DOUBLE-CRESTED CORMORANT DISTURBANCE:

RESTORATION POTENTIAL FOR A FORESTED URBAN PARK

By

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Double-crested cormorant disturbance:
Restoration potential for a forested urban park

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Abstract

This paper examines the relationship between double-crested cormorant nesting activity and urban deforestation in Toronto's Tommy Thompson Park (TTP). TTP is located on a human constructed spit, providing habitat for colonial waterbirds to nest along Lake Ontario's shoreline. In recent decades, double-crested cormorant colonization has resulted in the deforestation of the western edge of the park. This deforestation is causing a steady retreat of tree cover, where newly exposed soils are vulnerable to colonization by invasive plants and erosive wind and wave action. Following a 30x30 m systematic sampling approach, geospatial interpolation of point data describing current soil physical and chemical properties is used to create continuous soil prediction surfaces. Interpolated surfaces are then combined to create site suitability maps using multi-criteria evaluation (MCE) to weight the soil variables, and to provide a ranked output of desirable site locations for species-specific re-vegetation potential.

Keywords: double-crested cormorant, urban forestry, restoration, kriging, multi-criteria evaluation

Acknowledgements

Table of Contents

List of Tables

List of Figures

List of Appendices

CHAPTER 1

1.1   Introduction

Cormorants are a family of colonial waterbirds recognized globally by their webbed feet, black plumage, long beak, and habitat-altering behaviour (Ayers et al., 2015; Behrens et al., 2008; Hobara et al., 2005; Kennedy and Spencer, 2014; Taylor et al., 2011). The *Phalacrocorax auritus*, or double-crested cormorant (DCC), is the most prominent cormorant species in North America. The DCC is a migratory species, with coastal summer colonies along the Pacific and Atlantic as far north as Alaska and Newfoundland, and winter colonies as far south as Belize and the western Caribbean (Blackwell et al., 2002; Stapanian, 2002; Wilson and Cheskey, 2001). DCCs also form continental populations that migrate in-land. The world's largest DCC population is located along the shoreline of Lake Ontario on the outskirts of the Toronto Harbour in Ontario, Canada (TRCA, 2016). DCCs are typically tree and ground-nesters, forming colonies adjacent to waterways in rural environments; they are rarely urban-dwellers (Taylor et al., 2011; Weseloh and Ewins, 1994). A combination of increased environmental quality in the Great Lakes Basin and new forest canopy provided by a lake-fill project has resulted in the exponential increase of the rarely-seen urban DCC population in the City of Toronto (Weseloh and Ewins, 1994; Wires and Cuthbert, 2006).

In the 1950s, the Toronto Harbour Commission initiated a lake-fill project to expand the Port of Toronto to accommodate the growing metropolitan area's needs (MTRCA, 1992). The 'Leslie Street Spit', as it became known, was developed by filling a five-kilometre-long spine of brownfield waste and harbour dredgeate into Lake Ontario (MTRCA, 1992; Taylor et al., 2011; Toronto City Planning, 2012). The outer harbour expansion was eventually abandoned and, by 1972, the spit had been colonized by a great diversity of flora and fauna from the nearby Toronto

1

Islands (MTRCA, 1992; Yokohari and Amati, 2005). The Honourable Frank Miller of the Ontario Ministry of Natural Resources (OMNR) decided that this undeveloped urban-wilderness would be best utilized as a public space for waterfront recreation (MTRCA, 1992). The land was transferred to the Toronto and Region Conservation Authority (TRCA; prior to 1977, known as the Metropolitan Toronto and Region Conservation Authority (MTRCA)) in 1972 for park planning, development, and management (Taylor et al., 2011). Tommy Thompson Park (TTP), as it was named after a former parks commissioner, is now the second most biodiverse park in the Greater Toronto Area, an Environmentally Significant Area as protected by the City of Toronto Official Plan, and the only urban Important Bird Area in the world, as recognized by BirdLife International (MTRCA, 1992; Taylor et al., 2011; Toronto City Planning, 2012; Wilson and Cheskey, 2001). However, the ecological health and biodiversity of portions of TTP are now at risk due to increasing DCC disturbance (TRCA, 2017a).

DCCs began forming colonies at TTP in 1990 (MTRCA, 1992; Taylor et al., 2011). As of 2017, 30,000+ DCC nests were recorded both in the trees and on the ground at TTP (TRCA, 2017a). DCCs use twigs, branches, and other live material from vegetation in their colonies to construct their nests. Once the nests are built, the birds remain at the nesting site for 10-12 weeks while depositing highly acidic feces, or guano, onto the soil below. DCCs are considered 'ecosystem engineers'; their nesting behaviour drastically alters surrounding habitat, leaving behind unsightly and highly odorous dead forests (Stewart et al., 2015; Taylor et al., 2011; Wires and Cuthbert, 2006). DCC guano supplements soil with essential macronutrients for plant growth, including nitrogen and phosphorus; however, in the quantities seen in colonial breeding grounds, the guano can alter soil alkalinity, the retention capacity of water and nutrients, and the potential for

phytotoxic concentrations of nutrients to accumulate (Hebert et al., 2014; Ishida, 1996; Lafferty *et al.*, 2016; Taylor et al., 2011). Deposition of organic matter occurs directly from regurgitated food, carcasses, and feathers, and indirectly from the breaking and falling of weakened trees and falling nest material (Boutin et al., 2011; Hebert et al*.,* 2014; Lafferty et al., 2016). These depositions reduce vegetation growth, prevent seed germination, create toxic soil environments for plant and tree roots, and can lead to the ultimate demise of vegetation in the nesting areas (Boutin et al., 2011; Ishida, 1996; Lafferty et al., 2016; McGrath et al., 2012; Natusch et al*.,* 2017; Taylor et al., 2011). Habitat alteration at this extent can severely increase interspecific competition for nesting habitat between DCCs and other colonial waterbirds (Quinn et al., 1996; Somers et al., 2007; Somers et al., 2011; Wyman et al., 2018). It is estimated that 25% of the forest canopy at TTP has been lost as a result of DCCs (Taylor et al., 2011).

In Toronto, the DCC population is perceived as a nuisance and threat to urban forestry, urban biodiversity, fisheries, infrastructure, and human recreation (Andrews et al., 2012; Mercer et al., 2013; Muter et al., 2009; Stapanian, 2002; Taylor et al., 2011). Ecologists and conservation biologists in Toronto and throughout the world have studied the nesting impacts of diverse species of cormorants due to the extent of ecosystem alteration that occurs within colonies. The majority of studies that analyze ecosystem disturbance and degradation as a result of cormorant colonization are typically focused on the extent of disturbance and degradation, but not methods to restore. Human presence and activity are deterrents for cormorant nesting, so cormorants colonize rural areas, away from the presence of local stakeholders and urban citizens opposed to their co-existence (Taylor et al., 2011; Weseloh and Ewins, 1994). The present study is unique as it will provide an answer to the loud call to action from urban dwellers to assess and restore

Toronto's park lands for future human recreation and uniquely high levels of biodiversity. The purpose of the present study is to combine an exploratory assessment of the cormorant-caused ecological degradation at TTP with site suitability mapping in order to provide restoration recommendations to the TRCA. The conditions of this site exhibit the unique effects of DCC in urban parks, specifically in an artificial wilderness, therefore, the results of this study may be useful as guidelines for future recommendations toward the management and restoration of urban DCC populations.

1.2   Thesis Objectives

This study investigates the current plant and soil conditions, within and surrounding, a DCC colony at Tommy Thompson Park (TTP) in Toronto, Ontario, Canada. Using the results of this descriptive analysis and multi-criteria evaluation (MCE) site suitability mapping, the study recommends locations for future re-vegetation initiatives (Steinberg and Steinberg, 2015). This project is a collaboration between the Toronto and Region Conservation Authority (TRCA) and Ryerson University's Urban Forest Research and Ecological Disturbance (UFRED) Group. The output of this study is intended to inform and make recommendations to the TRCA for restoration of DCC degraded urban forest in TTP.

Current plant and soil site conditions were assessed by collecting soil samples and identifying vegetation from 100 sample locations across TTP's Peninsula C. The vegetation identification occurred at the time of the study, in the fall of 2017. The soil samples were collected in the fall of 2017 and were brought back to the UFRED laboratory at Ryerson University for further analysis over the fall and winter of 2017 and 2018, respectively. The three main objectives of this thesis are to:

1. Measure the physical and chemical properties of soil, and identify vegetation presence, across TTP's Peninsula C.

2. Identify which vegetation species are currently growing well on TTP's Peninsula C. Specifically, determine what native species of trees and shrubs survive under current site conditions. And, determine how these species may promote forest succession.

3. Determine which areas on TTP's Peninsula C are suitable for forest restoration and propose priority locations with species-specific vegetation planting recommendations.

The study of DCC colonization at TTP is not unique; however, the study of site suitability mapping for re-vegetation in DCC-disturbed urban forests will provide novel information for the TRCA, the City of Toronto's Department of Parks, Forestry, & Recreation, the federal *Migratory Birds Protection Act* (MBPA), as well as for international bird conservation and management groups.

1.3   Thesis Outline

This thesis is organized into five chapters and presented in a formal thesis format as per the requirements of Ryerson University's Master of Environmental Applied Science and Management program. Chapter One provides a supplementary background to the thesis content as well as a description of the study's objectives. Chapter Two includes a review of local and international literature on cormorant-caused impacts on soil physical and chemical factors that affect forest canopy health and succession. Details on the materials and methodology used are provided in Chapter 3. Chapter 4 presents the results and discussion of the objectives of this study. Finally, Chapter Five addresses study limitations and poses questions for future research. The appendices include tables and figures that present equipment specifications, additional findings, laboratory protocols, and supplementary datasets.

The following literature review contains studies, findings, and limitations of global research on DCCs and related species. The majority of the sources are from peer-reviewed, scholarly journals. Additionally, municipal reports, conservation authority research and even meeting minutes provide relevant information to support the findings from journal articles. Previous research has identified that cormorants caused distinct ecological impacts world-wide, independent of species. However, there is little research on how to manage and restore urban areas, especially urban forests, that have been degraded by cormorants as they are not typically categorized as urban wildlife (Taylor et al., 2011).

CHAPTER 2

2.1   Double-Crested Cormorants

2.1.1   Historical Range Distribution

The double-crested cormorant (DCC)*,* is a colonial waterbird whose native range spans across North America in continentally interior as well as coastally exterior populations (Blackwell et al., 2002; Stapanian, 2002; Wilson and Cheskey, 2001). Globally, cormorant species are well known and often persecuted due to their foundational behaviour – colonial behaviour results in the extreme modification of cormorant habitat (Taylor et al*.,* 2011). Over the past few centuries, the DCC's range has expanded and contracted in response to severe management techniques and anthropogenic environmental degradation.

DCCs have been persecuted since the first arrival of European settlers (Ewins et al., 1995; Wires, 2015). Settlers hunted DCCs to prevent them from degrading local ecosystems (DCC colonies are unsightly and highly odorous), preserve local fish stocks (DCCs are piscivorous), and resolve the annoyance people had with this highly abundant species (Blackwell et al., 2002; Ewins et al., 1995; Stewart et al., 2015; Wires, 2015). Human management efforts to reduce and eliminate nearby colonies resulted in short-term reductions of DCC populations (Wires and Cuthbert, 2006). Game-hunting and intensive culling of birds resulted in the creation of the US *Migratory Bird Treaty Act* (MBTA) in the United States and the Canadian *Migratory Birds Convention Act* (MBCA) in 1918 and 1917, respectively (Migratory Bird Treaty Act, 1918; Migratory Birds Convention Act, 1994; Wires and Cuthbert, 2006).

By 1950, DCCs populations were once again being reduced, this time by habitat loss and environmental degradation so severe that offspring were not likely to survive (Adkins et al., 2014;

Andrews et al., 2012; Ewins et al., 1995; Mercer et al., 2013; Stapanian, 2002). Persistent organic compounds like DDT (dichloro-diphenyl-trichloroethane), PCBs (polychlorinated-biphenyls), and other organochlorine contaminants were common contributors to poor overall health for many bird species at the time (Ewins and Weseloh, 1994; Muter et al., 2009). The widespread use of the insecticide, DDT, in particular had the greatest effect on cormorant extirpation (TRCA, 2008; Muter et al., 2009; Weseloh, 1995; Wilson and Cheskey, 2001; Wires and Cuthbert, 2006). DCCs are piscivorous; they eat large portions of fish that have the potential to be contaminated by chemicals like DDT due to agricultural runoff (Glaser and Connolly, 2002). When animals' bodies break down DDT, the fat-soluble by-product, DDE, becomes stored in their body fat. DDE inhibits the enzyme responsible for transferring calcium from the bones of female cormorants through to their egg shells during embryo and egg formation. The bioaccumulation of DDE in female DCCs led to reproductive failure in all regions that relied on DDT (Ewins and Weseloh, 1994; Ewins et al., 1995; Weseloh and Collier, 1995; Weseloh et al., 2002; Wilson and Cheskey, 2001). As a result, Lake Ontario had 10 recorded breeding pairs of cormorants by the 1970s (Andrews et al., 2012; Weseloh and Collier, 1995; Weseloh et al., 2002).

Scientists began recognizing the significant presence of anthropogenic chemicals in DCCs and bird species across the continent in the 1970s. DDT was officially banned by the US Environmental Protection Agency in 1972, and cormorants became protected under the Bird Treaty Act of 1972 as well as blue listed by the National Audubon Society (Adkins et al., 2014; Mercer et al., 2013; Wires and Cuthbert, 2006; Stewart et al., 2015). The goal of these actions was to protect the birds along with their nests and eggs from further human intervention (Wires, 2015). Almost immediately, the Laurentian Great Lakes DCC population began increasing at a rate

8

of 29% annually (Chastant et al., 2014; Ewins and Weseloh, 1994; Ewins et al., 1995), reaching 38,000 breeding pairs by 1991, a thousand-fold increase in their previous population (Muter et al., 2009; Stewart et al., 2015). This near-extirpation and rapid population re-expansion of DCCs resulted in an unprecedented social push-back; DCCs were often viewed as a new, invasive species, and therefore, a threat to local environmental health (Ewins et al., 1995; Wires and Cuthbert, 2006). Bird and environmental advocates recognized that the expansion of DCC populations signaled the exact opposite – that environmental health was improving (Muter et al., 2009). Additionally, research has shown that DCC diets do not include common fisheries species, but in fact include smaller baitfish including invasive species like the round goby and alewife (Johnson et al., 2015; Somers et al., 2003). However, when the public increasingly believes that cormorants are the perpetrators of disturbance, attitudes can ultimately become engrained into management policy (Wires, 2015).

In 1990, the first 6 DCC nests were found in the early successional eastern cottonwood (*Populus deltoides*) trees on the northwestern edge of Tommy Thompson Park (TTP). The nesting began at Peninsula B, spreading to three of the park's four peninsulas by 2007 and reaching a grand population total of 30,000 breeding pairs as of 2017 – making TTP home to the world's largest DCC colony (Taylor et al., 2011; TRCA, 2008; TRCA, 2017a). The forest canopy along the northwestern edge of the park has been impacted significantly, having been deforested by an estimated 24% as a direct result of DCC activity (TRCA, 2016; Taylor et al., 2011). The Toronto and Region Conservation Authority (TRCA), local stakeholder groups, and members of the general public began requesting that intervention be taken to prevent further harm to the forest and biodiversity at TTP, however, the level of intervention was, and still is, a controversial topic (Mercer

et al., 2013; Taylor et al., 2011). The TRCA faces the challenge of creating an effective localized management plan despite targeting a cormorant population that spans across jurisdictional boundaries.

2.1.2 Management

Canadian provinces as well as American states have taken radically different approaches to cormorant management, ranging from hands-off approaches to protect public lands, versus lethal approaches on private lands (Muter et al., 2009; Wires, 2015). In the United States, a Public Resource Depredation Order was established in 2003 by the US Fish and Wildlife Service and the US Agriculture/Wildlife Service, permitting the culling of DCCs in 24 eastern states including those adjacent to the Great Lakes (Mercer et al., 2013; Strickland et al., 2011; Weseloh et al., 2012; Wires and Cuthbert, 2006; Wyman et al., 2018). DCCs in the western states are not actively managed, and in British Columbia, Canada, they are listed as 'threatened' on the provincial Red List (Mercer et al., 2013). The variety of regulations, management protocols, and public perceptions regarding cormorants across political jurisdictions complicates the formation and initiation of localized management plans, and this becomes increasingly complex as little is known about cormorant population dynamics, including fecundity, fidelity, and cross-colony replenishment (Chastant et al., 2014; Guillaumet et al., 2014; Ridgway et al., 2006).

The TRCA has worked collaboratively with local stakeholders, public advocates, and policy makers when it comes to managing Toronto's urban DCC population. The TRCA faces the challenge of implementing an effective localized management plan for the DCC colony whose migratory range spans across jurisdictional boundaries during the winter months (Taylor et al., 2011). Public pressure, especially in urban areas near cormorant populations, has increased the level of research

funding being put toward DCC management (Weseloh et al., 2012). Funding is typically divided within jurisdictional boundaries, therefore, there is little to no effort being put toward assessing the influence of DCC management at the population level (Guillaumet et al., 2014). Additionally, there is little research into the population dynamics of the exponentially increasing interior DCC populations, making it less likely for a broad-sweeping management strategy to be effective (Chastant et al., 2014). DCC studies from across North America are calling for cormorant control, specifically requesting lethal management of adult birds, as the rapidity of cormorant-caused forest decline in unique forest habitats is outpacing current management efforts (Ayers et al., 2015; Hebert et al., 2005).

The Official Plan for TTP was approved in 1992 under conditions proposed in consultation with the Friends of the Spit (FOS), an advocacy group for the naturalization of the Leslie Street Spit. Their motto was 'Let It Be', which adhered to a laissez-faire approach for promoting the park as a public, urban wilderness. With the rapid colonization of DCCs at the park by the early 1990s, stakeholders like the FOS recognized that some interventionist action would have to be taken (Taylor et al., 2011). A Cormorant Advisory Group was formed with other stakeholders including the Cormorant Defenders International (CDI) and Peaceful Parks Coalition (PPC) (Taylor et al., 2011). The TRCA initiated their final Cormorant Management Workplan in 2008 with the help of the Cormorant Advisory Group (TRCA, 2008).

As cormorants are known to be tree and ground-nesters, the TRCA began management by removing inactive nests from trees, transplanting tree nests to the ground, and using pre-nesting deterrents to reduce the encroachment and density of cormorant nests in the forest canopy at TTP (Weseloh and Ewins, 1994; Wires and Cuthbert, 2006; TRCA, 2016). In 2017, nearly 8,000

ground nesting DCC's were recorded at Peninsulas A and B (TRCA, 2017a). These two peninsulas are designated cormorant-conservation areas, while the remaining Peninsulas C and D are cormorant-exclusion areas to help protect their remaining forest canopy (TRCA, 2017a). Peninsula C is the major active DCC area of the park with remaining forest habitat. The TRCA is focusing efforts here to ensure that they deter incoming cormorants each season to the cormorant-conservation areas, with the goal of eradicating cormorants from Peninsula C within the next few years (TRCA, 2016).

Human presence, as is common in an urban wilderness like TTP, cannot be forgotten while creating a management technique as the park was created by humans with the intent of providing a wilderness area for urban recreation (Taylor et al., 2011). In the past, the Ontario Ministry of Natural Resources legalized lethal management techniques like egg-oiling and culling to minimize population size and future expansion in Presqu'ile Provincial Park and Middle Island, Point Pelee National Park, but the Ministry did not notice an improvement in fisheries health and consequently made culling illegal (Wires, 2015). The management intervention currently taking place at TTP shows that there are non-lethal ways to manage nature for urban wilderness areas to exist.

2.2   Soil Chemical Properties

2.2.1   pH

Guano deposition in DCC colonies has been observed to lower soil pH, producing more acidic soils and potentially reactive conditions for plant-growth hindering metals (Ayers, 2015; Breuning-Madsen et al., 2010; Hebert et al., 2005; Ishida, 1996; Lafferty et al., 2016; Natusch et al., 2017). DCC guano contains large amounts of nitrogen and phosphorus, resulting in higher rates of nitrification in the soil and therefore acidification (Boutin et al., 2011; Doubt and McMullin, 2016;

Hobara et al., 2005; Ishida, 1996). Soil pH within cormorant colonies can be up to 10 times more acidic than adjacent reference sites (Ayers et al., 2015). Soil acidification can alter the species composition at a site, as pH levels may reach outside that of the native species' range tolerances. Due to this ecological shift, the soil growing medium often favours non-native vegetation species and reduces the diversity and abundance of native wildlife (Boutin et al., 2011; Ayers et al., 2015).

Elements may become more reactive under certain soil pH conditions. Phytotoxic elements, like aluminum, become increasingly bioavailable in acidic soils, especially when pH is less than 4. Al_3^+. Although often present in low concentrations in soil, aluminum (3+) becomes mobilized by acidic soils and results in aluminum toxicity, a stressor that is much more likely to kill plants and reduce seed germination success than acidic soil alone (Ayers et al., 2005; Ishida, 1996; Zushi et al., 1992). When present in moderate amounts, the nitrogen and phosphorus excreted by DCCs has a positive outcome on plants as they act as fertilizers (Ishida, 1996). However, excess nitrogen in the form of ammonium, like that present in dense DCC colonies, will accumulate and be up-taken by plants at high concentrations, which can result in ammonium toxicity (Hebert et al., 2005). Ultimately, the lowered pH of soil by ornithogenic deposition and nutrient cycling processes can have a negative impact on the quality and quantity of nutrients in the soil and inhibits the growth of native vegetation due to soil chemistry intolerance.

