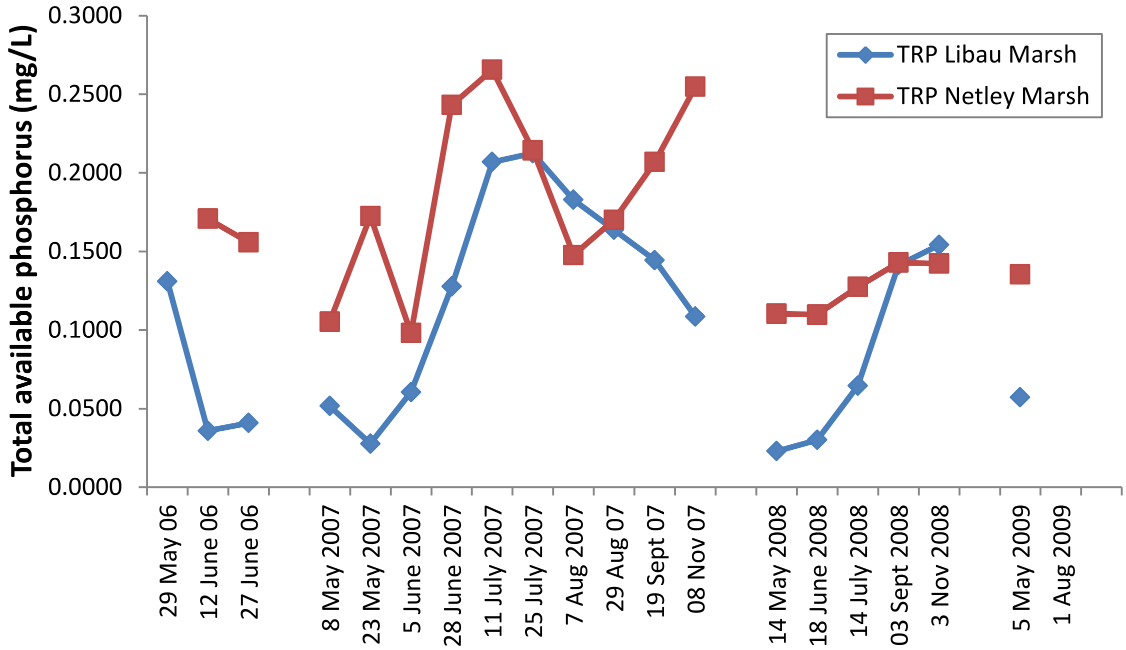

Figure 10.4. Total available phosphorus (PO_4) in the water column comparing Netley Marsh west of the Red River and Libau Marsh easts of the Red River.

10.2.4 TSS and Turbidity

Total suspended solids includes inorganic sediment and organic debris suspended in the water column. TSS for the cattail filled research sites was much lower compared to the open water bays and creeks of Netley Marsh (Netley Lake, Netley Creek, and Red River at Breezy Point) west of the Red River and Libau Marsh (Anderson Lake, Devils Lake) East of the Red River. The cattail within the research plots reduced wave and stirring actions reducing the amount of suspended sediments and debris in the water column, as did the more sheltered open water areas next to the cattail research plots (Figures 10.5, 10.6, 10.7, 10.8)

