The use of plant functional traits to detect changes in urban wetland management regimes within Kitchener, ON

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

ABSTRACT

Humans have modified their surrounding environment in ways that often lead to changes in ecosystem structure and function. Ecosystem management efforts are necessary to bring back functioning attributes of ecosystems for wildlife and human enjoyment. Ecosystem management provides a means of assessing ecosystem status, prioritizing, and outlining essential ecosystem goods and services. However, few projects are designed or funded to ensure that measures of success or failure are completed and reported so that lessons can be learned. Still, there are several conventional measures to assess success or site conditions that are used; many of these rely on assessment of taxonomic diversity. While useful as a fast, efficient and useful comparative indicator, diversity measures are usually an indirect measure of the need to conserve or restore ecosystem function. In contrast, plant functional traits potentially have a higher explanatory power in predicting ecosystem functionality, stability, invasibility, resource capture (i.e., allocation of nutrients to different plant structures), nutrient cycling, and the productivity of communities. A practical problem with functional traits may be that measuring them is more labour-intensive. This can be a problem for organisations with already limited funding. A more fundamental challenge is that functional trait measures were originally designed for use in phylogenetic studies, not as ecological indicators. Hence, this is the first research avenue to pursue.

My research focused on the comparison of above-ground and below-ground plant functional traits in *Typha* (cattail species) and *Phalaris arundinacea* (invasive reed canary grass) in different urban wetland management regimes within the City of Kitchener, Ontario, Canada. Passive management types included an on-line stormwater management facility (known as "no. 32"), a wetland created by agricultural activity ("Sunfish Pond, Huron Park Natural Area"), and a least disturbed natural wetland ("Borden Wetland"). Above-ground functional traits included maximum plant height, presence and absence of seedhead, and seedhead length in *Typha.* Below-ground plant functional traits were specific root length, root diameter, root length, root volume, root surface area, root tissue density, root density, and root ball volume. *Typha* measures included rhizome volume.

Comparing all urban wetland management regimes, there was a significant difference in maximum plant height of *Typha*. There was a significant difference in root volume measurements of *Phalaris arundinacea* between Borden Wetland and the on-line stormwater management facility. In *Phalaris arundinacea,* root length, root surface area, and root ball volume were significantly different between Sunfish Pond and Borden Wetland. *Typha* root diameter and root volume showed a statistically significant difference between Borden Wetland and the on-line stormwater management facility no. 32. Lastly, *Typha* showed a significant difference in specific root length and root density between Borden Wetland and Sunfish Pond versus the on-line stormwater management facility no. 32.

This study contributes to the state of knowledge regarding use of plant functional traits in measuring outcomes of choices (active or passive) of ecological management in these urban wetlands. Specifically, what this study showed is that root diameter, root volume, and maximum plant height in *Typha* species were the best traits to assess site conditions. These results suggest that there may be differences in the efficacy of different management regimes, or site characteristics, and that these are reflected by plant

functional traits. The caveat is that the results were inconsistent between and within the species used; what should be tested by a follow up study is whether these results can be explained by the inherent variation in urban wetland ecosystem dynamics (e.g., sudden changes in water depth during precipitation events) facilitating more extreme plasticity in plant traits.

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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

Anthropogenic influences on biodiversity loss are a great threat to the function of a healthy ecosystem and the valuable ecosystem services it provides. The continued increase in human population has converted more than three-quarters of terrestrial ecosystems into novel environments through urban and agricultural settlements (Ellis et al., 2012). In particular, the Earth's population has increased from 1.65 billion in 1900 to 5.98 billion in 1999 (United Nations, 1999). By 2030, it is estimated that more than 60% (4.9 billion) of the world's population (8.1 billion) will live in cities (Alberti et al., 2003). In 2011, 81% of Canada's population lived in urban centers (Statistics Canada, 2011).

While urban areas only cover 1 – 6% of the Earth's surface, they have a large ecological footprint with complex and negative synergistic effects on ecosystems (Alberti et al., 2003). Urbanization, agriculture, fragmentation, invasive species, and environmental pollution have lead to the formation of novel ecosystems. These systems have a composition or functional difference from any known historical ecosystem (Hobbs & Cramer, 2008; Hobbs, Higgs, & Hall, 2013) and exist along a different trajectory where traditional ecosystem management is not possible (Hobbs et al., 2014). Novel ecosystems can never return to a historical state (Hallet et al., 2013). Hybrid[1] and novel ecosystems are now more prevalent in human-dominated landscapes than natural or historical ones (Hobbs, Higgs, & Hall, 2013).

Landscapes dominated by humans have unique biophysical characteristics that range from differences in the flux of energy and materials, species composition, microclimates, hydrological processes, and air quality in comparison with historic landscapes (Alberti et al., 2003). The transformation of historic landscapes encourages the colonization of generalist species over highly specialized, endemic and sensitive ones. Consequently, urban landscapes often include novel combinations of species (Alberti et al., 2003; Clewell & Aronson, 2013). This often includes a high percentage of invasive species that outcompete fundamental native species and result in homogeneous landscapes with no inherent biological diversity. In the past, management goals attempted to eradicate invasive species.

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[1] An ecosystem comprised of new species combinations and/or abiotic conditions which has the opportunity to be returned to its historical state (Hallett et al., 2013).

Today, management goals in novel ecosystems often rest on a species of interest that involves a constant adaptive approach to control invasive species without any intention of eliminating them (Hobbs, Higgs, & Hall, 2013). While invasive species do pose a threat to the functioning of an ecosystem, the elimination of all invasive species may not be a realistic management goal in a novel ecosystem.

Novel ecosystems can be detrimental if managed or created without the integration of essential ecosystem components (abiotic and biotic). The application of traditional ecosystem management[2] goals may not be realistically applied to systems within an urban context influenced by anthropogenic stresses and climate change (Gobster, 2010). The success of ecosystem management within an urban context depends mostly on diversity and functional indicators (Gobster, 2010; Hobbs, 2007). The degree of functional similarity between ecosystems could help determine ecosystem management priorities. If historical versus hybrid and novel ecosystems are functionally similar, management may be a low priority. If key ecosystem functions of a hybrid or novel ecosystem are lost, the restoration of key ecosystem functions is essential. A hybrid system could achieve functional similarity with a historical ecosystem. On the other hand, key ecosystem functions can be restored in a novel ecosystem without restricting restoration efforts to include historical species (Hallett et al., 2013).

1.1 RESEARCH STATEMENT

The literature on restoration ecology provides some of the clearest examples of how ecological management has struggled to derive indicators to detect differences or assess site conditions between different urban wetland management regimes (reviewed by Ruiz-Jaen & Aide, 2005). Main conventional measures to assess site conditions often rely on taxonomic diversity (Durigan & Suganuma, 2015; Mouillot et al., 2013). While useful as a fast, efficient, and useful comparative indicator, diversity measures are usually an indirect measure of the need to conserve or restore ecosystem function (Mouillot et al., 2013). Plant

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[2] It is considered a holistic approach to resource management that integrates the sustainability of the human realm with ecological communities (balance between ecology, institutional, and the socioeconomic context). Its primary goal is to restore and sustain biological diversity while incorporating the interaction between social and ecological systems (Behnken, Groninger, & Akamani, 2016; Meffe, Nielsen, Knight & Schenborn, 2002).

functional traits potentially have a higher explanatory power in predicting ecosystem functionality, stability, invasibility, resource capture, nutrient cycling, and the productivity of communities (Mason et al., 2005; Petchey, Hector, & Gaston, 2004; Schleuter et al., 2010; Zhang et al., 2015). The recovery and maintenance of processes (function), rather than species (structure) is critical to ecosystem resilience and repair (Whisenant, 1999).

The research focused on the comparison of above-ground (maximum plant height of *Typha* species) and below-ground plant functional traits in *Typha* species (cattail) and *Phalaris arundinacea* (invasive reed canary grass). Below-ground functional traits included specific root length, root length, root diameter, root volume, root surface area, root tissue density, root density, root ball volume. The measurement of rhizome volume was included for *Typha* species. Plant functional trait comparisons were made between three different urban wetland management regimes within the City of Kitchener. Urban wetland management types included an on-line stormwater management facility (known as "no. 32"), a wetland created by agricultural activity ("Sunfish Pond, Huron Park Natural Area"), and a least disturbed natural wetland ("Borden Wetland").

1.2 ECOSYSTEM STRUCTURE AND FUNCTION

An ecosystem is an assemblage of species and individuals at a particular place. However, when Tansley (1935) devised the term *ecosystem*, he also included climate and soil with the notion that they, with species, formed an interacting whole (Bradshaw, 2004). Consequently, an ecosystem has many features that not only include animals and plants, but the functions taking place, such as growth, nutrient accumulation, and cycling. Hence, it is convenient to represent *structure* and *function* as two major attributes of an ecosystem. These attributes must be considered to make decisions as to actively[3] or passively[4] manage an ecosystem (Bradshaw, 2004). Additionally, these attributes can be visualized as two axes of a graph in which different levels and types of ecosystem degradation and restoration can be represented (**Figure 1.1**).

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[3] An ecosystem management decision that involves actively managing an ecosystem to reach a specific management goal (Hulvey et al., 2013).

[4] An ecosystem management decision that involves leaving an ecosystem to recover without further assistance (Hulvey et al., 2013).

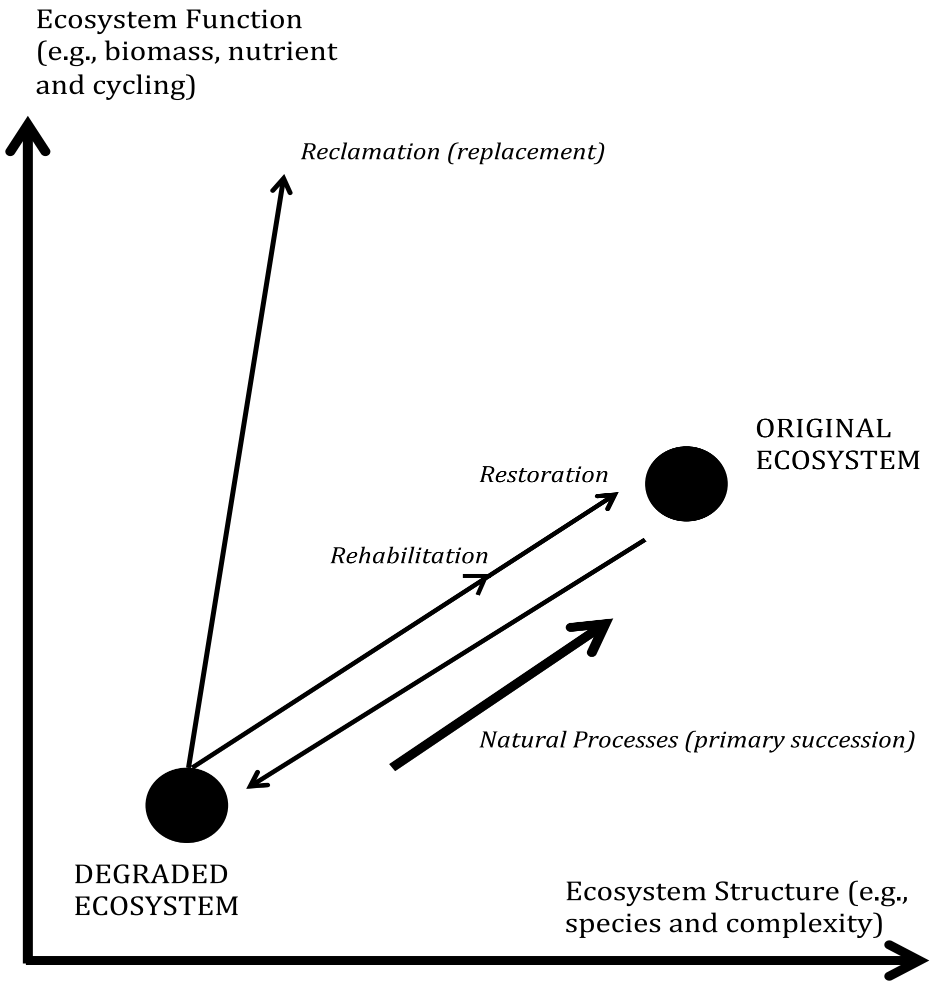

Figure 1.1: Graph representing natural succession and restoration processes in which ecosystem development can be quantified in two dimensions of structure, and function (Bradshaw, 1996). Republished with permission of *Canadian Science Publishing*, from "Underlying principles of restoration", Bradshaw, A.D., 53, 1996; permission conveyed through Copyright Clearance Center, Inc.

Ecosystem function is a broad term that encompasses a variety of phenomena including, ecosystem properties, ecosystem goods, and ecosystem services (Hooper et al., 2005). This term can also be used to define biological, biogeochemical, and physical processes that take place within an ecosystem and how they interact with each other. Ecosystem properties include goods that have direct market value. This can include food, construction materials, medicine, domestic plants, tourism, recreation, and biotechnology. On the other hand, ecosystem services directly or indirectly benefit human endeavors (e.g., hydrological cycles, regulating climate, cleansing air and water, pollinators, soils, nutrients and so on) (Hooper et al., 2005; Moor et al., 2017). These components are illustrated in **Figure 1.2**, which identifies properties, processes, functions, and services that are helpful in understanding complex ecosystems.

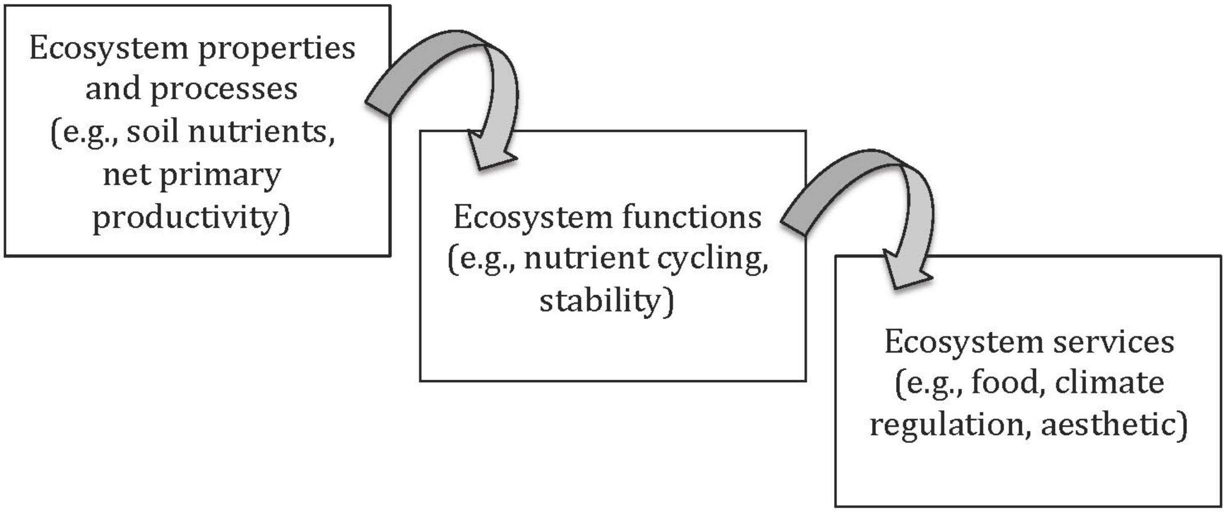

Figure 1.2: Cascade model illustrating the term 'ecosystem function' through ecosystem properties, functions, and services (Zhang et al., 2015). Republished from Zhang, Y., Wang, R., Kaplan, D., & Liu, J., pp. 229, (2015), with permission from Elsevier or applicable society copyright owner.

1.3 WETLAND ECOSYSTEM FUNCTIONS AND ECOSYSTEM SERVICES

Wetlands are known to provide three regulating ecosystem services including: (i) water flow regulation via water storage and flood mitigation; (ii) climate regulation via carbon sequestration and greenhouse gas attenuation; and (iii) water quality regulation via biogeochemical cycles (Moor et al., 2017). Novel wetlands – often constructed in urban areas – can provide ecosystem services analogous to more naturally occurring wetlands.

Natural wetlands are considered intermediate habitats that differ from terrestrial and aquatic habitats (Mitsch & Gosselink, 2015). Water may be permanent or temporary, resulting in aquatic to semiaquatic ecosystems (Burton and Tiner, 2009). Water levels exist either at the surface or within the root zone. Continuously waterlogged soils lead to anoxic conditions, as microorganisms consume oxygen faster than oxygen can diffuse between soil pores. When anoxic conditions prevail for extended periods different biological and chemical reactions dominate. Plants found in anoxic conditions often have aerenchyma[5], that allows for the transport of oxygen to the root zone (Keddy, 2010). Hence, the majority of primary producers in wetland environments consist of bryophytes (e.g., mosses) and vascular plants with plant growth firmly rooted in peat or waterlogged soils. Wetlands are defined as 'habitats that are inundated or saturated by water at a frequency and for a duration sufficient to support a prevalence of vegetation adapted for life in saturated soil conditions' (Mitsch & Gosselink, 2015). Properties (e.g., anoxia and highly organic soils) and processes (e.g., denitrification and carbon sequestration) uncommon in terrestrial environments characterize wetlands (Moor et al., 2017). However, wetlands are dynamic features on the landscape that change in relation to internal (e.g., plant competition and herbivory) and external factors (e.g., natural or anthropogenic influences) (Cronk & Fennessy, 2009).

1.4 ECOSYSTEM MANAGEMENT

Ecosystem management is often employed to make decisions as to actively or passively manage in the recovery of an ecosystem that has been degraded, damaged or destroyed (Clewell & Aronson, 2013; Harris & Hobbs, 2006; Hobbs & Cramer, 2008; Ruiz-Jaen & Aide, 2005; SER, 2004). Ecosystem management goals can involve a spectrum of ecosystems from local (specific – species orientated) to regional scales (landscape-scale – a mosaic of interacting ecosystems) (Clewell & Aronson, 2013; Hobbs & Norton, 1996; Hobbs & Cramer, 2008). Ecosystem management can seek to return a system to a pre-existing ecosystem, to one that has some form of functionality, to one that only aims to restore vegetation for erosion control or food production (Hobbs & Cramer, 2008).

Complex projects must include the deliberative modification of the current degraded state towards a more desirable trajectory (active management) (SER, 2004; Suding, 2011). The initial step in ecosystem management begins with dissecting how the system worked before degradation to understand how to reassemble and reinstate key ecological processes (Hobbs, 2007; Hobbs & Cramer, 2008). Also, the type and extent of ecological

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[5] Spongy material that forms spaces often found in the stems, leaves, and roots of wetland plants that aid in the exchange of gases between the shoot and root (Keddy, 2010).

damage are vital to determine, as they significantly influence the direction of ecosystem management (Hobbs, 2007). In practice, re-vegetation with native or non-native species to restore structure or function of an ecosystem is an active first step which does not ensure the establishment of previous ecosystem interactions and trophic levels (Bradshaw, 2004a; Durigan & Suganuma, 2015).

1.4.1 WHAT IS SUCCESSFUL ECOSYSTEM MANAGEMENT?

This leads to the question of: what do we mean by 'successful' ecosystem management? This term is misleadingly straightforward for a complex concept. Reference sites help gauge whether a degraded ecosystem is improving (Ruiz-Jaen & Aide, 2005; SER, 2004). This provides a baseline on what ecological processes, species composition, community structure, physical conditions of the abiotic environment, and cultural conditions[6] restoration of the disturbed system should achieve. Reference systems are usually historical in context, which is unrealistic, as ecosystems constantly change (Clewell & Aronson, 2013). Reference sites should occur in proximity to the proposed site, occur in the same life zone[7], be relatively undisturbed (Hobbs, 2007), and exposed to similar natural disturbances (Hobbs & Harris, 2001; SER, 2004). However, what happens when the system passes a threshold, and historical constituents are lost? As a result, ecosystem management usually does not strive to achieve a replica of a historical reference, but position the trajectory of the management of a degraded ecosystem to a more resilient and functional system.

The literature on restoration ecology provides some of the clearest examples of how ecological management has struggled to derive indicators to detect differences or assess site conditions between different urban wetland management regimes (reviewed by Ruiz-Jaen & Aide, 2005). It is well documented that there are nine specific ecological attributes of restored ecosystems (Ruiz-Jaen & Aide, 2005; SER, 2004; Shackelford et al., 2013; Wortley, Hero, & Howes, 2013). Although these attributes are geared towards ecological

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[6] Refers to the socioeconomic values and the relationship between a site and its stakeholders (Parks Canada, 2008; SER, 2018). Management decisions require social support to guide management to reach a collective goal.

[7] Defined as areas with similar flora and fauna communities in response to an increase of latitude at a constant elevation, or an increase in elevation at a constant latitude (McColl, 2005).

restoration efforts, the key ecological attributes of a restored ecosystem have parallels with ecosystem management goals. **Figure 1.3** illustrates eleven attributes of successfully restored ecosystems (Clewell & Aronson, 2013). An additional two characteristics were added to separate categories further or to broaden the goals of restoration and ecosystem management. This included graphically emphasizing the landscape context with a dashed line and the addition of the 'biotic environment' category. The attributes chosen for ecosystem management and restoration vary based on land-use planning priorities and goals.

Directly attainable ecological attributes include an appropriate species composition in comparison to the reference; the development of community structure; an abiotic environment to support biota; and how the project is situated within the broader landscape context (**Figure 1.3:** Clewell & Aronson, 2013; Hobbs & Norton, 1996; SER, 2004). Ecological attributes of success often equate to measurements of diversity, vegetation structure, and ecological processes (Ruiz-Jaen & Aide, 2005; Wortley et al., 2013). If possible, it is best to consider more than one group of organisms, different trophic levels (Ruiz-Jaen & Aide, 2005), and socioeconomic benefits (Wortley et al., 2013).

Landscape ecological attributes contribute a significant element to the success of the ecosystem management and ecological restoration goals. They can increase the colonization of native species and also allow for the spread and invasion by exotic species, diseases, and predators (Shackelford et al., 2013; Suding, 2011). Therefore, ecosystem management goals should go beyond site-focused involvement to consider landscape and regional scales (Hobbs et al., 2014).

Indirect ecological attributes of success are not well documented and often can only be partially satisfied. These include: ecological functionality; historical continuity – re-established historical trajectory; ecological complexity – niche and habitat diversity; self-organization – feedback loops; resilience – resist disturbance; self-sustainability; and biosphere support (**Figure 1.3:** Clewell & Aronson, 2013; SER, 2004**).**

Ongoing intervention and monitoring often are required to maintain the desired state or trajectory (Hobbs & Norton, 1996; Hobbs & Cramer, 2008; Shackelford et al., 2013). The direction of ecosystem management depends on who sets the goals or priorities and undertakes the project. Goals must be achievable and individually tailored for national, regional and local scales. Broad goals should also include sub-goals to relate to a particular ecosystem type (Hobbs & Cramer, 2008).

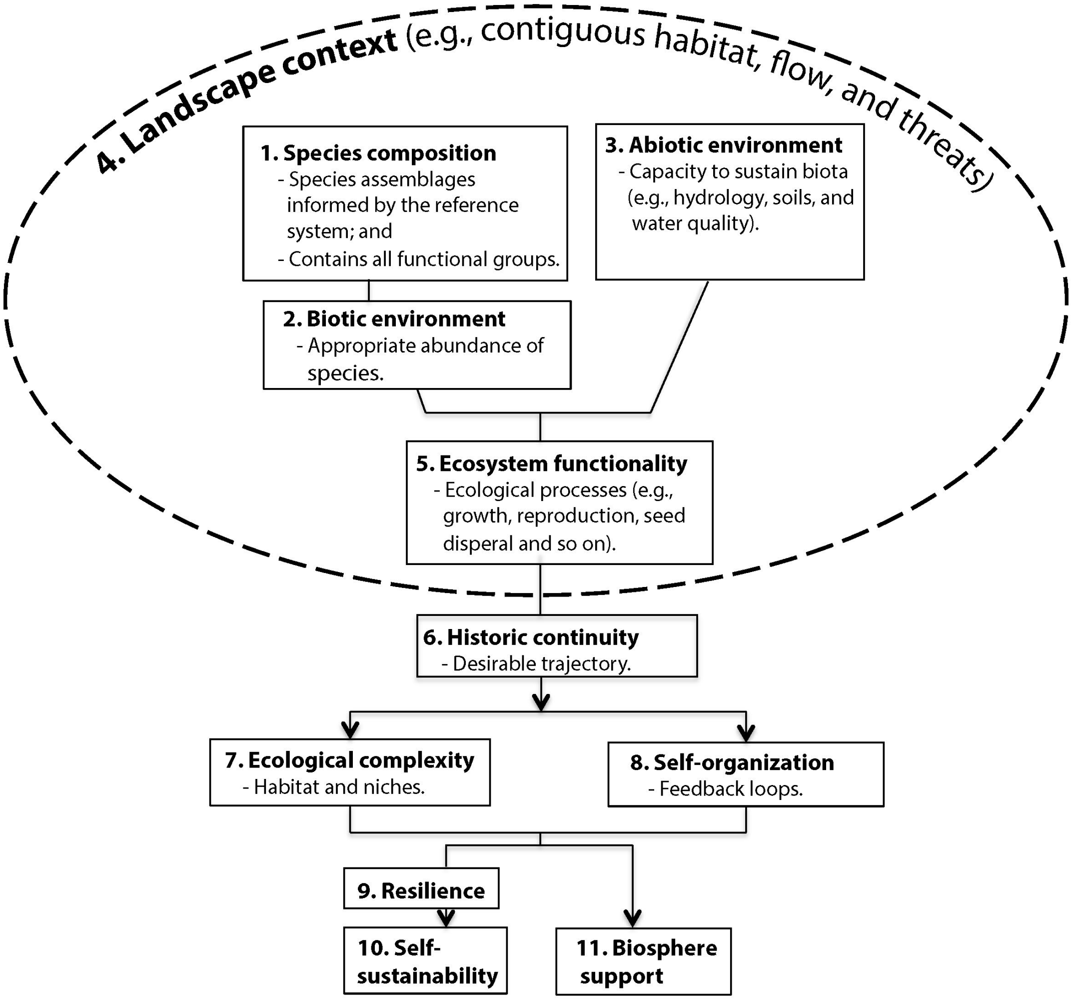

Figure 1.3: Eleven ecological attributes of restored ecosystems, their relationship with each other and order of priority in research and practice (Clewell & Aronson, 2013). Attributes of successfully restored ecosystems can also be applied from an ecosystem management approach. Adapted/ translated by permission from Springer Nature: *Ecological attributes of restored ecosystems*, Clewell, and Aronson (2013).