2.2.2   Macronutrients

2.2.2.1 Nitrogen

The greatest limiting factor for plant growth and diversity is nitrogen availability in the soil, as it is an essential macronutrient for plants (Bittsanszky et al., 2015; Bobbink et al., 2010; Ellis et al., 2006; Pregitzer et al., 2016). Nitrogen in the forms of nitrate and ammonium are readily taken up

by plant roots, and lead to increased plant productivity when at moderate levels, which is why these forms of nitrogen are key components in nutrient fertilizers (Boutin et al., 2011; Rush et al., 2011; Wright et al., 2011). In most non-human dominated ecosystems, initial nitrogen fixation in soils occurs by nitrogen fixing bacteria that remove nitrogen gas from the atmosphere, however, nitrogen-rich soils also form in avian-colonized environments due to the birds' nitrogen-rich piscivorous diets and resulting deposition of ammonium-rich excrement (Boutin et al., 2011; Breuning-Madsen et al., 2010; Doubt and McMullin, 2016; Hobara et al., 2005; Ishida, 1996; Rush et al., 2011). In DCC colonies, ammonium concentrations are typically twice as high as non-DCC colonies (Hobara et al., 2005). These excessive concentrations of ammonium can become phytotoxic (Bittsanszky et al., 2015; Hebert et al., 2005; Natusch et al., 2017; Rush et al., 2011; Van Der Eerden, 1982).

Consecutive years of high nitrogen loading in DCC colonies results in altered soil chemistry, vegetative species composition, and secondary stressors for plants (Hogberg et al., 2006; Rush et al., 2011). Ammonium accumulation leads to increased nitrification and resulting acidification of soils (Bobbink et al., 2010; Breuning-Madsen et al., 2010; Hebert et al., 2005; Ishida, 1996). Higher nitrogen content in the soil increases the overall level of soil nutrients, creating a less-favourable environment for the complex community of native plant species that typically live on lower-nutrient soils (Boutin et al., 2011). This gives exotic, nitrophilic species the opportunity to colonize the landscape and reduce native, and often more diverse, vegetation cover (Bobbink et al., 2010; Boutin et al., 2011). When native plants do uptake excessive nitrogen in the form of nitrates and ammonium, the toxicity that results can stunt root growth, cause leaf chlorosis, lower plant resistance to pathogens and pests, cause the plant to become more attractive for herbivory, alter

biomass allocation which can alter the root to shoot ratio and cause the plant to become more susceptible to frost and drought impacts (Bittsanszky et al., 2015; Bobbink et al., 2010; Van Der Eerden, 1982).

2.2.2.2 Phosphorus

Waterbirds have piscivorous diets that result in phosphorus-rich guano (Breuning-Madsen et al., 2010; Hobara et al., 2005). The concentrated deposition of guano beneath a DCC colony results in high concentrations of phosphorous that change the local soil chemistry (Hebert et al., 2005). Although moderate increases in phosphorus can actually be beneficial for plant health, as it is a fertilizing nutrient, excess phosphorus can result in toxicity that stunts plant growth (Hobara et al., 2005; Natusch et al., 2017; Rush et al., 2011; Wright et al., 2011). The distribution and species diversity of terrestrial plants can also become limited based on the threshold of phosphorous that is reached in soils (Ellis et al., 2006; Hobara et al., 2005). In soils within cormorant colonies, phosphorus has been measured at 80 times higher than control environments; if soil phosphorus accumulates above 330 ppm, reforestation studies have shown that soil remediation is required prior to any re-vegetation (Ayers et al., 2015; Breuning-Madsen et al., 2010; Doubt and McMullin, 2016).

2.2.2.3 Calcium

Higher order plants require essential macronutrients, like calcium, as a fertilizer for tree growth (Fromm, 2010; Halman et al., 2011). Specifically, calcium is directly responsible for wood formation, radial growth, and foliar enlargement (Fromm, 2010). The presence of calcium has been noted to severely increase re-vegetation in disturbed sites and areas that have been impacted by destructive events like ice storms, droughts, and pathogens (Fromm, 2010; Halman

et al., 2011). Soil calcium (Ca^{2+}) is a base cation that can be leached out of the soil with increasing nitrogen deposition, nitrification, and acidification (Breuning-Madsen et al., 2005; Halman et al., 2011). In cormorant colonies, the aquatic to terrestrial nutrient transport results in higher concentrations of base cations like calcium, but it is also known to become deficient in cormorant colonies due to increasing soil acidification (Breuning-Madsen et al., 2005; Lafferty, 2016).

2.2.3   Micronutrients

Essential micronutrients for plant growth include potassium and magnesium. These nutrients are base cations – positively charged, easily exchangeable molecules that are common in soils and required for plant productivity (Wright et al., 2011). Magnesium and potassium play key roles in the health of foliage formation, regulation of osmosis, cell expansion, respiration and photosynthesis, and flowering initiation in trees and plants (Fromm, 2010; Tripler et al., 2006). In soils within cormorant colonies, higher levels of these nutrients have been recorded in the top soil horizons due to extreme guano deposition (Breuning-Madsen et al., 2010; Hebert et al., 2005). Potassium and magnesium both have the ability to reduce the impact of ammonium toxicity by helping plants to optimize nitrogen use (Bittsanszky et al., 2015). However, these base cations are known to leach, like other nutrients, out of the top soil horizons when soils become acidic as is common to soil in the vicinity of DCC colonies (Ayers et al., 2015).

2.2.4   Electroconductivity

Electroconductivity is a measurement used to convey the level of dissolved salts in soil water (Saxton and Rawls, 2006). Soil water molecules typically flow from an area of low salt concentration in the soil to an area of high concentration within plant roots. Soil salinity increases the osmotic potential in a soil, requiring more total energy from plants to uptake water and

nutrients at their roots and ultimately hindering their growth (Alberta Agriculture and Forestry, 2018; Donghai et al., 2011; Saxton and Rawls, 2006). In DCC colonies, excrement adds salt ions into the soil at rates that exceed salt leaching rates (Breuning-Madsen, 2010). The pooling of soil salts can cause additional stress to plants by impacting the chemical composition of the soil, as the reduced uptake of minerals by plants results in the accumulation of potentially toxic levels of these minerals in the soil (Saxton and Rawls, 2006). These effects all contribute to reduced seed germination for even the most salt-tolerant vegetation species (Alberta Agriculture and Forestry, 2018; Li et al*.,* 2011).

2.2.5   Organic Matter

The top layer of a developed soil consists of carbon-rich organic material, called the organic layer (O Horizon). The organic layer forms as plant litter and biologically deposited materials begin to degrade and release nutrients into the soil (Osono et al., 2006). Organic matter (OM) can have positive and negative impacts on plant growth, it provides nutrients to improve plant growth, allowing for increased vegetation coverage and diversity, but it may also hinder plant coverage and diversity when levels become too high, favouring often exotic, high-nutrient tolerant plants (Natusch et al*.,* 2017). OM impacts soil structure similar to clay; as OM increases, the water holding capacity increases and influences soil particle aggregation (Saxton and Rawls, 2006). The physical structure of plant roots can be altered in soils with high OM, as the roots will tend to grow closer to the surface to take advantage of the high nutrient levels, where trees with very superficial lateral roots will have reduced stability (Weaver, 1938).

Ornithogenic depositions of guano and other organic material in DCC colonies can also mechanically disturb vegetation and soil (Breuning-Madsen et al., 2005; Natusch et al., 2017). Soils

directly under DCC nesting areas often have cakey, thick OM that can actually impede water and nutrients from infiltrating into the lower soil horizons (Breuning-Madsen et al., 2010; Ellis et al., 2006; Natusch et al., 2017, Osono et al., 2006). A higher accumulation of carbon in the surface can also cause recalcitrance, the slowing of nutrient cycling in lower soil layers, which can also be a stressor that leads to tree mortality (Osono et al., 2006).

2.2.6   Cation Exchange Capacity

The cation exchange capacity (CEC) of a soil is the soil's ability to hold exchangeable cations at a specific pH (Arthur, 2017; Olorunfemi et al., 2016; Sayedmohammadi and Matinfar, 2018). CEC is a prominent factor when assessing and modeling soil quality as it directly indicates soil fertility as a result of the soil's capacity to retain exchangeable cations and thereby, nutrients (Sayedmohammadi and Matinfar, 2018). CEC indicates a soil's ability to retain nutrients and water, which also act as a buffer against changes in soil pH (Arthur, 2017). Nutrients like potassium, magnesium, and phosphorus can be predicted directly in relation to the measure of CEC (Olorunfemi *et al.,* 2016).

CEC is directly affected by the levels of clay and organic matter present in the soil (Arthur, 2017; Sayedmohammadi and Matinfar, 2018). Both organic matter and clay are major sources of negative electrostatic sites; when the organic matter and clay levels are higher, there is a greater surface area of negative binding sites, and therefore a greater chance for positively charged cations to be retained in the soil (Olorunfemi et al., 2016). There are great depositions of organic matter within cormorant colonies which contribute to increased CEC. Vegetation growth is limited when CEC levels are low, as there is low nutrient retention and less available nutrients for uptake by plants for growth. However, in cormorant colonies with high levels of CEC, the water and

nutrient retention can alter soil acidity and overall soil quality, effectively limiting plant growth (Sayedmohammadi and Matinfar, 2018).

2.3   Soil Physical Properties

2.3.1   Texture

The base soils at TTP are part of the lake-fill project, consisting of debris from construction sites and harbour dredgeate and capped with sand and fill (MTRCA, 1992; Wilson and Cheskey, 2001). Lake-fill depositions range from the 1970s through to present-day; the sources of the soil may vary but the structure of the soils at the park are young, so soil horizons are not distinctly developed (MTRCA, 1992). Soil fertility can be greatly influenced by soil texture as it is the variable that determines how porous a soil is, and therefore how well it may retain water, air, and nutrients while promoting illuviation to deeper soil horizons (Day et al., 2010; Ellis et al., 2006; Millward et al., 2011; Saxton and Rawls, 2006). Soils with higher clay content have the capacity to bond with organic matter and nutrients that can cause recalcitrance in soil nutrient cycling (Saxton and Rawls, 2006). Soil texture can also impact the rooting depth and overall favourability of the soil toward diverse plant species (Millward et al., 2011).

2.3.2   Compaction

Soil compaction is the compression of soil that results in lower soil porosity, reducing the retention space for water, air, and nutrients (Carrara et al., 2007; Day et al., 2010; Millward et al., 2011). Severe compaction results in a degraded or destroyed soil structure as well as increased soil strength, reducing surface infiltration and root penetration (Day et al., 2010; Millward et al., 2011; Weaver, 1938). Compaction can be a consequence of anthropogenic and biological activities. Man-made ecosystems like TTP have less developed soils, meaning less developed O and A horizons.

The horizons that do exist here likely consist of material that is representative of lower soil horizons – less porous and more likely to be compacted (Day et al., 2010). Additionally, decreased vegetation cover and increased biological deposition in the form of guano, eggshells, nest material, carcasses, and feathers, as seen in DCC colonies, can result in the compression of soil surfaces (Hobara et al., 2005; Lafferty et al., 2016; Osono et al., 2006; Rush et al., 2011; Taylor et al., 2011).

Ninety percent of tree root growth occurs within the lateral roots in the top metre of soil, yet, the majority of compaction occurs within the first half metre of soil (Craul, 1999; Millward et al., 2011). In compacted soil, tree roots will grow in increasingly shallower soil in order to access water and oxygen, resulting in short stubby roots close to the soil surface and less stable trees (Day et al., 2010). Studies have found the critical compaction threshold for new root growth lies between 2,000 and 2,500 kPa (Carrara et al., 2007; Day et al., 2010; Millward et al., 2011). Increased soil moisture reduces soil strength, therefore aiding in root growth; moisture tolerant tree species do well in compacted soils when there is periodic moisture; however, species intolerant to moisture will struggle to grow in a compacted environment (Day et al., 2010).

2.4   Landscape Properties

2.4.1   Elevation

Landscape elevation has implications for the infiltration and storage of water. TTP is a relatively uniform lake-fill site; there is little variation in elevation (75 metres to 79.5 metres above sea level) except for on trails, in natural depressions, and on berms where roads are built. However, micro-topography can play an important role in plant growth. In high-nutrient sites, lower elevation can increase the magnitude of nutrient impacts on vegetation (Natusch et al., 2017). In 2017, Toronto experienced on-going floods due to record-high water levels in Lake Ontario. The flooding covered

areas colonized by DCCs at TTP, including ground-nesting conservation areas and forests (TRCA, 2017a). Extreme weather events and flooding, like that seen in 2017, are only projected to become more frequent by Canada's national climate change assessment (Henstra and Thistlethwaite, 2017). Microtopography can have strong effects on vegetation at Peninsula C due to the proximity of the soil surface to the water table around the peninsula, which creates a life-or-death scenario for moisture intolerant vegetation.

Historically, ecological restoration focused on the removal of microtopography in order to create a new, uniform forest. However, soil properties and species diversity can vary significantly within micro-topographically distinct areas. The heterogeneity in microtopography at Peninsula C is likely to help accelerate future ecological succession (Gilland and McCarthy, 2013).

2.5   Vegetation

Indirect effects of DCC-driven soil chemistry alteration are reduced vegetation health and species composition within the colony area. The allochthonous nutrient transfer from aquatic to terrestrial ecosystems due to cormorants' piscivorous diets results in nutrient-rich, acidic soils that exceed tolerance levels of native plant species (Bobbink et al., 2010; Boutin et al., 2011; Ellis et al., 2006; Natusch et al., 2017; Pregitzer et al., 2016). Terrestrial plants are directly limited by concentrations of phosphorous and nitrogen in the surrounding soil, and secondarily by base cations like calcium, potassium, and magnesium (Ellis et al., 2006). Higher levels of phosphorus and nitrogen can become phytotoxic for all vegetation present at the site, and this toxicity becomes magnified if the study site is in early-successional stages, like TTP (Ellis et al., 2006; Natusch et al., 2017). Phytotoxicity affects older, woody trees first (Natusch et al., 2017), but can curtail seed viability,

or prevent propagules from forming at all on parent trees (Ayers et al., 2015; McGrath and Murphy, 2012).

Tree mortality in locations within and proximate to DCC colonies opens up the forest canopy to sunlight and wind; factors that aid in the establishment of exotic species and weeds in the seedbank (Ayers et al., 2015; Natusch et al., 2018). A study by Boutin et al., (2011) found that exotics were common in both standing vegetation and seedbank analyses from within DCC colonies, and that there was little relationship between the standing vegetation and the seedbank. Canopy openings result in 'edges' where seeds from exotic vegetation may either blow in or be deposited via animal activity. When seeds of nitrophilic plant species are deposited along the edges of a DCC colony, the germination rate is high due eutrophic soil conditions (Ayers et al., 2015; Boutin et al., 2011; Natusch et al., 2017). Native plant seedlings are more tolerant of adverse soil conditions than older trees, but they are not likely to survive beyond the first couple of years of exposure (Natusch et al., 2017).

2.6   Impacts on Urban Forests

Urban forest cover is a crucial component of infrastructure in cities. Trees, especially those of greater diameter, provide significant ecological services to urban residents. Ecological services, including carbon sequestration, stormwater runoff mitigation, erosion control, air purification, nature conservation, climate comfort, property values, and aesthetics, are all beneficial to human health and save Toronto an average of $60 million per year (City of Toronto Urban Forestry, 2008; Day et al., 2010; Millward et al., 2011; Ordonez and Duinker, 2013). The preservation and improvement of ecological services in Canadian urban centres is increasingly important, as the majority of the country's population resides in urban areas (Ordonez and Duinker, 2013).

In the City of Toronto, urban forest accounts for 20% of the land cover – 15% less than the municipal target of 35% by 2050 (City of Toronto Urban Forestry, 2008). With an estimated 24% tree canopy loss at TTP that is directly attributed to DCC nesting, the management of DCCs into a primarily ground-nesting population must be supplemented with re-vegetation efforts (Taylor et al., 2011). However, urban forest systems cannot flourish, and will not provide the ecological services we require, if soil quality is less than ideal (Millward et al., 2011).

DCCs are known to degrade soils at a rate that correlates directly with increasing nest density (Boutin et al., 2011). Soil degradation results in tree decline, mortality, and the opening of the tree canopy, presenting favourable conditions for exotic species to colonize while reducing environments within native species' range tolerances. The greater the proportion of exotic species in the seedbank, the greater the probability that restoration efforts will be hindered (Boutin et al., 2011; McGrath et al., 2012). DDCs have nested at TTP's Peninsula C since 2002, and as of 2017, 2,710 nests were recorded (TRCA, 2017a). Consecutive years of DCC nesting at this density is likely to contribute to soil degradation in the form of increasingly acidic soils, the accumulation of nutrient concentrations that may cause phytotoxicity, nutrient levels that alter the bioavailability of other nutrients, and ultimately reduced primary productivity (Boutin et al., 2011; Breuning-Madsen et al., 2010; Kolb et al., 2012).

In order to the combat the effects of DCC colonies on soil quality, a study by Ayers et al. (2015), found that bird exclusion was the best non-lethal technique to allow soil quality to improve and forest growth and succession to resume. In a "laissez-faire" managed urban wilderness, especially one that is home to such a diverse array of avian species, bird exclusion is not a viable option for the local conservation authority (Taylor et al., 2011). Other studies focus on the

restoration of diverse native vegetation, as increased native plant diversity will add to the resilience of the ecosystem (Boutin et al., 2011; Hebert et al., 2014). McGrath et al. (2012), recommend a mixed-methods approach toward increasing understory vegetation diversity in currently forested sites to ensure their germination into the newly restored, adjacent sites in the future. Bare root plants were found to be the most viable candidates for survival in an abandoned/deforested DCC colony, especially when combined with weed barriers, bird barriers, and soil replacement or phytoremediation around the roots (Ayers et al., 2015).

Studies by Ayers et al. (2015), Hebert et al. (2005), and Strickland et al. (2011) found that lethal or partially lethal management of DCCs is the most effective first step toward restoration of a forest canopy. Boutin et al. (2011) suggest that cormorant culling is the only way to ensure DCC nest density remains optimal for the sustainability of the restored forest. However, in an urban DCC population that is within such close proximity to human recreation, biodiverse species, and stakeholders, lethal management techniques are rejected. Alternative methods include nest removal and harassment to deter cormorants from breeding at the site (Boutin et al., 2011). The TRCA currently uses these alternative methods to reduce tree-nesting cormorant numbers at TTP (Taylor et al., 2011). TTP provides a unique landscape to practice non-lethal DCC management. When paired with simultaneous re-vegetation efforts, TTP's Peninsula C will set a global example for non-lethal management within the world's largest DCC colony (TRCA, 2016).

CHAPTER 3

3.1   Methods

Among the ecological variables that affect re-vegetation potential at TTP's Peninsula C, eight are focused on in this study: landscape position, soil texture including percent sand and percent clay,

soil alkalinity, organic matter content, phosphorus content, nitrate content, and ammonium content. This study will explore and evaluate the current values for these landscape and soil variables in order to assess the quality of soil in this DCC colony. Typically, soil has greater penetrability, moisture content, and nutrient availability in the first half metre, and consequently, the largest number of tree roots are found here (Millward et al., 2011; Weaver, 1938). Because of this, the eight important ecological factors that were selected are all characteristics from the A soil horizon, which represented soil with a depth of 0 to 30 cm across the site. These soil variables will then be placed into a site suitability model to decipher which areas of TTP's Peninsula C can be re-vegetated, including species recommendations to facilitate the restoration and succession of a native urban forest at Peninsula C.

3.1.1   Site Selection

The focal point of this study is Peninsula C, located in Tommy Thompson Park (TTP), an urban park in the municipality of Toronto, Ontario, Canada (Figure 3.1). The park was developed by naturalizing a five-kilometre long, 500-hectare lake fill project on the eastern harbourfront of Canada's largest city, approximately 3.23 kilometres from the downtown core (43.6314°N, 79.3264°W) (Taylor et al., 2011). The land mass of the park protrudes south from the shoreline of Lake Ontario; the length of the park bounds the southeastern edge of the Toronto Harbour. The park is completely surrounded by water aside from the point of entry at the bottom of Leslie Street.