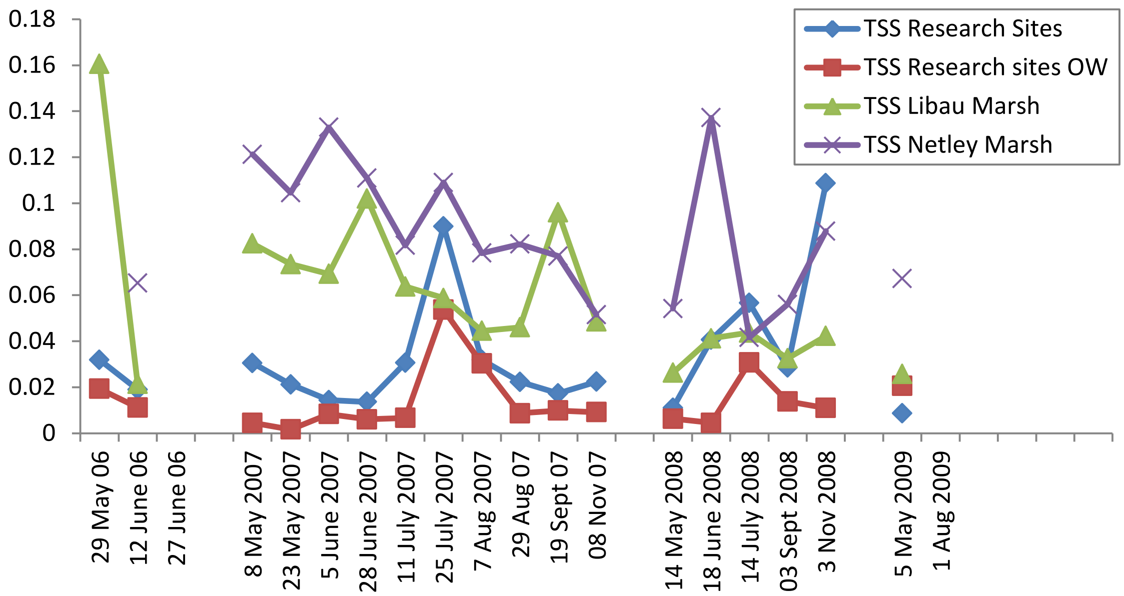

Figure 10.5. Total Suspended solids

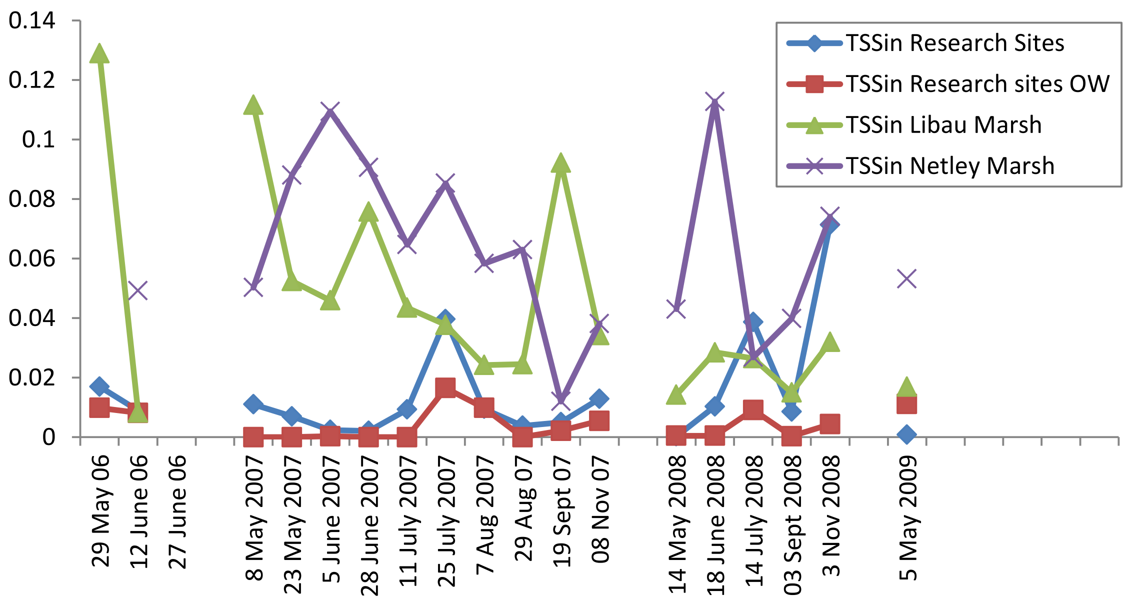