1.5 PLANT FUNCTIONAL TRAITS

Plant functional traits are defined as traits that influence ecosystem processes or ecosystem services ('effect traits' such as carbon storage, productivity, and nutrient availability) or a species response to environmental conditions ('response traits' such as larger root diameter, reduced root tissue density, and reduced root length due to an increase in nutrients) (Cornelissen et al., 2014; Faucon et al., 2017; Hooper et al., 2005; Lavorel & Garnier, 2002; Moor et al., 2017). These traits can be specific to an individual plant or encompass communities of plants at an ecosystem scale (Reich, 2014). Plant functional traits are seen as the key to predicting the stability, invasibility, resource capture (i.e., allocation of nutrients to different plant structures), nutrient cycling, and productivity of communities (Mason et al., 2003; Mason et al., 2005). Consequently, plant functional traits and the success of ecosystem functioning are considered the most ecologically relevant biodiversity measure (Mason et al., 2003).

1.5.1 PLANT FUNCTIONAL DIVERSITY

Ecosystem function is not dependent on the number of species itself, but the functional traits of species present. This corresponds with the fact that ecosystems with a greater diversity of functional traits will operate more efficiently (Hooper et al., 2005; Mason et al., 2003; Petchey & Gaston, 2002; Petchey et al., 2004). In other words, species diversity alone does not determine how effectively a plant can utilize the abiotic and biotic conditions or plants ability to complement each other (Mason et al., 2003). For example, in Tilman et al., 1997, C4 plants increased biomass production of other plant species by 40% (lower decomposable nitrogen concentrations), and the presence of a legume increased productivity by 59% (greater growth).

A more diverse community is more likely to include dominant species or a combination of complementary species (Hooper et al., 2005). There is a dual requirement of dominant (Schwartz et al., 2000) and minor species regarding ecosystem resilience (Walker, Kinzig, & Langridge, 1999). If a dominant species is lost, minor species can become a substitute for a dominant species, thereby stabilizing an ecosystem's response to a disturbance (Hooper et al., 2005; Walker et al., 1999). Hence, a monoculture dominant plant community often cannot withstand large-scale disturbances.

Plant functional diversity[8] focuses on the distribution and range of what organisms do in a community and ecosystem and considers the complementarity and redundancy of co-occurring species (Schleuter et al., 2010). Hence, plant functional diversity may be a better predictor of ecosystem productivity and vulnerability than traditional taxonomic species diversity (de Bello et al., 2016; Ricotta & Moretti, 2011; Schleuter et al., 2010; Villéger et al., 2008).

In addition, species dominance has an important influence on functional diversity. This is because ecosystem functioning is likely to be closely predictable from the most abundant species that contribute the most to total plant biomass. This is known as the mass-ratio hypothesis (Pla, 2012). Consequently, it is a common practice in the functional diversity approach to include enough species to account for 80% of the total biomass. When species biomass is not available, other measures like cover, basal area, or abundance may be used as a surrogate for biomass (Pla, 2012).

1.5.2 PLANT FUNCTIONAL TRAITS TO ASSESS ECOSYSTEM DYNAMICS

Some ecologists are adopting trait-based approaches to assess how plant community dynamics influence ecosystem processes (Bardgett et al., 2014; de Bello et al., 2010). In general, trait-based measures depend on the specific ecosystem management goal. Plant functional traits can be extremely specific or general. If the specific ecosystem management goal is to assess the wetland's ability to reduce nitrogen or phosphorous loads further downstream, specific traits (e.g., root nitrogen content) that directly influence nitrogen and phosphorous would be ideal. However, specific traits such as root nitrogen content may not be realistic or feasible for small environmental agencies with limited funding. This does not mean small agencies cannot use plant functional traits. For example, maximum plant height measured in this research is an option for ecosystem managers with limited funds to get an idea of how well specific plants or a wetland are doing overall. Maximum plant height is often associated with a plant's relative competitive vigour (Perez-Harguindeguy et al., 2013) and provides insight into the productive capacity of vegetation (Chapin, 2003). The

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[8] Defined as the number of different functional traits represented in an ecological community that influence ecosystem functioning (Tilman, 2001). Functional diversity consists of three components: functional richness, functional evenness, and functional divergence. Functional diversity is often reported as an index.

measurement of maximum plant height is fast and provides a good estimate of the relative biomass of any wetland. While maximum plant height does not directly measure the nutrients absorbed by plants, it is assumed that if the plant is growing larger, more nutrients are assimilated. Above-ground traits of seedhead size and presence or absence can also provide insight into the reproductive capacity via seed dispersal.

Response and Effect Traits Relationship within the Resource Economic Spectrum

Trait variation between species is extremely high and consequently is seen in the context of a resource economic spectrum[9] from traits that facilitate fast-growing species to traits that facilitate conservation of resources typical of slow-growing species (**Figure 1.4:** Bardgett et al., 2014; Reich, 2014). The resource economic spectrum often focuses on plant

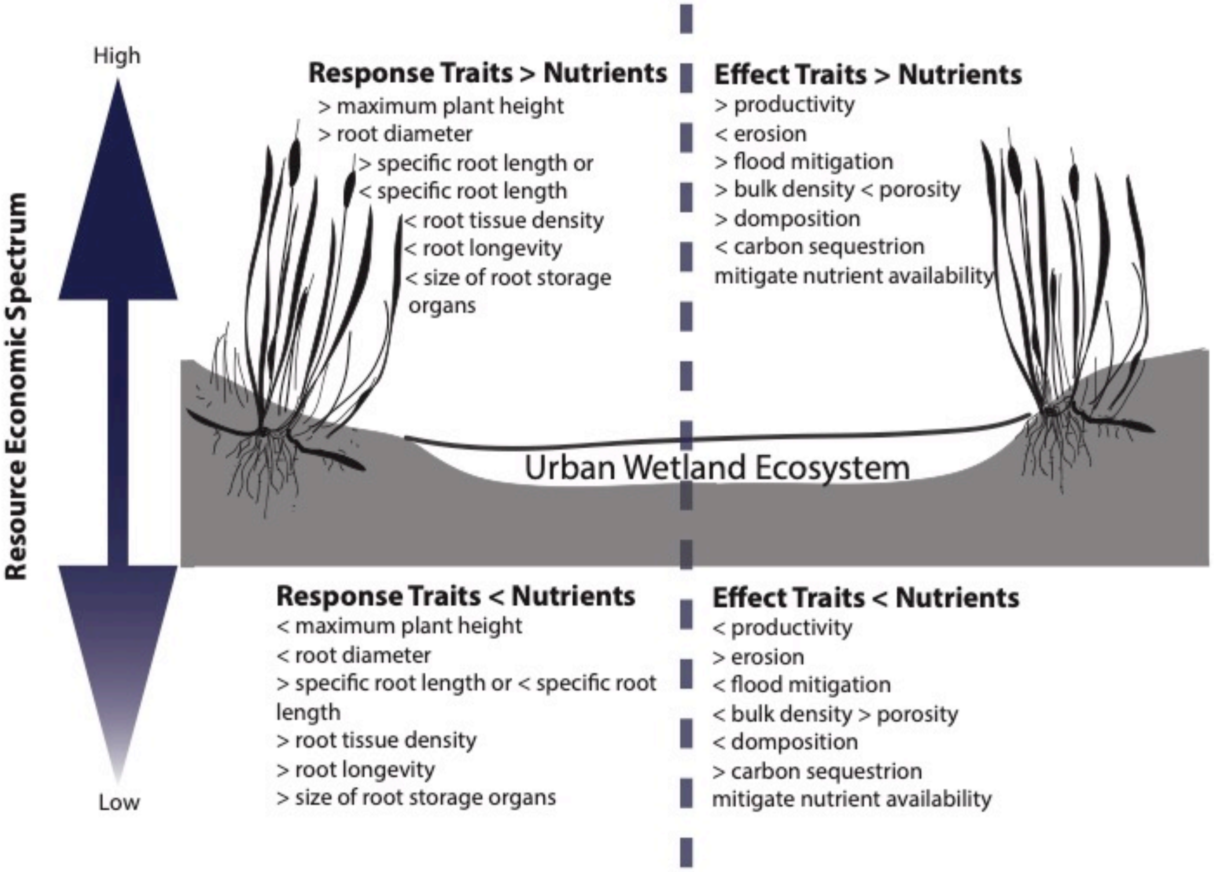

Figure 1.4: division of plant functional traits into response and effect traits along a resource economic spectrum from low to high according to available nutrients.

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[9] Also known as the plant economic spectrum. The idea behind the plant or resource economic spectrum is that all plant traits should correlate with an axis of variation (i.e., fast or slow) to reflect resource assimilation, growth, and life span (Valverde-Barrantes & Blackwood, 2016).

functional traits along a measurable gradient. For example, fast-growing plants with a high specific root length, low root tissue density, high nitrogen uptake, low carbon content, high root respiration, low root life span, large maximum plant height, and reduced carbon sequestration (Moor et al., 2017) are typical for a 'resource-acquisitive spectrum', and vice versa for the 'resource-conservation spectrum' (Bardgett et al., 2014; Mommer & Weemstra, 2012). In other words, the functional trait approach assumes that multiple traits vary together and reinforce the ecosystem effects of another trait (Eviner, 2010). However, traits can vary independently at local scales and variability within or among a species can be as large as a trait's response along a measureable environmental gradient (Eviner, 2010). **Figure 1.4** illustrates the division of functional traits into response and effect traits along an economic resource spectrum from high to low according to the literature. It poses a scenario in which there is an increase or decrease in available nutrients in an urban wetland ecosystem and a plausible plant trait response and effect traits on vital ecosystem processes or ecosystem services.

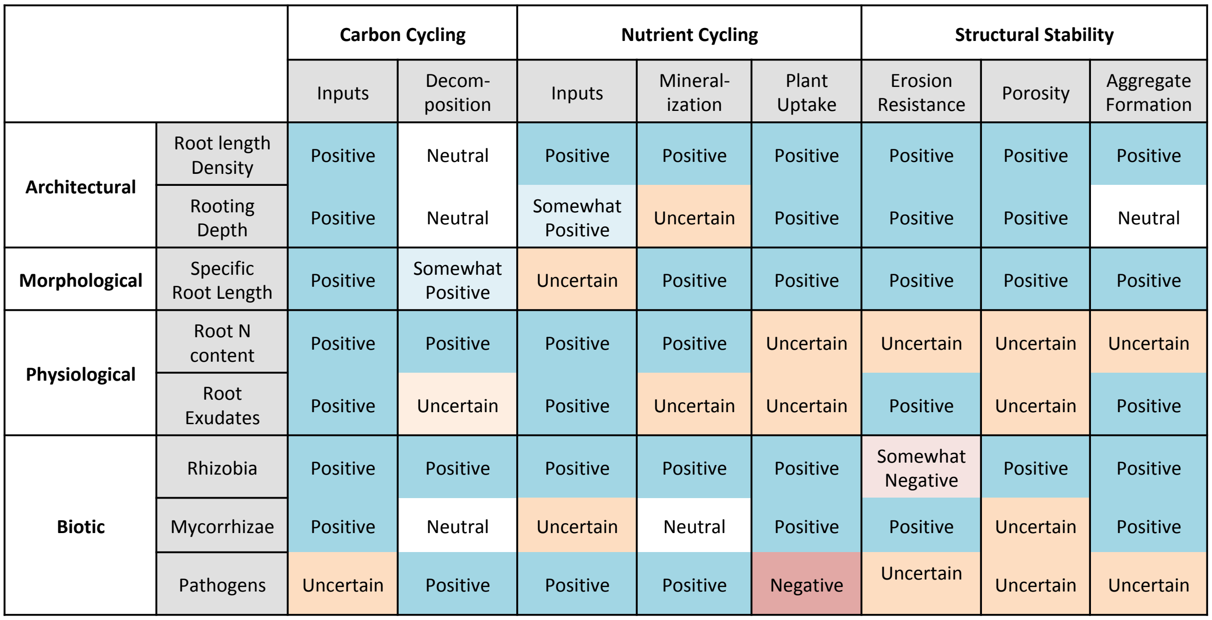
In this particular example, when a nutrient is limited, plant growth is reduced and slow-growing species dominate (slow or 'resource-conservative spectrum'), which results in poor quality litter. Consequently, the accumulation of carbon in the soil is slow and builds up over time (effect trait: carbon sequestration) (de Deyn et al., 2008). When nutrients are readily available, fast-growing plants (response trait: larger maximum plant height on the higher end of the resource spectrum) contribute a significant amount of carbon and decomposable litter to the soil. Specifically, fast-growing plants allocate most of their carbon to active photosynthetic structures of low density (response trait: lower root tissue density and root longevity). In all, plant traits that drive carbon sequestration and nutrient cycling greatly depend on high primary productivity (high relative growth rate/high carbon input) or slow decomposition (low relative growth rate/low carbon input) routes.

Research on Root Functional Traits

While most research has focused on above-ground functional traits, root traits are also important in ecosystem processes, namely, on carbon, nutrient cycling, decomposition, and the formation and structure of soil (Bardgett et al., 2014; Delory et al., 2017; Fitter, 2002; Gregory, 2006; Valverde-Barrantes & Blackwood, 2016). The main reason for the relative dearth of root functional trait research is because it is difficult to directly observe plant roots (Delory et al., 2017).

The general function of roots is to absorb water and nutrients and to provide anchorage (Bardgett et al., 2014; Gregory, 2006; Kramer-Walter, 2016). On the other hand, the shoots, stems, and leaves are responsible for photosynthesis, transpiration, and are often the location of sexual reproduction (while this is not always the case) (Gregory, 2006). It is estimated that up to 70% of plant photosynthetic productivity can be allocated to plant roots (Litton et al., 2007; Poorter et al., 2012; Valverde-barrantes et al., 2017)

Table 1.1: Root trait research categories and their potential impact on ecosystem processes of carbon cycling, nutrient cycling, and soil structural stability based on the literature reviewed in Bardgett et al., 2014. Reprinted from *Trends in Ecology & Evolution,* vol. 29, Bardgett, Mommer, and De Vries, Going underground: Root traits as drivers of ecosystem processes, pp. 692 – 699, 2014, with permission from Elsevier (or applicable society copyright owner).



		Carbon Cycling		**Nutrient Cycling**			**Structural Stability**		
		Inputs	Decom-position	Inputs	Mineral-ization	Plant Uptake	Erosion Resistance	Porosity	Aggregate Formation
Architectural	Root length Density	Positive	Neutral	Positive	Positive	Positive	Positive	Positive	Positive
	Rooting Depth	Positive	Neutral	Somewhat Positive	Uncertain	Positive	Positive	Positive	Neutral
Morphological	Specific Root Length	Positive	Somewhat Positive	Uncertain	Positive	Positive	Positive	Positive	Positive
Physiological	Root N content	Positive	Positive	Positive	Positive	Uncertain	Uncertain	Uncertain	Uncertain
	Root Exudates	Positive	Uncertain	Positive	Uncertain	Uncertain	Positive	Uncertain	Positive
Biotic	Rhizobia	Positive	Positive	Positive	Positive	Positive	Somewhat Negative	Positive	Positive
	Mycorrhizae	Positive	Neutral	Uncertain	Neutral	Positive	Positive	Uncertain	Positive
	Pathogens	Uncertain	Positive	Positive	Positive	Negative	Uncertain	Uncertain	Uncertain

There are several categories within root trait research that influence ecosystem processes that include architectural[10], morphological[11], physiological[12], and biotic root

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[10] Determines the spatial configuration of the root system including, rooting depth, root length density, and root branching (Bardgett et al., 2014).

traits[13]. **Table 1.1** summarizes root trait research categories with their specific influences on carbon cycling, nutrient cycling, and the structural stability of the soil. Specific root length and root diameter are common root traits measured within the morphological root trait category. Root functional trait research can also be divided into two broad categories: acquisitive (absorptive functions) and non-acquisitive functions. Non-acquisitive root functional traits can be further categorized into structural and non-structural compartments. The structural subcategory relates mainly to the function of plant root longevity and anchorage, and in clonal plants, resource transport along rhizomes or ramets (Klimešová, Martínková, & Ottaviani, 2018).

For my research, morphological root traits were the focus. **Table 1.2** reveals the morphological root traits under study and their functional importance

Table 1.2: Synthesis of morphological below-ground traits under study, definitions, and each root functional traits functional importance. Acronyms: SA = surface area; SRL = specific root length; RTD = Root Tissue Density

Root Parameters	**Definition and Functional Importance**
Root Length (cm)	- It is an indicator of a plants response to soil conditions; and - It provides an idea on the capacity roots have to acquire water and nutrients (Bouma, Nielsen, & Koutstaal, 2000).
Surface Area (cm^2)	- It is associated with root density and root diameter; - Thinner roots > SA > exchange zone between plants and soils for nutrients (Costa et al., 2014); and - It is related to the transport of water (Atkinson, 2000).
Diameter (cm)	- It determines a plant's potential for the uptake of water and nutrients (Costa et al., 2014; Kaspar & Ewing, 1997; Perez-Harguindeguy et al., 2013); - It is directly proportional to the uptake of water. Thinner roots exert less penetrative force on soils and transport less water (Perez-Harguindeguy et al., 2013; Atkinson, 2000); - Related positively to root longevity and negatively to nutrient

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[11] Features of roots including, but not limited to, root diameter, specific root length, and root tissue density (Bardgett et al., 2014).

[12] Characterize roots based on, but not limited to, nutrient uptake and root respiration (Bardgett et al., 2014).

[13] Involves direct interactions between roots and soil organisms that range from mycorrhizal fungi, pathogens, and rhizobia in legumes (Bardgett et al., 2014).

	uptake (Bardgett et al., 2014); and - It is known to influence soil stability. Larger root diameter < porosity > bulk density.[14] Finer roots tend to bind to soil more effectively (Bardgett et al., 2014; Faucon et al., 2017).
Volume (ml)	- It provides information on the explorative capacity of the root system.
Specific Root Length (cm g $^{-1}$)	- Length of root per gram of dried root; - It is an index of plant water and nutrient uptake strategy related to the amount of root in contact with soil; - It provides insight into soil nutrient and water exploitation (Atkinson, 2000); - A higher SRL > greater water and nutrient acquisition per unit carbon (Bouma et al., 2000) > growth rates (Perez-Harguindeguy et al., 2013; Sutton-Grier et al., 2013) < root longevity (Bardgett et al., 2014); - A high SRL can result from low diameter or low RTD measurements (Perez-Harguindeguy et al., 2013); and - It is seen to be negatively or positively correlated with leaf traits (e.g., specific leaf area).
Root Density (roots per cm ^{2})	- Number of roots within a cm ^{2}; and - It provides information on the explorative capacity of the root system.
Root Tissue Density (g cm ^{3} or g/ml)	- Resource strategy as it relates to plant growth and survival (Birouste et al., 2014); - A low RTD > faster resource acquisition under high nutrient conditions (not always the case) (Perez-Harguindeguy et al., 2013) < root lifespan > decomposition rates; - RTD is known to increase with decreasing nutrients (Kramer-Walter et al., 2016); - If RTD is lower, mass is less, and volume is greater; - Related positively to root longevity and negatively to nutrient uptake (Bardgett et al., 2014); and - It is known to align with leaf traits (Kramer-Walter et al., 2016).
Root Ball Volume (ml)	- Provides information on the size of the root, and its explorative capacity.
Rhizome *Typha* Volume (ml)	- It offers insight into carbon storage and successional capacity; - Rhizomes increase soil porosity and soil organic content (Bardgett et al., 2014; Cornelissen et al., 2014; Moor et al., 2017); - It provides information on the ability of a plant species to reproduce vegetatively, its competitive vigour, and ability to exploit areas rich in essential nutrients, water or light; and - May show the ability of a plant to migrate under poor seed

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[14] Defined as the weight of soil in a given volume. Bulk density reflects a soils structural properties and its ability to support water and soil aeration. An increase in bulk density can restrict root growth and indicate low porosity and soil compaction.

	dispersal conditions (Klimešová et al., 2018; Perez-Harguindeguy et al., 2013).

1.6 OUTLINE OF RESEARCH QUESTIONS AND EXPERIMENTAL DESIGN

All terrestrial ecosystem consists of above and below-ground components that interact to influence community and ecosystem-level processes and properties (Wardle et al., 2004); therefore, this research used both above and below-ground traits to determine which traits best assess site conditions. Research questions include the following:

- **Overarching research question 1 –** Can below ground functional traits[15] of specific root length, root diameter, root length, root surface area, root volume, root density, root tissue density, and root ball volume (dependent variables) detect differences in urban wetland management regimes (independent variables) in Kitchener, ON?
- **Overarching research question 2 –** Can above-ground functional traits of *Typha* species (e.g., plant height, seedhead length, and absence/presence of a seedhead) detect differences in urban wetland management regimes in Kitchener, ON?
- **General research question 3 –** What functional traits best predict differences in urban wetland management regimes and have the potential to reflect existing ecosystem processes or functions?
- **General research question 4 –** Is *Typha* species or *Phalaris arundinacea* a better predictor of changes in urban wetland management regimes and which better reflects ecosystem processes or functions?

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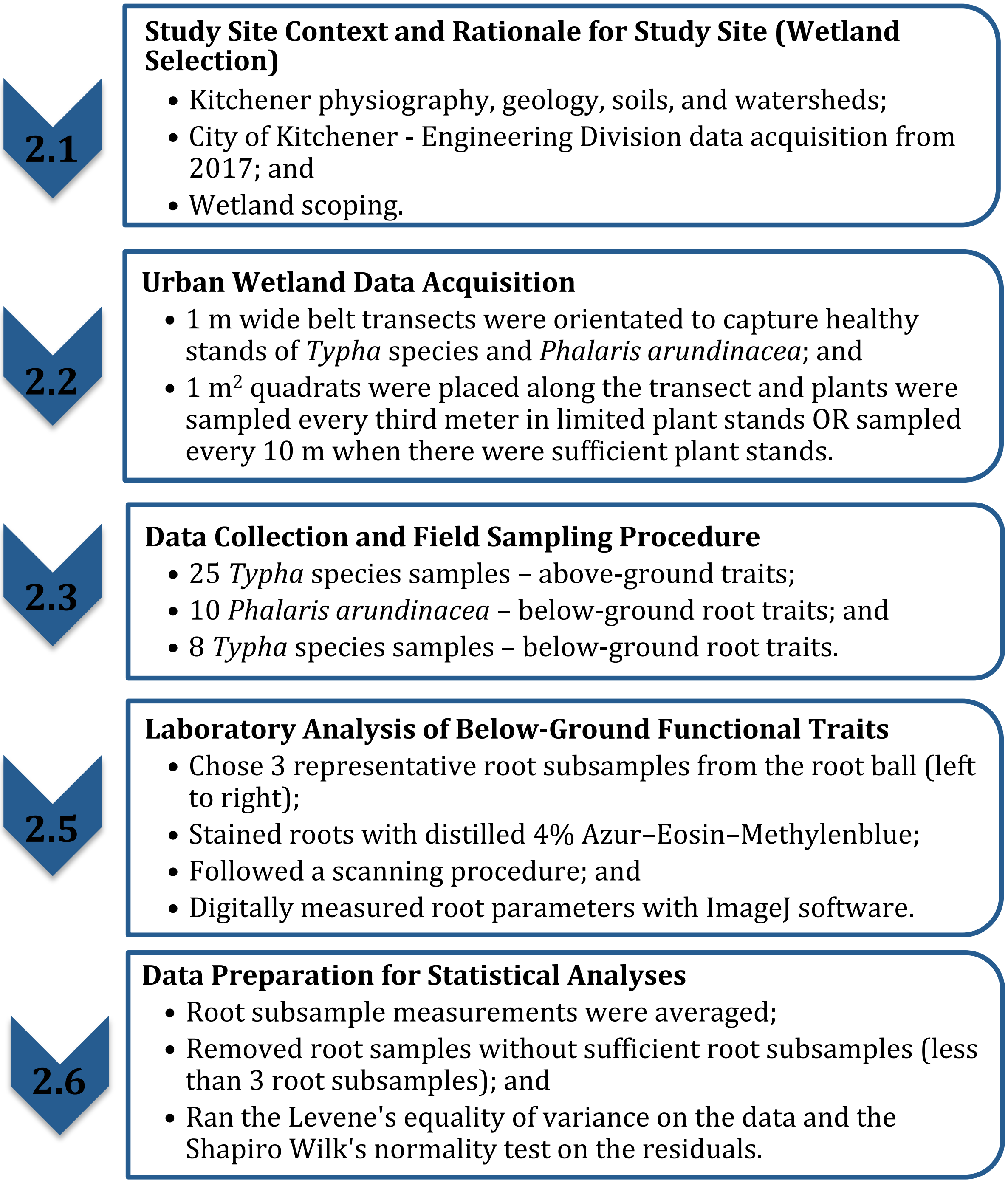
[15] Defined as traits that influence ecosystem processes or ecosystem services (effect traits) or a species response to environmental conditions (response traits) (Cornelissen et al., 2014; Faucon et al., 2017; Hooper et al., 2005; Lavorel & Garnier, 2002; Moor et al., 2017).