TTP was initially filled by the Toronto Harbour Commission to expand the port lands of the city. In the 1950s, materials including earth, brick, and rubble from construction sites downtown

25

were dumped at the foot of Leslie Street (MTRCA, 1992). The peninsulas of the park were developed in the 1970s; Peninsula C was filled with harbour dredgeate from 1973 to 1974 (MTRCA, 1992) (Figure 3.2, 3.3). Materials and sediment were inspected prior to being dumped at the site to ensure the chemical composition met provincial open water quality standards (MTRCA, 1992). The harbour dredgeate contained sediment from the Keating Channel, an outlet of the Don River that was recently developed to deter effluent from entering the inner Toronto Harbour (Nriagu et al., 1983). Nriagu et al. (1983) used Toronto Harbour sediment cores to assess pre-colonial, industrial, and current heavy metal concentrations in the harbour. This study found that even pre-colonial sediments of the Toronto Harbour included heavy metal concentrations from Don River effluent that exceeded open water quality standards, showing that dredgeate deposited at Tommy Thompson Park was likely contaminated (MTRCA, 1992; Nriagu et al., 1983).
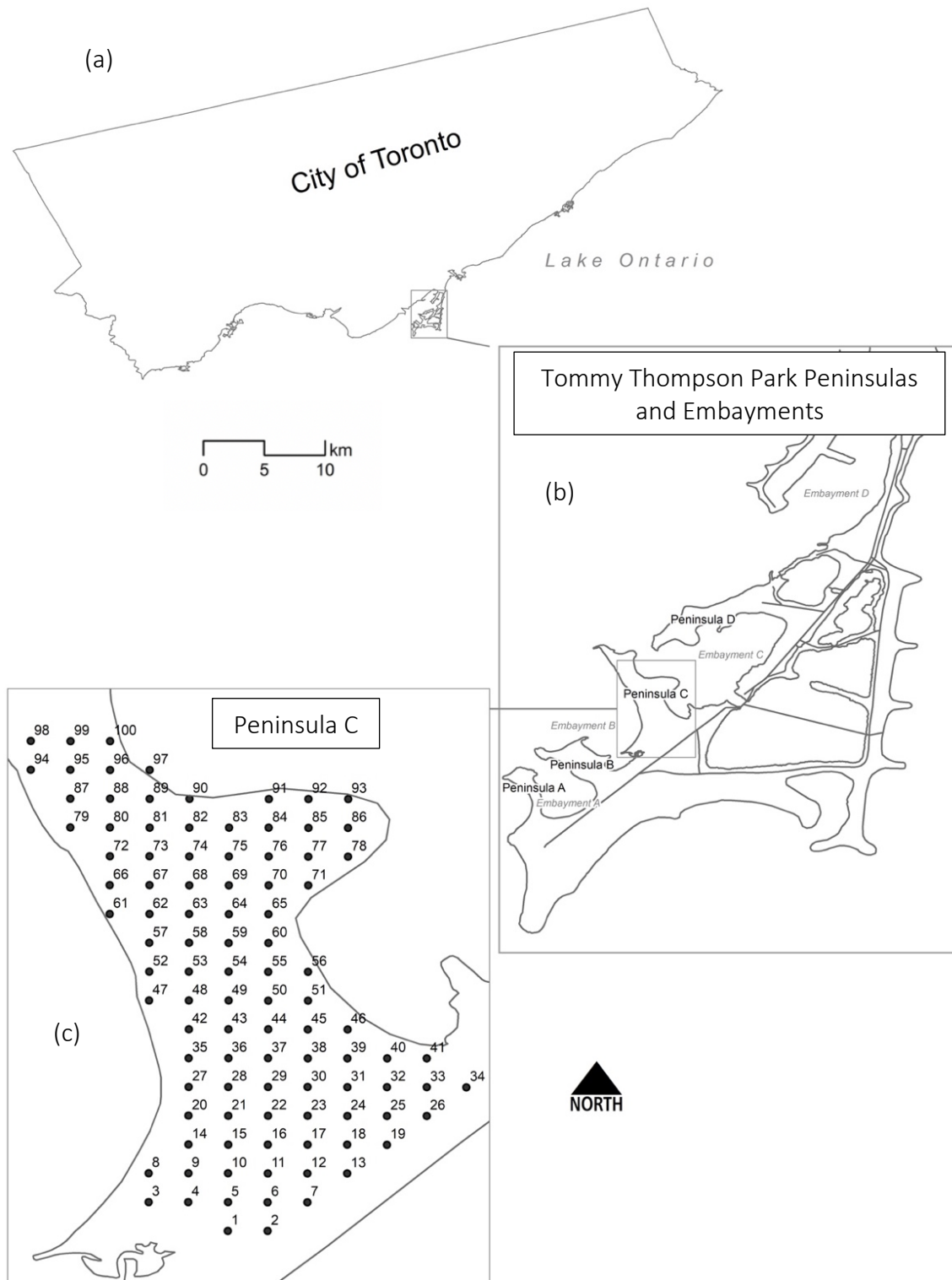
Figure 3.1: Reference map that illustrates: **(a)** the location of Tommy Thompson Park and Peninsula C in Toronto on the shoreline of Lake Ontario; **(b)** the peninsulas and embayments; and **(c)** the systematic sampling locations. Map scale references City of Toronto extent.

Figure 3.2: Map of Toronto Harbour dredging land-fill operation timeline at Tommy Thompson Park (MTRCA, 1992).

There is little development at the park aside from the TTP Bird Research Station, the Outer

Harbour Marina, the Aquatic Park Sailing Club, a public interpretation centre, and a storage

building for the TRCA; there is no infrastructure on Peninsula C. There is one main road along the

YEAR	TRUCK LOADS	CUBIC METRES	DREDGE SPOIL m³	TOTAL m³	ha
1956	26,000	99,385	–	99,385	5.50
1957	38,000	149,078	–	149,078	7.00
1958	13,894	58,867	–	58,867	6.68
1959	78,901	283,630	–	283,630	4.90
1960	107,880	347,542	–	347,542	9.35
1961	123,704	390,277	–	390,277	4.90
1962	114,725	408,702	416,653	825,355	6.47
1963	156,820	522,536	–	522,536	10.12
1964	266,826	1,034,904	–	1,034,904	15.78
1965	173,912	705,834	–	705,834	3.64
1966	180,561	757,620	252,285	1,009,905	4.86
1967	180,700	779,790	99,385	879,175	3.92
1968	238,918	1,110,482	77,054	1,187,536	3.72
1969	178,451	902,822	143,126	1,045,948	2.27
1970	184,600	893,067	82,310	975,377	2.55
1971	199,501	910,514	66,397	976,911	3.44
1972	157,921	690,835	51,650	742,485	1.78
1973	169,850	768,490	74,002	842,492	0.81*
1974	98,797	458,321	22,505	480,826	3.52**
1975	106,514	610,725	44,100	654,825	2.31
1976	78,817	451,917	–	451,917	2.75
1977	64,402	369,265	3,662	372,927	1.86
1978	16,496	94,584	13,341	107,925	0.16▫
1979	76,254	437,224	3,392	440,616	2.29•
1980	182,797	1,040,719	43,045	1,083,764	4.30
1981	182,616	1,438,131	102,875	1,541,006	3.50
1982	157,065	1,216,345	73,010	1,289,355	2.88
1983	113,702	895,430	29,760	925,190	1.62
1984	100,636	779,303	83,335	862,638	1.78
1985	98,067	689,565	83,214	772,779	1.91
1986	91,967	744,303	62,445	806,758	1.70
1987	53,352	431,769	93,591	525,360	1.55
1988	55,405	444,011	120,903	564,914	0.32
1989	89,374	721,265	107,724	828,989	3.30
1990	153,419	1,236,725	97,538	1,334,263	5.19
1991	55,625	446,858	95,329	542,187	1.70
Total	4,366,469	23,320,835	2,342,641	25,663,476	140.80
*'73			3,825,558		33.55●
**'74			2,640,562		32.34●

▫ Rubble Only 78/1/19
• Endikement 79/4/2
● Main Harbour Channel Dredging

Figure 3.3: Tommy Thompson Park annual lakefill data, 1956 – 1991 (MTRCA, 1992).

edge of the park and multiple designated walking trails. The park is primarily covered by early successional deciduous tree species, including eastern cottonwood (*Populus deltoides*), white birch (*Betula papyrifera*), European alder (*Alnus glutinosa*), trembling aspen (*Populus tremuloides*), and Manitoba maple (*Acer negundo*), especially along the western flank. These species' seed

sources are likely the nearby Toronto Islands, arriving from the 1950s through 1970s (Taylor et al., 2011). The eastern edge of the park was completed more recently; it contains shrubs, grasses, and wetland species planted by the TRCA for habitat creation (MTRCA, 1992).

In 2017, 2,710 DCC nests were counted on Peninsula C, a number which is lower than previous years likely due to the 2017 floods that would have decreased the area available for ground-nesting DCCs (TRCA, 2017a). Due to the incredible population sizes of over 300 avian species nesting at TTP, areas of the park are protected from disturbance and destruction during key periods (e.g., migration and nesting) under the *Migratory Birds Convention Act, 1994* (SC 1994, c 22, s 12). This legislation restricted researcher access to areas of interest for a four-month period from May to August in 2017.

3.1.2   Study Design

This study was based around a 100-point systematic sampling design. The conventional approach of sampling in a simple random manner was determined to be ineffective for this study because methods sought to use a point interpolation approach that would yield a two-dimensional prediction surface (Bloschl, 2002). As this study is concerned with geospatial analysis, the spatial correlation between biotic and abiotic factors is important (Liebhold and Gurevitch, 2002). The systematic sampling design was chosen with the supposition that the first point placed would satisfy the assumption of quasi-random placement of subsequent points (Bloschl, 2002). The systematic sampling approach utilizes a rectangular grid system that is easy to accurately ground truth while also ensuring the entire target area is represented fairly by spreading sample points evenly, requiring less points than the simple random approach. Random sampling in this study could result in clustered and gapped points, causing over and underrepresentation of the site

spatially. If too many points cluster closely together, information becomes duplicated as there is a correlation between space and value in geostatistics. If gaps are large between points, the analysis would require an increased number of points to compensate for this (Bloschl, 2002).

Using ArcMap (ESRI Inc., ArcGIS 10.5), a rectangular grid was overlaid on top of aerial imagery of the 8.12 ha Peninsula C. Based on the invariability and size of the target area, as confirmed during preliminary analyses, a 100-point study was found to be representative of conditions at the peninsula. The 100 points were selected by dividing the target area into 100-30 x 30 m grid cells, and selecting the centroids, or center points, of the cells as sample locations. Circular quadrats were created around the centroids in ArcMap using a 5 m radius. To ensure that no sample locations were placed along the ephemeral beach, a 5 m exclusion buffer was implemented inland from the Lake Ontario shoreline.

Originally, this study was to take place at the beginning of the 2017 growing and cormorant nesting season (April 2017) at Peninsula C; however, record high water conditions in Lake Ontario flooded many of the study points and blocked accessibility to the peninsula. This study was resumed in late September, at the end of the cormorant nesting season. Samples were collected over a three-week period, between September 18th and October 6th, 2017. By the completion date, the majority of the DCCs had migrated (left TTP) for the winter. The field study was designed and implemented with the expertise of a diverse team of forestry, ecosystem, and soil researchers with related field work experience and publications. The team included Dr. Andrew Millward (Principal Investigator with the Urban Forest Research & Ecological Disturbance (UFRED) Group in Ryerson University's Department of Geography & Environmental Studies), Christopher Scarpone (PhD Student, Ryerson University), Vadim Sabetski (MSA Graduate, Ryerson University), Joshua Ali

(Research Assistant, Ryerson University), and Taylor Posey (Research Assistant, Ryerson University).

3.1.3 Data Collection

In the field, soil and vegetation sampling were conducted to measure soil pH, electroconductivity, texture, compaction, and nutrient content, and vegetation diversity and forest composition (Table 3.1). The centroids of each of the 100 sample points were located in the field using a Topcon HiPer SR GNSS Receiver with Topcon FC-5000 Data Collector (TRK real-time accuracy, typically < 10 cm in horizontal) [Appendix A]. Sample points were flagged and marked with flagging tape to ensure they were accessible throughout the field study period. The soil and vegetation samples were collected simultaneously at each sample point; the soil was collected from the centroid, and the vegetation sampling took place by observing diversity within a 5 m circular quadrat.

Soil compaction profiles were created by taking compaction samples from each centroid using a cone penetrometer. A FieldScout SC 900 penetrometer was used to penetrate the soil to a depth of 45 cm using a 1.5" metal cone [Appendix D]. The device used sonar to detect the resistance of the soil in kPa, recording a pressure every 2.5 cm. The resulting compaction profile is beneficial to visualize how easily plant roots are able to penetrate the soil, gather nutrients, and up-take water throughout the study area.

Three 200 g samples were collected from each centroid from each the organic horizon, A horizon, and B horizon. A soil pit was dug at each centroid using a spade, ensuring that one side of the pit was completely vertical to assist in the identification of stratified soil layers and to minimize contamination between soil layers. Soil pits were dug to a depth of 50 cm, with the exception of 3 sample points where high-water tables interfered with the precise collection of B horizon soils. In

the case where it was not possible to reach a depth of 50 cm at the centroid due to physical impediments, like boulders or tree roots, the pit was dug within 1 m of the centroid. After digging each pit, a photograph was taken to visualize soil stratification. Using a trowel, samples from the three soil horizons were retrieved from the vertical side of the soil pit, taking first from the bottom (B horizon) and working upward to minimize through-fall and contamination between samples. It should be noted that a small number of sites had evident impact from the early-summer flooding experienced in Toronto. This flooding caused the visible deposition of sandy lake sediment on top of the organic layer. In these circumstances, a 200 g sample was taken from the superficial sediment as this top layer is not believed to be representative of the organic layer and the organic layer and subsequent horizons were clearly visible beneath it. As they were taken, the samples were placed into individual field bags that were numbered according to site number and sample depth. The samples were then stored in a trunk that was used to transport samples to the Urban Forestry Research and Ecological Disturbance (UFRED) Group laboratory at Ryerson University to be frozen for future analysis.

Figure 3.4: Vertical wall of soil extraction pit at a depth of 60 cm on TTP's Peninsula C.

Soil samples were processed at the UFRED laboratory from October 2017 – February 2018.

Samples were assessed for pH, electroconductivity, and texture according to UFRED soil analysis

protocols (Appendix E and F, respectively). Further assessment of nutrient content within the

organic and A horizons was completed by SGS Agrifood Laboratories in Guelph, Ontario. This

assessment included organic matter, phosphorus, nitrate, ammonium, calcium, magnesium,

potassium, and cation exchange capacity.

Vegetation diversity and forest composition data were collected while on site. Mature

trees were identified and counted, along with understory flora. As part of a preliminary vegetation

analysis, TRCA Peninsula C tree datasets were reviewed in order for the field crew to become

familiar with the common tree species and identification skills (TRCAb, 2017). This provided information on species richness at each sample location, which is important for visualizing the relationship between surviving species and the amount of growth in the understory under varying soil conditions.

Table 3.1: Chemical and physical soil properties measured and methods of measurement.

PROPERTY	METHOD OF MEASUREMENT
CHEMICAL	
pH	Soil core (Ryerson UFRED laboratory)
Electroconductivity	Soil core (Ryerson UFRED laboratory)
Organic Matter	Soil core (SGS Agrifood Laboratories, Guelph)
Nutrients (P, NO3-, NH4+, Ca, Mg, K)	Soil core (SGS Agrifood Laboratories, Guelph)
Cation Exchange Capacity	Soil core (SGS Agrifood Laboratories, Guelph)
PHYSICAL	
Soil compaction	Hand-held digital penetrometer (on site)
Soil texture	Soil core (Ryerson UFRED laboratory)

3.1.4   Data Analysis

The limitations of scope, time, team size, and funding restricted this study to primarily soil criteria. Although ecosystem variables, including soil microfauna and rhizosphere composition, are influential factors on plant growth and forest composition, they were considered outside of the scope of this study. The effects of urban soils on the condition of vegetation must also be considered, as human-impacts on soils can add to the detrimental effects caused by DCC nesting (Pregitzer et al., 2016). Specifically, the soil conditions of TTP as a result of the potentially bad-quality harbour dredgeate that was deposited over the past few decades, may also be considered influential for plant health and growth at Peninsula C (MTRCA, 1992; Nriagu et al., 1983). However,

healthy forests remain at other areas of the park, for example Peninsula D, that contain the same dredgeate as was deposited at Peninsula C (MTRCA, 1992).

The following analyses involved soil data taken from the A horizon at Peninsula C. This is due to the increased conditions in the first half metre of soils to have greater penetrability, moisture content, and nutrient availability, and consequently, the largest number of tree roots (Millward et al., 2011; Weaver, 1938). Despite the collection of a wide array of sample variables, the final analysis paired down those collected to a selection of eight significant landscape, physical, and chemical factors that are the most instrumental in plant growth and support for forest succession. Although compaction, electroconductivity, and micronutrient concentrations were measured, they each had low variability in the A horizon and would not have influenced change in soil quality across TTP's Peninsula C (Appendix H).

The landscape factor is elevation, which can influence the capacity for water retention and nutrient cycling across landscapes, especially at TTP because of its close proximity to the water table (Hobara et al., 2005). The physical factors include soil texture in the form of percent sand and percent clay, which can each directly affect species composition, nutrient availability, water retention, and seed germination (Scharenbroch and Catania, 2012). The chemical factors include: soil pH, which has the direct capacity to limit tree growth and cause mortality if levels become too acidic or basic (Lafferty et al., 2016; Natusch et al., 2017; Scharenbroch and Catania, 2012); organic matter, which can contain essential macronutrients required for plant growth, can alter the viability and germination of seeds in the seedbank, and can alter illuviation of water and nutrients into deeper soil layers (Arthur, 2017; Boutin et al., 2011; Scharenbroch and Catania, 2012); phosphorus and nitrate content in the A horizon, which are essential macronutrients that promote

plant growth but can also become toxic and recalcitrant when they accumulate in the upper soil layers (Boutin et al., 2011; Osono et al., 2006; Natusch et al., 2017; Rush et al., 2011); and ammonium content, which can become phytotoxic when present at high levels and contribute to increased acidification (Hobara et al., 2005; Natusch et al., 2017). In cormorant degraded sites, with the exception of elevation and soil texture, the above selected factors are known to become altered, as explained in Chapter 2. The alteration of these factors will ultimately influence the survival and succession of plants at TTP's Peninsula C.

<u>3.1.4.1 Ordinary Kriging</u>

To assess the distribution of soil characteristics geospatially, ordinary kriging (OK) was used to create maps for all of the soil variables stated above. OK is a process of interpolation that takes known values of sample variables, X, gathered at multiple sampling locations and estimates the unknown values, Z, for locations between the sample points (Steinberg and Steinberg, 2015). The basic kriging equation, which assumes that the mean of the dataset is unknown, is as follows:

$$\hat{Z}(\mathbf{x}_0) = \sum_{i=1}^{N} \lambda_i z(\mathbf{x}_i),$$

where the estimate of the unknown value, Z, at point x_o, with weights, λ_i, that typically sum to 1 to ensure unbiased predictions. The associated expected error, E, is calculated by:

$$E[\hat{Z}(\mathbf{x}_0) - Z(\mathbf{x}_0)] = 0.$$

(Webster and Oliver, 2007). Without interpolation, the site suitability analysis in this study would not represent site conditions to the fullest capacity possible (Forsythe et al., 2004). Interpolation

is done with the assumption that there will be location-based autocorrelation between values that are nearer, as Tobler's first law of geography states, ''All things are related, but nearby things are more related than distant things'' (Tobler, 1970, p. 236). The OK process interpolates values on a grid finer than the original sampling grid, and these values are connected via isarithms (Webster and Oliver, 2007). The estimated values receive the greatest influence from nearby sample points, and ultimately a continuous map surface is created (Steinberg and Steinberg, 2015; Webster and Oliver, 2007).

In ArcMap, centroids were joined with the attribute data of each collected soil variable (ESRI Inc., ArcGIS 10.5). The resulting database contained each of the sampled variables in combination with the corresponding geographic location (longitude and latitude). In ArcGIS Geostatistical Analyst, OK does not require data to be normally distributed; however, this can result in a suboptimal prediction map (Forsythe et al., 2004). To ensure that the most optimal prediction map was projected, data transformation was performed as a step within the OK process in ArcMap (ESRI Inc., ArcGIS 10.5).

Using Geostatistical Analyst (ESRI Inc., ArcGIS 10.5 extension), the Trend Analysis tool was implemented to assess whether each soil variable held unbalanced directional trends of autocorrelation by displaying the data on a three-dimensional trend surface. These differences in directional trends reveal anisotropy, where geospatial variables may differ in magnitude depending on the direction in which they are measured and visualized (Waller and Gotway, 2004). The resulting anisotropy identified in the data was removed for each soil variable using a second order polynomial within the OK process.

The model used to interpolate each soil variable was determined by assessing the average standard error (ASE) of different OK models and selecting the model with the smallest ASE (Millward et al., 2011). The error terms for each model were created in ArcMap by a cross-validation analysis. Cross-validation analysis involves the omittance of known point values, the prediction of said values, and the comparison of differences between known and estimated values (Forsythe et al., 2004).

<u>3.1.4.2 Site Suitability Mapping</u>

To identify the most optimal areas to begin revegetation at Peninsula C, site suitability mapping was employed using the landscape position, chemical, and physical factors assessed in this study. The seven selected soil chemical and physical factors are soil pH, organic matter, texture, ammonium content, nitrate content, and phosphorus content, as well as the eighth factor, landscape elevation (derived from 1 m spatial resolution LiDAR data). These soil factor datasets are each derived from the A horizon samples, as this mineral layer has predominant influence over tree lateral roots and root growth (Weaver, 1938).

Site suitability mapping is a method of organizing landscapes into sections based on a habitat suitability (Store and Jokimaki, 2003). This method has grown quite popular in restoration ecology, especially for its niche-based modeling capabilities; specific species of interest with known habitat requirements can be spatially located based on the geographic projection of known suitable conditions (Heumann et al., 2011; Romano et al., 2015). The present study used the multi-criteria evaluation (MCE) approach to suitability mapping, which allows for the assessment of a landscape by ranking habitat factors that are most influential over species survival. This produces

a map that displays optimal areas for the desired landscape use (Carver, 1991; Store and Jokimaki, 2003).

There are two methods of performing MCE – Boolean overlay and weighted linear combination (WLC). The first is a simple assessment of habitat quality based on the acceptance or rejection of varying factors; Boolean logic can be limiting to results as entire regions may be marked unsuitable if only one factor does not match the desired criteria (Eastman, 2006; Joss et al., 2008; O'Sullivan and Unwin, 2010; Romano et al., 2015; Store and Kangas, 2001). More recently, studies have used the WLC technique to numerically rank areas of a landscape that are the most suitable, providing more insight and alternative solutions than the Boolean approach (Eastman, 2006; Store and Kangas, 2001). In a WLC, single habitat factors are weighted and combined to produce an output map that displays locations indexed by overall suitability (Store and Kangas, 2001; Uribe et al., 2014). Weights are chosen by the decision maker based on previous research and expert knowledge, rather than on empirically set rules (Carver, 1991; O'Sullivan and Unwin, 2010; Store and Kangas, 2001). For purposes of the present study, the MCE will identify regions of TTP's Peninsula C that meet the habitat requirements for a selection of 15 native tree and shrub species, where vegetation selection is based on existing soil quality conditions.

In order to create a MCE, the WLC tool in ArcMap was employed (ESRI Inc., ArcGIS 10.5). The WLC required that all factors were first standardized on a common numerical scale, and then combined by weighted averaging (Romano et al., 2015; Store and Kangas, 2001). The factors were all standardized on a scale of one to seven, with seven representing the most favourable condition for plant survival and one representing the least favourable condition. The standardization of characteristics prioritizes the best possible value for species survival; it does not need to be linear,

as the best value is not necessarily represented by the largest or smallest value in the range (Store

and Kangas, 2001). The standardized factors were added into the WLC and weighted based on

predetermined values. The resulting output was a map that classified the landscape into a ranked

map of the most and least suitable locations for species-specific ecological conditions.

Chapter 4

4.1 Results

It is imperative, prior to restoration activities at the study area, that there is a basic understanding

of current ecological conditions that exist among soil and vegetation at the site. In order to provide

meaningful site suitability maps for revegetation, this study focused on the spatial distribution of

eight landscape, physical and chemical factors that most greatly impact plant growth and future

survival. A mean, standard deviation, standard error, median, minimum, and maximum for all of

these values with the exception of elevation, can be found in Table 4.1.