Figure 10.6. Total suspended solids, inorganic

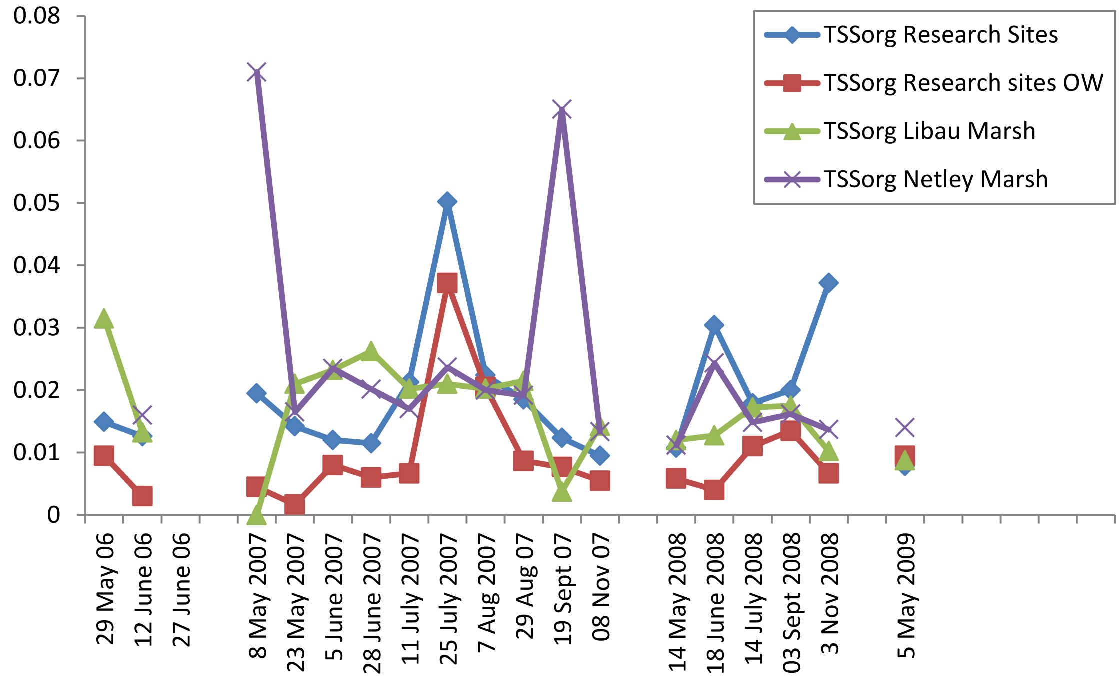

Figure 10.7. Total suspended solids, organic.