CHAPTER 2: TESTING WHETHER FUNCTIONAL TRAITS CAN BE USED TO ASSESS SITE CONDITIONS OR OUTCOMES OF ECOSYSTEM MANAGEMENT IN URBAN WETLANDS

METHODS

Chapter one outlined the rationale and comparative functional trait literature essential to guide the research in its main objective to determine whether traits can be used to assess site conditions or outcomes of ecosystem management in urban wetlands (Chapter 2 – Methods). Five conceptual steps were necessary to answer the overarching and general research questions. Urban wetland management types (independent variables) include on-line stormwater management facilities, wetlands created by agricultural activity, and least disturbed natural wetlands. **Figure 2.1** illustrates the general methodological design for the field, lab, and statistical analyses. The method section of the thesis involves: (1) City of Kitchener and wetland selection; (2) urban wetland data acquisition; (3) data collection and field sampling procedure; (4) below-ground functional traits lab procedure; and (5) data preparation for statistical analysis (**Figure 2.1**).



2.1

Study Site Context and Rationale for Study Site (Wetland Selection)

- Kitchener physiography, geology, soils, and watersheds;
- City of Kitchener - Engineering Division data acquisition from 2017; and
- Wetland scoping.

2.2

Urban Wetland Data Acquisition

- 1 m wide belt transects were orientated to capture healthy stands of *Typha* species and *Phalaris arundinacea*; and
- 1 m^2 quadrats were placed along the transect and plants were sampled every third meter in limited plant stands OR sampled every 10 m when there were sufficient plant stands.

2.3

Data Collection and Field Sampling Procedure

- 25 *Typha* species samples – above-ground traits;
- 10 *Phalaris arundinacea* – below-ground root traits; and
- 8 *Typha* species samples – below-ground root traits.

2.5

Laboratory Analysis of Below-Ground Functional Traits

- Chose 3 representative root subsamples from the root ball (left to right);
- Stained roots with distilled 4% Azur–Eosin–Methylenblue;
- Followed a scanning procedure; and
- Digitally measured root parameters with ImageJ software.

2.6

Data Preparation for Statistical Analyses

- Root subsample measurements were averaged;
- Removed root samples without sufficient root subsamples (less than 3 root subsamples); and
- Ran the Levene's equality of variance on the data and the Shapiro Wilk's normality test on the residuals.

Figure 2.1: General overview of the methodological design for the field, lab, and statistical analyses. Each step corresponds to a section within the methods.

2.1 STUDY SITE CONTEXT AND RATIONALE FOR STUDY SITE (WETLAND SELECTION)

Physiography, Geology, Soils, and Watersheds

European settlement in southwestern Ontario instigated substantial irreversible ecological change. The landscape was once an intricate mosaic of ecosystem types including, forests, wetlands, savannahs, and grasslands. These ecosystems have been altered or removed in favour of extensive agricultural and urban development. Today, the City of Kitchener is part of a larger metropolis that dominates southwestern Ontario. In 2016, the City of Kitchener had a population of 233,700 and is expected to increase to over 304,000 by 2031 (Aquafor Beech, 2016b). The City of Kitchener is situated in the centre of the Grand River Watershed and covers an area of 139 km^2. The Grand River Watershed in the City of Kitchener contains 29 distinct subwatersheds with variable watershed health metrics related to terrestrial ecology, stormwater management, water quality, stream health, and aquatic ecology. Each study site is within a unique subwatershed with diverse water quality issues; physiography; terrestrial ecology health rankings; and aquatic ecology (Aquafor Beech, 2016b). The scoring system follows most other watershed health metrics in that each component metric is given a score from 1 – 5, with 1 representing a 'a very good' score and 5 representing a 'poor' score. Each watershed health metric has additional categorization. Once all watershed health metrics are determined, an average score across all 5 metric components provides an overall score for each subwatershed within the City of Kitchener (Aquafor Beech, 2016b). Lastly, the watersheds are prioritized from 1 – 4. Priority 1 watersheds require the most environmental improvement (score over 20), whereas priority 4 watersheds are the least disturbed (score between 5 and 10).

Figure 2.2 illustrates the chosen urban wetland management regimes within Kitchener, ON which included an on-line stormwater management facility (no. 32), Borden Wetland (least disturbed wetland), and Sunfish Pond, Huron Park Natural Area (wetland created by agricultural activity). Specifically, Borden Wetland (least disturbed wetland) is priority 2 (score between 15 and 20), Sunfish Pond, Huron Park Area (wetland created by agricultural activity) is priority 4, and the on-line stormwater management facility (no. 32) is priority 2 (Aquafor Beech, 2016b).

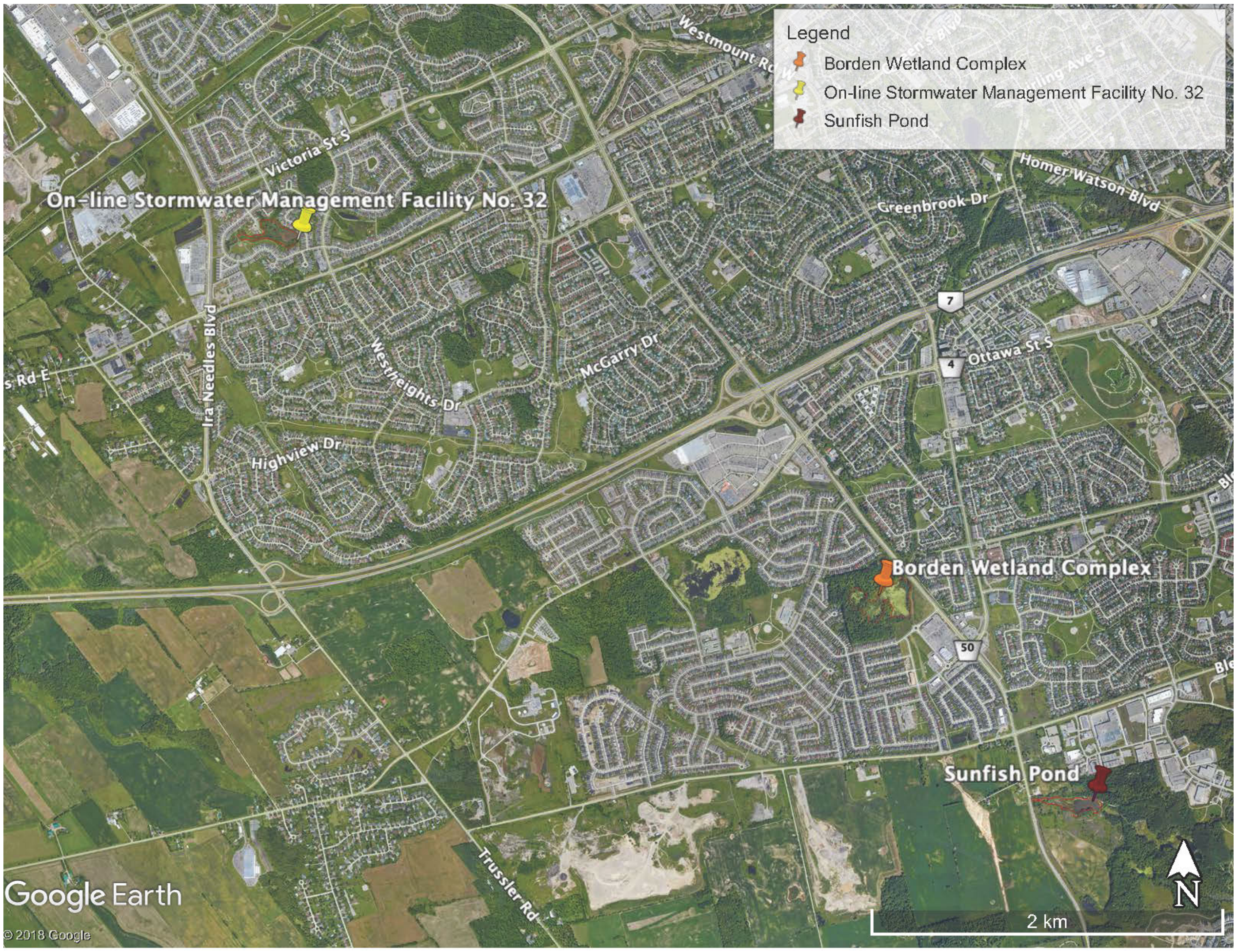


Figure 2.2: Chosen urban wetland management regimes within Kitchener, ON: On-line stormwater management facility (no. 32), least disturbed wetland (Borden Wetland), and wetland created by agricultural activity (Sunfish Pond, Huron Park Natural Area).

In terms of physiography, the City of Kitchener is within the Waterloo Hills physiographic area and is dominated by sandy hills, outwash plains and generally consists of well-drained soils. The Waterloo Moraine is the primary moraine structure within the City of Kitchener. It contains several aquifers, which provide approximately 50% of the groundwater used within the Region of Waterloo's drinking water supply system (Aquafor Beech Ltd., 2016b).

2.2 URBAN WETLAND DATA ACQUISITION

All study sites occurred within the City of Kitchener limits. For comparative purposes, I needed sites that had similar geographical or climatic regimes, life zones, and natural disturbances. This is essential in order to facilitate an accurate comparison between urban wetland management regimes (Hobbs & Harris, 2001; Ruiz-Jaen & Aide, 2005; SER, 2004). Ecological systems are inherently complex and differ within the same management type. Preferably, there should be more than one study site within each urban wetland management regime to account for natural variation (Ruiz-Jaen & Aide, 2005). Unfortunately, due to time constraints and a lack of similar plant species across study sites, there was only one study location within each urban wetland management regime.

Information on wetland sites within the City of Kitchener was gathered from Chris Nechacov (City of Kitchener – Engineering Division: Civil Technologist)[16]. The chosen urban wetland management regimes for the study were determined through the use of an online interactive map, information gathered from Chris Nechacov, orthoimagery, and Google satellite imagery. There are 179 active stormwater management facilities in Kitchener that range from dry ponds, wet ponds, natural ponds, constructed wetlands, and hybrid wet ponds/wetlands (**APPENDIX A**). Dry ponds are those designed to prevent urban flooding during periods of heavy rainfall. They are generally 'dry.' They are designed for erosion and flood control (Aquafor Beech Ltd., 2016b). Wet ponds are the most common stormwater management facility in the City of Kitchener. They hold a permanent pool of water that ranges from 1 – 3 m deep. Constructed wetlands are the least common stormwater management facility in the City of Kitchener due to their initial construction costs. As a result, constructed wetlands are often only suggested for drainage areas less than 10 ha. Constructed wetlands are 150 – 300 mm deep (Aquafor Beech Ltd., 2016 & Chris Nechacov e-mail correspondences). Hybrid wet ponds/ wetlands use a combination of wet ponds and constructed wetlands. They require a permanent pool of water.

For simplicity, only wet ponds, constructed wetlands, natural ponds (on-line facilities), and hybrid wet ponds/ wetlands that were at least 0.125 m long were eligible for

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[16] All real-time data on stormwater management facilities were obtained from Chris Nechacov in the summer of 2017.

the study. Two dominant plant species were identified from site visits to facilitate a comparison between contrasting urban wetland management regimes: *Typha* species and *Phalaris arundinacea.* I chose only to sample *Typha* and *Phalaris arundinacea* as these species were common between urban wetland management regimes.

Within the category of natural ponds exists a subcategory of on-line stormwater management facilities. Natural ponds are not explicitly labeled as on-line stormwater management facilities on Kitchener's active stormwater management facility map but are understood by the engineering department to exist (**APPENDIX A**). On-line stormwater management facilities are the older version of stormwater management facilities. They were created through excavating natural streams to create a large standing body of water – the retention pond. On-line stormwater management facilities are no longer in practice due to logistical issues. It is difficult to routinely clean out sediment from on-line stormwater management facilities due to their natural locale on existing streams. On-line stormwater management facilities also pose conflicts with conservation if there are sensitive plant or animal species, and the modification of any 'navigable waterway' requires a federal permit.

Ontario Cattail Species Description

There are three species of cattail in Ontario: *Typha latifolia* (broadleaf cattail), *Typha angustifolia* (narrowleaf cattail), and a hybrid cattail (*Typha x glauca*). *Typha latifolia* has a competitive advantage in shallow water (less than 15 cm), and *Typha angustifolia* has an advantage in deeper water (Grace, Wetzel, & Kellogg, 1982). *Typha latifolia* has a competitive advantage in shallower water because it has a greater surface leaf area. *Typha latifolia's* higher leaf area allows it to capture light more efficiently and results in a low allocation to sexual reproduction. On the other hand, *Typha angustifolia* has an advantage in deeper water through its ability to produce an extensive rhizome network, which allows it to grow taller. Additionally, *Typha angustifolia* has a higher ability to regrow from previous years' rhizomes (Grace et al., 1982).

It is rare for mixed stands of *Typha angustifolia* and *Typha latifolia* not to hybridize. Molecular analyses are necessary to accurately discern *Typha angustifolia* and *Typha latifolia* from each other (Travis et al., 2010). Consequently, hybrid species are the most common species of *Typha* found in a natural system and have a competitive advantage over parent *Typha*. Hence, for this study, *Typha* species were not discerned from each other.

Phalaris arundinacea Description

Phalaris arundinacea is an invasive perennial wetland grass that occurs chiefly throughout the Northern Hemisphere (Martina & Von Ende, 2012). *Phalaris arundinacea* is native to Eurasia and North America. Non-native genotypes or cultivars were introduced to North America to aid in agricultural (e.g., forage crops) and soil stabilization practices (Lavergne & Molofsky, 2004; Martina & Von Ende, 2012). *Phalaris arundinacea* grows best under cool, moist, and high light environmental conditions (Lavergne & Molofsky, 2004). It can be found in a range of wet habitats, including wet meadows, wetlands, lakeshores, dynamic riverbanks, and floodplains (Lavergne & Molofsky, 2004). It is highly aggressive through its ability to produce large monotypic stands, a large number of seeds, and its rapid growth. It also can produce large underground rhizome networks, which allows for aggressive vegetative spread (Lavergne & Molofsky, 2004). Hence, *Phalaris arundinacea* can successively outcompete native species for essential soil resources. In addition, its competitive advantage is increased through its ability to increase root growth under low moisture conditions; its efficient use of water; elastic cell walls; ability to switch life forms (e.g., expansive stands versus bunches); and the colonization of roots with endomycorrhizal fungi to increase the uptake of phosphorous in dry conditions (Lavergne & Molofsky, 2004).

Phalaris arundinacea is also known to increase in biomass to a higher degree with an increase in nutrient enrichment in comparison to native species (Green & Galatowitsch, 2002; Lavergne & Molofsky, 2004; Martina & Von Ende, 2012).

Label Re-categorization: Preliminary Study Site Narrowing

Labels acquired from the City of Kitchener’s engineering department were not always an accurate depiction of the history of stormwater management ponds. Specifically, some of the stormwater management facilities labeled ‘natural’ are not ‘natural.’ Consequently, I sorted the data received from the engineering department and re-categorized information based on their actual history. New labels were created for stormwater management facilities through the use of Google imagery and orthoimagery dated as far back as 1930. Isolated wetland features displayed through orthoimagery were labeled as ‘least disturbed wetlands.’ Least disturbed wetlands are considered ‘natural’ and occurred before human interference.

Wetland features with small water channels originating from stationary water bodies are not natural wetlands. These features likely existed due to previous draining or damming activities on agricultural land. They were re-categorized as ‘wetlands created by agricultural activity.’

The last category – on-line stormwater management facilities represent the most engineered and disturbed wetland feature found within the City of Kitchener.

Preliminary Study Site Randomization

Randomization followed preliminary study site narrowing. This was critical to reduce experimental and personal biases. Least disturbed natural wetlands, wetlands created by agricultural activity, and stormwater management facilities within the City of Kitchener were assigned a number. Afterward, I used R to derive a list of random numbers for each urban wetland management regime. A total of seven study sites were chosen for each urban wetland management regime (**APPENDIX A, B, and C**). This was narrowed to a list of three sites which could be sampled, which was then reduced to one based on time, access issues (private land), and presence of vegetation to sample (greater than 1 m of emergent *Phalaris arundinacea* and *Typha* along the fringe of wetland features). **Table 2.1** reveals the list of eliminated and chosen stormwater management facilities within the City of Kitchener, ON (**Table 2.1**). After elimination, the chosen study sites included one on-line stormwater management facility (no. 32), a wetland created by agricultural activity (Sunfish Pond, Huron Park Natural Area), and one least disturbed wetland (Borden Wetland) within the City of Kitchener, ON (**Table 2.1** & **Figure 2.2**).

Table 2.1: List of eliminated and chosen urban wetland management regimes within Kitchener, ON that included stormwater management facilities, least disturbed natural wetlands, and wetlands created by agricultural activity. * Eliminated due to time constraints.

Stormwater Management Facilities		**Least Disturbed Natural Wetlands (Reference)**		**Wetlands Created by Agricultural Activity**	
Chosen	Eliminated	Chosen	Eliminated	Chosen	Eliminated
No. 32 – on-line facility	#100, #124, #49 & #144 – no vegetation	Grand River Wetland *	2 Ag. Wetlands – access issues	Stanley Park *	Board of Education Pond, Huron Park Natural Area – no vegetation
	#76 & #33 – no *Phalaris arundinacea*	Borden Wetland	Large Huron Park Wetland & Laurentian Wetland – no vegetation	Sunfish Pond, Huron Park Natural Area	Hidden Valley Wetland – access issues
	# 101, #61, #126 – no significant *Phalaris arundinacea*		Small Huron Park Natural Area Wetland – dominated by *Phalaris arundinacea*; very little Typha species	Lakeside Park *	Idlewood Creek – no vegetation
	#125 – external issues (bulldozed vegetation)				

2.3 DATA COLLECTION AND FIELD SAMPLING PROCEDURE

Root Functional Traits General Field Procedure

The *handbook on the measurement of plant functional traits worldwide* was essential to outline key plant functional traits, how to collect plant samples, and the measurement of plant functional traits (Cornelissen et al., 2003; Perez-Harguindeguy et al., 2013). **Table 2.1** illustrates the general sampling schedule in the summer of 2017; the chosen plant functional traits; the recommended number of replicates; and the actual number of replicates collected in the field. Within each quadrat, I sampled healthy and similar sized *Typha* and *Phalaris arundinacea* within a radial 10 m vicinity of quadrats. Dwarfed, diseased, or insect-infested plants were excluded from the plant collection.

A large garden shovel was used to uproot *Typha* and *Phalaris arundinacea.* The top 20 cm is the standard basis for comparing specific root length between plants (Cornelissen et al., 2003; Perez-Harguindeguy et al., 2013). Uprooting *Typha* was extremely labour intensive and took up substantial space in the fridge. Therefore, I sampled 8 *Typha* per transect. I was able to collect the recommended maximum number of root samples for *Phalaris arundinacea* (10), as they were easily excavated and compactable. Once plants were collected in the field, they were stored in a refrigerator at 2 – 6° C for a maximum of seven days.

Above-ground Functional Trait Field Procedure: Maximum Plant Height, Presence and Absence of Seedhead, and Seedhead Length of *Typha*

Maximum heights of 25 *Typha* were obtained on September 18 and 19, 2017 within a 10 m radial vicinity of quadrats (**Table 2.2**). This was determined through the use of a straight metre stick placed at the base of the plant to the highest stretched height of the plant. The maximum height of *Phalaris arundinacea* was excluded because this species tends to senesce and decompose relatively early (August).

The presence or absence and seedhead length measurements of 25 *Typha* were manually taken from the quadrats on September 18 and 19, 2017.

Table 2.2: Plant functional traits, unit of measurement, recommended number of replicates (after Perez-Harguindeguy et al., 2013), and the actual number of replicates. Acronyms: SRL = specific root length; TY = *Typha*; IRCG = invasive reed canary grass; n/a = not applicable.

			Number of replicates		
TY	**Plant Trait**	**Unit**	**Recommended No.**		**Actual No. Sampled**
			Min.	**Max.**	
	SRL	cm g^{-1}	5	10	8
	Max Plant Height	m	n/a	25	25
IRCG	SRL	cm g^{-1}	5	10	10
	Max Plant Height	n/a	n/a	25	25

Transect and Quadrat Location

Belt transects were conveniently placed in large healthy stands of *Typha* and *Phalaris arunindinacea.* Ideally, 3 – 4 transects for each species should have been placed in each urban wetland management regime to increase the sample size, thereby reducing scientific error. However, this was not realistic in the field. As a result, 2 belt transects per species were placed in the most extensive stand. Each belt transect was stratified into numerous 1 m^2 quadrats. In expansive stands, 1 m^2 quadrats were placed every 10 m (0 – 1 m; 11 – 12 m). In non-expansive stands, 1 m^2 quadrats were placed every 3 m (0 – 1 m; 4 – 5 m). Belt transects began where the plants under study were most prominent and ended where the plant stand terminated. Each quadrat was assigned a GPS coordinate.

Summer 2017 Plant Sampling Schedule

Table 2.3 shows the detailed plant sampling schedule for root and maximum plant height parameters in the stormwater management on-line facility (no. 32), the wetland created by agricultural activity (Sunfish Pond), and the least disturbed natural wetland (Borden Wetland). Plant sampling commenced in the summer of 2017 from June 27 –

September 19. Maximum plant height was collected at the end of the growing season (September 17 – September 19).

Table 2.3: Summer 2017 sampling schedule for chosen plant functional traits (root parameters and maximum height) within urban wetland management regimes: on-line stormwater management facility, wetland created by agricultural activity, and least disturbed natural wetlands. Acronyms: STMWM = Stormwater Management; Ag = Agricultural; IRCG = Invasive Reed Canary Grass; TY = *Typha*

Plant Trait	Urban Wetland Management Regime	Study Site	Start	End
Specific Root Length and Other Root Parameters	On-line STMWM Facility	No. 32 – TY	9-Aug-17	16-Aug-17
		No. 32 – IRCG	10-Aug-17	11-Aug-17
	Created by Ag. Activity	Sunfish Pond - TY	27-Jun-17	28-Jun-17
		Sunfish Pond - IRCG	8-Jul-17	8-Jul-17
	Least Disturbed	Borden Wetland - TY	14-Jul-17	17-Jul-17
		Borden Wetland - IRCG	14-Jul-17	15-Jul-17
Maximum Plant Height (m), Seed Head Length (cm), and Presence/ Absence	Least Disturbed	Borden Wetland – TY	17-Sept-17	17-Sept-17
	Created by Ag. Activity	Sunfish Pond – TY	19-Sept-17	19-Sept-17
	On-line STMWM facility	No. 32 – TY	19-Sept-17	19-Sept-17
	*Did not measure IRCG as plant structure began to break down.			

2.3.1 ON-LINE STORMWATER MANAGEMENT FACILITY NO. 32

Detweiler Creek Subwatershed Description

The on-line stormwater management facility no. 32 is located in the Detweiler Creek subwatershed (201.3 ha). Warm-water streams dominate Detweiler Creek subwatershed. In terms of water quality, Detweiler Creek subwatershed has a score of 3 or fair (Aquafor Beech, 2016b). In response to stormwater management practices, water quality, stream health, aquatic ecology, and terrestrial ecology, Detweiler Creek subwatershed has an average score of 16.4 (priority 2). This score means that Detweiler Creek subwatershed could use improvement in some or all categories, but on average, it is not considered to be the worst within the City of Kitchener. Detweiler Creek subwatershed's worst ranking was due to its stormwater management practices (Aquafor Beech, 2016a).