Table 4.1: Descriptive statistics of the key physical and chemical soil variables in the A horizon.

VARIABLE	MEAN	STANDARD DEVIATION	STANDARD ERROR	MEDIAN	MINIMUM	MAXIMUM
PHYSICAL						
Texture (% Sand)	81.4	3.6	0.36	81	74	99.9
Texture (% Clay)	18.6	3.7	0.37	19	0	26
CHEMICAL						
pH	7.71	0.57	0.06	7.7	6.65	9.31
Organic Matter %	0.5	0.3	0.03	0.5	0	1.7
Phosphorus ppm	506.5	938.9	93.89	32.59	1.3	4504.31
Nitrate ppm	10.0	16.9	1.69	4.6	0.9	101.7
Ammonium ppm	2.5	1.6	0.16	2.2	0.8	15.3

4.1.1   Ordinary Kriging

Using Geostatistical Analyst (ESRI Inc., ArcGIS 10.5), trend analysis modeling was employed to investigate each of the soil physical and chemical characteristics for spatial anisotropy prior to kriging, (with the exception of elevation, for which this study utilized a 1 m LiDAR dataset that did not require further interpolation in the form of kriging as shown in Figure 4.1. The trend analysis model displayed the spread of each dataset on a three-dimensional point map and identified that each of the variables assessed showed second order trends. As a result, second order global trend removal was performed as the first step in the ordinary kriging (OK) process. The trend order, skew, and required normalization transformation associated with each factor are shown in Table 4.2. Using ESRI's Geostatistical Analyst, different OK models were tested for each factor, and the model with the lowest average standard error (ASE) was selected to ensure best results (ESRI Inc., ArcGIS 10.5; Forsythe et al., 2004). The results of the cross-validation analysis that determined the accuracy of the interpolated values calculated during OK are shown in Table 4.3.

The results of the OK in this study are considered robust, as the mean error (ME) is close to zero indicating that the modelling has produced accurate predictions (Forsythe et al., 2004). The root mean square error of estimation (RMSEE) is close to 1 for all variables; texture, organic matter, phosphorus, nitrate, and ammonium prediction surfaces, the RMSEE was greater than 1 indicating a modest under-estimation of the variability of the predictions. Similarly, the pH RMSEE was less than 1, indicating a modest over-estimation of the variability of the predictions. In all instances, except for the pH prediction surface, the ASE was less than the root mean square error (RMSE), indicating a slight under-estimation of the variability of the predictions. For the pH prediction surface, the ASE and RMSEE are less than 1, representing a modest over-estimation – additionally the ASE is greater than the RMSE which further identifies some model overestimation

(Forsythe et al., 2004; Johnston et al., 2001). The results of this analysis were continuous prediction surface maps for each of the assessed soil physical and chemical characteristics, allowing for the visualization of the change in these properties over the study area.
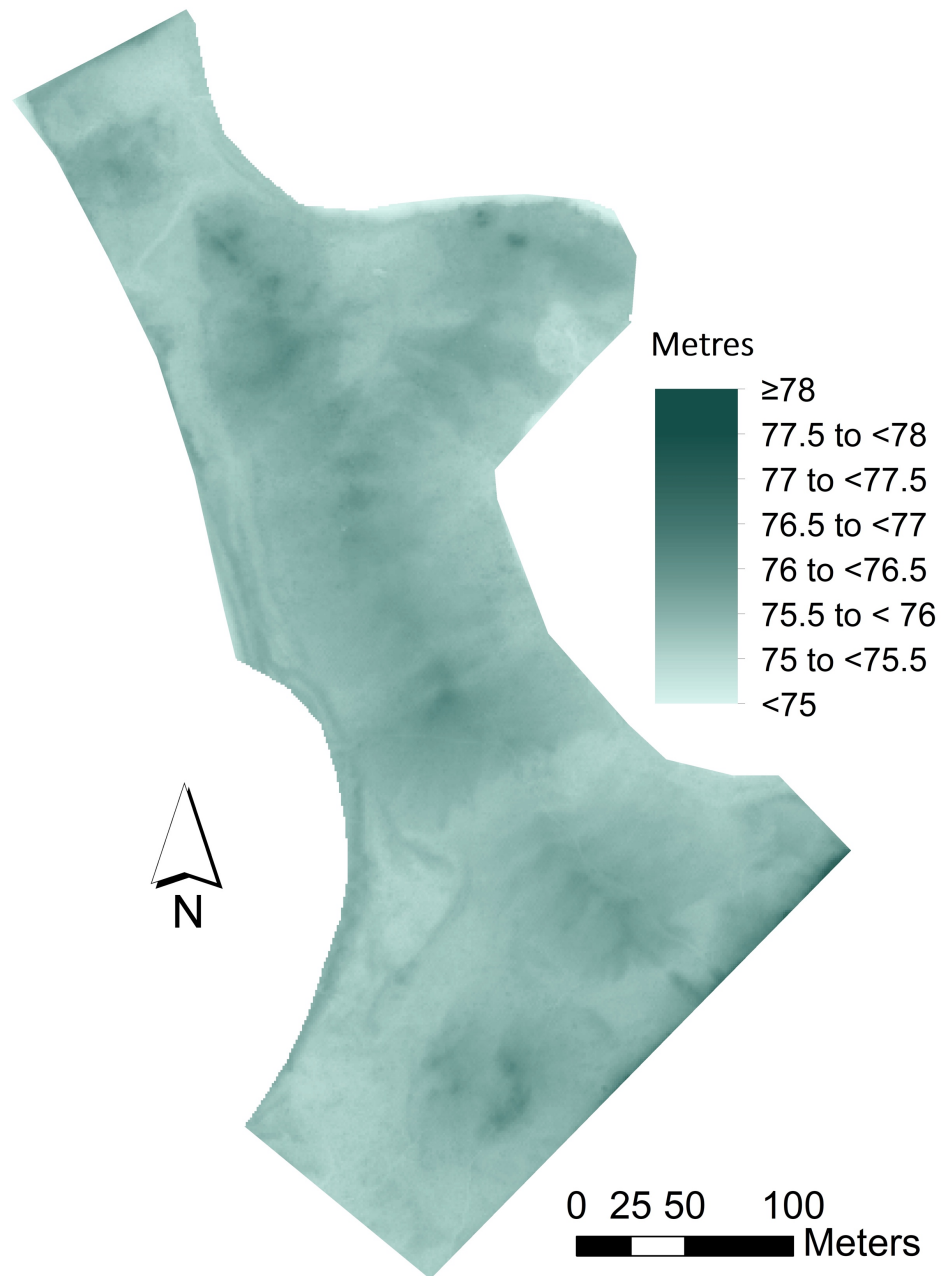
Figure 4.1: Elevation surface (metres above sea level) for Peninsula C at Tommy Thompson Park. Pixel resolution is 1 m a side.

Table 4.2: Trend order, skew, and associated normalization transformation applied to each soil variable.

SOIL CHARACTERISTIC	TREND ORDER	SKEW	TRANSFORMATION
PHYSICAL			
Texture (% Sand)	Second	0.9125	log
Texture (% Clay)	Second	0.9125	log
CHEMICAL			
pH	Second	0.1836	log
Organic Matter	Second	1.2	log
Phosphorus	Second	2.2717	log
Nitrate	Second	3.5115	log
Ammonium	Second	5.6539	log

Table 4.3: Ordinary kriging model used to interpolate soil physical and chemical characteristic prediction surfaces and the associated cross validation results. Error terms are: Mean Error (ME), Root Mean Square Error (RMSE), Average standard error (ASE), Mean Standard Error (MSE), Root Mean Square Error of Estimation (RMSEE). All soil variables were sampled in the A Horizon.

SOIL CHARACTERISTIC	MODEL	ME	RMSE	ASE	MSE	RMSEE
PHYSICAL						
Texture (% Sand)	GAUSSIAN	0.02226256	4.099332	3.584021	0.006274589	1.141869
Texture (% Clay)	GAUSSIAN	0.02226256	4.099332	3.584021	0.006274589	1.141869
CHEMICAL						
pH	EXPONENTIAL	-0.000291891	0.02692762	0.03274263	0.01173773	0.7785989
Organic Matter	GAUSSIAN	-0.000286467	0.02272036	0.01902786	-0.08775846	2.528109
Phosphorus	GAUSSIAN	0.01221421	11.89268	8.073005	-0.05157669	2.404818
Nitrate	GAUSSIAN	-0.003959102	0.2400172	0.1673327	-0.04997624	2.373688
Ammonium	GAUSSIAN	-0.000194284	0.02645944	0.02076799	-0.01257211	1.726264

4.1.1.1 Soil Texture

The soil texture of the A horizon at Peninsula C was found to be primarily sandy clay loam (49%), followed by sandy loam (45%), loamy sand (3%), and sand (3%). The northeast shoreline of the study area had the highest percentage of sand content, as much as 99%, whereas the middle area of the study area had the highest percentage of clay content, as much as 26% (Figure 4.2). The average particle size distribution across the study site is 18.8% clay (SD=3.5%), 0.02% silt (SD=0.07%), and 81.2% sand (SD=3.3%), which directly influences the classification of soil texture. Soil fertility can be greatly influenced by soil texture as it is the variable that determines how porous a soil is, and therefore how well it may retain water, air, and nutrients while promoting illuviation to deeper soil horizons (Day et al., 2010; Ellis et al., 2006; Millward et al., 2011; Saxton and Rawls, 2006). Soils with higher clay content have the capacity to bond with organic matter and nutrients that can cause recalcitrance in soil nutrient cycling (Saxton and Rawls, 2006).

4.1.1.2 Soil Alkalinity

The soil pH distribution at Peninsula C is quite variable, especially when it comes to inter-strata differences. As shown in Figure 4.3, the pH ranges from an acidic 2.96 in the organic horizon to an alkaline 9.34 in the B horizon (non-spatially coincident locations). The organic horizon is more acidic than any other soil layer, with the lowest average pH of 6.20 (SD=1.07), followed by the A horizon with an average of 7.71 (SD=0.57), and the B horizon with an average of 7.87 (SD=0.68) (Figure 4.4a). In all three measured soil horizons, soil acidity is concentrated in the centre of the Peninsula, which coincides with the most historically popular areas for consecutive years of DCC nesting. The soil with the greatest alkalinity is found, inversely, at the tip and the base of the peninsula.

Consecutive years of DCC nesting along the outer edges and centre of Peninsula C have resulted in ongoing and high intensity guano deposition. The nitrification of ammonium-rich guano causes acidification, producing more acidic soils and potentially reactive conditions for phytotoxic metals (Ayers et al., 2015; Breuning-Madsen, et al., 2010; Hebert et al., 2005; Ishida, 1996; Lafferty et al., 2016; Natusch et al., 2017). When soil chemistry varies so rapidly in a small study area, the species composition at the site may also shift, as soil pH no longer coincides with the present native species' range tolerances. Moreover, soil pH extremes in the organic layer at this site are likely to be outside of the tolerance range for both native and non-native vegetation species (Boutin et al., 2011; Ayers et al., 2015).
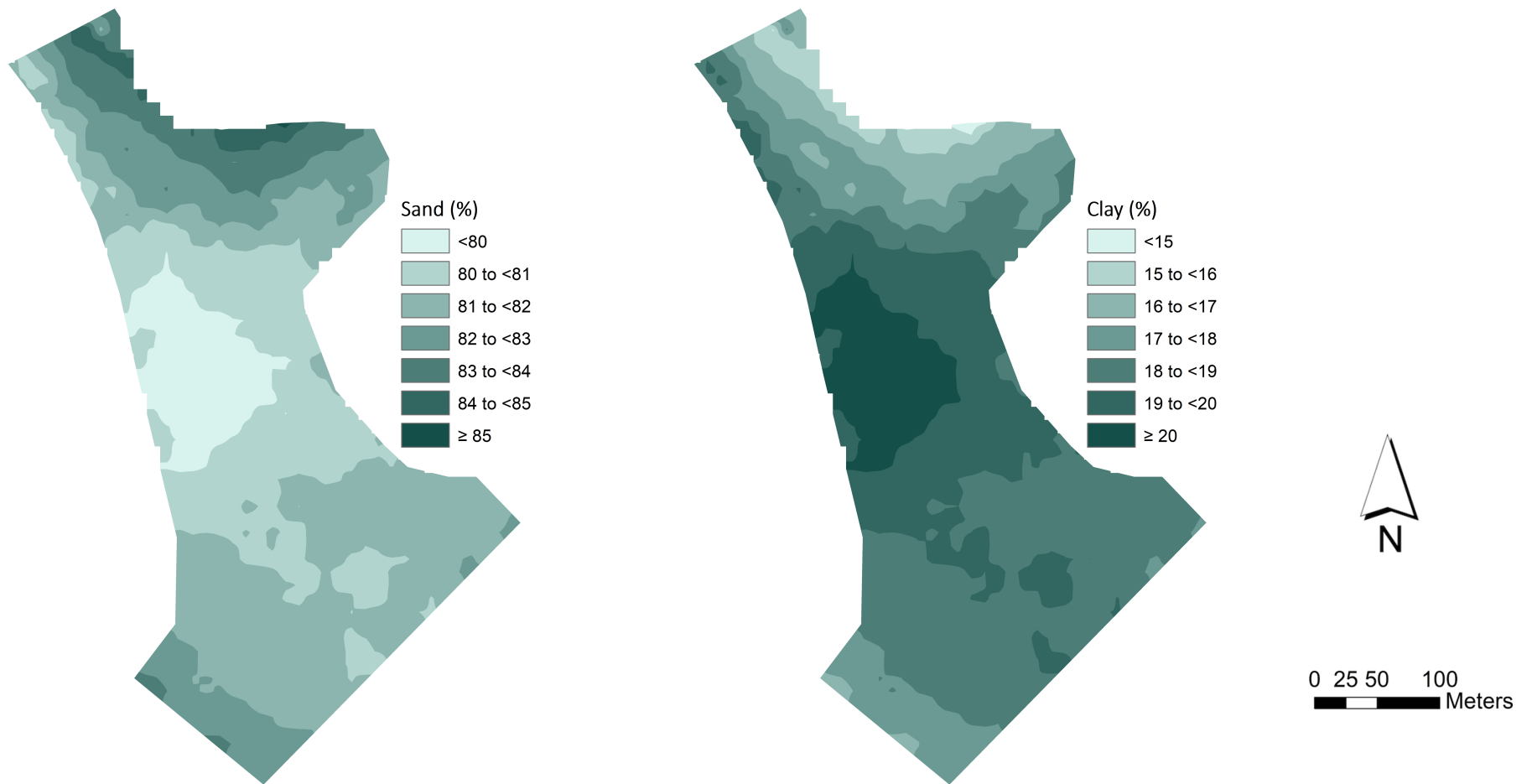
Figure 4.2: Soil texture prediction surfaces in the A horizon where (a): Sand Content and (b): Clay Content. Estimation used ordinary kriging with 100 sample points selected using a systematic sampling design. Pixel resolution is 10 m a side.
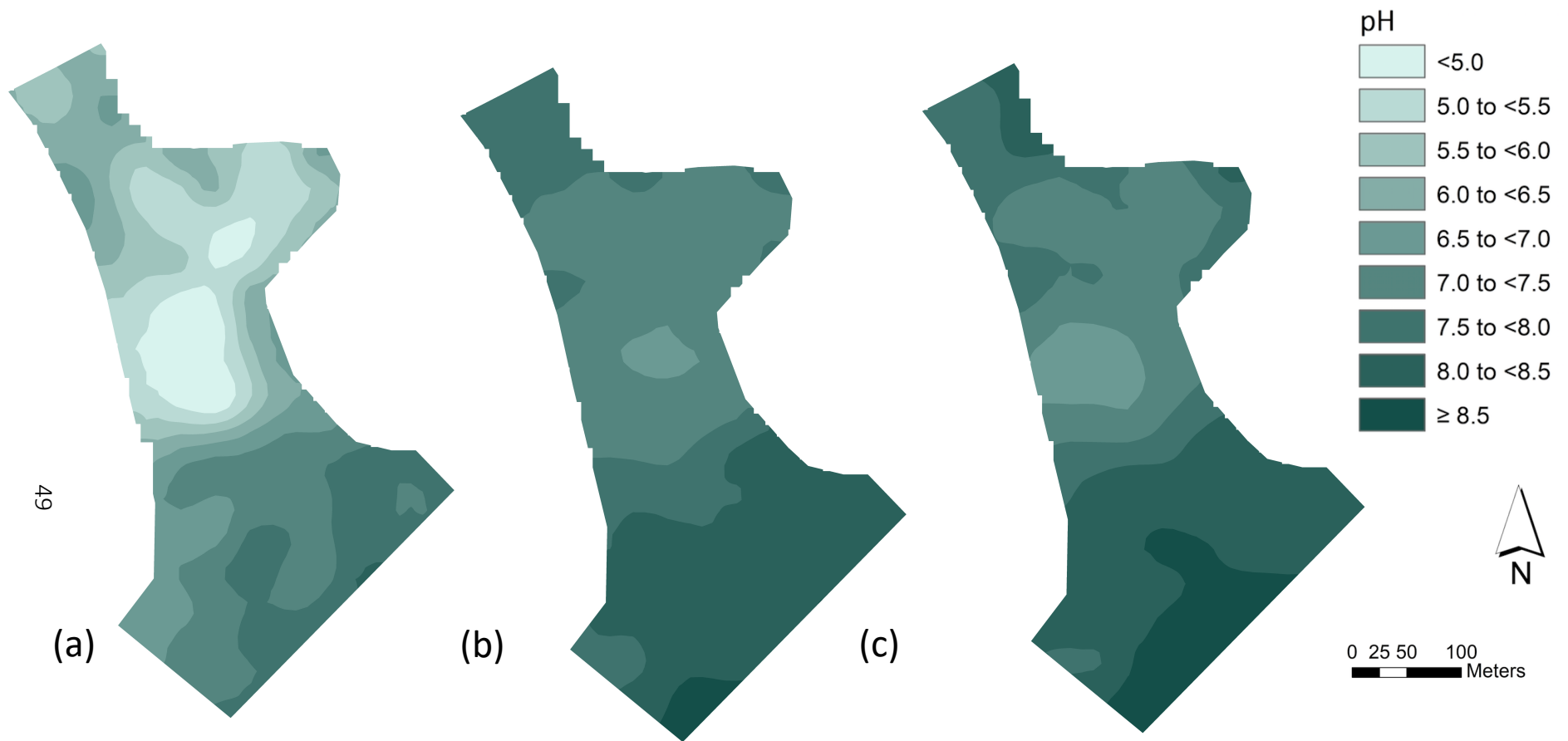
Figure 4.3: Soil pH prediction surfaces at different soil horizons, where **(a)**: Organic Horizon, **(b)**: A Horizon, and **(c)**: B Horizon. Estimation used ordinary kriging with 100 sample points selected using a systematic sampling design. Pixel resolution is 10 m a side.
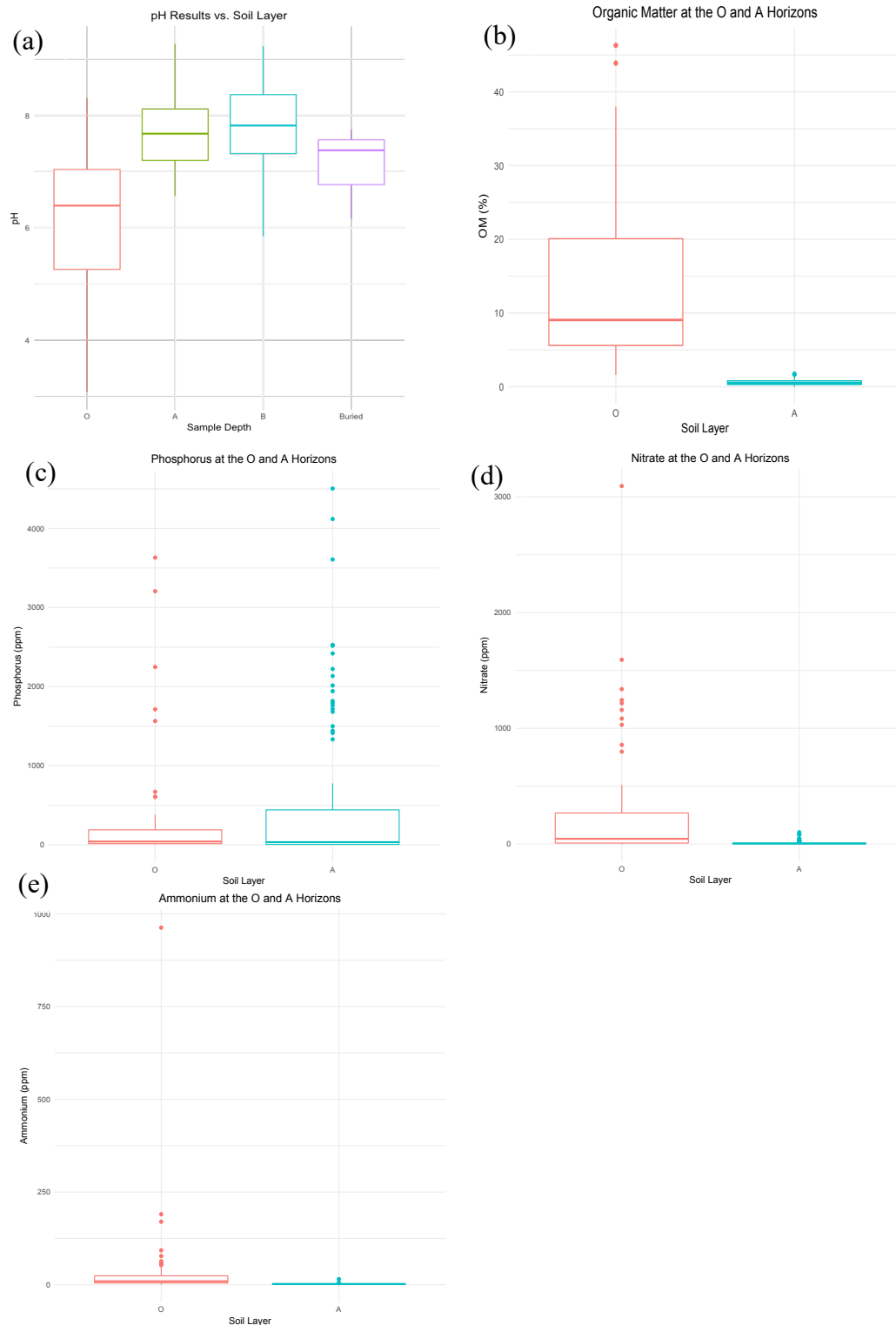
Figure 4.4: Boxplots showing the median variation in soil characteristics for **(a)** pH, **(b)** organic matter, **(c)** phosphorus, **(d)** nitrate, and **(e)** ammonium at different soil horizons (Organic, A, and B). pH values for a superficial sand layer that was deposited on top of the organic layer during the 2017 Toronto floods (Buried) is also shown in **(a)**.