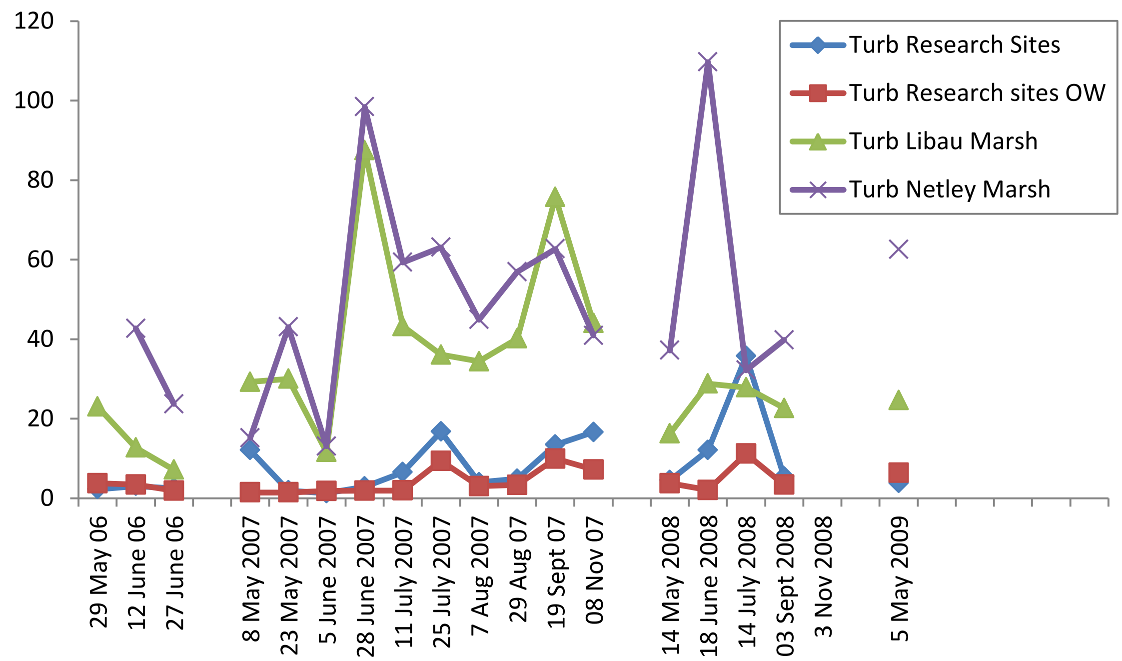

Figure 10.8. Turbidity.

10.3 Soil chemistry

10.3.1 Soil and litter calcium

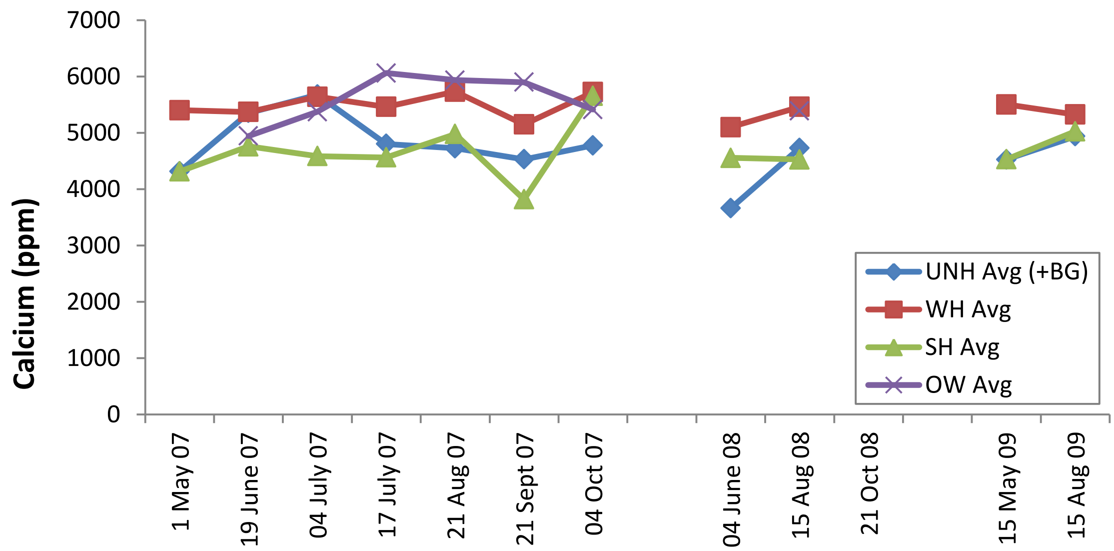

Figure 10.9. Soil calcium (ppm).