Detweiler Creek subwatershed includes a number of natural heritage system[17] features including locally significant wetlands (**APPENDIX D**); locally significant woodlands (**APPENDIX E**); locally significant valleylands (**APPENDIX F**); and valleyland/stream restoration (**APPENDIX H**). Specifically, the on-line stormwater management no. 32 includes locally significant woodlands (**APPENDIX E**), locally significant wetlands (**APPENDIX D**), and valleyland/stream restoration (**APPENDIX H**).

Site Description

The stormwater management facility itself was created in 1994 and has a catchment area of 16.7 ha (Chris Nechacov e-mail correspondence & Aquafor Beech Ltd., 2016b). The study site is 0.04 ha (Google Earth measurements). It is labeled as a 'natural pond,' but is understood by the engineering department as an on-line stormwater management facility. **Figure 2.2** and **2.3** illustrates the on-line stormwater management facility no. 32 surrounded by a residential development within the context of the City of Kitchener. The eastern portion of the on-line stormwater management facility was open water (**Figure 2.3**). There was no emergent vegetation for sampling within the open water section of the stormwater management facility.

Stormwater management facility no. 32 was surrounded by woody and vegetative upland species including: *Solidago* species (golden rod), invasive *Lonicera maackii* (amur honeysuckle), invasive *Dipsacus fullonum* (wild teasel), *Rubus idaeus* (wild red raspberry), *Arctium* species (burdock), *Erigeron* species (fleabane), *Galium boreale* (northern bedstraw), *Bromus commutatus* (smooth brome), *Populus* species (poplar), invasive *Cirsium arvense* (creeping thistle), *Vitis riparia* (riverbank grape), *Trifolium* species (clover), *Salix* species (willow), *Asclepias speciosa* (showy milkweed), *Impatiens capensis* (jewel weed), and invasive *Rhamnus cathartica* (common European buckthorn).

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[17] Defined as a system of natural heritage features and linkages to encourage habitat connectivity at regional and local levels necessary to support natural processes to maintain biological and geological diversity, natural functions, and adequate populations of native species and ecosystems (Aquafor Beech Ltd., 2016a). A natural heritage system can include natural areas, restoration areas, habitat corridors, wetlands, valleylands, woodlands, fish, plants and wildlife, significant landforms, and groundwater recharge/discharge areas (The City of Kitchener, 2014).

Figure 2.3: Overview of belt transects and quadrat locations in the on-line stormwater management facility (no. 32) within Kitchener, ON. The study site consists of 2 *Phalaris arundinacea* (= IRCG label) transects and 2 *Typha* (= TY label) transects.

The vast majority of *Typha* existed directly west of the open water feature of the on-line stormwater management facility. **Figure 2.3** also provides a visual overview of the belt transects and quadrat locations. The on-line stormwater management facility no. 32 had 3 transects. Transect 1 from quadrat 1 – 6 was dominated by a dense stand of *Typha* species (**Figure 2.4**). The understory of transect 1 (up to and including quadrat 6) consisted of *Solanum dulcamara* (climbing nightshade), *Decodon verticillatus* (purple loosestrife), *Cornus stolonifera* (red osier dogwood), *Leersia oryzoides* (rice cut grass), *Impatiens capensis* (jewel weed), and *Vitis riparia* (riverbank grape). **Figure 2.5** illustrates some of the understory species present from transect 1 (quadrats 1 – 6).

Figure 2.4: Photo illustrating the beginning of transect 1 with dense *Typha* stands orientated northward.

Transect Plant Species

As transect 1 progressed north (past quadrat 6), the vegetation transitioned to more upland species. The dominant plant species north of the *Typha* was *Phalaris arundinacea* (second plant species under study). Other species present from quadrant 7 – 11 were *Decodon verticillatus* (purple loosestrife), non-native *Daucus carota* (Queen Anne's lace), and *Solidago* species (golden rod).

Transect 2 was dominated by *Typha*. The understory of transect 2 consisted of *Cornus stolonifera* (red osier dogwood), *Leersia oryzoides* (rice cut grass), and *Decodon verticillatus* (purple loosestrife).

Transect 3 was dominated by *Phalaris arundinacea.* The understory of transect 3 included *Impatiens capensis* (jewel weed), *Decodon verticillatus* (purple loosestrife), and *Cornus sericea* (red osier dogwood).

Cattail Species Observations

Although *Typha* hybridize with each other, *Typha* within this urban wetland management regime appeared visually different from other study sites within the City of Kitchener. Specifically, *Typha* in the on-line stormwater management facility no. 32 had a narrower leaf and seedheed width. This suggests that *Typha* in the on-line stormwater management facility were a different species – *Typha angustifolia* (narrow-leaf cattail).

Figure 2.5: Photo of common understory species from transect 1 (quadrats 1 – 6). Photo is orientated northward.

2.3.2 WETLAND CREATED BY AGRICULTURAL ACTIVITY (SUNFISH POND)

Middle Strasburg Creek Subwatershed Description

Sunfish Pond in Huron Park Natural Area is situated within the Middle Strasburg Creek subwatershed (673.9 ha). Cold-water streams dominate Middle Strasburg Creek subwatershed. In terms of water quality, Middle Strasburg Creek subwatershed has an average score of 4 (good) (Aquafor Beech, 2016b). In response to stormwater management practices, water quality, stream health, aquatic ecology, and terrestrial ecology, Middle Strasburg Creek subwatershed has an overall average score of 9.7 (priority 4). This score means that Middle Strasburg Creek subwatershed is considered the closest to the natural environmental conditions of subwatersheds in the City of Kitchener. Middle Strasburg Creek subwatershed's worst ranking was from its terrestrial score.

Middle Strasburg Creek subwatershed includes a number of natural heritage system features including locally significant wetlands (**APPENDIX D**); locally and regionally significant woodlands (**APPENDIX E**); locally significant valleylands (**APPENDIX F**); and significant groundwater recharge areas (**APPENDIX G**).

Specifically, Sunfish Pond in Huron Park Natural Area includes locally and regionally significant wetlands (**APPENDIX D**), regionally significant woodlands (**APPENDIX E**), locally significant valleylands (**APPENDIX F**), and high/medium/low groundwater recharge areas (**APPENDIX G**). Sunfish Pond is a relatively young feature on the landscape that existed after 1966 (orthoimagery). It was created through agricultural damming activities. Sunfish Pond has an area of 4.2 ha (Google Earth measurement). **Figure 2.2** and **2.6** illustrates Sunfish Pond on the fringe of rural and urban development within the City of Kitchener. Sunfish Pond is part of a larger natural network – the Huron Park Natural Area and is surrounded by a hilly agricultural and wooded topography.

Figure 2.6: Overview of belt transects and quadrat locations in Sunfish Pond, Huron Park Natural Area within Kitchener, ON. The study site consists of 2 *Phalaris arundinacea* (= IRCG label) transects and 2 *Typha* (= TY label) transects.

Site Description

Upland woody and vegetative species included: *Solidago* species (golden rod), *Gallium boreale* (northern bedstraw), *Rhus typhina* (staghorn sumac), invasive *Lonicera maackii* (amur honeysuckle), *Arctium* species (burdock), *Rubus* species (raspberry), *Trifolium* species (clover), *Vitis riparia* (riverbank grape), *Galium boreale* (northern bedstraw), invasive *Dipsacus fullonum* (wild teasel), non-native *Daucus carota* (Queen Anne's lace), invasive *Cirsium arvense* (creeping thistle), *Anemone canadensis* (Canada anemone), *Convolvulus arvensis* (field bindweed), *Parthenocissus quinquefolia* (Virginia creeper), *Asclepias syriaca* (common milkweed), *Picea* species (spruce), *Acer negundo* (Manitoba Maple), and *Acer saccharium* (silver maple).

Water-loving or semi-wet species seen in or surrounding Sunfish Pond included: *Salix* species (willow), invasive *Fallopia japonica* (Japanese knotweed), *Equisetum* species (horsetail), invasive *Lythrum salicaria* (purple loosestrife), Cornus species (dogwood), *Solanum dulcamara* (climbing nightshade), *Impatiens capensis* (jewel weed) 2 Carex species (sedge), 2 *Eleocharis* (spike rush species), and *Typha* (cattail).

Figure 2.7: Photo of dense stands of *Phragmites australis* east of Fischer-Hallman Road. The photo is orientated eastward.

Phalaris arundinacea dominated the eastern portion of Sunfish Pond (directly adjacent to Fischer-Hallman Road). Eastward, dense stands of *Phragmites australis* subspecies *australis* (invasive phragmites) overshadow *Phalaris arundinacea.* **Figure 2.7** illustrates *Phragmites australis* on either side of Sunfish Pond. As one progressed further eastward, water-loving plant communities consisted of *Typha* (cattail species), *Carex* species (sedge species), and *Eleocharis* species (spike rush species).

Transect Plant Species

Transect 6 and 7 were dominated by *Phalaris arundinacea.* The understory of transect 6 and 7 consisted of *Impatiens capensis* (jewel weed), *Parthenocissus quinquefolia* (Virginia creeper), *Convolvulus arvensis* (field bindweed), and *Vitis riparia* (riverbank grape).

Transect 3 was dominated by *Typha*. The understory of transect 3 consisted an unknown *Carex* species (sedge), and *Galium boreale* (northern bedstraw).

Transect 5 was placed in a stand of *Typha*. The understory of transect 5 consisted of an unknown *Carex* species (sedge), *Impatiens capensis* (jewel weed), and *Galium boreale* (northern bedstraw).

Cattail Species Observations

Although all *Typha* species hybridize with each other, *Typha* in Sunfish Pond appeared to have a mix of plants with a broader leaf/seedhead and a narrow leaf/seedhead. This suggests that *Typha* in Sunfish Pond had a mix of *Typha angustifolia* and *Typha latifolia.* **Figure 2.8** illustrates the mix of *Typha* found in Sunfish Pond, Huron Park.

Figure 2.8: Photo illustrating the mix of *Typha* found in Sunfish Pond, Huron Park.

2.3.3 LEAST DISTURBED NATURAL WETLAND (BORDEN WETLAND)

Borden Creek Subwatershed Description

Borden Wetland is situated within the Borden Creek subwatershed (518.9 ha). Warm-water streams dominate Borden Creek subwatershed. In terms of water quality (Aquafor Beech, 2016b), Borden Creek subwatershed has a score of 1 (poor). In response to stormwater management practices, water quality, stream health, aquatic ecology, and terrestrial ecology, Borden Creek subwatershed has an overall average score of 17.5 (priority 2). This score means that Borden Creek subwatershed could use improvement in some or all categories, but on average, it is not considered to be the worst within the City of Kitchener. Borden Creek subwatershed's worst category was its water quality score.

Borden Creek subwatershed includes a number of natural heritage system features including locally significant wetlands (**APPENDIX D**); regionally significant woodlands (**APPENDIX E**); locally significant valleylands (**APPENDIX F**); and high/medium groundwater recharge areas (**APPENDIX G**). Specifically, Borden Creek study area includes locally significant wetlands (**APPENDIX D**); regionally significant woodlands (**APPENDIX E**); locally significant valleylands (**APPENDIX F**), and medium groundwater recharge areas (**APPENDIX G**).

Borden Wetland is the least disturbed wetland in comparison to the other study sites in the City of Kitchener. It visibly existed before 1955 (orthoimagery) and has a catchment area of 122.1 ha. While Borden Wetland is a natural feature, it was modified in 2002 to act as a drainage area for stormwater runoff. Culverts for surface runoff were evident during site visits. The study site itself has an area of 6.2 ha (Google Earth measurement). **Figure 2.2** and **2.9** illustrates how Borden Wetland is situated within the City of Kitchener. It is surrounded by residential and commercial development.

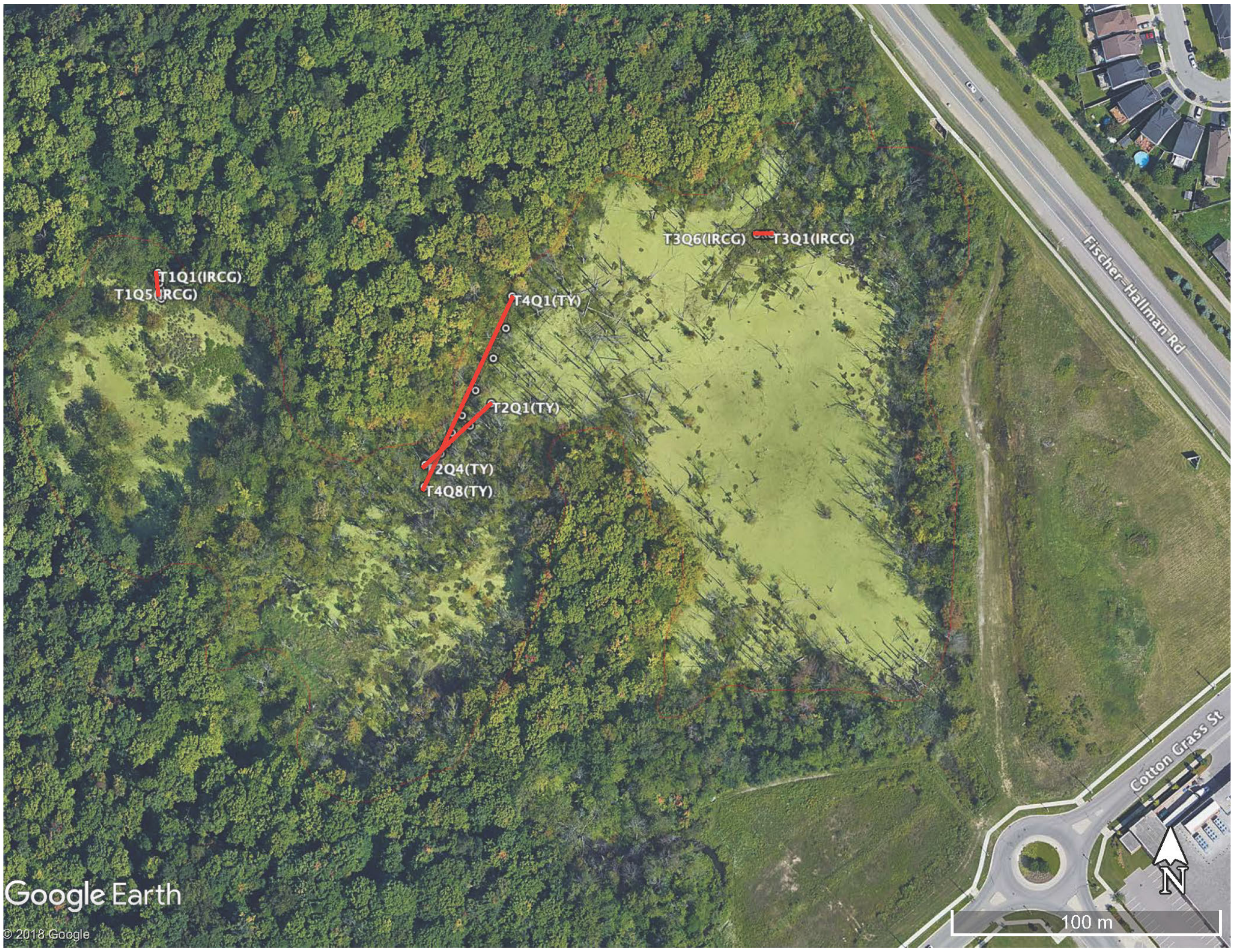

Figure 2.9: Overview of belt transects and quadrat locations in Borden Wetland within Kitchener, ON. The study site consists of 2 *Phalaris arundinacea* (= IRCG label) transects and 2 *Typha* (= TY label) transects.

Site Description

Borden Wetland is a unique wetland feature on the landscape. The wetland complex had *Acer x freemanii* (freeman's maple) and *Fagus grandifolia* (American beech) trees growing on 'islands' above the water. Often these 'islands' included clumps of *Iris versicolor* (blue-flag iris) (**Figure 2.10**). A maple-beech woodland surrounded Borden Wetland.

Figure 2.10: Photo of Borden Wetland with 'islands' of *Iris versicolor* (blue-flag iris), *Fagus grandifolia* (American beech), and *Acer x freemanii* (freeman's maple). This photo was taken near transect 2 and 4, orientated northeast.

Small *Acer x freemanii* (freeman's maple saplings), Rubus species, *Chelidonium majus* (Celandin), *Hydrophyllum virginianum* (Virginia waterleaf), *Maianthemum racemosum* (false soloman seal), *Tussilango farfara* (coltsfoot), *Polypodiopsida* species (ferns), *viola* species (violet) and *Caulophyllum thalictroides* (blue cohosh) dominated the understory in Borden Wetland.

Semi-wet or wet species within or surrounding Borden wetland included: 4 different *Carex* species (sedges), *Sagittaire latifoliee* (broad-leaved arrowhead), *Iris versicolor* (blue-flag iris), *Nymphaea odorata* (fragrant water lily), *Ascelpia incarnate* (swamp milkweed), *Polypodiopsida* species (fern), *Typha* (cattail), an unknown *Urticaceae* species (nettle), an unknown *Caryophyllaceae* species (chickweed), and *Phalaris arundinacea* (invasive reed canary grass).

Figure 2.11: Transect 1 sampling location for *Phalaris arundinacea.* The photo is orientated southwest in the western portion of Borden Wetland.

Transect Plant Species

Phalaris arundinacea dominated

the western portion (transect 1) of Borden Wetland (**Figure 2.11**). The understory of transect 1 included an unknown *Polypodiopsida* species (fern).

Transect 2 was located in the centre of Borden Wetland (**Figure 2.12**). It was dominated by *Typha* species. Transect 2 was intermittent with an unknown *Polypodiopsida* species (fern), *Sagittaire latifoliee* (broad-leaved arrowhead), and an unknown *Carex* species (sedge). The understory of transect 2 included an unknown *Caryophyllaceae* species (chickweed), *Sagittaire latifoliee* (broad-leaved arrowhead), Cornus species (dogwood), *Phalaris arundinacea* (invasive reed canary grass), Urticaceae species (nettle), *Leersia oryzoides* (rice cut grass), an unknown Carex species (unknown sedge), *Galium boreale* (northern bedstraw), *Impatiens capensis* (jewel weed), and an unknown *Polypodiopsida* species (fern). **Figure 2.12** reveals some of the understory species seen in transect 2.

Transect 3 was dominated by *Phalaris arundinacea* and was located on the northeastern section of Borden Wetland (**Figure 2.9**). The understory of transect 3 included an unknown Carex species (sedge), an unknown *Polypodiopsida* species (fern), *Sagittaire latifoliee* (broad-leaved arrowhead), and *Ascelpia incarnate* (swamp milkweed).

Transect 4 had an understory of *Sagittaire latifoliee* (broad-leaved arrowhead), an unknown Carex species (sedge), *Leersia oryzoides* (rice cut grass), an unknown Urticaceae species (nettle), *Iris versicolor* (blue-flag iris), an unknown *Equisetum* species (horsetail), an unknown *Polypodiopsida* species (fern), and *Galium boreale* (northern bedstraw).

Figure 2.12: Photo of some of transect 2 understory – an unknown Polypodiopsida species, *Leersia oryzoides, Sagittaire latifoliee*, and *Phalaris arundinacea*.

***Typha* Species Observations**

Although all *Typha* hybridize with each other, *Typha* in Borden Wetland appeared to have a broader leaf and seedhead. This suggests that *Typha* in Borden Wetland was *Typha latifolia.*

2.4 LABORATORY ANALYSIS OF BELOW-GROUND FUNCTIONAL TRAITS

Only live roots were used for the analysis of the identified root traits: specific root length, root density, root tissue density, root volume, surface area, diameter, root length, root ball volume, and volume of rhizomes (in *Typha*).

Unwashed root samples were stored under chilled conditions for no more than a week. Root samples were washed carefully under running water in the sink and stored in fifty percent ethanol solution within a week.

Root Morphological Categories Under Study

The root ball, secondary roots coming off the root ball (associated with the transport of water and nutrients), and rhizomes in *Typha* were the focus. Secondary roots provide insight into how much exploratory space and resources roots utilize for growth. While fine roots say more on the potential for nutrient absorption from the soil, the focus was on secondary roots. Fine roots were not separated from the main root ball in the calculation of specific root length, and root tissue density as fine roots represent an insignificant weight error in comparison to the final root weight calculation.

The roots were categorized into two main categories: the root ball, and the underground stem (rhizome). Rhizomes can provide insight into the carbon and successional capacity of plants. *Phalaris arundinacea* and *Typha* both have rhizomes. However, it was difficult to separate rhizomes from secondary roots in *Phalaris arundinacea* samples*.* As a result, only *Typha*'s rhizome volume was measured and included in statistical analyses.

2.4.1 PRE-ROOT IMAGE ANALYSIS: ROOT PREPARATION

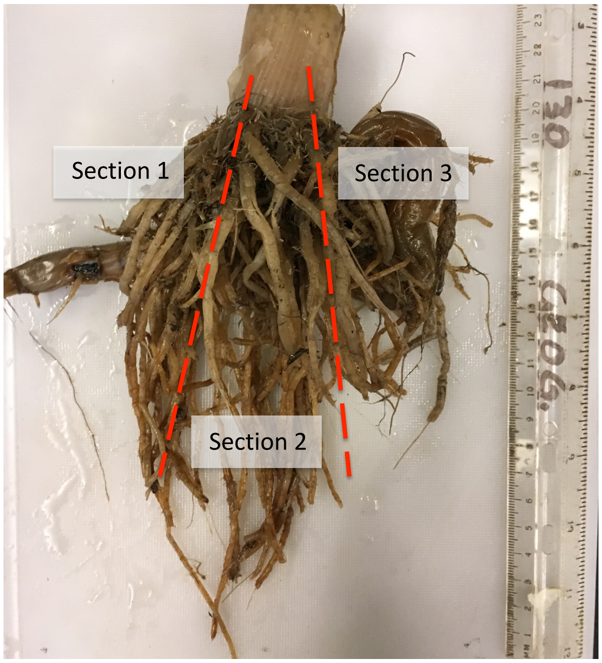

Figure 2.13: Example of how *Typha* were divided into three sections. This root sample was taken from transect 3 in Sunfish Pond.

Root parameters – specific root length, root density, root tissue density, root volume, root length, and surface area had a separate methodology from the *Typha* rhizome and root ball volume lab procedures. Secondary roots were placed into smaller length-wise subsamples and handled individually (Bouma et al., 2000; Costa et al., 2000; Costa et al., 2014; Himmelbauer et al., 2004). In Costa et al., 2000, it was verified that for expansive roots, approximately 10% of the total root volume is enough for an accurate estimation of root length through image-analysis programs. This also helps to minimize overlapping roots: a significant source of error (Bouma et al., 2000; Costa et al., 2014). Each root ball was divided into three sections from left to right to get an accurate depiction of the entire root ball (**Figure 2.13**). While *Phalaris arundinacea* is morphologically different, *Phalaris arundinacea* samples were also partitioned into three sections. A subsample was taken from each section from left to right.

The number of roots were counted within a 0.5 cm^2 (*Phalaris arundinacea*) and 1 cm^2 (*Typha*) to account for 10% of the root ball volume. This is also known as root density – a root parameter compared between root samples. A smaller area was necessary for *Phalaris arundinacea* as it has a smaller root ball volume in comparison to *Typha* species. This procedure was done for each section of the root in order to gather 3 root subsamples for 1 root ball sample. If 10 roots were tallied within 0.5 cm^2 (*Phalaris arundinacea*) or 1 cm^2 (*Typha*), 1 root sample was taken from that section. If there were more than 10 roots within 1 cm^2 (*Typha*) or 0.5 cm^2 (*Phalaris arundinacea*), 2 or more root subsamples were gathered. There were never more than 2 subsamples gathered from the root samples. **Figure 2.14** illustrates how the number of roots within a 1 cm^2 was determined in a *Typha* sample. This method was also necessary for the determination of root density (number of roots per unit area).

Dividing the root ball into 3 sections was required to get an accurate overall measurement for root parameters. For example, there was a visual difference from left to right in *Typha* root balls. Roots in section 1 and 3 appeared thicker in diameter and shorter in length. Section 2 often seemed finer in diameter and longer in length. In addition, severely cut roots were excluded from lab analyses. If there were no roots within a section, the entire root ball sample was excluded from lab and statistical analyses.

Figure 2.14: Photo illustrates the determination of the number of roots within 1 cm^2 from a *Typha* root ball. This method was also used to determine the root density root parameter.

Phalaris arundinacea Root morphology: Subsampling procedure

Figure 2.15: Photo illustrates root variability in *Phalaris arundinacea* and plausible root ball locations from which subsamples could be taken. Root sample is from the on-line stormwater management facility no. 32, transect 1, sample 9.

Phalaris arundinacea has an extensive, complex, and diverse rhizome network. A specific root subsampling procedure had to be developed to account for *Phalaris arundinacea's* great diversity in root morphology. *Phalaris arundinacea* is similar to *Typha* in that it reproduces vegetatively and through seed dispersal. However, *Phalaris arundinacea's* root ball is extremely variable. Often there were numerous plausible root ball locations from which subsequent subsamples could have been taken. **Figure 2.15** illustrates 3 possible root ball locations on *Phalaris arundinacea.*

Only the most intact root ball was subsampled from to account for root ball variability. If there was an extensive rhizome network attached to the root ball, the root ball measurement was extended 0.5 cm horizontally and vertically if there was a rhizome in those directions. **Figure 2.16** reveals how the rhizome extends beyond the root ball area in the right direction (Borden Wetland, transect 3, sample 1).