4.1.1.3 Organic Matter Content

The percentage of organic matter (OM) at Peninsula C was found to vary by up to 20 times between the organic and A horizons (Figure 4.4b). The highest levels of OM occurred in the organic horizon, specifically in the middle of the peninsula (Figure 4.5). This was expected, as this area of the peninsula has experienced the greatest number of consecutive years of DCC deposition. However, conditions in the A horizon were much more variable, with patches of increased OM spread throughout the peninsula in both the strongly forested and DCC-deforested areas. The organic horizon has a mean OM content of 14.3% (SD=10.7). This can be compared to the mean OM content of the A horizon, 0.5% (SD=0.3), which is quite low for a productive growth system Ontario Ministry of Agriculture, Food and Rural Affairs, 2018).

The OM levels in the organic horizon are mostly due to superficial deposits of carbon-rich plant litter and other biological material (Osono et al., 2006). The low levels seen in the A horizon mean that there has been little breakdown of the organic horizon into the subsequent mineral layers. This is likely due to the young age of the soil and vegetation at the park (between 40-50 years), where there has been little potential for carbon-rich material from past and present vegetation to accumulate deeper in the soil profile (MTRCA, 1992; Taylor et al., 2011). Additionally, soils directly under DCC nesting areas often have cakey, thick OM that can actually impede water and nutrients from infiltrating into the lower soil horizons (Breuning-Madsen et al., 2010; Ellis et al., 2006; Natusch et al., 2017, Osono et al., 2006). The small variability in OM in the A horizon will not have a strong influence on the distribution of root growth across the site. However, it is evident that DCC nesting created a strong pattern of increased OM in the organic horizon.
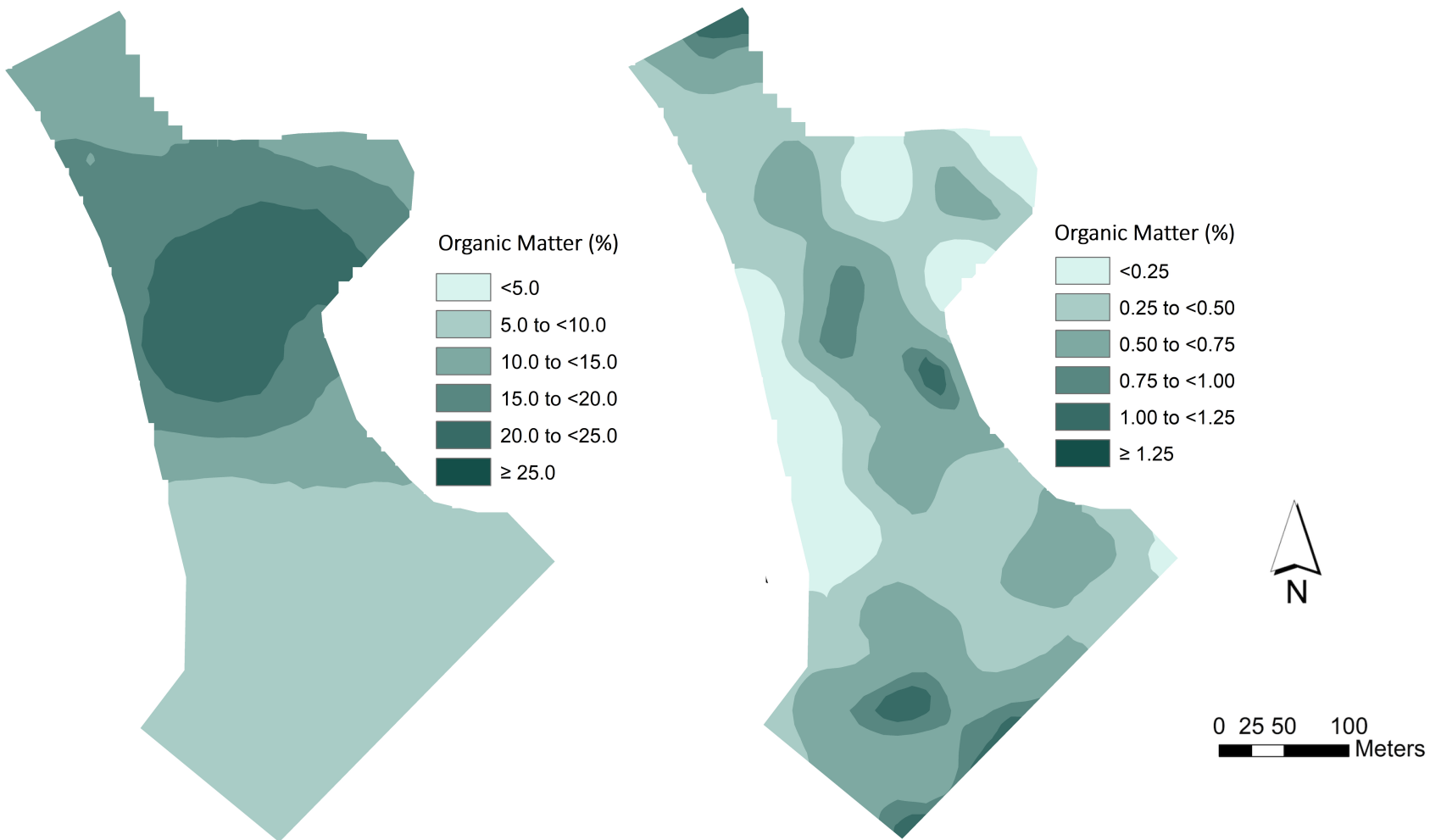
Figure 4.5: Soil organic matter prediction surfaces for **(a)**: Organic Horizon and **(b)**: A Horizon. Estimation used ordinary kriging with 100 sample points selected using a systematic sampling design. Pixel resolution is 10 m a side.

4.1.1.4 Phosphorus Content

The content of phosphorus in the soil at Peninsula C was lower in the organic horizon than in the A horizon (Figure 4.4c). The highest levels of phosphorus occurred in the A horizon, at 4504 ppm, in comparison to 3631 ppm in the organic horizon. The highest levels of phosphorus in both soil layers occurred in the middle of the peninsula, with the high organic horizon levels occurring along the boundaries of the 2017 DCC nesting habitat, and the high A horizon levels occurring along the boundaries of more historic DCC nesting habitat (Figure 4.6). The mean phosphorus content in the organic horizon is 259 ppm (SD=608), whereas the mean in the A horizon is 507 ppm (SD=939). The standard deviations measured for both of the soil horizons show that the dataset is not only wide-ranging, but extremely variable between sampling locations.

DCC guano is known to be rich in phosphorous (Breuning-Madsen et al., 2010; Hobara et al., 2005). Colony sites have high levels of phosphorus in the sediment, especially in the upper soil horizon (Breuning-Madsen et al., 2010). Unlike nitrogen, which leaches through the soil, phosphorus in its inorganic form accumulates by binding with sediment particles, especially in the presence of clay molecules (Hobara et al., 2005). This can explain why phosphorus in the organic horizon, which likely only accounts for recent depositions, is less than the phosphorus that has accumulated long-term in the sediment in the A horizon. Although moderate increases in soil phosphorus can actually be beneficial, as it is a required macronutrient for plant survival, excess phosphorus can result in toxicity that stunts plant growth (Hobara et al., 2005; Natusch et al., 2017; Rush et al., 2011; Wright et al., 2011). Levels above 330 ppm require remediation for the support of future growth for many plant species (Ayers et al., 2015).
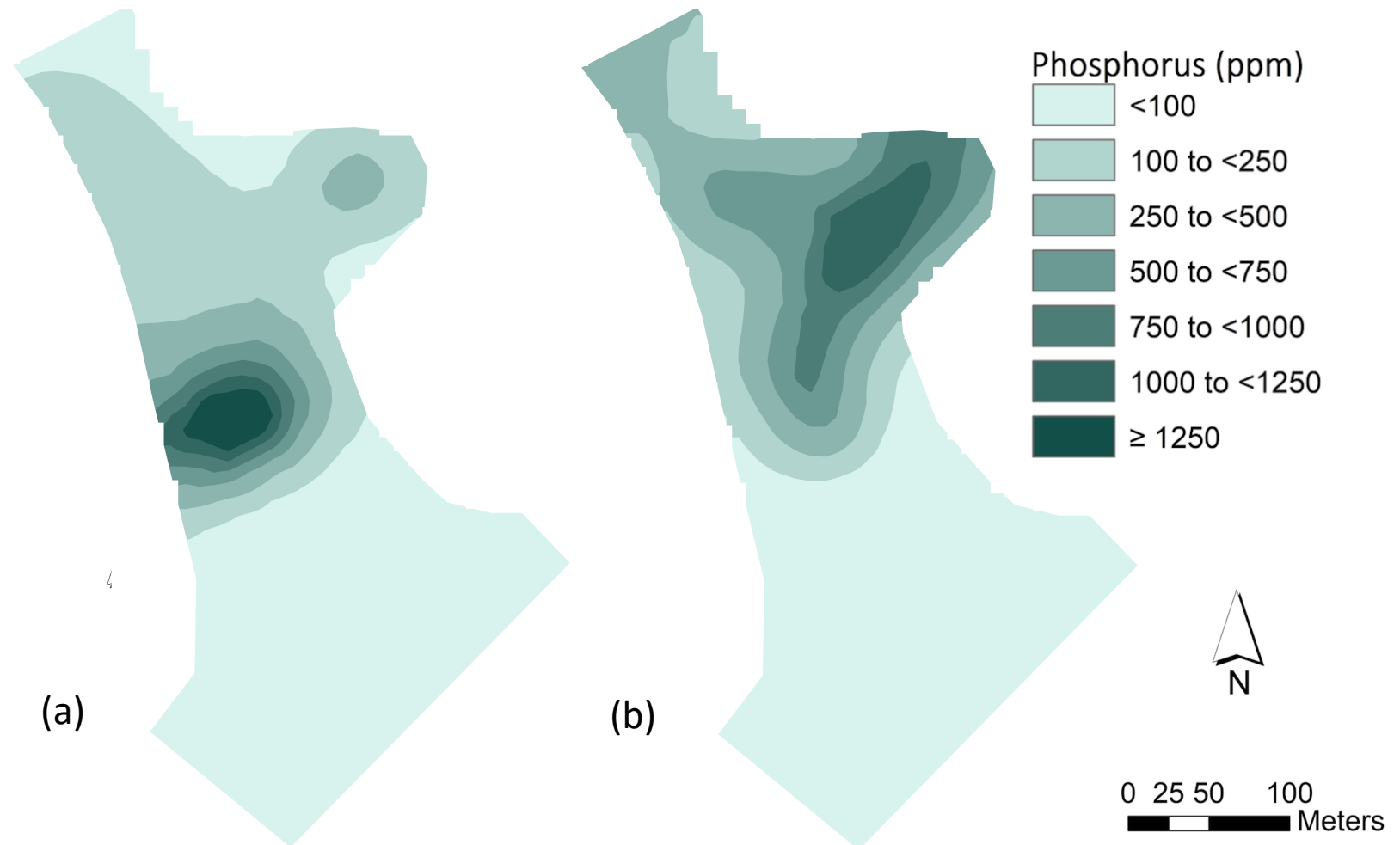
Figure 4.6: Soil phosphorus content prediction surfaces in **(a)**: Organic Horizon and **(b)**: A Horizon. Estimation used ordinary kriging with 100 sample points selected using a systematic sampling design. Pixel resolution is 10 m a side.

4.1.1.5 Nitrate Content

The content of nitrate in the soil at Peninsula C was much greater in the organic horizon than in the A horizon (Figure 4.4d). The highest levels of nitrate were also observed in the middle of the peninsula, reaching up to 3094 ppm (Figure 4.7). The highest levels of nitrate in the A horizon coincided spatially with those of the organic horizon, but only reached a maximum of 102 ppm. The mean nitrate content in the organic horizon is 262 ppm (SD=470), whereas the mean in the A horizon is 10 ppm (SD=17).

The high levels of nitrate are a result of strong nitrification of the ornithogenically-deposited ammonium in the soil (Boutin et al., 2011; Doubt and McMullin, 2016; Hobara et al., 2005; Ishida, 1996). Additionally, the clearly evidenced high nitrification occurring here means that more hydrogen ions are being release from ammonium particles during the formation of nitrates, and the soils are becoming more acidic, which was shown earlier in the results. Such high levels of nitrate in the organic horizon can be detrimental via nitrogen phytotoxicity, but it may also aid in increasing plant tolerances toward ammonium phytotoxicity, as plants that are exposed to high levels of nitrates and ammonium fair better than those exposed to just high ammonium (Bittsanszky et al., 2015).

4.1.1.6 Ammonium Content

The content of ammonium in the soil at Peninsula C was much greater in the organic horizon than in the A horizon, reaching up to 963 ppm near the middle of the Peninsula (Figure 4.4e). The highest levels of ammonium in the A horizon coincided spatially with those of the organic horizon, but only reached a maximum of 15.3 ppm (Figure 4.8). The large amount of ammonium in the middle of the peninsula is a direct result of deposition from the DCC nests overhead; this area has

been most greatly impacted by ammonium deposition from bird excreta. The mean ammonium

content in the organic horizon is 33 ppm (SD=106.8), whereas the mean in the A horizon is 2.5

ppm (SD=1.6).

In Ontario, the average soil ammonium concentration is 1 ppm (Ontario Ministry of

Agriculture, Food and Rural Affairs, 2018). Soil ammonium is readily taken up by tree roots, but

the concentration seen in the organic horizon here is so high that it may result in ammonium

phytotoxicity, which stunts tree growth, causes leaf chlorosis, and reduces seed germination

(Bittsanszky et al., 2015; Bobbink et al., 2010; Ellis et al., 2006; Hebert et al., 2005; Natusch et al.,

2017; Rush et al., 2011, Pregitzer et al., 2016; Van Der Eerden, 1982). Early successional tree

species, as are present on Peninsula C, tend to be more sensitive to increased ammonium levels

in the soil. However, when moderate levels of nitrates are co-provided with the ammonium,

tolerance and growth is usually more favourable (Britto and Kronzucker, 2002). High ammonium

environments consequently mean increased nitrification and resulting acidification (Bobbink et al.,

2010; Breuning-Madsen et al., 2010; Hebert et al., 2005; Ishida, 1996). Despite the high levels of

ammonium seen in the organic horizon, the A horizon levels are less offensive to tree productivity

and therefore the impact on tree roots by DCC ammonium deposition is seemingly low. However,

the seedbank and herbaceous plants that are located in shallower soils are likely to be negatively

impacted by the ammonium content in the organic horizon. Additionally, acid tolerant vegetation

species will have a better chance of survival in high ammonium environments due to the increased

likelihood of acidic soils (Britto and Kronzuker, 2002).

Figure 4.7: Soil nitrate content prediction surfaces in **(a)**: Organic Horizon and **(b)**: A Horizon. Estimation used ordinary kriging with 100 sample points selected using a systematic sampling design. Pixel resolution is 10 m a side.
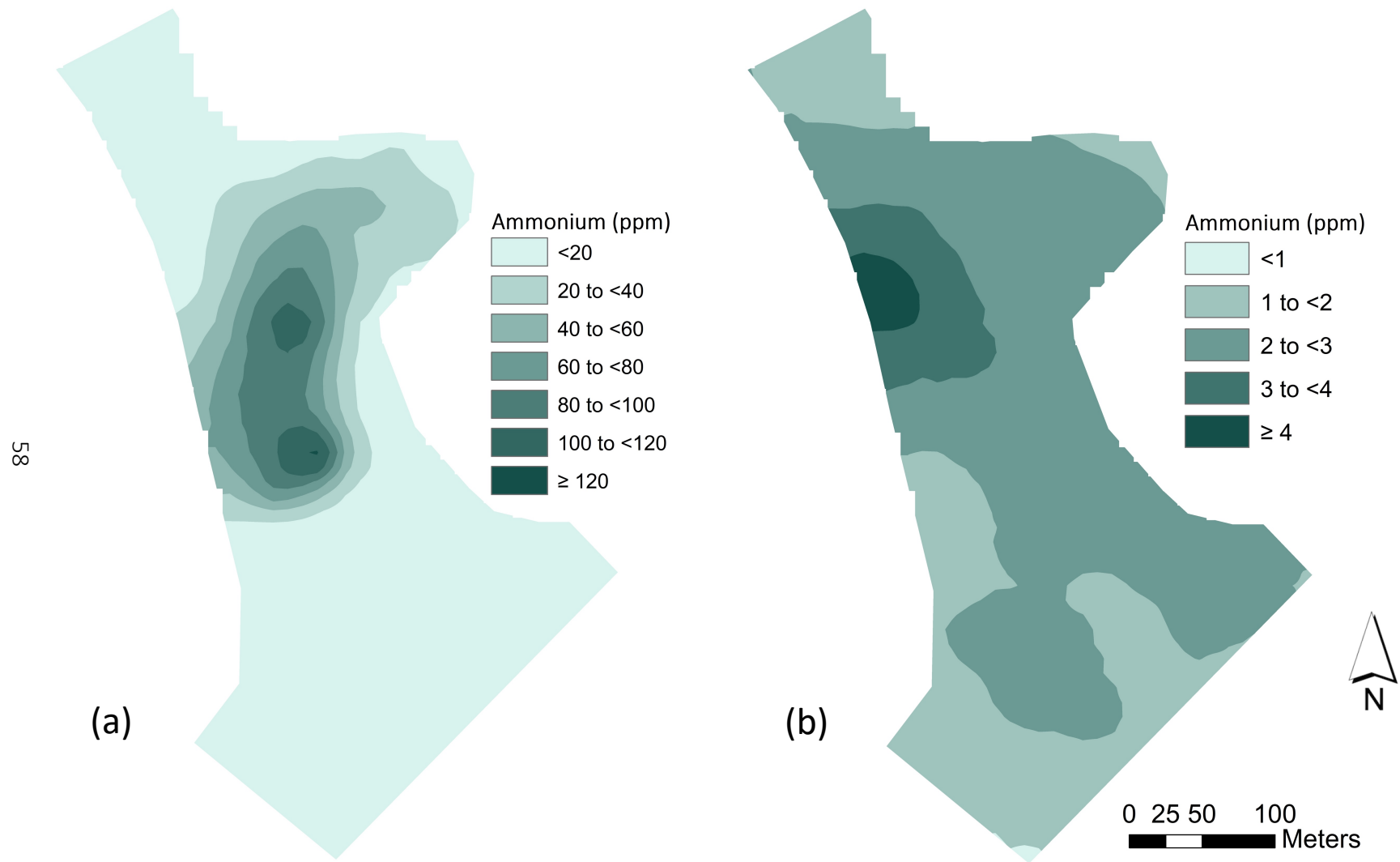
Figure 4.8: Soil ammonium content prediction surfaces in **(a)**: Organic Horizon and **(b)**: A Horizon. Estimation used ordinary kriging with 100 sample points selected using a systematic sampling design. Pixel resolution is 10 m a side.

4.1.2 Suitability Mapping

The eight landscape, physical, and chemical factors selected for site suitability mapping were ranked and weighted based on their comparative influences on plant growth and survival (Table 4.4). A study of urban soil characteristics by Scharenbroch and Catania, (2012), found that the three most informative soil factors to rank soil quality for urban tree performance were pH, organic matter, and texture. This study considers that the most dominant factor on soil quality at TTP's Peninsula C is alkalinity, as DCC colonies directly lower the pH of soils within their colony area (Breuning-Madsen et al., 2010). Additionally, pH directly impacts the other chemical factors assessed in this study including bioavailability and up-take of nutrients, nutrient cycling and recalcitrance, and the most basic fact that increasingly acidic soils can become outside of the range tolerance for the native vegetation species that initially colonized the site (Lafferty et al., 2016; Natusch et al., 2017; Strickland et al., 2011). Therefore, soil pH was ranked with a weighting of 25%.

Each of the other factors were considered relative to the impact of soil pH on vegetation growth and survival. It is important to note that although soil moisture is not a measured variable in this study, other physical soil properties have the capacity to directly impact soil moisture and largely impact tree growth (Scharenbroch and Catania, 2012). Soil organic matter content was ranked with a weighting of 20%, due to its influence on nutrient content in the soil as well as illuviation. Nutrient-rich soils can affect the survival of seeds in the seedbank, potentially inhibiting the regrowth of native species on Peninsula C (Boutin et al., 2011). The increased deposition of organic matter in clay-rich soils can result in cohesion, limited illuviation, and therefore nutrient and water pooling on the surface of the soil (Arthur, 2017; Sayedmohammadi and Matinfar, 2018).

Due to the effects of clay on soil, and the fact that many species do not tolerate clay-rich environments (for example the sandbar willow, which prefers sandy, well-drained soils [Coladonato, 1993]), soil clay content and soil sand content were each ranked with 10% weightings, for a total of 20% soil texture.

The soil chemical factors that include nutrient content (phosphorus, nitrate, and ammonium), can all be altered with increased DCC guano deposition (Boutin et al., 2011; Breuning-Madsen et al., 2010; Doubt and McMullin, 2016; Hebert et al., 2005; Hobara et al., 2005; Ishida, 1996; Rush et al., 2011). Each of these three nutrients were given a weighting of 5% due to the influence they have on plant growth as macronutrients, while also maintaining the ability to become phytotoxic when present in high concentrations in the soil (Bobbink et al., 2016; Hobara et al., 2005; Natusch et al., 2017; Rush et al., 2011).