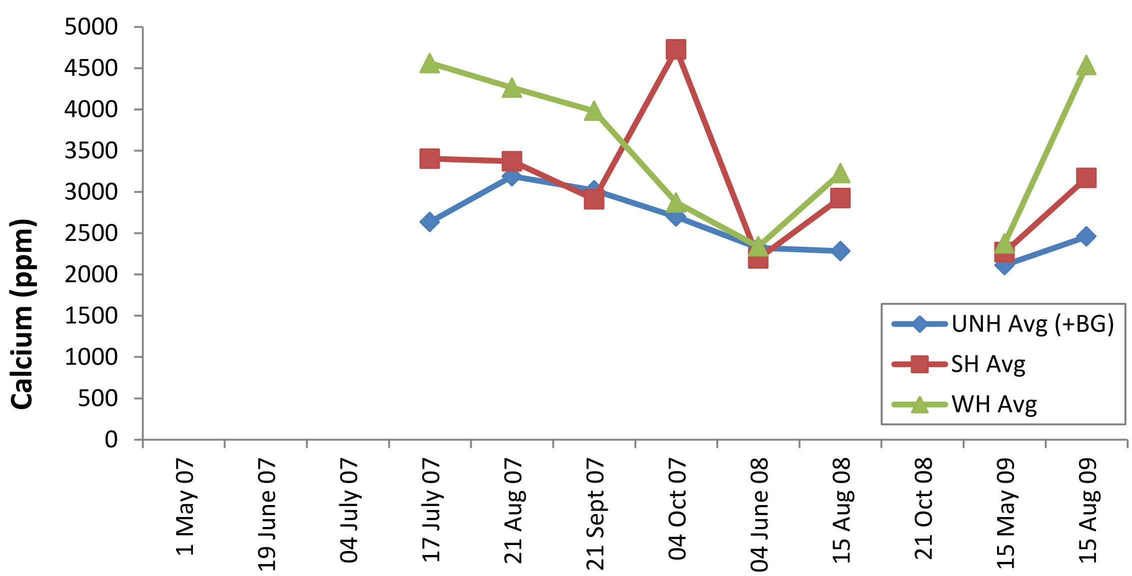

Figure 10.10. Litter calcium (ppm).

10.3.2 Soil and litter organic matter

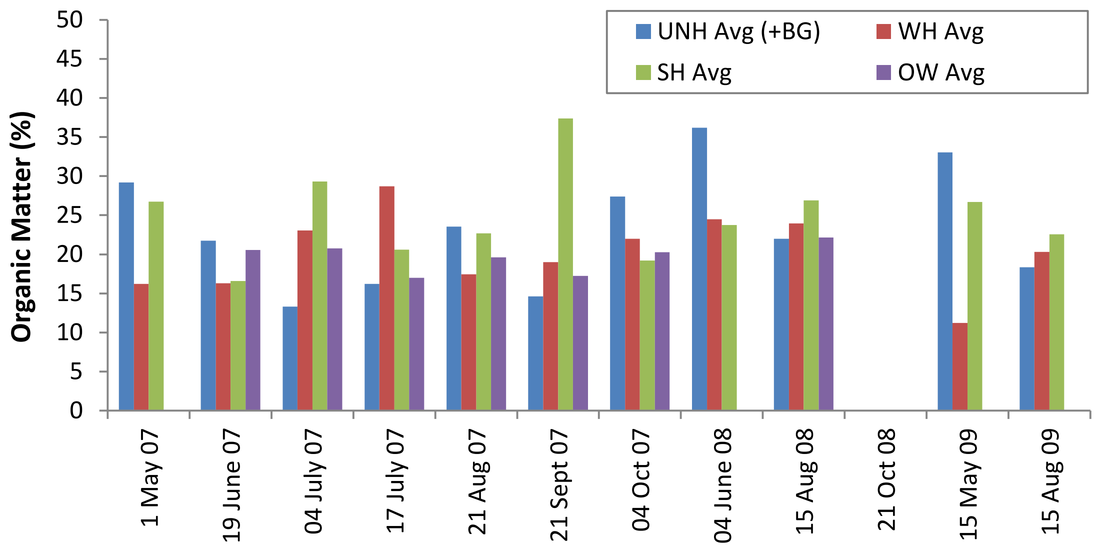

Figure 10.11. Soil organic matter (%).