Figure 2.16: Photo demonstrates how rhizomes can come off the main root ball in *Phalaris arundinacea*. Root ball includes 0.5 cm in the right direction. The root sample was taken from Borden Wetland, transect 3, sample 1.

Phalaris arundinacea has a series of nodes along its stem. Every node has the potential to take hold of the soil and grow. This morphological feature of *Phalaris arundinacea* is not present in *Typha* species. This was considered one plant. **Figure 2.17** illustrates how *Phalaris arundinacea* can have more than one plant on a stem. The plant with the most intact roots was used for further analyses, and other attached stems were discarded.

Figure 2.17: Photo reveals how numerous nodes and plants can grow on an individual *Phalaris arundinacea* stem. The photo on the left has three plants growing on what appears to be one root ball. The photo on the right has several nodes with roots growing along an erect stem. Each photo represents one root sample.

2.4.2 ROOT IMAGE ANALYSIS

In the lab, roots were first drained of the 50% ethanol solution and washed under running water. A photo was taken of each root ball sample. Roots were stained with 4% Azur–Eosin–Methylenblue Giemza to enhance image contrast (Himmelbauer et al., 2004; Vamerali et al., 2003; Richner et al., 2000). The diluted stain was divided into three large beakers – one beaker for each root subsample. An additional beaker was filled with tap water. The roots were placed in the diluted stain solution and warmed in the dry oven at 40°C for 10 minutes (Costa et al., 2001; Himmelbauer et al., 2004). The stain was refreshed after every third subsample. Afterward, the roots were dipped in the beaker filled with tap water and rinsed under running water for approximately 3 minutes. Lastly, the roots were placed in a petri dish and submerged in a thin film of distilled water to aid in illuminating (Cornelissen et al., 2003; Costa, Cunha et al., 2014; Perez-Harguindeguy et al., 2013; Vamerali et al., 2003) and separating the roots (Vamerali et al., 2003). A scale bar was drawn and placed in the background of the petri dish with the distilled water and root subsample. The scale bar was essential to calibrate the root in ImageJ. **Figure 2.18** illustrates the root ball and scanned subsamples from a root ball sample from Borden Wetland.

Image digitization was possible through the use of the Canon CanoScan LiDE 210 flatbed scanner, with a set resolution of 400 dpi (11.8 pixel mm^{-1}), saved as a TIFF file (Gupta & Ibaraki, 2015), and analyzed as an 8-bit image (greyscale) (Costa et al., 2014; Vamerali et al., 2003). If the roots were very fine, the resolution was increased to 600 dpi. ImageJ, an open-source, image-processing program written in Java software was utilized to directly measure root diameter and root length (Costa et al., 2014) from the scanned image. Basic root measurements were then used to calculate root volume, specific root length, root surface area, and root tissue density. To ensure ImageJ could account for roots curled over 45 – 60°, roots were first measured manually and with ImageJ software.

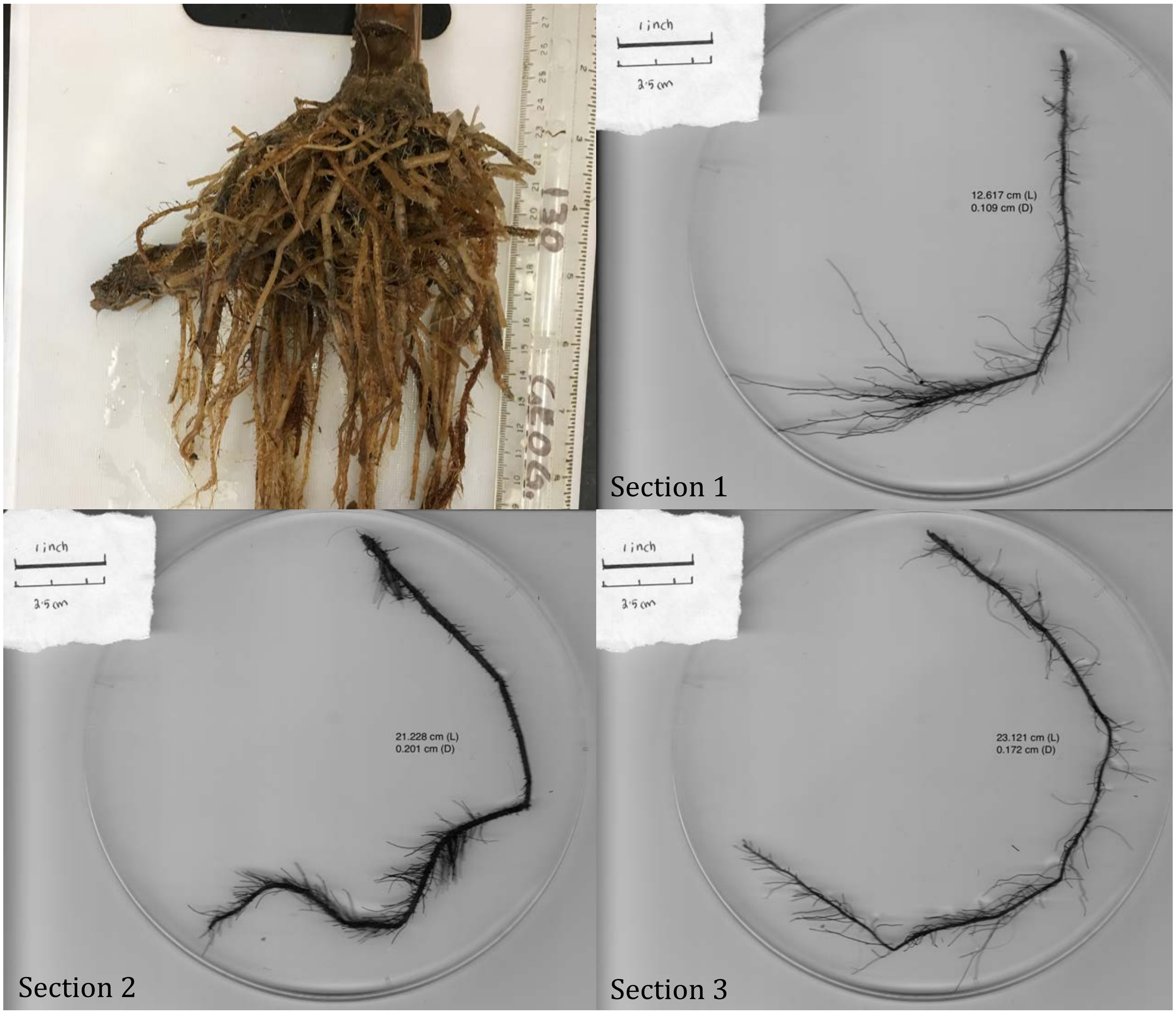

Figure 2.18: Photo illustrates the procedure in organizing root data. This included taking photos of each root sample and taking a separate scan of each root subsample. The photo is *Typha*, sample 2, transect 2, in Borden Wetland.

Table 2.4 outlines the root parameters under study, definitions, method of measurement, and each trait's functional importance. These root parameters are important to evaluate root function, soils influence, and to understand the soil-plant relation (Bouma et al., 2000; Costa et al., 2000; Costa et al., 2014; Gaiser et al., 2013; Grant et al., 2012; Pakeman & Eastwood, 2013). ImageJ software and a flatbed scanner were not required for the measurement of the rhizome, root density, and root ball volume.

Specific Root length and Root Tissue Density

After roots were scanned, roots were placed in a drying oven at 60°C for a minimum of 48 hours (**Table 2.4:** Atkinson, 2000; Perez-Harguindeguy et al., 2013). The dry mass of the fine roots was essential for calculating specific root length and root tissue density.

Table 2.4: Synthesis of root parameters under study and method of calculation. Acronyms: SA = surface area; SRL = specific root length; RTD = root tissue density.

Root Parameters	**Method of Measurement**
Root Length (cm)	- Measured directly from scanned root images in ImageJ.
Surface Area (cm^2)	$SA = 2\pi rL + 2\pi\left(\frac{D}{2}\right)^2$ L = root length (cm) D = root diameter (cm r = root radius (cm) - Diameter and length measurements were determined from scanned root images in ImageJ.
Diameter (cm)	- Determined from scanned root images in ImageJ; - The measurement was taken from the largest width on the root.
Volume (ml)	$V = \pi\left(\frac{D}{2}\right)^2 * L$ D = root diameter (cm) L = root length (cm) - Diameter and length measurements were determined from scanned images in ImageJ.
Specific Root Length (cm g^{-1})	- Average root length to dry mass of roots (48 hours at 60°C) (Atkinson, 2000; Perez-Harguindeguy et al., 2013); - Length measurements were determined with imageJ.
Root Density (roots per cm^{-2})	- Number of roots that intersect the root ball within a unit area; - Number of roots within 1 cm^2 (Typha species) or 0.5 cm^2 (*Phalaris arundinacea*).
Root Tissue Density (g cm^3 or g/ml)	RTD = m/v RTD= density; m = root dry mass (g); v = root volume (ml) - The ratio of root dry mass (48 hours at 60°C) to root volume (Atkinson, 2000; Perez-Harguindeguy et al., 2013); - Diameter and length measurements were determined from scanned images in ImageJ

Root Ball Volume (ml)	$v = \pi\left(\frac{D}{2}\right)^2 * L$ D = root diameter (cm) L = root length (cm) - Diameter and length measurements were determined manually with a ruler.
Rhizome *Typha* Volume (ml)	- Determined based on the volume of a cylinder. $V = \pi\left(\frac{D}{2}\right)^2 * L$ D = root diameter (cm) L = root length (cm) - Diameter and length measurements were determined manually through the use of a ruler.

2.4.3 OTHER ROOT PARAMETERS: RHIZOME AND ROOT BALL VOLUME

The root ball and rhizome volume, and root density were handled and calculated separately from other root parameters.

Figure 2.19: Example of a root ball on a *Typha* species from transect 2, sample 1, Borden Wetland.

***Typha* Species Lab Procedure: Root Ball and Rhizome Volume**

Typha species root ball and rhizome volume were calculated based on the volume of a cylinder (**Table 2.4**). The root ball was defined as the area in which the roots began and ended on the rootstalk. **Figure 2.19** reveals the area on the *Typha* root that was identified as the root ball and utilized in calculating root ball volume. The length and width of the root ball were determined manually through the use of a ruler.

Typha species rhizome volume was determined based on the volume of a cylinder. **Figure 2.19** illustrates three visible rhizomes. Rhizomes over 1 cm^3 were counted and manually measured with a ruler.

2.5 DATA PREPARATION FOR STATISTICAL ANALYSES

All root subsamples (sections) measurements were entered into an Excel spreadsheet. All subsample measurements were averaged for each root ball and entered into an Excel spreadsheet to account for variability between root samples. If there were no roots within a root ball section, the entire root ball sample was excluded from the lab and statistical analyses. The averaging procedure was essential for each functional trait. In the end, there were two datasets for each functional trait – one dataset for each species. Functional traits of similar species were compared between different urban wetland management regimes to determine whether there was a statistically significant difference.

R (open-source statistical software) was used to run all statistical tests. **Figure 2.20** illustrates the rationale in deciding which statistical test to use. Two main questions had to be asked of the data to determine which statistical test was the most appropriate. This included: is the variance equal between groups (Levene's test: $p > 0.05$), and were the data normally distributed (Shapiro Wilk's test: $p > 0.05$) (**Figure 2.20**)?

Generally, an ANOVA is considered the most powerful test in determining whether there is a statistically significant difference between treatment groups (Spina, 2011). Welch's ANOVA (Games-Howell post hoc test: $\alpha < 0.05$) was used when the data did not have equal variances. Kruskal Wallis (Dunn post hoc test: $\alpha < 0.05$) was used for non-normal data (**Figure 2.20**). If the data did not meet normality AND the equality variances assumption, the data were log (x) transformed and the appropriate test was selected.

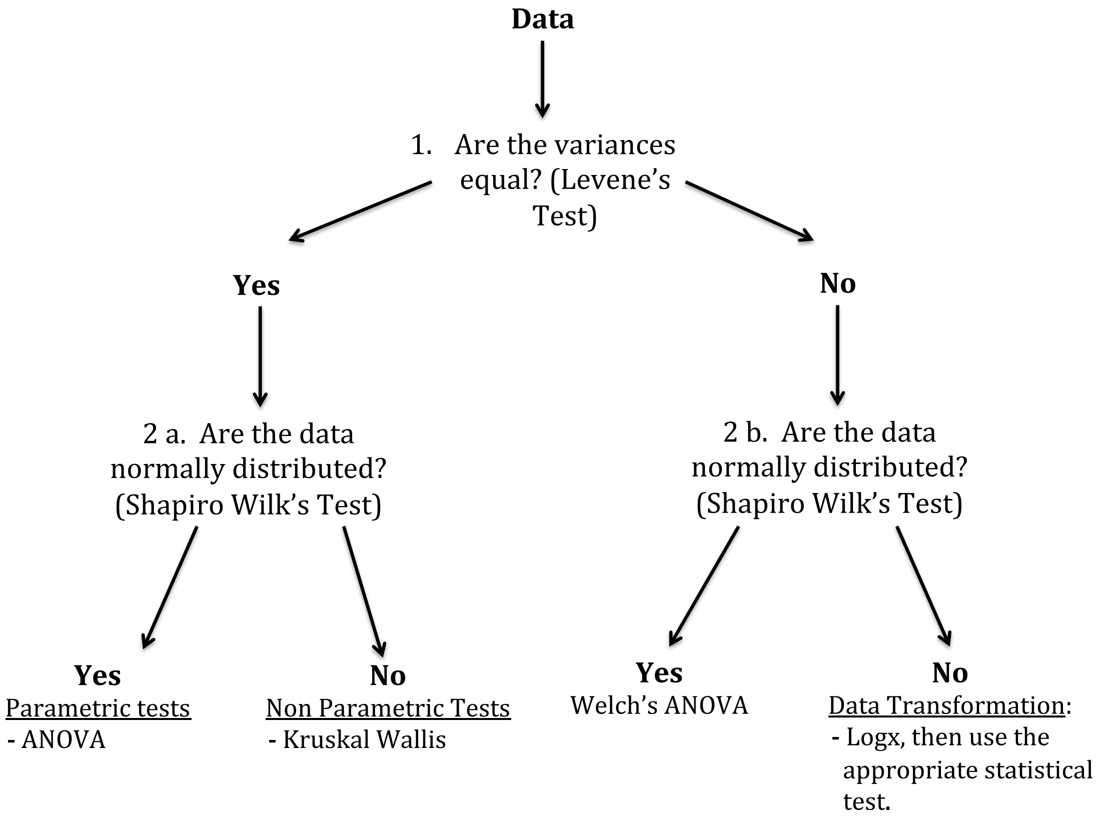

Figure 2.20: Rationale on the determination of appropriate statistical analyses.

RESULTS

2.6 ABOVE-GROUND *TYPHA* SPECIES FUNCTIONAL TRAITS

Maximum plant height, Seedhead Length, and Presence or Absence of a Seedhead in *Typha* samples

Table 2.5 provides a summary of descriptive statistics for *Typha* species above-ground functional traits of maximum height and seedhead length. For the functional trait, maximum plant height, the on-line stormwater management facility no. 32 had the largest mean *Typha* species height at 2.85 metres, and largest range of height measurements (2.74 – 3.92 m).

Table 2.5: Summary of descriptive statistics, statistical tests, and statistical significance for *Typha* above-ground functional traits. Descriptive statistics include the mean, standard deviation (SD), median (M), minimum, maximum, and kurtosis (K) values for three urban wetland management regimes or sites: SF = Sunfish Pond, Huron Park Natural Area (wetland created by agricultural activity); BW = Borden Wetland (least disturbed natural wetland); STRM = on-line stormwater management facility (no. 32). Completely different letters beside the mean or median indicate that there is a statistical significant difference between urban wetland management regimes.

Trait	Site	n	Mean	SD	M	Min	Max	K	Statistical Test
Max Height (m)	SF	25	**2.05^a**	0.28	2.02	1.56	2.77	0.17	Welch's ANOVA
	BW	25	**2.20^b**	0.21	2.20	1.76	2.70	-0.47	
	STRM	25	**2.85^c**	0.40	2.74	2.16	3.92	-0.31	
Seedhead Length (cm)	SF	37	17.86	4.69	18	10	26	-0.94	Kruskal Wallis
	BW	37	19.51	3.96	20	11	30	-0.68	
	STRM	30	19.57	4.66	20	12	27	-1.30	

The Welch's ANOVA indicated that there was a statistically significant difference between some of the urban wetland management regimes maximum plant heights at $\alpha < 0.05$, F (2, 72) = 69.7, $p < 0.0001$. The Games-Howell post hoc test indicated that there was a statistically significant difference in maximum plant height measurements between all sites. Sunfish Pond and the on-line stormwater management facility no. 32 had a $p < 0.0001$. The on-line stormwater management facility no. 32 and Borden Wetland had a $p < 0.0001$. Lastly, Sunfish Pond and Borden Wetland had a $p < 0.01$.

The Kruskal Wallis indicated that there was no statistically significant difference between *Typha* seedhead lengths from the different urban wetland management regimes.

Presence and absence of a seedhead in *Typha* samples

Table 2.6 illustrates the data on the presence or absence of a seedhead in *Typha* species across three treatments or sites. The chi-squared test of independence indicated that there was no statistically significant difference between urban wetland management regimes: a wetland created by agricultural activity (Sunfish Pond), least disturbed wetland (Borden Wetland), and the on-line stormwater management facility (no. 32).

Table 2.6: Presence or absence of a *Typha* seedhead across three urban wetland management regimes or sites: SF = Sunfish Pond, Huron Park Natural Area (wetland created by agricultural activity); BW = Borden Wetland (least disturbed wetland); and STRM = on-line stormwater management facility (no. 32). There was no statistically significant difference between sites.

	SF	**BW**	**STRM**	**Total**
Presence	37	38	30	**105**
Absence	13	12	20	**45**
Total	**50**	**50**	**50**	**150**

2.7 BELOW-GROUND *TYPHA* SPECIES FUNCTIONAL TRAITS

Table 2.7 provides a summary of descriptive statistics for *Typha* below-ground functional traits. There was statistical significance in root diameter, specific root length, root volume, and root density. There were no statistically significant differences in root length, root surface area, root tissue density, rhizome volume, or root ball volume in *Typha* samples between urban wetland management regimes: Sunfish Pond (wetland created by agricultural activity), Borden Wetland (least disturbed wetland), and the on-line stormwater management facility (no. 32).

Table 2.7: Summary of descriptive statistics, statistical tests, and statistical significance for *Typha* species below-ground functional traits. Descriptive statistics include the mean, standard deviation (SD), median (M), minimum, maximum, and kurtosis (K) values for three urban wetland management regimes or sites: SF = Sunfish Pond, Huron Park Natural Area (wetland created by agricultural activity); BW = Borden Wetland (least disturbed natural wetland); STRM = on-line stormwater management facility (no. 32). Completely different letters on the mean or median indicate that there is a statistical significant difference between urban wetland management regimes.

Trait	Site	n	Mean	SD	M	Min	Max	K	Statistical Test
Root Diameter (cm)	SF	16	0.18	0.07	0.14	0.08	0.31	-1.30	Welch's ANOVA
	BW	20	**0.18**^{a}	0.04	0.17	0.12	0.27	0.40	
	STRM	19	**0.13**^{b}	0.04	0.12	0.08	0.22	-0.64	
Root Length (cm)	SF	16	12.09	3.78	12.79	5.66	18.96	-0.57	ANOVA
	BW	20	13.18	3.82	11.67	8.04	20.31	-0.84	
	STRM	19	11.97	3.08	11.16	7.34	17.21	-0.82	
Root Surface Area (cm^{2})	SF	16	76.04	23.81	80.50	35.57	119.21	-0.57	ANOVA
	BW	20	82.87	23.98	73.35	50.57	127.65	-0.84	
	STRM	19	75.13	19.43	70.16	46.15	108.14	-0.84	
Specific Root Length (g/cm)	SF	16	16.10	31.69	7.33	2.67	134.30	15.57	Kruskal Wallis
	BW	20	8.47	2.62	**8.01**^{a}	4.81	14.34	0.40	
	STRM	19	14.01	8.40	**13.34**^{b}	0.53	39.91	4.24	
Root Volume (ml)	SF	16	0.40	0.35	0.21	0.05	0.93	-1.33	Welch's ANOVA
	BW	20	**0.32**^{a}	0.21	0.32	0.11	0.89	3.03	
	STRM	19	**0.18**^{b}	0.12	0.12	0.04	0.40	-0.45	
Root Density (roots/cm^{2})	SF	16	**6.21**^{a}	1.43	6.5	4	9	-0.44	Welch's ANOVA
	BW	19	**6.32**^{a}	1.27	6.67	4.33	9	-0.12	
	STRM	20	**9.75**^{b}	3.05	10.17	4.33	15.33	-0.84	
Root Tissue Density (g cm^{3})	SF	16	0.11	0.13	0.06	0.03	0.54	10.38	Kruskal Wallis
	BW	19	0.07	0.03	0.06	0.03	0.16	3.33	
	STRM	20	0.13	0.18	0.08	0.04	0.85	16.54	
Rhizome Volume (ml)	SF	15	17.98	13.04	15.71	3.98	57.02	5.59	Kruskal Wallis
	BW	20	13.41	5.86	12.11	5.43	26.37	0.26	
	STRM	20	16.46	7.92	15.04	5.88	39.05	2.47	
Root Ball Volume (ml)	SF	16	213.36	115.32	212.63	50.64	450.73	-0.52	Kruskal Wallis
	BW	19	238.15	138.74	208.87	104.27	626.14	2.21	
	STRM	20	215.01	119.63	198.02	76.86	521.96	1.27	

Root diameters in *Typha* samples

Sunfish Pond and Borden Wetland had the largest root diameter at 0.18 cm. Sunfish Pond had the greatest range of values (0.08 – 0.31 cm) (**Table 2.7**). The Welch's ANOVA indicated that there was a statistically significant difference between some of the urban wetland management regimes at $\alpha < 0.05$, $F(2, 52) = 9.15$, $p = 0.001$. The Games-Howell post-hoc test indicated that there was a statistically significant difference in mean root diameter measurements between Borden Wetland and the on-line stormwater management facility no. 32 ($p < 0.001$).

Specific root lengths in *Typha* samples

Sunfish Pond had largest mean specific root length at 16.10 cm/g and the greatest range in specific root length measurements (2.67 – 134.30 cm/g) (**Table 2.7**). The Kruskal Wallis test indicated that there were statistically significant differences between some urban wetland management regimes at $\alpha< 0.025$, H(2,52) = 8.93, $p < 0.03$. The Dunn post-hoc test indicated that there was a statistically significant difference in median specific root length measurements between the on-line stormwater management facility no. 32 and Borden Wetland ($p < 0.03$). There was also a statistically significant difference between the on-line stormwater management facility no. 32 and Sunfish Pond ($p < 0.03$). However, there was no statistically significant difference between Sunfish Pond and Borden Wetland.

Root volumes in *Typha* samples

Sunfish Pond had the largest mean root volume measurement at 0.40 ml and the greatest range in root volume measurements (0.05 – 0.98 ml) (**Table 2.7**). After a logx transformation, the Welch's ANOVA parametric test indicated that there were statistically significant differences between some urban wetland management regimes at $\alpha< 0.05$, F(2, 52) = 7.30, $p < 0.01$. The Games-Howell post-hoc test indicated that there was a statistically significant difference in mean root volume measurements between the on-line stormwater management facility no. 32 and Borden Wetland ($p < 0.01$). However, there was no statistically significant difference between Sunfish Pond and Borden Wetland. There was also no statistically significant difference between the on-line stormwater management facility no. 32 and Sunfish Pond.

Root Densities in *Typha* samples

The on-line stormwater management facility no. 32 had largest mean root density measurement at 9.75 roots/cm^2 and the greatest range in root density measurements (4.33 – 15.33 roots/cm^2) (**Table 2.7**). The Welch's ANOVA indicated that there was a statistically significant difference between some of the urban wetland management regimes at $\alpha < 0.05$, F(2,55) = 10.46, $p < 0.001$. The Games-Howell post-hoc test indicated that there was a statistically significant difference in mean root density measurements between the on-line stormwater management facility no. 32 and Borden Wetland ($p < 0.001$). There was also a statistically significant difference between the on-line stormwater management facility no. 32 and Sunfish Pond ($p < 0.001$). However, there was no statistical significance between Sunfish Pond and Borden Wetland.

Table 2.8: Summary of descriptive statistics, statistical tests, and statistical significance for *Phalaris arundinacea* below-ground functional traits. Descriptive statistics include the mean, median (M), standard deviation (SD), median, minimum, maximum, and kurtosis (K) values for three urban wetland management regimes or sites: SF = Sunfish Pond, Huron Park Natural Area (wetland created by agricultural activity); BW = Borden Wetland (least disturbed natural wetland); and STRM = on-line stormwater management facility (no. 32). Completely different letters on the mean or median indicate that there is a statistical significant difference between urban wetland management regimes.