Finally, landscape elevation was given a ranking of 20% due to the potential for microtopography to create variable conditions for soil properties and species diversity in pits and mounds across the peninsula (Gilland and McCarthy, 2013). Although the elevation only varies by a few metres, it can cause pooling of nutrients and water on the soil surface at TTP's Peninsula C because of the close proximity of the water table.

To account for landscape variability and provide restoration recommendations for the multiple needs of the landscape, 15 native tree and shrub species were identified based on their abilities to restore degraded sites, improve soil stability, and re-sprout in the case of future disturbance (Anderson, 2006; Fryer, 2012; Howard, 1996; Snyder, 1992). The species selected for re-vegetation have different ecological and soil tolerances, which aids in the customization of restoration needs for the 8.12 ha study area. Groups of species were created by gathering those

with similar range tolerances (Table 4.5), for a resulting five groups. Five individual site suitability

maps were produced in the MCE by creating an individual range for each preferred factor for all

five species groupings (Figure 4.9).

Table 4.4: Factor pairwise comparison and derived weightings of eight ecological factors selected for site suitability mapping.

Factor	pH	OM	Elevation	Sand	Clay	Phosphorus	Nitrate	Ammonium	Weights
pH	1								0.25
OM	0.8	1							0.2
Elevation	0.8	1	1						0.2
Sand	0.4	0.5	0.5	1					0.1
Clay	0.4	0.5	0.5	1	1				0.1
Phosphorus	0.2	0.25	0.25	0.5	0.5	1			0.05
Nitrate	0.2	0.25	0.25	0.5	0.5	1	1		0.05
Ammonium	0.2	0.25	0.25	0.5	0.5	1	1	1	0.05

Table 4.5: Native tree and shrub species selected for site suitability mapping and future restoration of Peninsula C at Tommy Thompson Park. Trees and shrubs are grouped by planting site conditions based on pH and soil moisture preferences and given their group designation (A – E).

SPECIES COMMON NAME	SPECIES SCIENTIFIC NAME	CONSISTENTLY SATURATED OR VERY WET SOIL	OFTEN MOIST, WELL-DRAINED SOIL
pH ≤ 7.0			
Black willow (B)	*Salix nigra*	X	
Eastern white pine (A)	*Pinus strobus*		X
Pin oak (A)	*Quercus palustris*		X
Red maple (B)	*Acer rubrum*	X	
Red-osier dogwood (B)	*Cornus sericea*	X	
Silver maple (B)	*Acer saccharinum*	X	
pH ≤ 7.5			
Downy serviceberry (E)	*Amelanchier arborea*		X
Gray dogwood (E)	*Cornus racemosa*		X
Trembling aspen (E)	*Populus tremuloides*		X
pH ≤ 8.2			
Bur oak (D)	*Quercus macrocarpa*	X	
Choke cherry (C)	*Prunus virginiana*		X
Common Honeylocust (D)	*Gleditsia triacanthos*	X	
Peachleaf willow (C)	*Salix amygdaloides*		X
Sandbar willow (C)	*Salix exigua*		X

The table of species' optimal pH and soil moisture tolerances was compiled from the following resources (Anderson, 2006; "Black Willow", 2018; "Black Willow", n.d.; Carey, 1992, 1993; Coladonato, 1993; "Eastern White Pine", 2018; "Eastern White Pine", n.d.; Farrar, 1995; Fryer, 2012; Gilman and Watson, 1994; Gucker, 2011, 2012; Howard, 1996; Johnson, 2000; Kershaw, 2001; "Peachleaf Willow", 2018; "Peachleaf Willow", n.d.; Sheahan, 2015; "Silver Maple", 2018; "Silver Maple", n.d.; Snyder, 1992; Sullivan, 1994a, 1994b, 1994c; Tesky, 1994; Tirmenstein, 1991; "Trembling Aspen", 2015; "Trembling Aspen", 2018; "Trembling Aspen", n.d.
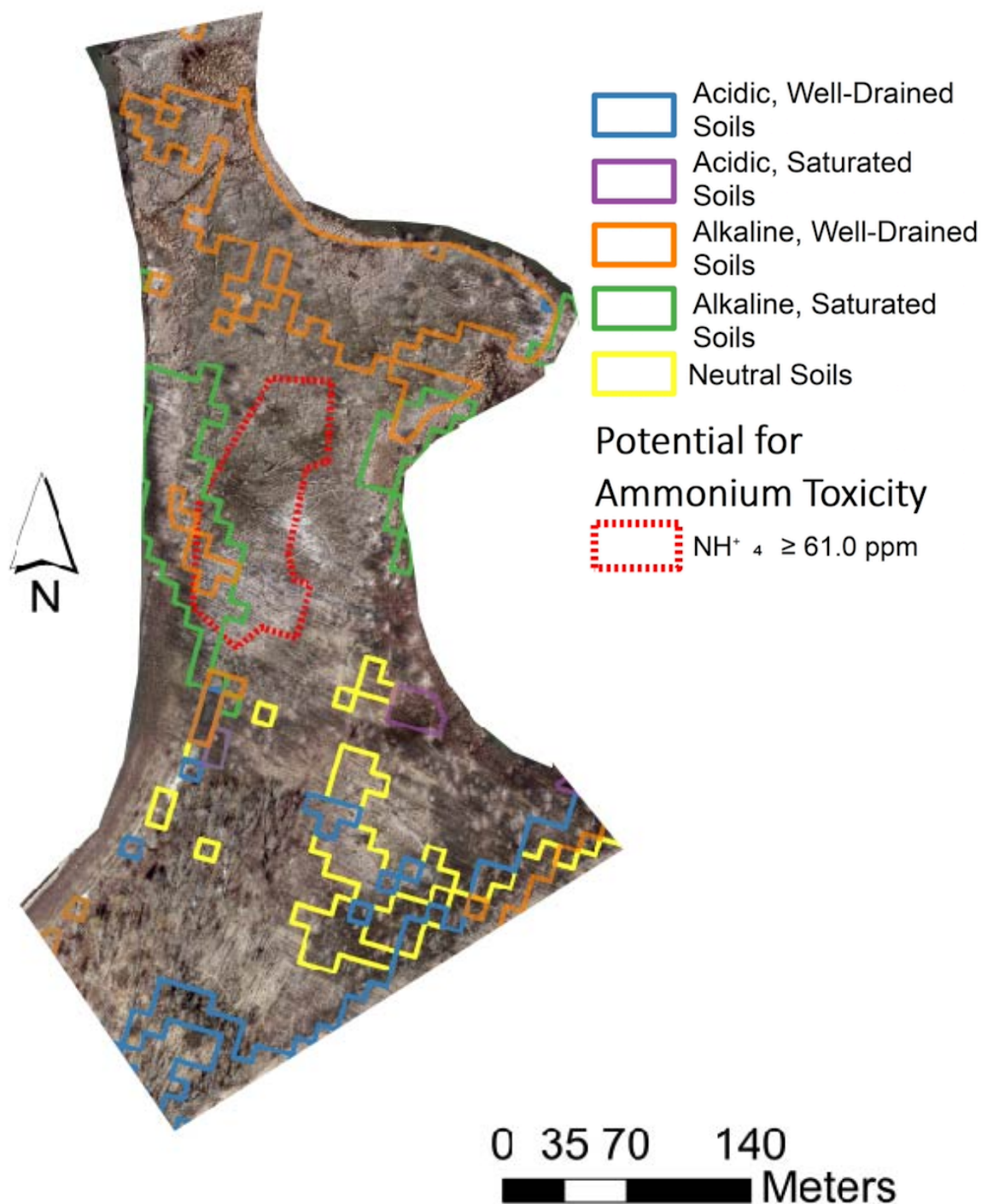
Figure 4.9: Site suitability map showing areas selected as most favourable for the five species-specific groupings. The red polygon designates the area of Peninsula C with the most extreme levels of ammonium, likely to stunt plant growth and cause mortality.

Areas of Peninsula C that were the most favourable for vegetation that prefer acidic, well-drained soils (Group A) were most strongly associated with the ecological conditions closer to the base of the peninsula, with moderate suitability occurring on the outer tip of the peninsula (Figure 3.10a). This area was, interestingly enough, the only area on the peninsula where young eastern white pine trees are growing, which is one of the species that are recommended for revegetation in this group. Group A also includes pin oak, which is similar to eastern white pine in that it prefers moderately acidic soil that is well-aerated (Carey, 1992; 1993). Both species prefer soils that range from clays to sandy loams, and the areas of the site that were selected as most suitable consist of either high to moderate clay content at higher elevations to decrease the probability of waterlogging (Carey, 1992; 1993; Natusch et al., 2017). Further, both species have a high tolerance for soil nutrients, including phosphorus and nitrogen, which will prove beneficial as the areas selected near the base and western edge of the peninsula are higher in nitrate content (Carey, 1992; 1993).

The species that tolerate acidic, saturated soils (Group B) are modeled to perform best primarily along the eastern edge of the peninsula, closer to the base of the peninsula that overlooked Embayment C (Figure 3.10b). Group B had the most limited area selection for any of the 5 groups. Black willow, red maple, red-osier dogwood, and silver maple tolerate a variety of nitrogen rich soils, with a preference for moist or even saturated conditions in low-lying bottomlands (Anderson, 2006; Sullivan, 1994; Tesky, 1994; Tirmenstien, 1991). The species in Group B prefer moist soils, which are represented in TTP by being in low-lying areas with soils close to the water table, moderate clay content, and neutral pH with moderate ammonium concentration. There is little organic matter, phosphorus, and nitrate in the selected areas.

Group C consists of species that tolerate alkaline, well-drained soils. The sites selected for Group C were located along the eastern shoreline at the northern tip of the peninsula. This area of the peninsula has a higher elevation range and is covered by sandy shoreline with little clay content (Figure 3.10c). The species included in this group are choke cherry, peachleaf willow, and sandbar willow, all of which prefer sandy or gravelly soils with low clay content. Group C species prefer moderate amounts of nutrients, which is present except for the high phosphorus levels in this area of the peninsula (Coladonato, 1993; Fryer, 2012; Johnson, 2000). Sandbar willow is the most tolerant of high nutrient content and would therefore be an ideal species for the soils that are extremely rich in phosphorus (Coladonato, 1993).

Areas of Peninsula C that were the most favourable for Group D were located along the western edge of the peninsula that overlooks Embayment B, with a smaller parallel grouping on the eastern side of the peninsula (Figure 3.10d). These areas have neutral pH levels, clay-rich soils, and a low-lying elevation that brings tree roots extremely close to, if not within, the water table – perfect for species like bur oak and common honeylocust that prefer alkaline, saturated soils. Both species do well in a variety of soils but prefer low nutrient content (Gucker, 2011; Sullivan, 1994). These areas do have moderate levels of phosphorus, ammonium, and nitrate in the soil.

Finally, the centre of the southern portion of the peninsula would be most favourable for species in Group E, whose tolerance of alkalinity and soil drainage tends to be neutral (Figure 3.10e). Downy serviceberry, gray dogwood, and trembling aspen are shrub and tree species that prefer moist, but not overly saturated sandy loam soils. Their pH tolerances hover between 6.0 and 7.5, and they are tolerant of high nutrient conditions (Gucker, 2012; Howard, 1996; Sheahan, 2015). The areas selected for Group E have sandy loam soils with moderate to high pH levels, and

66

comparatively lower nutrient content, other than ammonium. These species are likely to do well in the broadest range of conditions, and therefore, the soil's variability in nutrients and alkalinity will be tolerated.

4.1.3   Vegetation Survey

The results of the species identification analysis found that approximately 20% of vegetation species, considering richness, growing at Peninsula C were non-native. The non-native species included ornamental trees and flowers that likely germinated from decorative municipal gardens in the city. Additionally, many of the non-native species including cow vetch, lamb's quarters, and *Phragmites australis*, are opportunistic species that are able to rapidly grow and germinate on disturbed soils whose characteristics are outside of the range of native vegetation (Boutin et al., 2011; Ellis et al., 2006; Herbert Howell, 2014; Natusch et al., 2017). Table 4.6 contains a complete list of native and non-native tree species, and Table 4.7 contains a list of all other native and non-native vegetation species identified during the field study.

The majority of the tree and shrub canopy cover at the study area was dominated by fast-growing, moisture tolerant, deciduous vegetation species. The most prominent species include eastern cottonwood (24.6%), sandbar willow (24.4%), and red-osier dogwood (22.9%). These trees are all capable pioneers for early-successional forest landscapes; they grow quickly, tolerate sandy, moist conditions, and have the ability to re-sprout via base or root suckers (Anderson, 2006; Farrar, 1995; Howard, 1996; Kershaw, 2001; Snyder, 1992). The eastern cottonwood trees are the most popular for DCC nesting due to their height and accessibility at the peninsula; the TRCA has counted as many as 46 nests per tree on peninsula C (TRCA, 2017b). The outer half of the peninsula was once completely forested, mainly by eastern cottonwood trees, however it is now deforested.

Although eastern cottonwood has been historically abundant, their height attracts DCC nests and their survival DCC colony soil conditions is not strong, and therefore, this study does not recommend them for use in re-vegetation plans. Sandbar willow and red-osier dogwood, on the other hand, are shrubby trees capable of re-sprouting and densely covering the peninsula in a way that makes DCC nesting more difficult and increases the proximity of DCC nests to ground level predation. For the restoration of the landscape, it will be vital to use species like these and similar to help pioneer the site and promote forest succession while simultaneously deterring DCCs from building their nests.

Table 4.6: Native and non-native tree species identified and counted on TTP's Peninsula C.

SPECIES COMMON NAME	SPECIES SCIENTIFIC NAME	NATIVE (Y/N)	COUNT (#)	ABUNDANCE (% TOTAL)
Paper birch	*Betula papyrifera*	Y	6	1.05
European white birch	*Betula pendula*	N	68	11.86
Ironwood	*Ostrya virginiana*	Y	1	0.17
European alder	*Alnus glutinosa*	N	48	8.38
Eastern cottonwood	*Populus deltoides*	Y	141	24.61
Trembling aspen	*Populus tremuloides*	Y	6	1.05
Bebb's willow	*Salix bebbiana*	Y	1	0.17
Sandbar willow	*Salix exigua*	Y	140	24.43
Peachleaf willow	*Salix amygdaloides*	Y	3	0.53
Heartleaf willow	*Salix cordata*	Y	3	0.53
Manitoba maple	*Acer negundo*	Y	21	3.66
Silver maple	*Acer saccharinum*	Y	1	0.17
Red-osier dogwood	*Cornus sericea*	Y	131	22.86
Staghorn sumac	*Rhus typhina*	Y	1	0.17
White spruce	*Picea glauca*	Y	1	0.17
Eastern white pine	*Pinus strobus*	Y	2	0.35

Table 4.7: Native and non-native understory flora identified on Peninsula C.

SPECIES COMMON NAME	SPECIES SCIENTIFIC NAME	NATIVE? (Y/N)
Cocklebur	*Xanthium strumarium*	Y
Canada fleabane	*Erigeron canadensis*	Y
Common tansy	*Tanacetum vulgare*	N
New England aster	*Symphyotrichum novae-angliae*	Y
Dandelion	*Taraxacum*	N
Boneset	*Eupatorium perfoliatum*	Y
Canadian thistle	*Cirsium arvense*	N
Woodland sunflower	*Helianthus divaricatus*	Y
Canada goldenrod	*Solidago canadensis*	Y
Stinging nettle	*Urtica dioica*	Y
Lamb's quarters	*Chenopodium album*	N
Golden dock	*Rumex maritimus*	Y
Curly dock	*Rumex crispus*	Y
North American jewelweed	*Impatiens capensis*	Y
Hedge bindweed	*Calystegia sepium*	Y
Common reed	*Phragmites australis*	N
Wild strawberry	*Fragaria virginiana*	Y
Silverweed	*Argentina anserina*	Y
Purslane	*Portulaca oleracea*	N
Garlic mustard	*Alliaria petiolata*	N
Wild mint	*Mentha arvensis*	Y
Purple loosestrife	*Lythrum salicaria*	N
Scouring rush	*Equisetum hyemale*	Y
White sweet clover	*Melilotus albus*	N
Cow vetch	*Vicia cracca*	N
Swamp milkweed	*Asclepias incarnata*	Y
Canada moonseed	*Menispermum canadense*	Y
Virginia creeper	*Parthenocissus quinquefolia*	Y
Wild carrot	*Daucus carota*	N
Buttercup	*Ranunculaceae spp.*	Y
Morning glory	*Ipomoea*	N

4.2   Conclusion

The study of the impacts of double-crested cormorants (DCCs) on forests is not a new field of

study; however, the proximity of the DCC colony at Tommy Thompson Park (TTP)to a highly urban

area provides a unique human-wilderness conflict: the ongoing public call to action and restoration of cormorant degraded areas. In the present study, field analysis determined the current ecological conditions of Peninsula C at TTP by sampling for vegetation diversity and soil physical and chemical characteristics, including pH, organic matter, texture, phosphorus content, nitrate content, and ammonium content. The study provided interpolated maps of continuous prediction surfaces for these values in order to spatially view the current ecological conditions, especially soil properties. Finally, a series of 15 native tree and shrub species were selected for their potential ability to re-vegetate degraded environments, stabilize soils, and re-sprout during disturbance. Site suitability maps were produced using known species' growth and habitat preferences, to identify key locations within the study area for species-specific revegetation and the promotion of forest succession.

This study was limited because it was only concerned with the ecological conditions during a snapshot in time. Future studies can utilize temporal analysis to review the effects of restoration initiatives in the DCC colony over time, including the effectiveness and health of test-plantings in different zones of the study area. This study showed the highly variable conditions that exist at Peninsula C in regards to the spatial variation across the peninsula, and also within the soil strata. This study has helped to clarify and visualize the quality of soil physical and chemical characteristics across a DCC impacted site, as well as the growth of native and non-native vegetation at the site.

CHAPTER 5

5.1   Limitations of Research

Limitations to this study included restricted access to the study area, site-related constraints, and the extent of the area studied. From April 1 to September 1, annually, the study area is a designated 'Sensitive Bird Area', and human access is limited. The study was intended to commence in early April of 2017 and conclude before major bird staging had begun in May. However, Toronto experienced record high water levels and flooding at this time, making the study area inaccessible. The study was postponed until September 2017. This delay altered the design of the study; originally, soil data collection was to be completed in the spring, and vegetation data collection was to take place in the fall. To compensate for the delay, the vegetation sampling component was significantly condensed. Regarding site-related constraints, data collection was limited by the discovery of bricks and in-fill material buried in the soil, as well as high water table levels that prevented soil samples from being taken at lower depths. In these cases, it was impossible to collect soil from clearly differentiated strata, and it limited the use of the hand-held compaction meter that could not penetrate through in-fill material. Finally, data collection across the extent of the study area was limited by the human capacity to complete on-site analysis while carrying samples. 293 samples of 200 g were successfully collected across the 8.12 ha study site. If time and human capacity permitted, greater coverage of the study area could be completed. Acknowledging these data collection limitations, this study provides valuable baseline data to inform of the current ecological conditions at the site and can be built upon in future temporal analyses.

5.2   Future Research

This project was part of a research collaboration with the Toronto and Region Conservation Authority to assess current ecological conditions of TTP's Peninsula C and provide insight into future restoration potential. This study is an exploratory venture to begin understanding ecological conditions at the site, and to set a baseline dataset to be built upon in future studies; it does not assess the impact of DCC nests on ecological conditions over time. Additionally, more in-depth vegetation analysis would help to build the baseline dataset and inform restoration recommendations.

This exploratory study provides information at a snapshot in time, but it cannot assess the effects of consecutive years of cormorant colonization at the site. A temporally longitudinal study can use this baseline dataset to help inform of site conditions in 2017 and build upon this dataset with enhanced timing of measurements. The methods used to collect and assess data in this study are highly replicable. Additionally, with the TRCA's goal of excluding DCC nests from Peninsula within the next few years, this dataset may be used to inform studies that look at site conditions during and post-DCC colonization.

The time allocated to the field component of this study was limited, and therefore, a tree health analysis was not created. The TRCA also has limited resources and only conducts assessments of the health of select trees at the site. Future studies have the opportunity to create a strong vegetation health analysis that can be compared to the present soil physical and chemical characteristics. An assessment of species richness and health in relation to DCC nesting locations and soil conditions will help restoration efforts by strengthening the knowledge of what species

are the most likely to experience fatalities and reduced seed germination and growth due to DCC nests.

Additionally, future restoration studies can and should look into test plantings of selected restoration species prior to the initiation of a large-scale restoration project. A study that focuses on the test planting of desired species will re-enforce the appropriateness of particular species for use in the restoration of TTP's Peninsula C, and it would also inform future studies that look into what species are the most successful for the reforestation of DCC colonies in North America. This type of practice was undertaken by researchers in Wisconsin to assess the response of black elderberry tree plantings in a DCC colonized site (Ayers et al., 2015). Using different methods of planting and tree protection, the study was able to conclude that planting larger, bare-root trees with burlap protection and soil enhancement improved the establishment and growth of the tree species in the DCC colony (Ayers et al., 2015). Optimizing methods for tree growth prior to investing in a large reforestation project will help to save time and resources for the conservation authority.