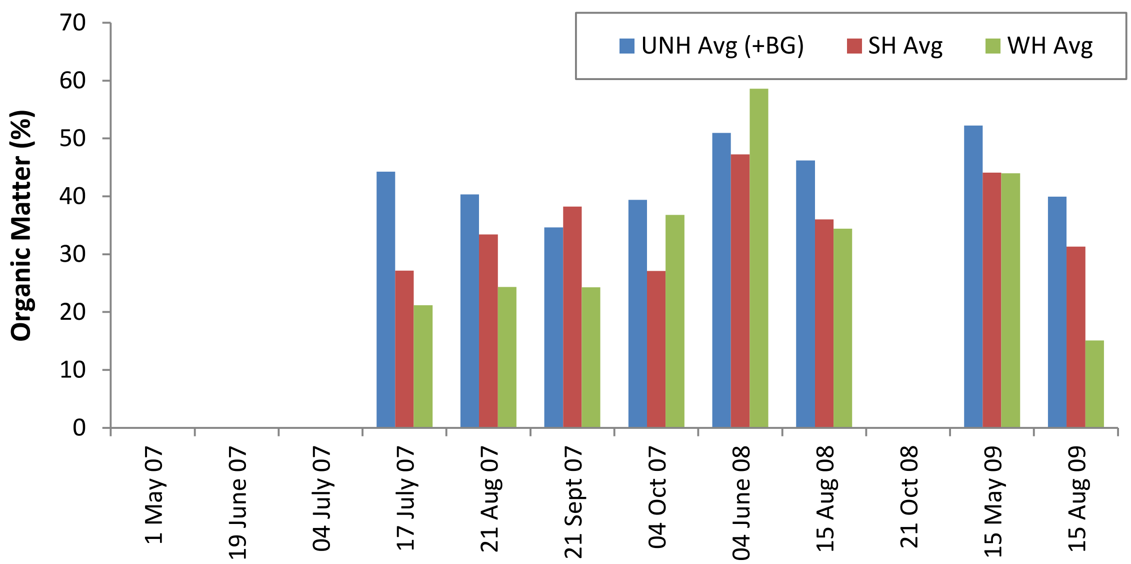

Figure 10.12. Litter organic matter (%).

10.3.3 Soil and litter potassium

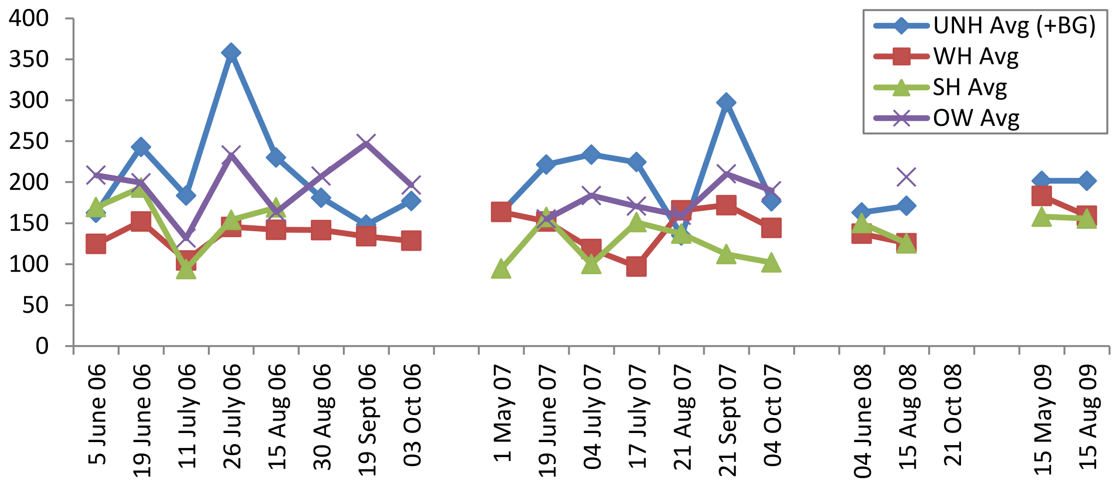

Figure 10.13. Soil potassium (ppm).