Trait	Site	n	Mean	M	SD	Min	Max	K	Statistical Test
Root Diameter (cm)	SF	20	0.06	0.06	0.01	0.04	0.09	-0.75	Kruskal Wallis
	BW	20	0.06	0.06	0.02	0.04	0.10	0.95	
	STRM	18	0.07	0.07	0.02	0.05	0.13	2.22	
Root Length (cm)	SF	20	**9.25**^{a}	9.04	2.63	6.33	18.54	8.06	ANOVA
	BW	20	**11.49**^{b}	11.68	3.11	5.34	17.54	-0.003	
	STRM	18	11.22	11.39	3.05	6.74	18.03	-0.19	
Root Surface Area (cm^2)	SF	20	58.11	56.80	16.55	39.78	76.70	8.06	ANOVA
	BW	20	**72.22**^{a}	73.39	19.56	33.59	76.62	-0.003	
	STRM	18	**70.50**^{b}	71.59	19.15	42.32	70.96	-0.19	
Specific Root Length (g/cm)	SF	20	16.61	16.39	4.87	9.43	24.40	-1.03	Kruskal Wallis
	BW	20	25.56	12.41	42.54	6.89	192.35	13.37	
	STRM	18	12.58	12.69	5.46	5.22	25.45	0.06	
Root Volume (ml)	SF	20	0.03	**0.03**^{a}	0.02	0.008	0.07	-0.40	Kruskal Wallis
	BW	20	0.04	0.04	0.03	0.008	0.10	0.20	
	STRM	18	0.06	**0.05**^{b}	0.05	0.01	0.23	9.00	
Root Density (roots/cm^2)	SF	20	4.17	4.00	1.06	2.67	6.33	-0.22	ANOVA
	BW	20	3.63	3.67	0.67	2.33	5.00	-0.29	
	STRM	18	4.17	4.17	1.21	2.33	7.50	1.83	
Root Tissue Density (g cm^3)	SF	20	0.46	0.47	0.28	0.11	1.40	5.77	Kruskal Wallis
	BW	20	0.41	0.31	0.26	0.12	0.94	-1.01	
	STRM	18	0.34	0.29	0.21	0.12	0.84	0.90	
Root Ball Volume (ml)	SF	20	14.30	9.52	9.08	1.55	33.74	-0.10	ANOVA
	BW	20	**39.97**^{a}	28.11	35.08	5.94	126.31	1.35	
	STRM	19	**30.20**^{b}	22.49	29.04	2.56	106.93	2.30	

2.8 BELOW-GROUND *PHALARIS ARUNDINACEA* FUNCTIONAL TRAITS

Table 2.8 provides a summary of descriptive statistics for *Phalaris arundinacea* below-ground functional traits. There was statistical significance in root length, root surface area, root volume, and root ball volume. There were no statistically significant differences in root diameter, specific root length, root density, or root tissue density in *Phalaris arundinacea* samples between urban wetland management regimes: Sunfish Pond (wetland created by agricultural activity), Borden Wetland (least disturbed wetland), and the on-line stormwater management facility (no. 32).

Root Lengths in *Phalaris arundinacea* samples

Borden Wetland had the largest mean root length at 11.49 cm and the greatest range in root length measurements (6.33 – 18.54 cm) (**Table 2.8**). The ANOVA indicated that there were statistically significant differences between some urban wetland management regimes at $\alpha < 0.05$, F(2,55) = 3.35, p = 0.04. The Tukey-Kramer post-hoc test indicated that the mean root length measurement for Borden Wetland was statistically significantly different than Sunfish Pond (p = 0.05). However, there was no statistically significant difference between the on-line stormwater management facility no. 32 and Sunfish Pond or between the on-line stormwater management facility no. 32 and Borden Wetland.

Root Surface Areas in *Phalaris arundinacea* samples

Borden Wetland had the largest mean root surface area at 72.22 cm^2 and Sunfish Pond had the greatest range in root surface areas (39.78 – 116.48 cm^2) (**Table 2.8**). The ANOVA indicated that there were statistically significant differences between some urban wetland management regimes at $\alpha < 0.05$, F(2,55) = 3.35, p = 0.04. The Tukey-Kramer post-hoc test indicated that the mean root surface area measurement for Borden Wetland was statistically significantly different than Sunfish Pond (p = 0.05). However, there was no statistically significant difference between the on-line stormwater management facility no. 32 and Sunfish Pond or between the on-line stormwater management facility no. 32 and Borden Wetland.

Root Volumes in *Phalaris arundinacea* samples

The on-line stormwater management facility no. 32 had the largest mean root volume measurement at 0.06 ml and the greatest range in root volume measurements (0.01 – 0.23 ml) (**Table 2.8**). The Kruskal Wallis indicated that there were statistically significant differences between some urban wetland management regimes at $\alpha < 0.03$, H(2,55) = 7.55, $p < 0.03$. The Dunn post-hoc test indicated that there was a statistically significant difference in median root volume measurements between Sunfish Pond and the on-line stormwater management facility no. 32 ($p < 0.03$). There was also a statistically significant difference between the on-line stormwater management facility no. 32 and Borden Wetland or between Sunfish Pond and Borden Wetland.

Root Ball Volumes in *Phalaris arundinacea* samples

Borden Wetland had the largest mean root ball volume at 39.97ml and the greatest range in root ball volume measurements (5.94 –126.31 ml) (**Table 2.8**). After a logx transformation, the ANOVA parametric test indicated that there were statistically significant differences between some urban wetland management regimes at $\alpha < 0.05$, F(2, 56) = 5.49, $p < 0.01$. The Tukey-Kramer post-hoc test indicated that there was a statistically significant difference in mean root ball volume measurements between Borden Wetland and Sunfish Pond ($p < 0.01$). However, there was no statistically significant difference between the on-line stormwater management facility no. 32 and Borden Wetland or between the on-line stormwater management facility no. 32 and Sunfish Pond.

DISCUSSION

2.9 INCONSISTENT DIFFERENCES BETWEEN URBAN WETLAND MANAGEMENT REGIMES IN BELOW AND ABOVE-GROUND PLANT FUNCTIONAL TRAITS

Plant functional traits did show statistically significant differences between urban wetland management regimes; however, the results were inconsistent between and within the species I used. **Table 2.9** reveals a summary of the statistically significant results and the mean size of trait measurements between urban wetland management regimes. Comparing all urban wetland management regimes, there was a significant difference in the maximum plant height of *Typha*. There was a significant difference in root volume measurements of *Phalaris arundinacea* between Borden Wetland and the on-line stormwater management facility. In *Phalaris arundinacea,* root length, root surface area, and root ball volume were significantly different between Sunfish Pond and Borden Wetland. *Typha* root diameter and root volume showed a statistically significant difference between Borden Wetland and the on-line stormwater management facility no. 32. Lastly, *Typha* showed a significant difference in specific root length and root density between Borden Wetland and Sunfish Pond versus the on-line stormwater management facility (no. 32).

The mean size of trait measurements between urban wetland regimes in *Phalaris arundinacea* was largest in Borden Wetland for root length, root surface area, and root ball volume. Root volume was the largest in the on-line stormwater management facility in *Phalaris arundinacea.* In *Typha* samples, the largest trait measurements were evident in Sunfish Pond and Borden Wetland Borden for root diameter. Root volume, specific root length were the largest in Sunfish Pond. Lastly, the on-line stormwater management facility (no. 32) had the largest measurements for root density and maximum plant height (**Table 2.9**).

Broadly, I suspect that the inherent variation in urban wetland ecosystem dynamics (e.g., sudden changes in water depth during precipitation events) facilitates more extreme plasticity in plant traits than in other ecosystem types. Although *Typha* and *Phalaris arundinacea* were in the same wetland, they were in different locations with a different set of environmental conditions. *Typha* was more common in standing water, whereas *Phalaris arundinacea* was often found on the fringe or in areas that were not continuously waterlogged. Therefore, water depth may be one of the reasons why different species have opposing statistically significant differences (**Table 2.9**).

Table 2.9: Statistically significant results and differences in mean trait size measurements between urban wetland management regimes in *Phalaris arundinacea* and *Typha.* Acronyms: BW = Borden Wetland (least disturbed natural wetland); SF = Sunfish Pond, Huron Park Natural Area (wetland created by agricultural activity); STRM = on-line stormwater management facility (no. 32)

	Plant Functional Trait	**Statistical Significance and Size Differences in Traits**
Phalaris arundinacea	Root Length (cm)	BW – SF: $p = 0.05$ SF < STRM < BW
	Root Volume (cm^3)	STRM – SF: $p < 0.025$ SF < BW < STRM
	Root Surface Area (cm^2)	BW – SF: $p = 0.05$ SF < STRM < BW
	Root Ball Volume (cm^3)	BW – SF: $p < 0.01$ SF < STRM < BW
Typha	Root diameter (cm)	BW – STRM: $p < 0.001$ STRM < SF = BW
	Root Volume (cm^3)	BW – STRM: $p < 0.01$ STRM < BW < SF
	Root Density (roots/cm^2)	BW & SF vs. STRM: $p < 0.001$ SF < BW < STRM
	Specific Root Length (g/cm)	BW & SF vs. STRM: $p < 0.0001$ BW < STRM < SF
	Maximum Plant Height (m)	SF – BW: $p < 0.001$ SF & BW vs. STRM: $p < 0.0001$ SF < BW < STRM

Plant functional traits that best predict different urban wetland management regimes

Below-ground functional traits of root diameter and root volume appear to be the best predictors in detecting differences between urban wetland management regimes. Root diameter and root volume are the least prone to experimental error. Root diameter shows a more accurate depiction of the effects of the environmental conditions on a root system and does not depend on an intact root system. Root volume's environmental error is minimized through the incorporation of root length and root diameter measurements in the final calculation.

The best measure of the differences in urban wetland management regimes in measured above-ground functional traits was maximum plant height in *Typha*. Through visual inspection, maximum plant height seemed to depict differences between urban wetland management regimes more accurately than the other plant functional traits under study. Borden Wetland and the on-line stormwater management facility appeared to be thriving the most (tallest) even though the on-line stormwater management facility no. 32 was the most disturbed urban wetland management regime category. This could have been due to excess nutrients or the variable water level conditions between urban wetland management regimes. In terms of nutrients, root growth is known to increase or decrease when there is an excess of nutrients in the soil (Costa et al., 2002; Forde & Lorenzo, 2001). The combined application of nitrogen of phosphorous often increases root surface area, root length, root-shoot mass (Song et al., 2010), and plant height (Razaq et al., 2017). *Typha* species in Sunfish Pond were struggling (e.g., flooding). This reveals the importance of incorporating other environmental parameters (e.g., water depth, nutrient load, diversity) into the measurement of plant functional traits.

Plant functional traits that were not the best to predict different urban wetland management regimes

Specific root length and root tissue density measurements are common in root functional trait research. I found these traits prone to extreme outliers. This resulted from the ratio between a dimension and weight measurement. If roots were cut short in the field or too light, extreme outliers were common. Also, root length and root ball volume was a difficult trait to accurately measure as it was often hard to excavate an intact root ball.

Species that best depict different urban wetland management regimes

Typha provides a more accurate depiction of differences between urban wetland management regimes. *Typha* roots have larger diameter measurements and roots (subsamples) that came from a distinct root ball. An intact root ball is ideal when choosing an appropriate plant species. It is also important to have the same *Typha* species in trait-based research. For example, *Typha* showed a statistically significant difference between Borden Wetland and Sunfish versus the on-line stormwater management facility no. 32. In the lab, root diameter and root density measurements between these urban wetland management regimes noticeably differed. This may be due to the fact that the on-line stormwater management facility no. 32 appeared to have a different species of cattail – *Typha angustifolia*. Although it is nearly impossible to visually distinguish *Typha angustifolia* from *Typha latifolia,* due to the hybridization between species, this outlines the importance of sampling the same species, even if they readily hybridize.

Phalaris arundinacea has a series of nodes along its stem. Each has the potential to take hold of the soil and grow. Consequently, there were numerous areas along the stem in which one could sample from the 'root ball.' The variable root morphological features in *Phalaris arundinacea* made it difficult to completely replicate the root subsampling protocol and trust the statistical significance between urban wetland management regimes. Also, *Phalaris arundinacea* has thinner roots that made it more prone to experimental error in the dimension and weight measurements.

CHAPTER 3: CONCLUSION

3.1 PRACTICAL APPLICATION OF TRAIT-BASED RESEARCH

Although plant functional traits are touted as superior to traditional taxonomic measures when trying to comprehend complex ecosystem functions, this research demonstrated that plant functional traits are limited and variable in predicting differences in urban wetland management regimes. At this time, it is difficult if not impossible, to use plant functional traits to understand all ecosystem functions simultaneously. Most research focuses on plant functional traits along a measurable environmental gradient. While plant functional traits have only been quantified for single or few ecosystem services, there is still promise in the practical application of plant functional traits in combination with other traditional measures (e.g., taxonomic diversity).

The practical applicability of trait-based measures depends on the specific ecosystem management goal. If the specific ecosystem management goal is to assess the wetlands ability to reduce nitrogen or phosphorous loads further downstream, specific traits (e.g., root nitrogen or phosphorous content) that directly influence nitrogen and phosphorous cycling would be ideal. However, specific traits such as root nitrogen content may not be realistic or feasible for small environmental agencies with limited funding. This does not mean that small agencies cannot use plant functional traits.

For example, maximum plant height measured in this research project is an option for ecosystem managers with limited funds to get an idea of how well specific plants or how a wetland is doing overall. In general, if there are more readily available nutrients, plants have the potential to grow larger (Chapin, 2003; Perez-Harguindeguy et al., 2013). The measurement of maximum plant height is fast and provides a good estimate of the relative biomass of any wetland. While maximum plant height does not directly measure the nutrients absorbed by plants, it is assumed that if the plant is growing larger, more nutrients are assimilated. This is especially true with invasive species as they are often able to produce more biomass under nutrient-rich environments in comparison to native species (Funk, 2013; Gross, Mittelbach, & Reynolds, 2005; James, Ziegenhagen, & Aanderud, 2010). In addition, ecosystem managers with limited funds can use more generalizable functional traits or known functional attributes of specific plants. For example, to control erosion, grasses are better than cereal crops in stabilizing aggregates, as grasses tend to have larger root biomass with exudates (Gyssels et al., 2005).

Although the research indicates that plant functional trait research should move beyond the measurement of plant functional traits along an environmental gradient (Fiedler, Perring, & Tietjen, 2018; Sandra Lavorel, 2013), this is not realistic or practical for ecosystem managers. While it is important to have an expansive knowledge of a wetland when prioritizing management decisions, it may not be realistic when a resource manager wants to make a specific management decision. It may be more feasible to look at a specific function of a wetland and allocate resources to that particular area. In other words, ecosystem management goals should focus on a specific function, conservation priority, or ecosystem service of an identified plant functional trait.

Plant functional traits have the potential to fill the gap in understanding the complexities of wetland ecosystem functions where traditional plant diversity measures are lacking. However, plant functional traits are not the answer to every wetland management decision. It is important to adapt and use a suite of ecological indicators or tools given the specific management concern. For example, Borden Wetland appeared the most biologically diverse, but had poor water quality according to the City of Kitchener's existing report. This highlights the importance of using a range of environmental parameters to guide ecosystem management decisions. In addition, most plant functional trait research is extremely destructive and requires extensive storage space. Destructive plant sampling is not possible in certain management regimes (e.g., protected areas). In the end, this research shows that pragmatically it may not be feasible for most ecosystem managers, but collaboratively, it could be possible. In the end, the use of plant functional traits may be more useful for the scholarly audience.

Recommendations for practitioners

It is important before conducting any plant functional trait field collection to understand the plant's life cycle in the ecosystem under question. When measuring above-ground plant functional traits of maximum plant height or seedhead traits, know when that plant's life cycle finishes for the season. Otherwise, it may not be possible to measure that particular plant functional trait. For example, *Phalaris arundinacea* above-ground biomass began to degrade by the beginning of August. All above-ground plant functional traits of *Phalaris arundinacea* should have been measured before August.

Lastly, arrange the logistics of how much storage and dry oven space is available when measuring above-ground plant functional traits that require dry mass measurements. Wetland plants are often large and require extensive storage and oven space. If there is limited dry oven and storage space, above-ground functional traits may not be feasible or realistic.

3.2 BENEFITS FOR THE CITY OF KITCHENER

The Natural Heritage System in the City of Kitchener

The *Provincial Policy Statement*[18] under section 3 of the *Planning Act* guides municipal planning to include natural heritage policies, water resource management policies, and natural hazard policies in Ontario. The *Provincial Policy Statement* defines a Natural Heritage System as a system of natural heritage features and linkages to encourage habitat connectivity at regional and local levels necessary to support natural processes to maintain biological and geological diversity[19], natural functions, and adequate populations of native species and ecosystems (Aquafor Beech Ltd., 2016a). A natural heritage system can include natural areas, restoration areas, habitat corridors, wetlands, valleylands, woodlands, fish, plants and wildlife, significant landforms, and groundwater recharge/discharge areas (The City of Kitchener, 2014). While specific areas are important to preserve (e.g., Areas of Natural and Scientific Interest[20]), habitat linkages are key and essential for a successful

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[18] It is a statement on the Province of Ontario's polices on land-use planning. It helps municipalities to develop plans to guide and inform land-use planning decisions (Province of Ontario, 2014).

[19] Geological diversity is also known as geodiversity or the variety within abiotic nature diversity, which includes environmental patterns and processes that are drivers of biodiversity. Geodiversity is composed of climate, topography, geology, and hydrology and is used as a measure of environmental resource availability (Parks & Mulligan, 2010). In terms of nutrient functionality, climate influences carbon, and nutrient cycles, topography and geology influence soil properties, and hydrology distributes nutrients. Parks & Mulligan (2010) proposed using geodiversity as a surrogate for mapping and prioritizing areas of concern to minimize biodiversity loss. For example, plant distribution maps can be devised through associating certain plant communities with specific environmental properties.

[20] Defined as an area of land or water that contains natural features that have natural heritage, scientific, or educational value as deemed by the Province of Ontario (Ministry of Natural Resources, 2011).

Natural Heritage System. Habitat connectivity builds upon a landscape ecology approach to land-use planning.

Although plant functional traits are often specific to sites or individual ecosystems, plant functional trait research has the potential to be incorporated into existing Natural Heritage System maps, land-use policies, and ecosystem management goals. Plant functional traits could be integrated into future prioritization of land-use to reach Ontario's biodiversity mandate to safeguard Ontario's variety of species and ecosystems. Often Natural Heritage System map design relies on orthoimagery and secondary data interpretation. This fails to identify land-use priorities based on ecosystem functions. In other words, ecosystems should be assessed and included in the Natural Heritage System based on their ecosystem functions or ecosystem services (e.g., flood mitigation), and not just their 'uniqueness' or 'significance.' If ecosystems were only preserved based on their ecological significance, ecosystems would be omitted that are just as important for other reasons. Plant functional traits go beyond structural indicators of ecological significance.

In 2016, a decrease in surface and groundwater quality, increased sediment loads, and flooding were some of the environmental concerns identified for the City of Kitchener (Aquafor Beech, 2016b). The incorporation of generalizable plant functional traits into existing political structures (e.g., Natural Heritage Systems) has the potential to minimize some environmental concerns in Kitchener. For example, to control erosion, grasses are better than cereal crops in stabilizing aggregates in the soil. Maximum plant height measurements could be used to monitor or assess the overall health of key wetland plants (e.g., *Typha*) and indirectly their potential for nutrient uptake or stabilization capacity.

3.3 GENERALIZABLE CONTRIBUTIONS

The Use of Plant Functional Traits in Ecosystem Management

It is estimated that approximately 60% of wetland species have extensive geographical distributions that span beyond one continent. Monocots tend to be the most widely dispersed species (e.g., common reed and duckweed) (Cronk & Fennessy, 2009). Hence, the distribution of wetland species often follows a predictable pattern. This makes plant functional traits an exciting medium for research and management objectives. While the ecosystem under study may change, many plant species are similar between wetland ecosystem types – even in urban wetlands. Plant functional traits are complex and often unrealistic when trying to understand the function of an ecosystem. While there has been research on the scale-up of plant functional traits to ecosystem properties and functions, trade-offs between plant functional traits to ecosystem functions remain scarce (Lavorel & Grigulis, 2012). For example, an increase in plant height increases a plant's ability to capture light but comes at a cost. With an increase in height, plant tissues can become weak and prone to breakage. Hypothetically, taller plants would have a slower metabolism and therefore, lower carbon sequestration capacity. The trade-offs between height and other plant traits to ecosystem functions have not been a focus of research. With additional research, plant functional traits can begin to become more reliable for resource managers to prioritize the management of urban wetlands based on vital ecosystem services.

Rapid Functional Assessments of Wetlands

Plant functional trait research has the potential to influence ecosystem management through its incorporation into the functional assessments of wetlands. In other words, urban and natural wetlands can be seen based on their ecosystem services or functions (e.g., carbon sequestration) rather than their descriptive diversity and plant characteristics (Maltby, 2009). This would include not only the ecological functioning aspect of wetlands but also their societal values. This also helps non-specialists understand and interpret the challenges of wetland management and priorities for future water policy objectives. Traditional management approaches of wetlands characterized by 'rarity or uniqueness' may not be suitable for safeguarding the wider functions of wetlands (Maltby, 2009). Numerous countries, including Canada, use the functional assessment of wetlands to 'score' the functions of wetlands based on hydrological, biogeochemical, and ecological processes. Through further research, plant functional traits have the potential to be implemented into the existing functional analyses of wetland functions.

In Ontario, under the Provincial Policy Statement, the Ontario Wetland Evaluation System exists to help 'define, identify, assess the functions, and values of wetlands and rank them relative to each other' (Varrin & Zeran, 2018, p. 413) to make land-use decisions. After the wetland is mapped, the wetland's functions and values are evaluated against 50 scored criteria separated into biological[21], social[22], hydrological[23], and special features[24]. A wetland can receive a maximum score of 1000. A wetland with a total score of at least 600 or a wetland with 200 or more points in the biological or special feature category is considered 'provincially significant' (Varrin & Zeran, 2018). Currently, the Ontario Wetland Evaluation System only focuses on natural wetlands. Although my research focuses on urban wetland ecosystems, that are frequently not 'natural,' these wetlands provide or have the potential to be habitat refuge to a suite of animals and plants. We should not choose to ignore these systems as being unworthy of conservation or landscape management. As more and more people reside in urban environments, there is a need for a wetland evaluation system not only for natural wetlands but novel and constructed ecologies in an urban setting. Further research and the practical experimentation of plant functional traits are required before plant functional traits can be incorporated into existing wetland functional assessments – namely the biological and hydrological category of the Ontario Wetland Evaluation System.

Although the Ontario Wetland Evaluation System was initially created to determine the appropriate land-use action for wetlands under threat, it has potential to be adapted to address specific ecosystem functions (e.g., nutrient retention and removal from water). It may not be economical or practically feasible for ecosystem managers to look at all ecosystem functions simultaneously.

Landscape Ecology and Transdisciplinary Engagements

A landscape management framework that incorporates a spectrum of systems provides a more comprehensive set of options for how and when to intervene and achieve management goals (Hobbs et al., 2014). In particular, recent literature highlights the need for management and restoration efforts to move beyond site-focused interventions to consider the inclusion of the landscape and regional scales. From a landscape ecology

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[21] Relates to the productivity and habitat diversity of the wetland under question.

[22] Defined as the direct human use of wetlands including economic, recreation, education, and cultural values.

[23] Includes information on the capacity of the wetland to reduce flood peaks, contribution to groundwater recharge/ discharge, and improvements to water quality.

[24] Considers the rarity, species at risk, age, and habitat quality of terrestrial and aquatic ecosystems.

perspective, the landscape consists of multiple ecosystems or patches with distinct characteristics and functions (Hobbs et al., 2014). There must be the incorporation of the broader connective landscape into ecosystem management goals and the execution of ecological restoration projects (Harris & Hobbs, 2006; Hobbs & Norton, 1996). Lastly, to become a useful tool to bring back dysfunctional ecosystems, ecosystem management goals and ecological restoration must respond and adapt to anticipated change.

The central assumption in the landscape management approach is that there will be transdisciplinary engagements between landscape ecologists, urban planners, and landscape designers to mobilize knowledge. There must be a 'bridging' of knowledge to progress towards an increase in functional habitats through the use of a working method for adaptive design or to 'learn-by-doing.' There are many parallels between disciplines of landscape design and urban planning, yet a lot of knowledge is not incorporated into each other's fields. Differences can be seen in how each discipline approaches a site; their language; perceptions; and the highly specialized nature of science (Grose, 2014).

To learn each other's 'language,' ecologists must provide a more general framework for designers and delve into other disciplines as opposed to producing knowledge often only available within an academic institution. The incorporation of highly specialized expertise from ecologists can then be used to make meaningful change.