Appendix A   GPS Receiver and Data Collector Specifications

Company: Topcon
Website: http://www.topconpositioning.com
Manufacturer: Topcon Corporation, 75-1 Hasunuma-cho, Itabashi-ku, Tokyo, 174-8580, Japan

Topcon HiPer SR GNSS Receiver

GNSS TRACKING
Number of Channels   226-Channel Vanguard Technology with Universal Tracking Channels
Signals Tracked   GPS, GLONASS, SBAS, QZSS
Antenna Type   Fence Antenna

ACCURACY
Accuracy   Static/Fast Static: H: 3.0 mm + 0.4 ppm V: 5.0 mm + 0.6 ppm
                            Precision Static: H: 3.0 mm + 0.1 ppm V: 3.5 mm + 0.4 ppm
                            TRK (L1+L2): H: 10 mm + 0.8 ppm V: 15 mm + 1.0 ppm
DGPS   H: 0.4 m, V: 0.6 m
SBAS   H: 1.0 m, V: 1.5 m

COMMUNICATIONS
I/O Communications   Bluetooth, Serial, USB
Cellular   Integrated HSPA+/CDMA

MEMORY
Memory   2 GB internal
Real Time Data Output   TPS, RTCM, SC104 v2.x, 3.x and MSM, CMR/CMR+
ASCII output   NMEA 0183 version 2.x, 3.x and 4.x

PHYSICAL AND ENVIRONMENTAL
Dimensions   W: 5.9* (150 mm) D: 5.9" (150 mm) H:2.5" (64 mm)
Weight   1.87 lbs. (850g) – Basic 2.04 lbs. (925g) – Cellular
Operating Temperature   -20°C to 65°C
Storage Temperature   -40°C to 70°C

CERTIFICATIONS AND STANDARDS
Dust/Water Protection   IP67

POWER AND ELECTRICAL
External Power Connector Yes

PERFORMANCE
Operation Time   UP to 20 hours

Topcon FC-5000 Data Collector

GNSS TRACKING

Type	uBlox NEO M8M
Accuracy	2-5 m
Number of Channels	72
Update/Output rate	5 Hz

PHYSICAL AND ENVIRONMENTAL

Water Resistance	IP68 Certified
Dust/Humidity	IP68 Certified
Operating Temperature	-20°C to 50°C
Storage Temperature	-30°C to 70°C
Thermal Shock	MIL-STD 810G
Drop Test	MIL-STD 810G: Drop 4 ft (1.2m)
Dimensions	13.71 x 3.45 x 21.5 cm (L x W x H)
Operation Time	Up to 15 hours (5 hours internal batteries, 10 hours swappable batteries)

WIRELESS CONNECTIVITY

Bluetooth	Long-range Bluetooth Smart Ready wireless technology, v4.0 0 +EDR, Class 1.5
Wi-Fi	802.11 a/b/g/n 2.4 GHz and 5 GHz
Cellular	Internal GSM 4G LTE

GENERAL

Processor	Intel Atom Z3745 Processor
Operating System	Windows 10
Memory	4 GB LPDDR3 RAM, SD slot, user accessible
Display	7 in. Sharp screen, Wide XGA at 1280 x 800
Camera	Rear: 8 megapixel with LED Illumination Front: 2 megapixel

Appendix B   pH Meter Specifications

Company: Aquasol Digital
Website: http://www.aquasoldigital.com
Manufacturer: Rakiro Biotech Systems Private Limited. R-466, TTC Industrial Area, MIDC Rabale, Navi Mumbai – 400 701

Aquasol Handheld Meter AM-PH-01)

Model	AM-PH-01
Measuring Range	0 to 14
Accuracy	+/- 0.1+1 digit
Resolution	0.1 pH
Display	3 Digit
Power	3V x 2 Lithium battery CR2032
Dimension	33.5 mm x 170 mm
Weight	85 g
Electrode	Replaceable
Product Manual	Handhel pH Meter – Procedure

Product Material Safety Data Sheet: Digital Instruments - MSDS

Appendix C   EC Meter Specifications

Company: Extech
Website: http://www.extech.com
Manufacturer: Extech, Nashua, New Hamshire, United States of America.

Extech EC 400 ExStik II Handheld Meter

Conductivity	0 to 199.9 uS, 200 to 1999 uS, 2.00 to 19.99 mS
TDS/Salinity/Fluoride	TDS/Salinity: 0 to 99.9 ppm (mg/L), 100 to 999 ppm (mg/L), 1.00 to 9.99 ppt (g/L)
Temperature	0 to 65°C
Max. Resolution	0.1 uS, 0.1 ppm (mg/L), 0.01 pH, 0.1°C
Basic Accuracy	+/- %FS, +/- 0.01 pH, +/- 1.8°C
Dimensions	1.4 x 6.8 x 1.6" (33.6 x 172.7 x 40.6 mm)
Weight	3.8 oz (110g)

Appendix D   Compaction Meter Specifications

Company Name: Spectrum Technologies, Inc.
Website: https://www.specmeters.com
Manufacturer: Spectrum Technologies, Inc., 3600 Thayer Court, Aurora, IL 60504 USA

FieldScout SC 900 Meter

Measurement Units:	Cone Index (PSI or kPA)
Resolution:	1 in (2.5 cm), 5 PSI (35kPA)
Accuracy:	+/- 0.5 in (1.25 cm) Depth, +/- 15 PSI (103 kPa) Pressure
Range:	0 to 18 in (0 to 45 cm), 0 to 1,000 PSI (0 to 7,000 kPa)
Battery/Life:	4 AAA alkaline batteries; approximately 12-month life
Data Logger Capacity	772 profiles without GPS; 579 profiles with GPS

Appendix E   Laboratory Protocol for Soil Texture Analysis

Soil Texture Analysis Protocol – Adjusted Pipette Method

Materials

- Scale (0.01g)
- Evaporating cups (paper cupcake cups)
- Marker for labeling
- Pipette & syringe
- Plastic test tubes
- 250ml graduated cylinders

- Rubber stopper for graduated cylinder
- Agitator
- Mortar and pestle
- Timers
- Baking sheets (to hold samples in the oven)

Protocol Specifications

- Run oven at 150°C
- Calibrate scale before every use
  - When **weighing warm/hot soil samples with scale use Styrofoam plate**
- Make sure all lab equipment is clean (vacuum sieve and mortar, rinse test tubes, flush pipette)
- 5% hexametaphosphate solution (200g for 4L)
- Use distilled water for all processing
- "**Completely Dry**" – weigh sample when visibly dry, weigh again after 30min, and then at 15min intervals until the weight change is <0.05g

Method

1. Completely dry sample
2. Crush dry sample using mortar and pestle
3. Thoroughly mix crushed sample
4. Place in sieve for 5min to remove gravel (>2mm particles – discard gravel in waste bin)
5. **Mix sample and extract 20g (to nearest 0.01g) of soil into sample cup (paper cup)**
6. Pour ~5ml of hexametaphosphate solution into plastic test tube, add sample, fill to full with hexametaphosphate solution
   a. Shake to mix sample, then keep test tube on agitator for 3min
7. **Weigh and label two evaporating cups (double up the cups): "A" =** silt+clay, and **"B" =** clay
8. Pour contents of test tube into 250ml graduated cylinder. Wash all remnants of agitated solution into the 250ml cylinder using spray bottle (distilled water). Bring solution volume to 250ml using distilled water
9. Use rubber stopper, keep hand over top of stopper, invert cylinder three times to resuspend soil
10. Set on flat surface, begin timer (**set timer to 41min**)
11. Extract **12.5ml aliquot (1)** from near the surface of solution at **48 seconds**
12. Transfer aliquot to evaporating **cup labeled "A"**. Place in oven, **weigh when sample is completely dry**, dispose of sample
13. Extract **12.5ml aliquot (2)** from surface of solution at **40 minutes**, dispose of solution
14. **Transfer aliquot to evaporating **cup labeled "B."** Place in oven, **weigh when sample is completely dry**, dispose of sample

*mas of silt and clay = mass of aliquot A – mass of evaporating cup

*mass of clay = mass of aliquot B – mass of evaporating cup

Calculating Soil Texture

% clay   = (20 * [mass of clay / total mass of soil sample]) * 100

% silt   = (20 * ([mass of silt and clay – mass of clay] / total mass of soil sample)) * 100

% sand = 100 – (% silt + % clay)

<u>Texture</u>

The texture of the soil, or characterization of the soil, was measured in the lab for each sample site using soil samples from two depths – the A horizon and B horizon. Texture measures the percentage of clay, silt, and sand that make up a soil. The organic layer was not assessed for texture because it is the immature, active layer of soil that consists of humus, fibrous material, and leaf litter, as opposed to raw soil components (Hazelton and Murphy, 2011). Dry soil samples were mixed and divided into 20 g samples for this measurement. The samples were diluted with 5% sodium hexametaphosphate solution and placed on an agitator. After 3 minutes, the soil became thoroughly displaced in the sodium hexametaphosphate solution. The soil solution was poured into a graduated cylinder that was then diluted by filling with distilled water up to 250 ml. The sample was then turned upside down three times and placed on an anti-agitation mat to settle. Using a pipette, a 12.5 ml aliquot was taken from the top of the solution after 40 seconds had passed. A time period of 40 seconds was used because this is how long it takes sand to settle out of a solution, leaving silt and clay suspended. The final 12.5 ml aliquot was taken at 41 minutes, a time where all silt has settled, leaving only clay suspended. Using the following calculations, the percentage of sand, silt, and clay were measured from the initial sample mass (20 g):

% clay = (20 g * [mass of clay / total mass of soil sample]) * 100

% silt = (20 g * ([mass of silt and clay – mass of clay) / total mass of soil sample)) * 100

% sand = 100 – (% silt + % clay)

Appendix F   Laboratory Protocol for pH and EC Analysis

Electro-conductivity (EC) and pH Analysis Protocol – Water Method

Materials

- Scale (0.01g)
- Evaporating cups (paper cupcake cups, for weighing)
- Marker, for labeling paper cups
- Beaker 50-200ml or plastic ones same size
- Agitator

- Distilled water
- Mortar and pestle
- EC Probe
- pH Probe
- Plastic test tubes

Protocol Specifications

- Run oven at 150 $^{\circ}$C
- Calibrate scale before every use
- Make sure all lab equipment is **clean**; **rinse** with distilled water all containers before use
- Make sure all equipment is **cleaned** and **rinsed** with distilled water **after each sample** is analyzed
- Use **"triplicates"** (three at once) for each sample
- Make sure you dry enough sample, since you'll need >60g of each sample
- Use distilled water for all processing
- "**Completely Dry**" – weigh sample when visibly dry, weigh again after 30min, and then at 15min intervals until the weight change is <0.05g

Drying and Preparing Samples

1. Thaw samples in plastic bags for about ½ day
2. Once loose, label and fill paper cups with samples (you will need >60g total of each sample, so fill two cups)
3. Place in oven at 150 $^{\circ}$C for 4-6hrs till completely dry
4. Crush dry sample using mortar and pestle (vacuum clean between samples)
5. Thoroughly mix crushed sample

pH and EC Measurements

Make triplicates for each sample

1. Weigh 20g of sample and place in 50-200ml beaker or plastic one same size
2. Fill beaker with water up to 50ml
3. Stir or shake the suspension until all soil is loose
4. Let suspension sit for 30min until all sediment settles
5. Stick the tip of the probe into the surface of the partially settled suspension to take either EC or pH measurements. **Do not** stick the probe all the way to the bottom
6. Record measurements clearly

pH

The soil pH was measured in the lab for every site using each of the three soil depth samples. This is a measurement of the alkalinity of the sample sites, and rates soil pH as acidic or basic using the logarithmic pH scale. The dry soil samples were mixed and divided into 20 g (approximately 25 ml) samples for this measurement. The samples were then diluted in test tubes with distilled water until a 50 ml measurement was reached; this ensured a 1:1 soil to distilled water solution, by volume. For pH readings, replicate readings were taken using two 20 g samples from each soil depth (of which the mean measurement was used). For this measurement, an Aquasol handheld pH meter was used.

EC

Electroconductivity was measured in the lab for all soil samples. For this measurement, an ExTech EC 400 ExStik II, handheld EC meter was used to record the salinity of samples by testing for the presence of salt ions. Dry soil samples were mixed and divided into 20 g (approximately 25 ml) samples for this measurement. The samples were then diluted in test tubes with distilled water until a 50 ml measurement was reached; this ensured a 1:1 soil to distilled water solution, by volume. Replicate readings were taken by using two 20 g samples from each soil depth (of which the mean measurement was used).

Appendix G   Site Suitability Model Results

(a) acidic, well-drained soils; (b) acidic, saturated soils; (c) alkaline, well-drained soils; (d) alkaline, saturated soils; (e) neutral soils.
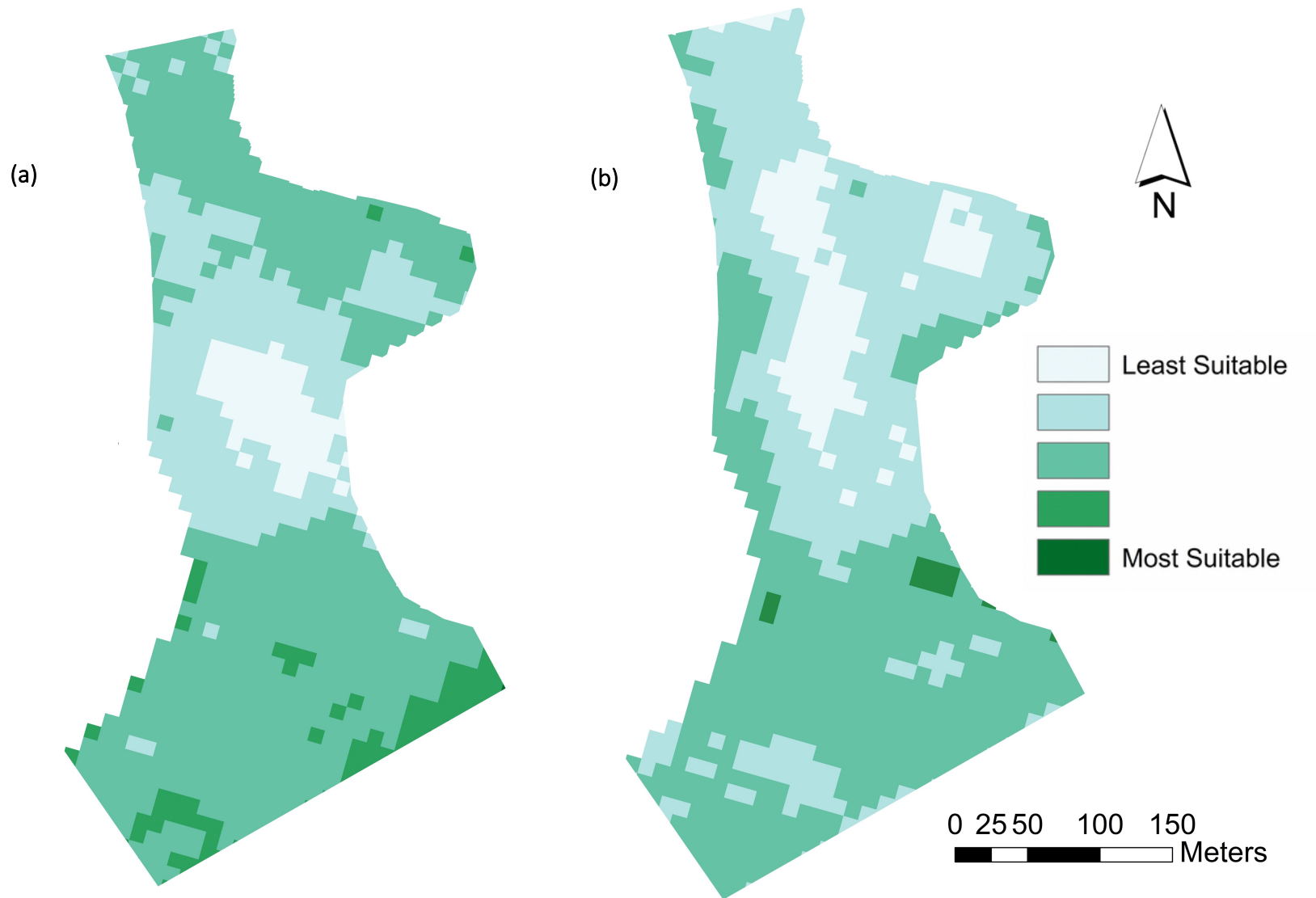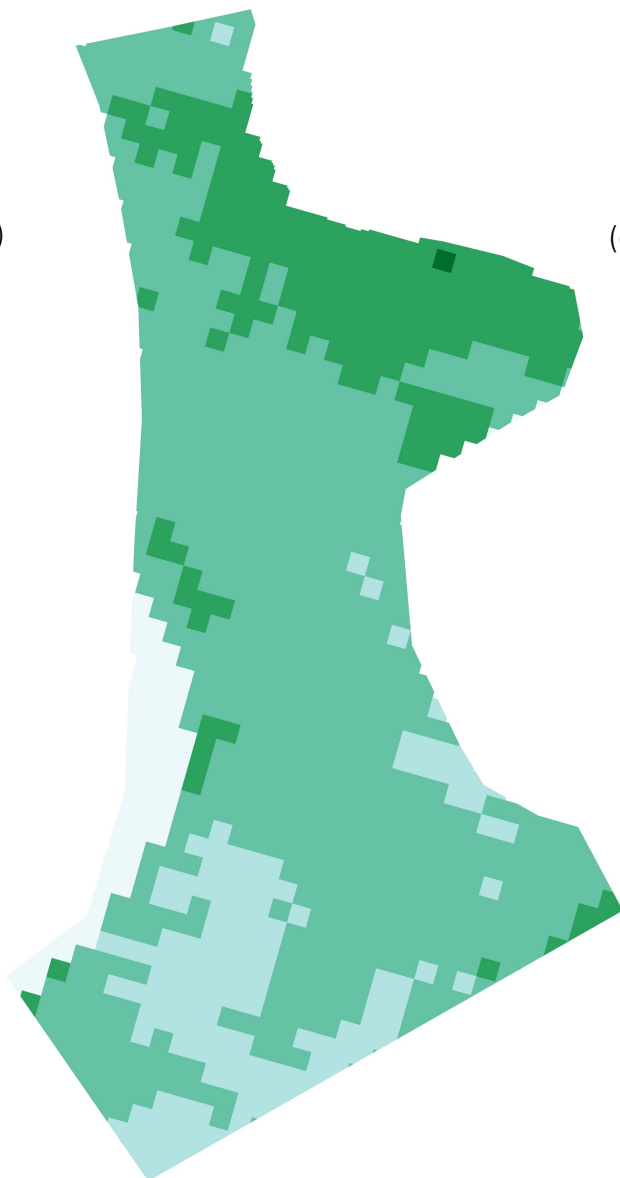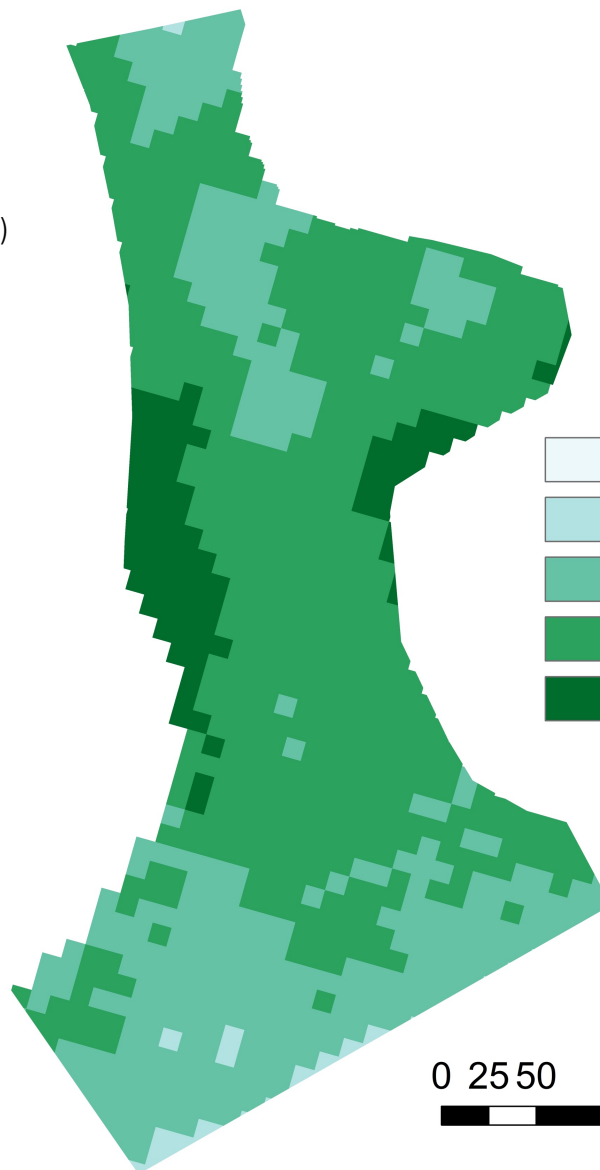
(a)

(b)

N

Least Suitable

Most Suitable

0 25 50   100   150
Meters

(e)

Least Suitable

Most Suitable

0 25 50   100   150
Meters
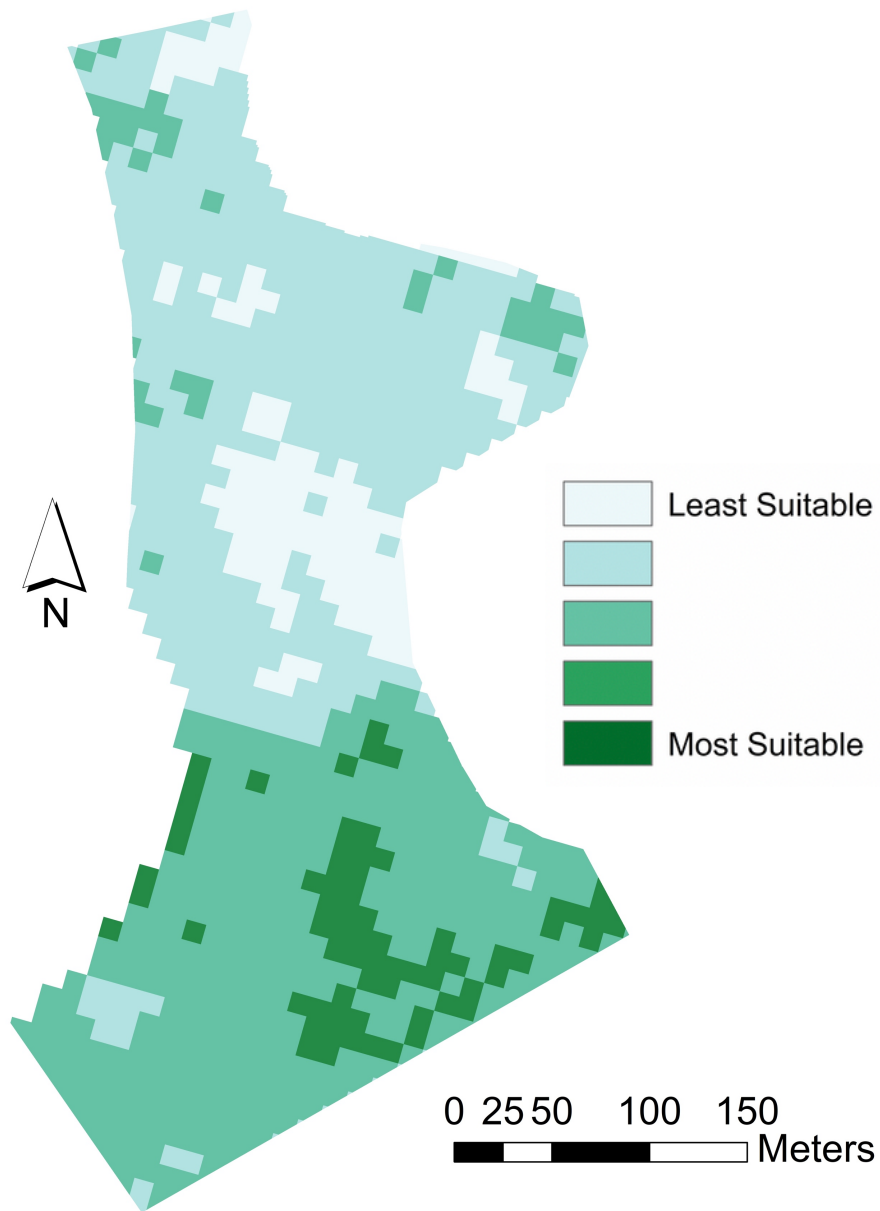
Appendix H   Raw Soil Chemistry and Compaction Data

Raw soil chemistry data and compaction data. Sample ID according to site number and soil depth (A = A horizon, O = O horizon).