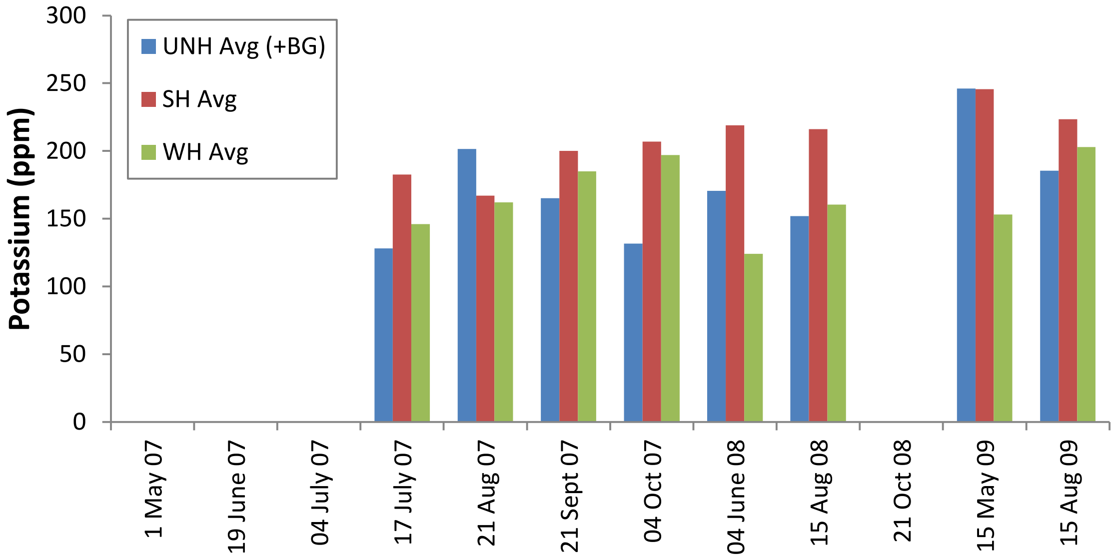

Figure 10.14. Litter potassium (ppm).

10.3.4 Soil phosphorus in open water areas

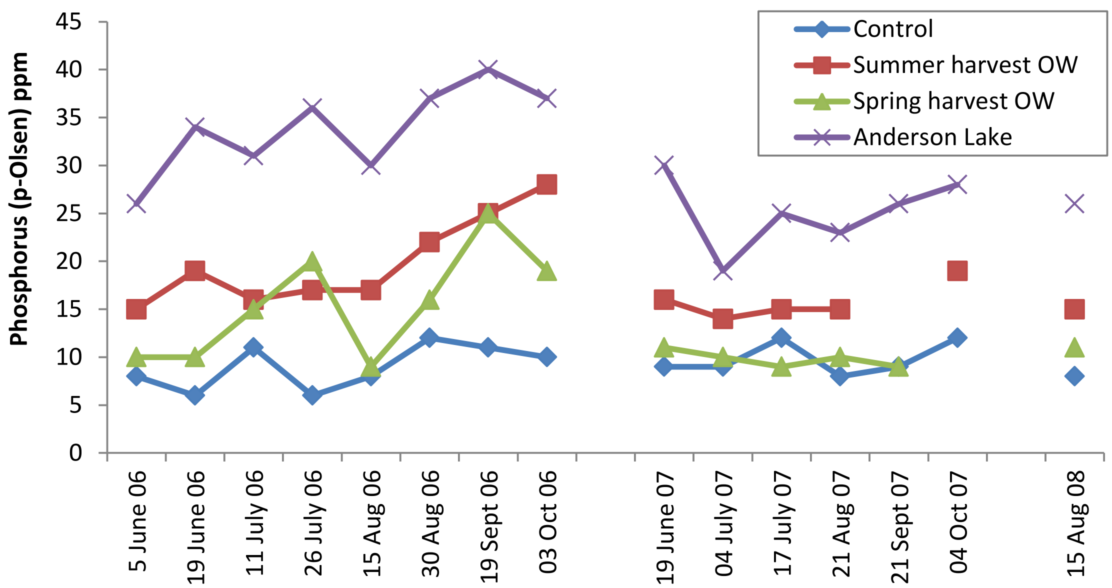

Figure 10.15. Soil phosphorus in open water areas, comparing Anderson Lake, which is a large open water bay in Libau Marsh, and the open water areas near the control and treatment sites.