When dealing with constructed ecologies, such as stormwater management facilities, there is a need for ecologists to 'lean-in' to other disciplines. Science can inform design, but cannot be produced through compartmentalizing ecosystems into easily understandable components. Global issues will require scientists to take on unconventional roles through transdisciplinary collaboration processes where science is on the same level as other stakeholders (Milkoreit et al., 2015). There must be a coherent position for scientists and politicians to mobilize useable knowledge. A comprehensive theoretical framework instilled with ecosystem protection, conservation, and participatory governance is necessary to advance biodiversity and habitat loss concerns. The publication method also reinforces the separation of disciplines as most work done by landscape architects, and planners lie in built projects that are outside of academic journals (Grose, 2014). Once the urban landscape is recognized and accepted as a dynamic, self-organizing system, the coproduction of new knowledge between researchers, landscape ecologists, urban planners and designers can be realized. Design can then be understood as a continuum of opportunities for ecologists to apply their work.

3.4 FUTURE RESEARCH IN FUNCTIONAL TRAITS

Functional Traits and Ecosystem Processes

Based on this research and others (Eviner, 2010; Lavorel & Garnier, 2002), plant functional traits in isolation are limited in their ability to depict ecosystem processes and functions accurately. Often, below and above-ground plant functional traits are independent of each other and multiple traits are required to determine a plant's effect on an ecosystem (de Bello et al., 2010; Eviner, 2010). In addition, plant functional traits can vary over environmental gradients at local scales. It is essential for future research to use a diversity of independent traits and species from a variety of ecosystem types (Bardgett et al., 2014; Eviner, 2010) and to consider the trade-offs between ecosystem functions, ecosystem services, and ecosystem properties (Lavorel & Grigulis, 2012). This would include not only plant functional traits, but also other organisms that interact within the larger ecosystem (Lavorel, 2013). Although traditional diversity measures are limited in their ability to reflect a complex ecosystem, diverse communities are needed in order to support multiple ecosystem functions simultaneously (Sutton-Grier et al., 2013).

There is functional trait variability between and within species (Eviner, 2010; Kattge, 2011). While most plant functional trait variation is between different species (60%), up to 40% intraspecific variation is documented in the global plant functional trait database, TRY[25] (Kattge, 2011). The main assumption of trait-based research is that while there is variation within a species, the variation is less than the difference between species (Kattge, 2011). Intraspecific and interspecific variation was also evident in the results of this research. However, it is difficult to say which functional traits reflect ecosystem processes if there are no environmental parameters or management goals for comparison (e.g., species diversity, phosphorous loading). Ecosystems are highly complex. While the

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[25] Project TRY initiated in 2007. TRY is a global plant functional trait repository for worldwide community research. It makes data available to other researchers through a single portal with its main objective to provide a global representation of plant functional diversity (Kattge, 2011).

research did show a statistically significant difference between different urban wetland management regimes, it does not provide insight as to why functional traits respond the way they do or how they affect an ecosystem. Functional traits that directly relate to a particular ecosystem function or management goal (e.g., nitrogen fixers and nitrogen root tissue content) may provide more useful information. In order to better manage our natural resources and mitigate undesirable change, it is critical that we understand the effects of different organisms on ecosystem processes. Plant species have diverse morphological, architectural, physiological, and biotic attributes that interact and influence ecosystem functioning differently. Although trait-based ecology has been proposed as a method to link species with ecosystem functions (Sutton-Grier et al., 2013), one challenge is determining which trait influences a specific ecosystem function of interest. Also, a majority of trait-based research has been on the response or effect of plant traits along a measurable environmental gradient (Eviner, 2010; Fiedler et al., 2018). Research often fails to address plausible trade-offs to complex ecosystem functions. **Figure 3.1** illustrates a generalized framework of some of the parallels and contrasts in ecosystem services between different trophic levels and plant functional traits beyond a wetland. Through a collaborative effort, researchers from numerous disciplines could come together to draw out the trade-offs and important ecological patterns between and across trophic levels to guide ecosystem management goals.

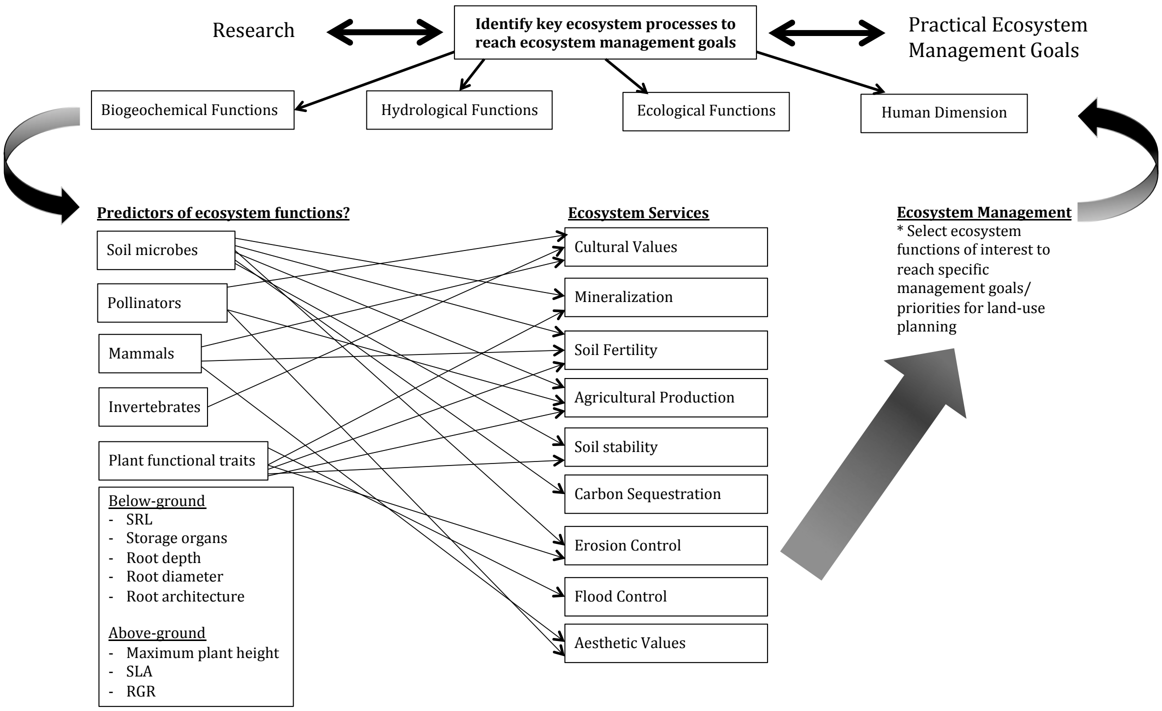

Figure 3.1: Interactive framework to guide collaborative research and ecosystem management goals that scales up from plant functional traits. Please note that this figure only addresses known relationships between plants, animals, and ecosystem services. Additional linkages and predictors of ecosystem functions exist. Acronyms: SRL = specific root length; SLA = specific leaf area; RGR = relative growth rate.

In **Figure 3.1**, research is the initial step in connecting or informing trait-based research to reach specific ecosystem management goals and vice versa. The specific trait-based research and ecosystem management goals determine what key wetland processes or functions must be addressed to answer identified ecosystem management goals. Ecosystem management goals may address biogeochemical, hydrological, ecological, or even human dimensional concerns. Within these categories, there are several indicators or predictors of ecosystem functions that can be utilized to reach a specific ecosystem management goal. Ideally, environmental parameters or predictors of ecosystem functions should include numerous trophic levels. **Figure 3.1** reveals numerous predictors of ecosystem functions that may include not only functional traits, but also other traditional indicators. For example, the producer trophic level predictors of ecosystem functions may include traditional taxonomic diversity to guide the success of a planting design in conjunction with functional traits from other trophic levels. Predictors of ecosystem functions can then be used to address vital ecosystem services vital in managing an ecosystem. In all, ecosystem management goals should focus on a specific function, conservation priorities and ecosystem services of an identified plant functional trait or traditional indicator (e.g., species diversity) along a measurable environmental gradient (e.g., water level). It is important to adapt and use a suite of ecological indicators or tools given the specific management concern.

Future Research in a Wetland Setting

An accumulation of plant functional trait data from a wetland ecosystem is required before more complex ecosystem linkages can be realized. Currently, there are databases, such as the TRY Plant Trait Database. Unfortunately, to my knowledge, there were limited morphological plant functional traits documented in a wetland setting.

3.4.1 IMPROVING ROOT FUNCTIONAL TRAIT RESEARCH

Root Methodology

The improved measurements of root functional traits will help improve the prediction of the consequences of vegetation change for ecosystem functioning (Bardgett et al., 2014). Unfortunately, many decisions made in the lab were based on logical reasoning, not from the scientific literature. There needs to be standard root methodology for the field and lab sampling, processing, and storing of roots. Most plant functional trait research focuses on above-ground traits in grasslands and forest ecosystems (de Bello et al., 2010; Moor et al., 2017). There is limited wetland plant functional trait research and even less on root methodologies in these specific ecosystem types.

Root Functional Trait Research

A complete picture of the underlying ecology is required to provide meaningful recommendations on ecosystem management priority and goals (Moor et al., 2017). All terrestrial ecosystems consist of above and below-ground components that interact to influence community and ecosystem-level processes and properties (Wardle et al., 2004). There must be a trait-based approach extended underground. Above-ground plant functional traits, plant diversity, and structure have cascading effects on ecosystem processes through changing the quantity and quality of plant material entering the soil. However, above-ground functional traits are limited in their ability to reveal how plant traits affect soil communities (Grigulis et al., 2013). It is evident that numerous root traits operate simultaneously to impact ecosystem processes, often with opposing and uncertain effects. Therefore, understanding how traits and trade-offs among them respond to environmental change and their impact on multiple ecosystem processes is crucial for future predictions on the impacts of global change (Bardgett et al., 2014). One of the most substantial challenges in root trait research is the need for advanced knowledge of the variation within root traits and within and between species across a large range of communities, ecosystems, and biomes. Currently, there are databases, such as the TRY Plant Trait Database. The improved measurements of root functional traits will help improve the prediction of the consequences of vegetation change for ecosystem functioning (Bardgett et al., 2014).

Despite the growing recognition of the functional importance of the interaction between roots and the soil, our knowledge of specific traits and their impact on soil microbial communities and how they relate to plant ecological strategies is limited. Future research must continue to untangle the influence root functional traits have on soil microbial communities, their activities, and impact on soil processes on which the functioning of terrestrial ecosystems depend (Bardgett et al., 2014). Also, functional traits of above-ground and below-ground plant parts often pose opposing effects on ecosystem properties or functions (Grigulis et al., 2013). For example, frequently specific root length and leaf dry matter content are inversely correlated. In other words, slow-growing species with a low specific root length and high leaf dry matter content are common in infertile soil (Kramer-Walter et al., 2016). This equates to opposing influences on an ecosystem's ability to sequester carbon. Lastly, the incorporation of soil microbes into below-ground plant functional traits may be important to understand below-ground ecosystem processes more effectively. Grigulis et al., 2013 quantified the relative contributions of plant and microbial properties related to nitrogen cycling through analyzing the direct effects of plant traits and then soil microbes. A step-wise multiple variable model fitting was designed that included an explanatory variable in order of perceived biological importance (i.e., plant traits, functional diversity, and microbial variables). At the end of the study, Grigulis et al., 2013 found that the incorporation of soil microbe parameters into a plant functional trait research model increased the understanding of soil ecosystem processes from less than 30% of the variance explained with plant traits in alone, to 60 – 80% with soil microbial parameters. Although most of the variance in the model was explained through the incorporation of microbial parameters, plant traits are important to incorporate to develop a complete understanding of soil ecosystems.

Weighted mean trait measurements and functional diversity indices

Functional diversity[26] indices and community-weighted trait means[27] are proposed as a viable option to minimize variability through the averaging process. Functional diversity indices may be better for future research into the use of plant functional traits to detect differences between urban wetland management regimes – wetland created by agricultural activity (Sunfish Pond), least disturbed wetland (Borden Wetland), and the on-line stormwater management facility (no. 32). Functional diversity is categorized into a number of indices. The common functional diversity indices are functional richness[28], evenness[29], or divergence indices[30] (Schleuter et al., 2010). While functional diversity indices and weighted mean trait values would complicate the practical use of plant functional traits for ecosystem managers, it is an option for collaborative researchers with access to sufficient funds. Also, functional diversity and community-weighted mean trait values should be

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[26] Defined as the number of different functional traits represented in an ecological community that influences ecosystem functioning (Tilman, 2001). Functional diversity consists of three components: functional richness, functional evenness, and functional divergence. Functional diversity is often reported as an index.

[27] Defined as the average trait value in a community weighted by the relative abundance of a species (i.e., how rare a species is in comparison to other species within a community or percent composition of a specific species relative to the total number of species in the community), population, and functional group (Duarte, Debastiani, Carlucci, & Diniz-Filho, 2018; Lavorel & Grigulis, 2012; Muscarella & Uriarte, 2016).

[28] It is defined as the number of different traits within an ecological community. It is positively related to the number of species present within a community (Schleuter et al., 2010).

[29] Determines how close in numbers or equal each trait is within an ecological community of traits. For example, if an ecosystem has five species classified as nitrogen fixers and four as non-nitrogen fixers, the functional evenness of that plant community is considered fairly 'even.' One functional trait is not dominating over another in the ecosystem.

[30] Measures the variance of a species function within a community. It can be calculated as the abundance-weighted (or rarity) functional variance using mean species values (Schleuter et al., 2010). For example, a low functional divergence indicates a small number of individuals occupy a narrow functional role.

compared against an environmental gradient. This would aid in understanding the response of functional traits to differences in environmental conditions.

3.5 MY RESEARCH IN A BROADER PERSPECTIVE

The increasing rate of change in climate, land-use, environmental pollution, and the influx of exotic species has led to an uncertain future (Hobbs & Cramer, 2008). The creation of novel ecosystems from unprecedented change has led to the need to manage the environment with new approaches from a revised understanding of how nature operates. That is, the management of an ecosystem from in 'equilibrium' to one that is dynamic, complex, and mostly in 'non-equilibrium' (Hobbs & Cramer, 2008). This demands a move away from the separation of nature into absolute categories (natural/ unnatural, production/conservation, intact/degraded) to a continuum of ecosystem states or 'patches' within the landscape mosaic (Hobbs et al., 2014). The way in which people intervene must change by evolving our understanding of the mechanics of a complex ecosystem. There must be the incorporation of the broader connective landscape into the goals of ecosystem management and the execution of ecological restoration projects (Harris & Hobbs, 2006; Hobbs & Norton, 1996). In addition, ecosystem management goals should anticipate uncertainties and integrate resilience considerations to ensure the system can transition to a more sustainable trajectory. Some of these externalities can be prevented through long-term ecosystem monitoring, and the adaptation of the framework as new information becomes available.

Although plant functional traits are touted as superior to traditional taxonomic measures when trying to comprehend complex ecosystem functions, this research demonstrated that plant functional traits are limited and variable in predicting differences in urban wetland management regimes. There was variation in plant functional traits within and between species of *Typha* and *Phalaris arundinacea.* This resulted in different statistically significant differences between urban wetland management regimes – wetland caused by agricultural activity (Sunfish Pond), least disturbed wetland (Borden Wetland), and the on-line stormwater management facility (no. 32). At this time, it is difficult if not impossible, to use plant functional traits to understand all ecosystem functions simultaneously. Most research focuses on plant functional traits along a measurable environmental gradient. While plant functional traits have only been quantified for single or few ecosystem services, there is still promise in the practical application of plant functional traits in combination with other traditional measures (e.g., taxonomic diversity).

To better manage our natural resources and mitigate undesirable change, it is critical that we understand the effects of different organisms on ecosystem processes. Although trait-based ecology has been proposed as a method to link species with ecosystem functions, one challenge is determining which trait influences a specific ecosystem function of interest. Although some traits vary independently from each other, many traits are correlated (Sutton-Grier et al., 2013). Research often fails to address plausible trade-offs of plant functional traits to complex ecosystem functions. Trait values vary between species and influence ecosystem functioning differently. For example, if soil nutrient cycling is the focus of a researcher or ecosystem manager, they may ask: what plant functional traits influence denitrification in the soil? Are plant functional traits independent of these soil ecosystem functions? What combinations of traits and species regulate denitrification functions? Through a collaborative effort, researchers from numerous disciplines could come together to draw out the trade-offs and important ecological patterns between and across trophic levels to guide ecosystem management goals.

If society fails to recognize the link between biodiversity and habitat loss and human well-being, future generations will face substantial ecological, economic, and social repercussions. While my research is narrow in focus, it has the potential to influence different social, ecological, and economic realms at various spatial and temporal scales. If one is to progress towards sustainability, one must prevent trade-offs whenever possible through integrating the community in project proposals before, during, and after implementation through a deliberative democracy process. Beyond my specific research, translational ecology[31], transdisciplinary engagements, and the mobilization of actionable science and research offer a unique opportunity to progress thoughts, models, and guidelines from research. These arrangements can thereby nurture mutual relationships

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[31] Translational ecologists seek to link ecological knowledge to decision-makers through the integration of ecology into the social realm which underlies environmental issues. It deliberatively extends research beyond theory to form ‘scientist-practitioner ‘partnerships to promote hands-on mutual learning (Enquist et al., 2017).

between people, the environment, and across disciplines to inform policy to make institutional change to address biodiversity and habitat loss. Nature can then be seen as something that provides essential ecosystem services, and that is worth conserving or bringing back.

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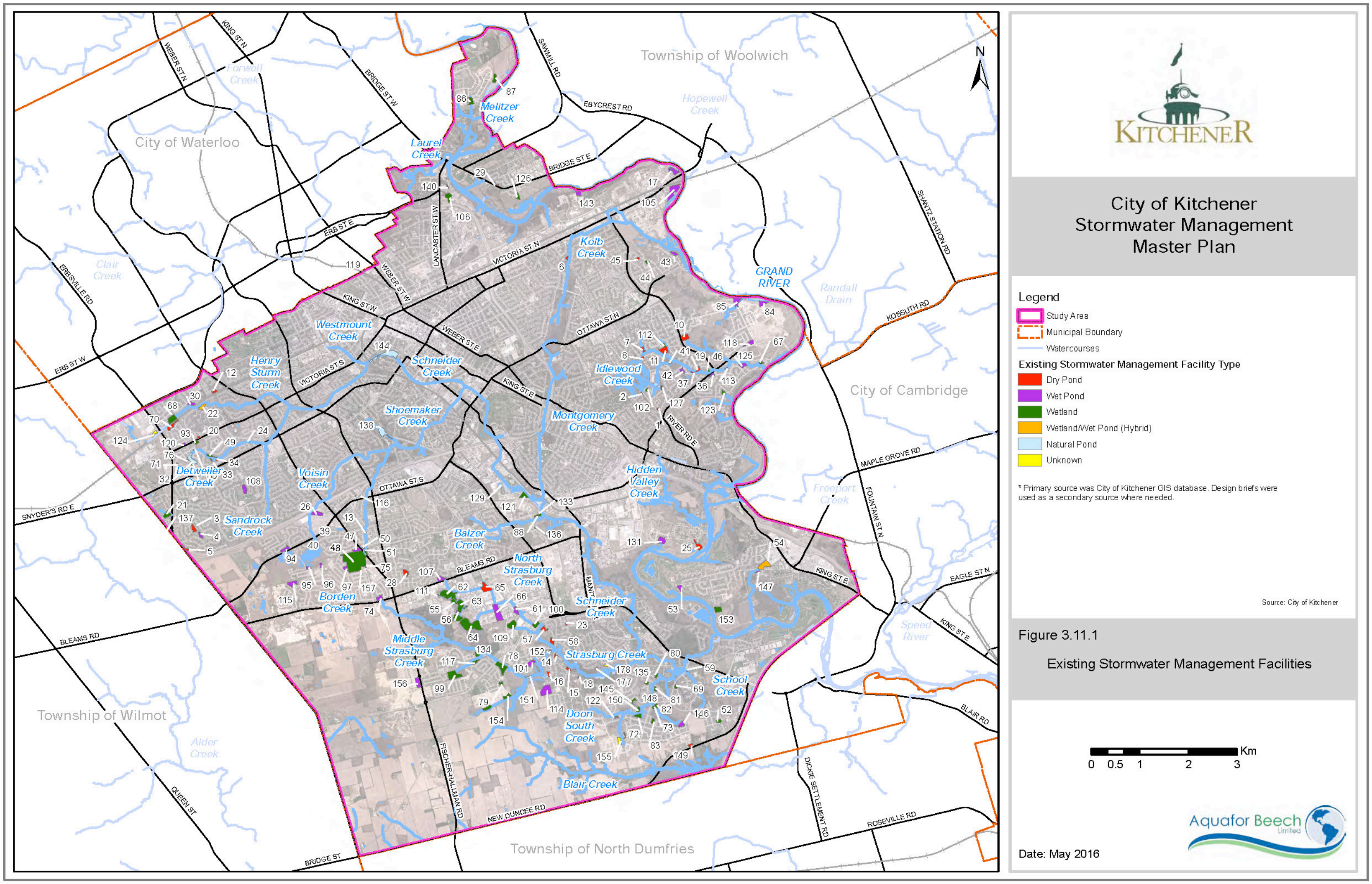
APPENDIX A – EXISTING STORMWATER MANAGEMENT FACILITIES WITHIN THE CITY OF KITCHENER, ON



City of Kitchener
Stormwater Management
Master Plan

Legend

- ▭ Study Area
- ⬚ Municipal Boundary
- — Watercourses

Existing Stormwater Management Facility Type

- 🟥 Dry Pond
- 🟪 Wet Pond
- 🟩 Wetland
- 🟧 Wetland/Wet Pond (Hybrid)
- ▭ Natural Pond
- 🟨 Unknown

* Primary source was City of Kitchener GIS database. Design briefs were used as a secondary source where needed.