10.4 Cattail Crop Production and Energy Calculations

Cattail biomass costs of production (Table 6.1) and energy calculations (Table 6.2) were compared to straw as a solid fuel source. Calculations for crop production were based on current crop production guidelines from Manitoba Agriculture, Food and Rural Initiatives available in "Guidelines for Estimating Crop Production Costs 2013 in Western Manitoba" (MAFRI 2013a), and "Farm Machinery Custom and Rental Rate Guide (MAFRI 2013b). Energy value and costs were calculated from Manitoba Agriculture, Food and Rural Initiative's "Costs of production in a wheat straw biomass enterprise" (MAFRI 2012). These guides provide planning information and a format for calculating the costs of production in cattail biomass compared to a wheat straw biomass enterprise.

Table 10.1 Wheat straw energy calculations and cost

Wheat Straw			
		7713	BTU per pound
x		0.89	dry matter
equals		6864.57	BTU per pound as received
x		2000	pounds per ton
equals		13729140	
x		65%	heat efficiency
equals		**8923941**	**NET BTU per ton**
	$	152.02	cost of production per ton
x		15%	Producer margin
plus	$	22.80	
equals	**$**	**174.82**	**cost per ton**
/		*8.9239*	*million BTU per ton*
equals	**$**	**19.59**	**per Million BTU**
		8923941	**NET BTU per ton**
/		*3413*	BTU per KWh
equals		**2614.691181**	**KWh per ton**
	$	174.82	**cost per ton**
/		2614.691181	KWh per ton
equals	**$**	**0.06686**	**per KWh**

Table 10.2 Cattail loose biomass, and densified pellets and cubes energy calculations and costs based on wheat straw.

CATTAIL - based on straw			
		7800	BTU per pound
x		0.89	dry matter
equals		6942	BTU per pound as received
x		*2000*	*pounds per ton*
equals		13884000	
x		65%	heat efficiency
equals		**9024600**	**NET BTU per ton**
	$ 33.41		cost of production per ton
x		*15%*	*Producer margin*
plus	$ 5.01		
equals	**$ 38.42**		**cost per ton**
/		*8.9239*	*million BTU per ton*
equals	**$ 4.31**		**per Million BTU**
		9024600	**NET BTU per ton**
/		*3413*	BTU per KWh
equals		**2644.184002**	**KWh per ton**
	$ 38.42		**cost per ton**
/		2644.184002	KWh per ton
equals	**$ 0.01453**		**per KWh**
CATTAIL pellets - based on straw			
		7800	BTU per pound
x		0.89	dry matter
equals		6942	BTU per pound as received
x		*2000*	*pounds per ton*
equals		13884000	
x		65%	heat efficiency
equals		**9024600**	**NET BTU per ton**
	$ 133.41		cost of production per ton
x		*15%*	*Producer margin*
plus	$ 20.01		
equals	**$ 153.42**		**cost per ton**
/		*8.9239*	*million BTU per ton*
equals	**$ 17.19**		**per Million BTU**
		9024600	**NET BTU per ton**
/		*3413*	BTU per KWh
equals		**2644.184002**	**KWh per ton**

	$ 153.42		**cost per ton**
/		2644.184002	KWh per ton
equals	**$ 0.05802**		**per KWh**

CATTAIL cubes - based on straw

		7800	BTU per pound
x		0.89	dry matter
equals		6942	BTU per pound as received
x		*2000*	*pounds per ton*
equals		13884000	
x		65%	heat efficiency
equals		**9024600**	**NET BTU per ton**
	$ 82.91		cost of production per ton
x		*15%*	*Producer margin*
plus	$ 12.44		
equals	**$ 95.35**		**cost per ton**
/		*8.9239*	*million BTU per ton*
equals	**$ 10.68**		**per Million BTU**
		9024600	**NET BTU per ton**
/		*3413*	BTU per KWh
equals		**2644.184002**	**KWh per ton**
	$ 95.35		**cost per ton**
/		2644.184002	KWh per ton
equals	**$ 0.03606**		**per KWh**