Source: City of Kitchener

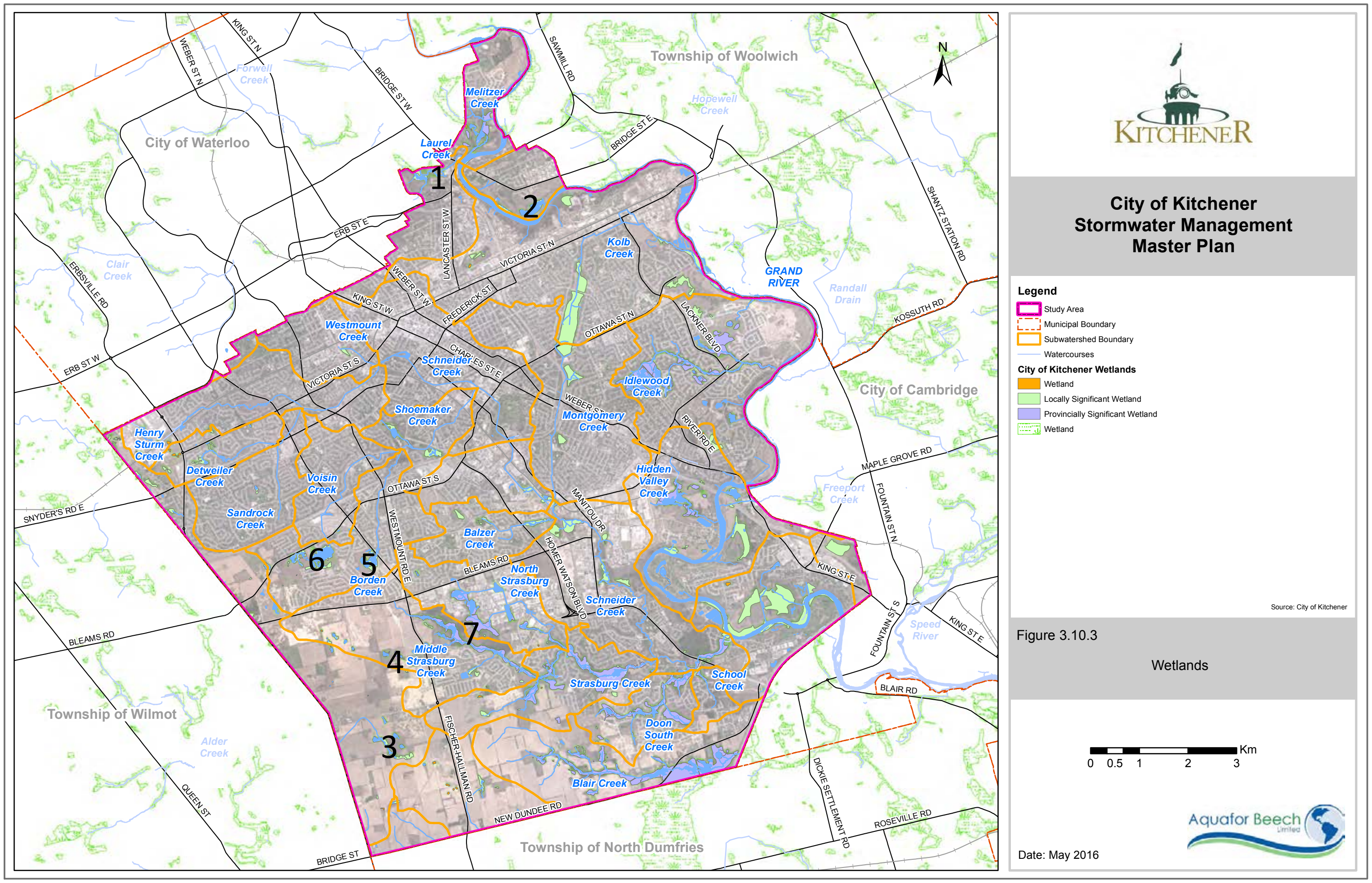
Figure 3.11.1

Existing Stormwater Management Facilities

0 0.5 1 2 3 Km

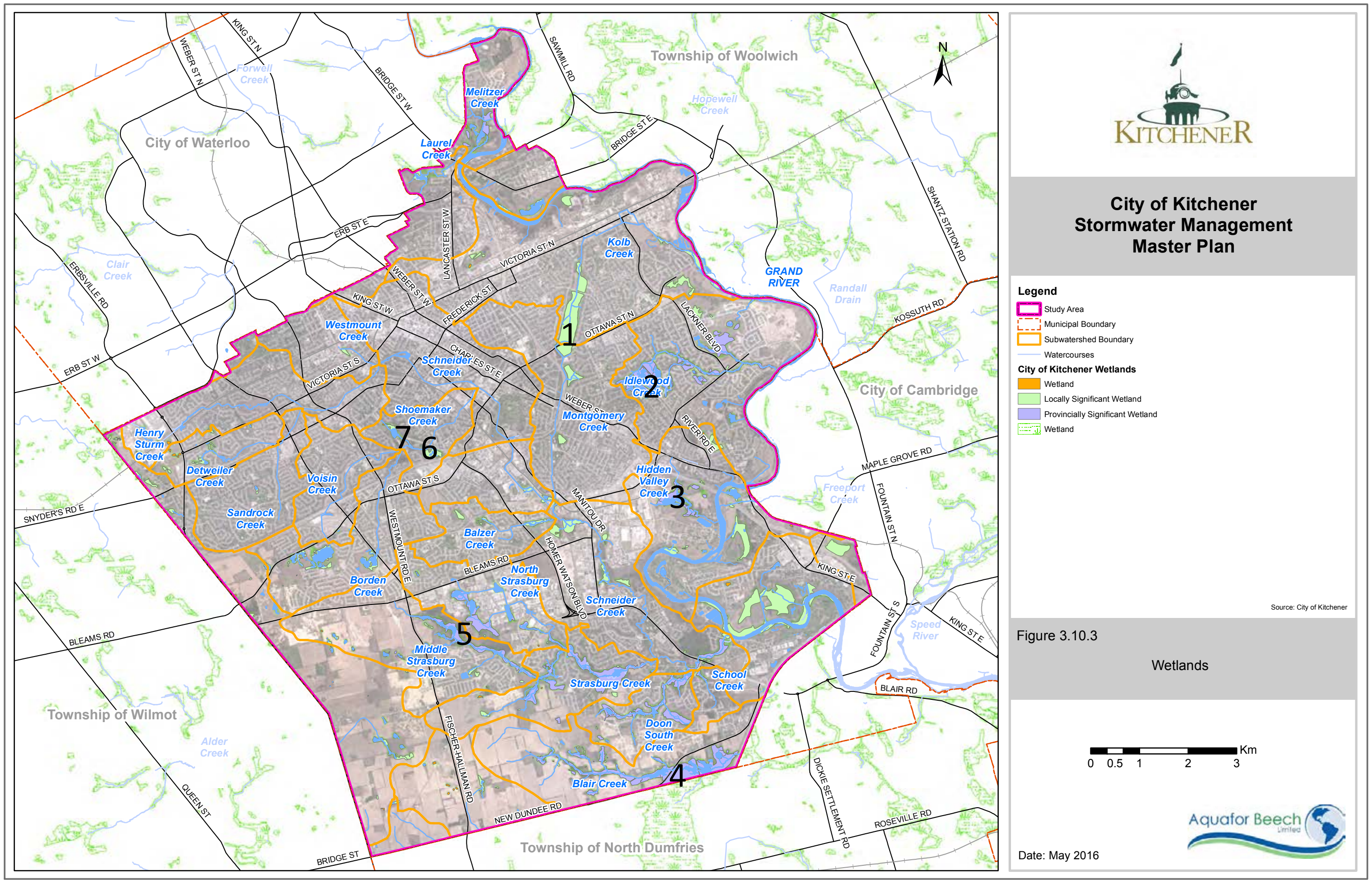
Date: May 2016

APPENDIX B – LEAST DISTURBED WETLANDS WITHIN THE CITY OF KITCHENER, ON



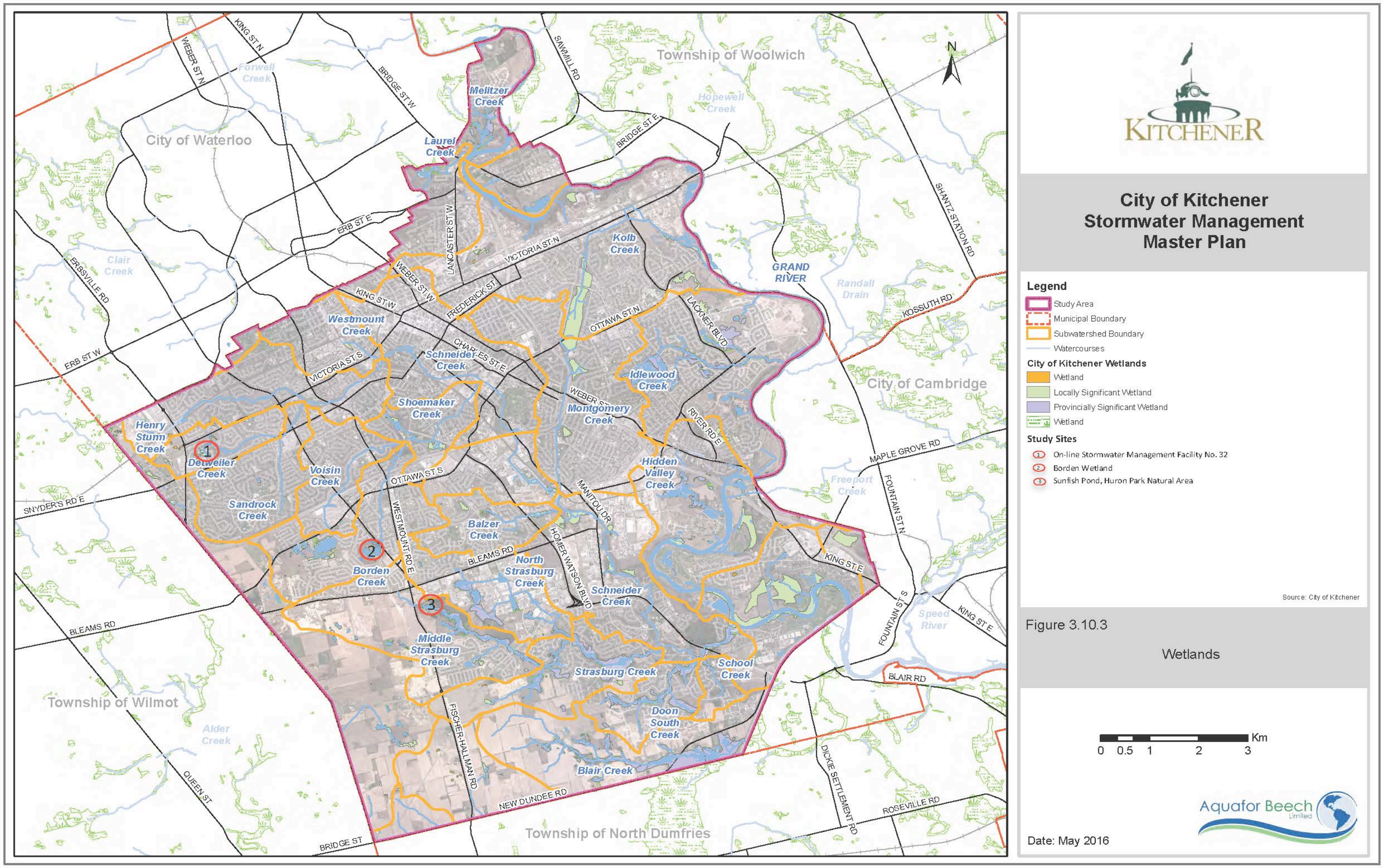
1: Laurel Creek
2: The Grand Wetland – due to seasonal flooding
3: Agricultural Wetland
4: Wetland off Huron Park Natural Area
5: Borden Wetland
6: Laurentian Wetland
7: Huron Park Natural Area Wetland

APPENDIX C – WETLANDS AS A RESULT OF PREVIOUS AGRICULTURAL ACTIVITY WITHIN THE CITY OF KITCHENER, ON

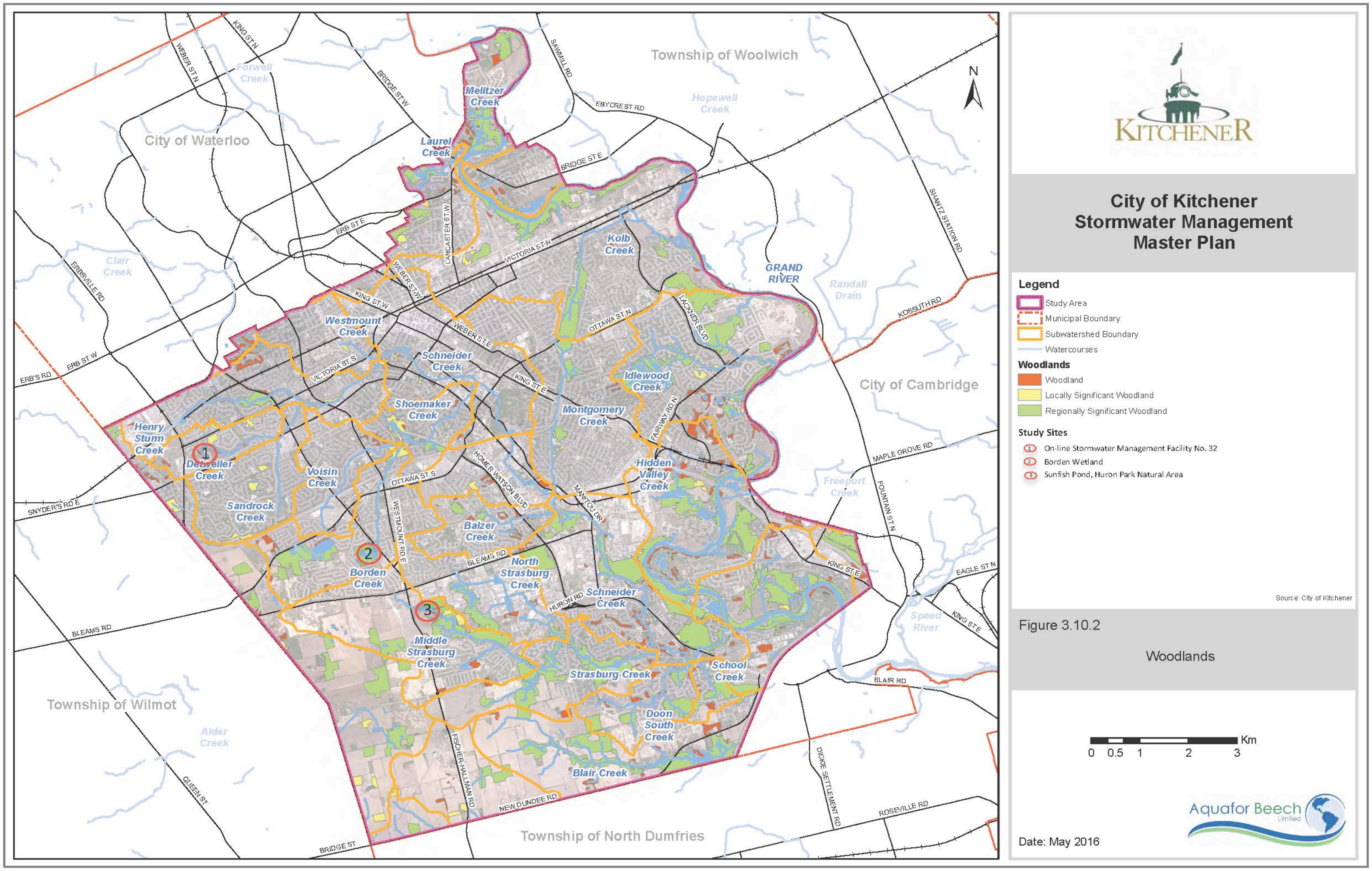


1: Stanley Park
2: Idlewood Creek
3: Hidden Valley Creek
4: Doon South – Blair Creek
5: Huron Park Natural Area
6: #138 – Wetland off a 'Natural' Pond
7: 'Natural' Pond (Engineering Division)

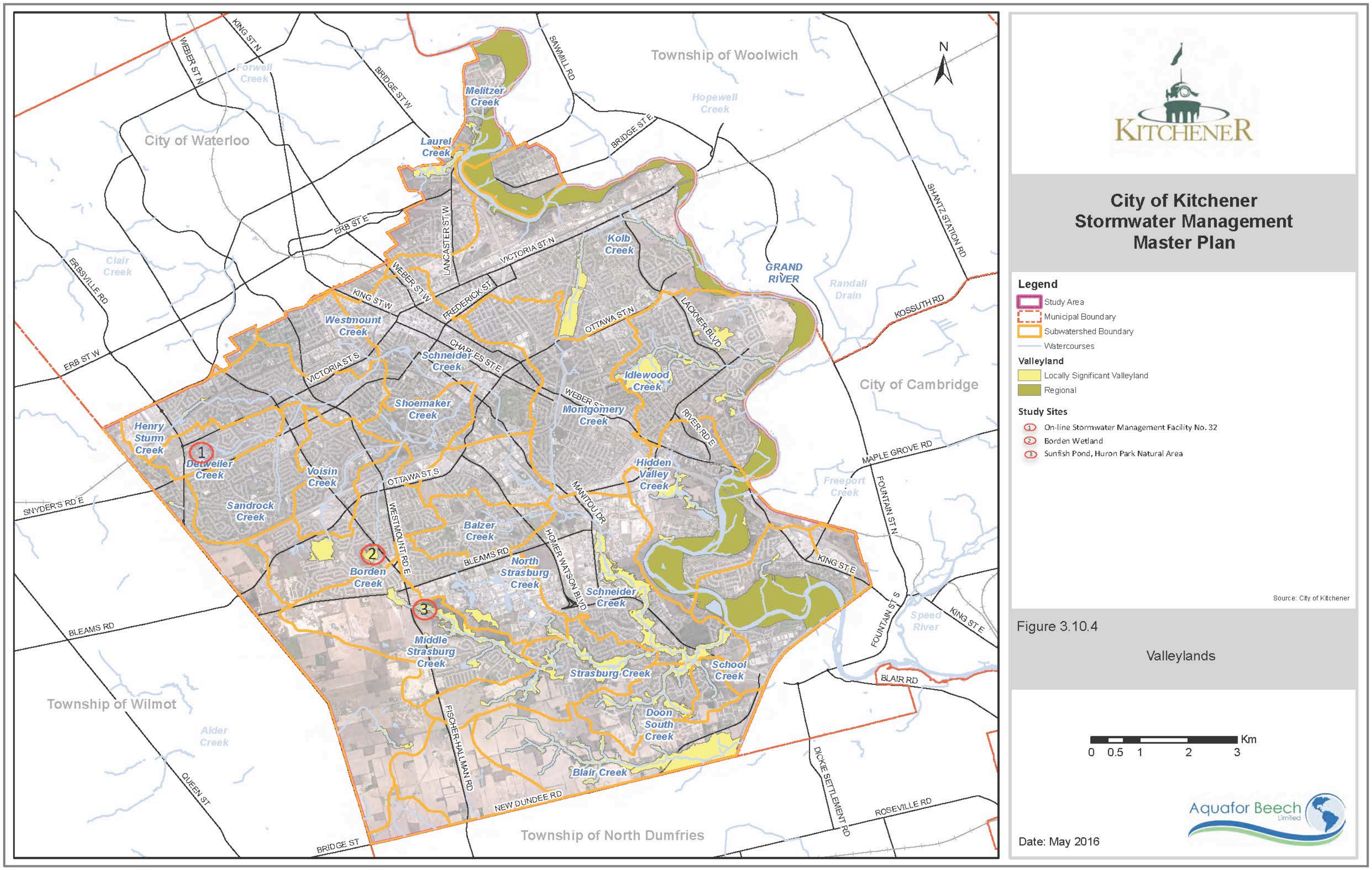
APPENDIX D – SIGNIFICANT WETLANDS WITHIN THE CITY OF KITCHENER, ON



APPENDIX E – WOODLANDS WITHIN THE CITY OF KITCHENER, ON



APPENDIX F – VALLEYLANDS WITHIN THE CITY OF KITCHENER, ON



APPENDIX G – SIGNIFICANT GROUNDWATER RECHARGE AREAS WITHIN THE CITY OF KITCHENER, ON

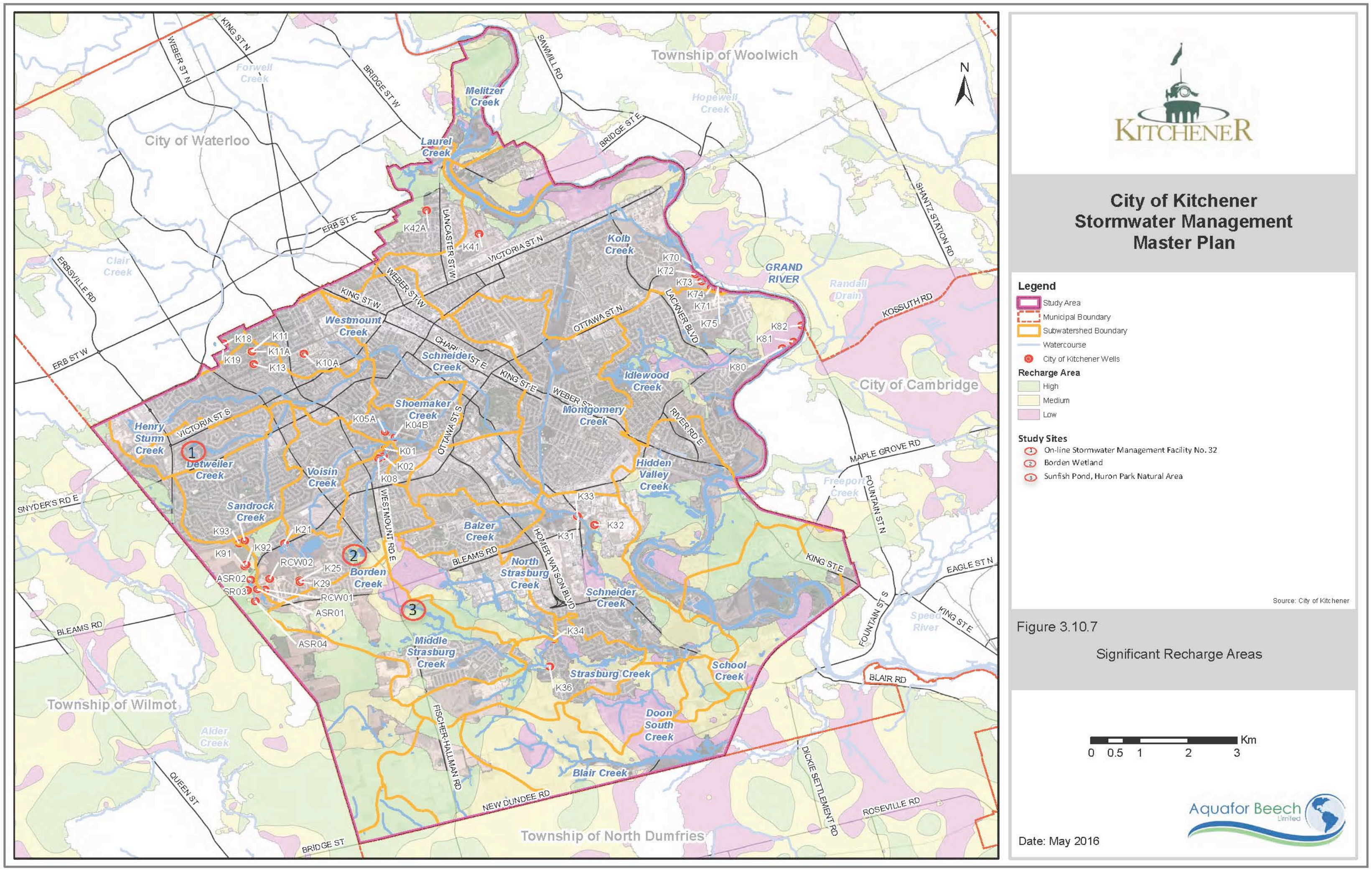
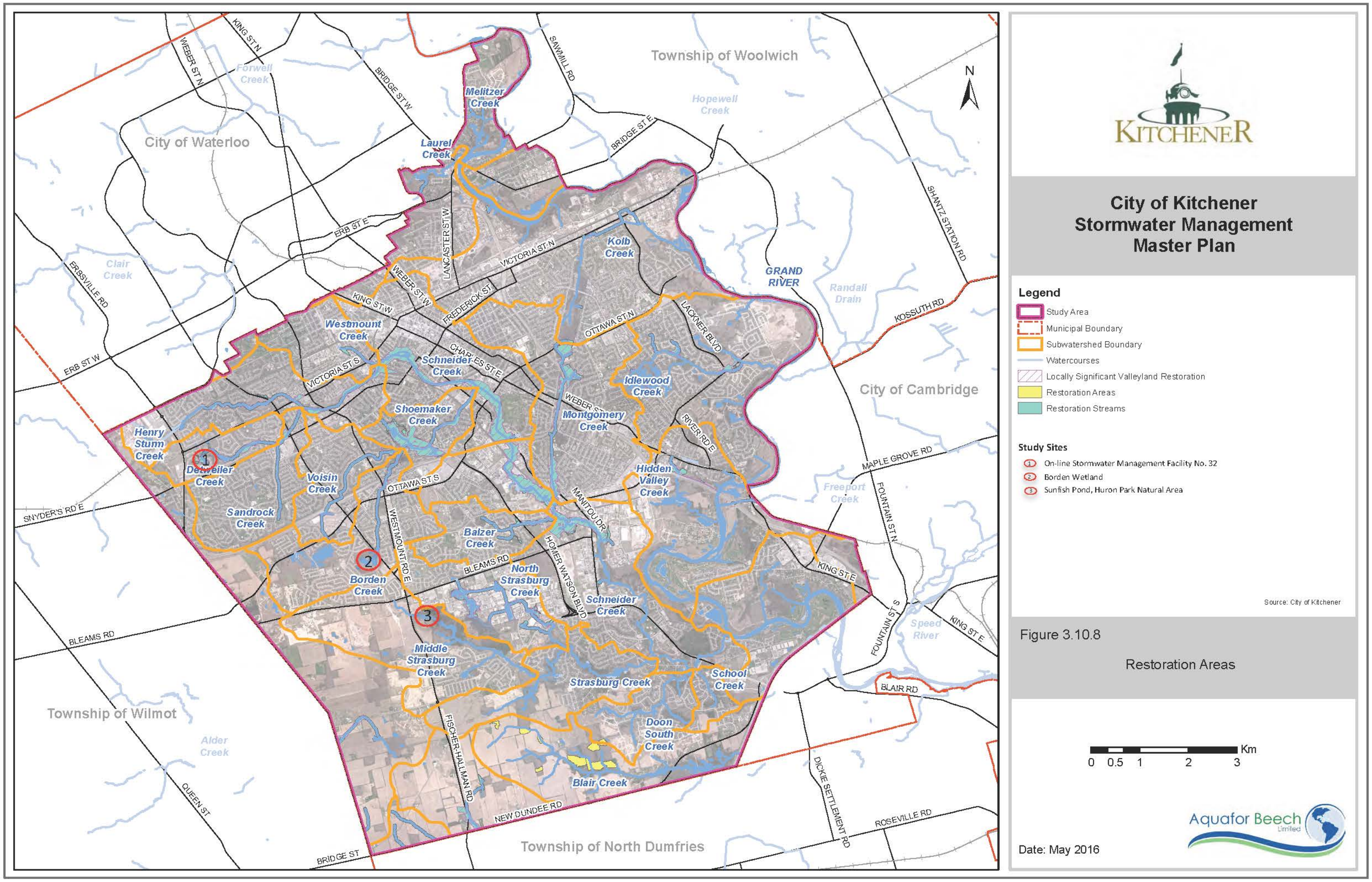


Figure 3.10.7

Significant Recharge Areas

APPENDIX H – STREAM AND VALLEYLAND RESTORATION WITHIN THE CITY OF KITCHENER, ON



City of Kitchener
Stormwater Management
Master Plan

Source: City of Kitchener

Figure 3.10.8

Restoration Areas

Date: May 2016