SAMPLE ID	pH	EC	ORGANIC MATTER (%)	NITRATE (ppm)	AMMONIUM (ppm)	PHOSPHORUS (ppm)	POTASSIUM (ppm)	CALCIUM (ppm)	MAGNESIUM (ppm)	COMPACTION (kPa)
1A	7.82	116.15	0.8	1.8	1.3	5.8	23.79	3004.79	52.41	1719
2A	7.89	108.15	0.5	1.3	1	4.18	22.45	2843.58	52.58	1369
3A	7.79	155.45	0.5	2.3	1	4.09	21.25	2768.23	61.37	1930
4A	7.69	133.50	0.5	1	0.8	2.38	17.39	2951.85	58.7	1333
5A	7.86	111.15	0.5	4.8	1.2	2.37	28.79	2881.79	50.35	1123
6A	7.84	185.25	0.5	1.5	2.6	2.91	36.36	2961.19	57.75	1719
7A	7.81	188.60	0.8	1.2	1.8	3.82	33.44	2745.65	52.79	1930
8A	7.36	143.35	0.8	5.2	1.6	8.33	16.89	2318.25	52.67	737
9A	7.74	124.70	0.8	1.6	1.6	4.86	16.8	2612.02	58.34	1790
10A	7.71	-	1.5	3.5	3.6	12.8	29.84	2594.87	59.03	1930
11A	7.68	104.05	1	2.6	1.9	5.46	34.87	2673.05	62.64	2035
12A	7.82	80.50	0.5	1.8	2.8	3.9	31.86	2764.31	55.26	2246
13A	7.61	273.50	1	1.1	1.9	2.37	30.15	2969.17	55.52	2070
14A	8.12	110.95	0.3	1.2	1.3	1.95	16.96	2718.34	51.24	1333
15A	7.86	65.00	0.3	6	2.5	13.24	25.28	2657.72	51.87	1333
16A	7.5	91.55	0.8	1.3	2.1	5	32	2321	54	2070
17A	7.94	425.00	0.3	1.8	1.8	3.71	26.65	2818.47	47.09	2491
18A	8.01	113.80	0.3	3.6	1.7	2.05	35.73	2752.91	51.5	1790
19A	7.81	180.80	0.5	1.1	1.7	2.23	41.22	2876.25	52.22	1088
20A	7.36	242.00	0.5	23.9	3.3	12.85	22.59	2256.27	47.75	912
21A	7.71	71.85	0.8	6.1	5.3	10.94	25.52	2509.92	56.57	1053
22A	7.9	74.50	0.5	7.7	2	11.44	27.96	2661.4	54	1930
23A	7.88	87.85	0.5	2.5	2.1	2.65	29.53	2650.37	54.58	3404

24A	7.83	75.70	0.3	1.4	1.1	1.91	17.18	2689.13	48.36	-
25A	7.9	96.10	0.5	1.4	3.2	2.11	33.03	2525.93	57.3	1544
26A	7.86	106.60	0.3	1	2.1	1.92	44.86	2624.11	52.04	1439
27A	7.86	86.90	0.3	3.8	1.3	5.31	18.3	2484.95	47.58	2983
28A	8.06	143.75	0.5	1	1.3	7.27	23.19	2668.45	58.98	1614
29A	8.04	137.75	0.3	1	1.6	1.3	25.25	2608.38	47.33	2667
30A	8.04	88.90	0.3	1.2	1.7	2.08	24.82	2859.15	52.55	-
31A	7.76	93.35	0.8	1.8	2.3	3.55	27.68	2677.04	57	3298
32A	7.89	64.50	0.5	6	1.6	1.8	25.18	2666.68	54.45	-
33A	7.9	113.00	0.5	1.3	2.9	1.43	23.16	2638.21	48.71	1088
34A	7.91	79.00	0.3	0.9	1.9	1.7	37.61	2805.2	56.73	2386
35A	7.77	354.00	0	2.9	1.8	5.4	17.49	2540.64	49.23	2386
36A	8.11	90.40	0.3	2.6	2.3	3.28	31.29	2546.65	54.68	2140
37A	7.83	510.00	0.5	2.3	2.3	4.28	25.93	2556.51	48.97	2491
38A	8.04	92.45	0.3	1.3	1.6	2.62	22.68	2784.7	49.43	4702
39A	7.98	75.75	0.3	1.1	2.2	2.96	20.94	2575.72	58.45	1930
40A	7.94	81.70	0.8	1	3.4	4.32	24.88	2769.81	73.33	2983
41A	7.72	357.50	0.8	5.5	2.2	3.23	19.99	2866.29	55.81	1649
42A	7.2	481.00	0.5	12.4	1.5	43	86	1829	54	1614
43A	7.36	143.25	0.8	25.9	2.6	23.09	23.55	2550.3	65.33	-
44A	7.66	109.15	0.5	10.1	2.8	10.27	31.63	2618.65	60.62	-
45A	7.79	77.60	0.3	2.7	3.1	2.85	27.35	2554.51	51.72	1755
46A	7.92	63.35	0.3	4.2	1.6	7.16	17.5	2860.79	55.52	772
47A	7.7	188.40	0	38	1.4	33.62	72.33	2147.48	46.43	386
48A	6.8	375.00	0.3	44.2	1.9	1817.14	63.82	1402.55	42.86	3930
49A	6.33	476.00	0.5	101.7	2.3	2222.41	106.82	2193.46	49.23	4737
50A	6.86	317.50	0.5	84.3	1.7	154.22	80.7	1813.16	60.96	6492
51A	7.43	171.15	0.5	15.9	2.6	31.56	30.64	2356.13	50.37	1404
52A	7.61	172.85	0	31.1	1.7	48.36	56.37	2181.36	45.01	456

53A	6.82	242.00	0.8	9.4	3	1498.61	25.77	1351.91	41.68	3439
54A	6.82	164.85	0.3	32	2.2	203.01	21.47	1671.82	44.93	-
55A	7.09	163.55	0.8	24.2	2.6	176.91	32.37	2216.5	52.12	1930
56A	7.61	182.75	0.8	10	2.3	13.01	32.36	2702.68	50.87	3439
57A	6.5	362.50	1.2	50.5	3.3	316.31	47.02	1323.12	43.41	912
58A	6.31	297.50	1	12.8	3.9	1789.97	32.54	1651.5	40.93	5266
59A	6.16	361.00	0.5	80.4	3.3	522.41	29.85	1071.54	41.69	1965
60A	7.41	150.30	1.5	10.5	4.7	39.52	31.04	2118.76	47.14	1193
61A	7.46	121.45	0	21.2	3.3	40.05	27.46	1594.8	45.36	1895
62A	6.86	325.00	0.8	5.7	5.6	2133.26	31.93	1831.02	38.36	1439
63A	7.01	164.20	0.5	4.4	2.7	1332.68	41.36	1106.96	36.29	1930
64A	6.57	278.50	0.8	5.2	2.2	1715.74	19.74	1679.04	36.66	1474
65A	7.16	145.35	0.3	6.1	2.1	337.85	35.59	1399.03	41.57	1018
66A	7.71	121.45	0.3	6.6	15.3	81.93	49.03	1912.26	44.87	807
67A	7.21	529.50	0.3	13.2	4.2	46.32	42.58	2057.77	44.28	1053
68A	7.6	78.10	1.5	7.9	2.5	26.8	36.22	2309.01	55.15	632
69A	6.86	229.00	0.5	14.5	2.5	2516.39	25.1	2052.07	35.22	1369
70A	6.85	205.00	0.3	2.5	3.4	1941.66	19.35	1625.84	32.2	1544
71A	7.66	82.50	0	1.6	2.9	44.85	19.69	1967.1	44.31	1053
72A	6.83	158.60	0.5	4.3	3.1	1441.62	35.96	1281.11	33.58	1649
73A	7.03	258.25	0.3	6.7	2.4	423.76	31.6	1150.64	39.62	2632
74A	6.68	220.50	0.5	5.6	2.6	1760.67	36.53	1414.65	35.33	1439
75A	6.53	259.00	0.5	5.6	3.1	4504.31	34.79	2878.6	34.58	1439
76A	6.8	175.00	0.3	2.7	2.4	776.5	28.41	1060.23	34.29	1649
77A	6.96	275.50	0.5	7.4	2	4118.73	30.1	2805.9	34.45	1474
78A	7.67	266.00	1.2	2.2	1.8	260.71	16.34	2497.74	62.89	2702
79A	7.48	79.40	0.5	4.2	2.2	50.52	20.78	2258.43	48.82	175
80A	7.08	306.00	0.3	9.5	2.8	1681.61	63.16	1340.79	36.7	4878
81A	6.84	143.45	1.7	5.4	4.5	326.41	55.62	1306.73	58.63	-

82A	7.21	218.50	0.3	6	1.9	1413.81	85.21	1142.21	40.02	3579
83A	7.4	136.60	0	10	2.2	166.35	36.17	1916.55	42.83	1474
84A	6.75	195.30	0.8	5.2	3.4	491.93	26.96	1145.37	40.98	2176
85A	6.61	293.50	0.8	5.5	2.8	2418.68	26.9	2406.92	40.69	2737
86A	6.89	161.40	0.3	8.4	2.5	614.22	28.97	1095.29	37.27	2316
87A	6.77	200.50	0.5	29.7	3.3	493.66	58.9	1366.4	41.84	632
88A	7.42	129.05	0.3	8.2	2.1	318.62	57.54	1694.29	45.49	3018
89A	6.75	270.00	0.5	4.1	2.4	2526.89	20.07	1904.85	37.25	1790
90A	7.67	103.75	0.3	2.8	1.9	57.65	23.26	2146.59	45.71	983
91A	7.16	193.45	0.3	7.7	1.9	387.68	19.79	1420.13	37.93	1790
92A	6.52	190.00	0.5	3.7	1.8	2013.72	29.49	1657.57	32.15	1895
93A	7.65	35.45	0	1.7	1.6	279.19	18.73	2035.58	49.93	1509
94A	7.76	45.00	0.3	0.9	1.3	108.64	24.93	2637.64	64.93	1719
95A	7.05	143.45	0.3	3.9	1.4	620.66	29.59	1035.07	36.1	737
96A	7.61	60.30	0.3	5.9	1.2	39.23	18.01	2070.93	44.63	1088
97A	7.64	112.60	0.5	2.7	1.7	19.34	19.16	2543.32	53.77	1649
98A	6.58	413.50	0.5	21.2	2.5	3607.03	44.07	3016.83	43.15	1509
99A	7.39	108.20	1.2	8.9	2.8	343.27	29.03	2051.89	51.06	1053
100A	7.6	158.10	0.5	2.4	1.7	31.44	16.41	2628.45	58.69	1298
1O	7.38	738.00	5	2.4	7.9	14.72	43.36	3098.13	79.55	526
2O	7.37	607.00	5	4.8	11	13.76	74.2	3117.52	78.77	386
3O	7.23	852.00	7	25.3	3.2	12.73	36.23	3506.28	138.27	386
4O	7.25	223.00	7.4	12.9	4.2	16.51	45.98	3831.37	160.07	316
5O	7.33	607.00	5.4	8	9.3	10.74	45.2	2828.29	85.18	246
6O	7.38	144.85	5.2	3.9	22.1	13.49	97.8	2756.46	100.32	737
7O	7.32	442.00	7.4	1.2	22.4	13.2	69.19	3560.57	109.06	386
8O	6.98	893.00	6.3	16.8	16.2	15.38	58.44	3072.78	96.87	316
9O	7.36	1000.00	6.1	9.2	12.8	17.07	37.79	3541.93	142.95	246
10O	7.31	526.00	4.1	14.7	5.2	12.52	35.64	2675.54	82.26	70

11O	7.41	690.50	5.6	4.3	5.3	16.62	182.51	2484.71	79.1	737
12O	7.45	572.50	4.7	1.3	6.4	7.83	97.77	2310.33	64.75	772
13O	7.43	405.50	4.5	1	8.3	7.42	52.11	2961.99	66.55	491
14O	7.17	740.50	5	16.5	21.2	37.54	66.74	3143.81	133.16	456
15O	7.18	247.50	5.2	32.9	5	22.32	35.02	3083.25	99.77	246
16O	7.2	261.00	7	25.3	13.8	15	43	3074	127	316
17O	7.28	523.50	6.5	8.9	12.6	11.13	45.08	3108.27	83.6	386
18O	7.44	814.50	4.3	1.6	4	4.93	34.96	3165.92	72.44	561
19O	7.41	164.30	3.8	0.8	4	10.69	116.92	2929.85	85.64	281
20O	6.44	1036.50	5.9	262.5	2.7	46.6	32.96	2763.43	99.42	632
21O	7.22	965.50	5.6	42.8	10.3	29.59	52.72	3436.75	129.8	281
22O	7.27	331.00	5.9	27.1	3	19.36	49	2918.61	97.42	386
23O	7.37	428.00	4.7	8	3.4	10.51	52.58	2585.45	80.76	772
24O	7.49	508.00	2.5	1.6	1.2	5.05	31.9	2160.6	50.6	1088
25O	7.55	505.50	3.6	4.6	4	7.69	73.9	2526.17	81.17	351
26O	7.37	702.00	6.5	1	5.2	9.68	105.86	3281.89	110.74	351
27O	7.29	446.00	2.3	7.6	0.8	16.47	17.21	2274.73	64.46	667
28O	7.32	811.50	7	4.5	7.5	14.66	63.75	3806.14	151.76	526
29O	7.35	159.55	6.1	11.2	8	9.61	31.65	3053.72	84.6	632
30O	7.54	439.00	1.6	2.5	1.5	6.84	65.3	2274.3	52.87	667
31O	7.39	222.80	6.5	1.2	3.1	13.62	181.94	3250.24	132.84	561
32O	7.5	133.45	5.4	1.1	3	9.38	67.83	3573.52	126.83	597
33O	7.34	582.50	4.3	8.6	4.3	7.41	27.67	2869.56	95.9	386
34O	7.34	542.50	12.6	6.2	7.4	9.53	80.25	3194.08	129.73	561
35O	7.24	185.80	3.6	11.1	1.8	21.57	33.08	2087.7	64.05	1404
36O	7.19	446.75	5.6	26.2	1.6	14.12	42.05	3006.92	102.74	386
37O	7.28	692.50	5.6	26.9	1.5	16.11	24.78	3251.89	99.66	456
38O	6.98	524.50	14.5	47.2	20.5	16.98	82.42	4316.91	230.3	386
39O	7.2	460.50	11.5	10.1	5.7	8.3	34.24	3234.63	149.74	246

40O	7.11	486.00	5.7	6.5	3.8	8.5	32.66	3288.25	130.08	386
41O	7.12	707.00	7.9	4.1	10	8.74	30.33	3156.81	134.3	526
42O	6.1	2900.00	3.9	1592.9	170	606	584	2760	214	526
43O	6.34	1282.50	6.4	509.4	37	175.66	121.42	2444.27	99.87	491
44O	7.01	5520.00	8	165.6	2.8	17.98	67.53	2982.31	110.81	351
45O	7.09	564.50	10	38.8	6.9	15.63	90.51	3182.95	98.96	316
46O	7.11	879.50	14.1	87.5	17.6	15.69	56.23	3939.01	179.93	140
47O	-	-	-	-	-	-	-	-	-	316
48O	5.19	4835.00	21.2	1339.4	51.9	1712.98	457.34	3385.33	208.62	351
49O	3.79	2575.00	32.4	3093.8	963	1563.78	697.54	2730.63	136.85	316
50O	5.62	1243.50	11.5	1084.7	23.8	381.82	327.73	2524.11	104.02	702
51O	5.9	1149.50	19	798.8	8.7	197.74	143.05	4375.24	221.83	526
52O	-	-	-	-	-	-	-	-	-	70
53O	5.19	660.00	30.1	1159.3	34.1	3205.57	58.59	3926.47	139.11	281
54O	5.58	867.00	12.3	278.4	43.6	605.89	110.36	1980.93	105.3	1369
55O	5.93	1384.50	19.2	454.4	9.5	283.26	48.03	3524.82	172.5	386
56O	7	351.00	5.7	181.1	1.1	53.54	34.82	2756.16	133.35	316
57O	5.71	2520.00	22.2	857.3	53.2	348.88	256.88	2574.58	167.38	491
58O	4.64	342.80	37.2	237.5	77.4	373.8	55.41	2304.49	85.07	386
59O	4.6	2023.50	20.6	1243.9	63.4	3630.86	188.44	3735.63	149.29	175
60O	6.53	617.50	16	449.1	8.2	355.82	45.16	3764.57	152.77	105
61O	-	-	-	-	-	-	-	-	-	807
62O	5.6	1592.00	20.6	1216.8	36.1	305.38	181.16	2706.66	191.56	105
63O	5.57	640.50	20.1	229.3	92.9	249.26	75.75	2288.1	106.25	211
64O	5.86	689.00	43.9	407.3	190.2	133.82	63.13	2338.58	137.6	211
65O	6.72	367.00	15.1	43.6	6.9	119.75	47.19	3086.45	106.66	211
66O	6.36	2030.50	12.7	390.5	4.9	108.98	83.54	2864.31	103.43	281
67O	5.71	1007.00	30.9	426	30.4	192.13	86.85	3298.06	155.54	70
68O	6.3	263.00	21	250.4	56.4	162.71	292.92	3246.06	116.6	526

69O	5.18	1519.00	32.1	1030.8	57.7	180.9	101.83	2756.86	146.08	316
70O	5.53	782.50	22.4	284.1	34.6	174.39	85.01	2772	126.82	386
71O	6.83	1820.00	21.1	134.1	6.7	27.03	36.81	4400.11	274.86	175
72O	6.36	225.55	11.9	129.8	10	174.81	44.04	2526.33	121.67	140
73O	6.52	424.50	20	98.6	18	142.62	136.02	2642.67	102.47	807
74O	5.21	410.50	23.9	284.2	42.5	193.95	56.28	2409.11	100.83	175
75O	5.66	448.00	20	75.3	51.4	154.75	28.41	2419	86.75	70
76O	5.47	531.00	11.3	11.9	11.8	128.9	40.16	1986.44	60.62	351
77O	5.97	1570.00	25.6	112.5	40.8	123.82	66.05	2933.65	155.84	211
78O	6.75	575.00	32	96.3	22.4	43.65	95.26	4887.65	300.53	316
79O	7.03	270.00	21.9	111.3	4.8	190.67	28.06	3974.11	129.74	526
80O	6.55	736.00	8.7	16.1	7.8	170.31	36.56	2388.86	109.48	281
81O	6.55	251.50	38	91.1	17.7	151.65	131.98	3743.18	215.33	702
82O	5.54	487.50	33.2	55.6	24.2	151.97	57.17	2351.55	124.28	211
83O	6.98	591.00	16.5	348.7	49.7	54.82	39.88	2904.94	214.92	175
84O	5.94	762.00	29.6	181.1	51.6	222.09	72.46	2812.52	141.96	105
85O	5.86	652.00	32	95.7	21.4	2247.89	42.36	2325.72	110.24	140
86O	5.76	1022.00	20.5	271.1	24.7	669.31	53.74	2627.1	151.46	526
87O	6.51	1262.00	9.4	346.7	6.9	320.3	96.27	2749.44	157.38	351
88O	-	-	-	-	-	-	-	-	-	70
89O	6.08	921.00	18.4	209.9	17.1	208.62	49.68	2466.99	174.62	351
90O	7.05	352.00	3.7	14.7	2.3	30	28.3	2370.57	78.93	281
91O	6.13	2003.50	14.9	401.9	5.5	62.95	34.79	2702.23	201	246
92O	5.64	637.00	16.4	149.8	35.7	360.74	41.78	2167.46	100.17	105
93O	7.01	161.15	1.9	15.1	2	35.37	23.98	2219.41	110.18	175
94O	-	-	-	-	-	-	-	-	-	526
95O	6.31	1225.00	46.3	270.9	21	219.09	63.83	3239.73	180.16	316
96O	6.89	481.00	13.3	89.2	9.1	44.33	23.8	3336.3	184.27	140
97O	-	-	-	-	-	-	-	-	-	491

98O	5.96	908.50	20	155.5	17	65.9	75.66	2254.6	124.8	1088
99O	7.05	1249.00	4.8	20.1	5.2	131.32	31.46	2862.38	99.62	491
100O	7.09	17.37	7.9	34.8	3.5	30.75	31.24	3891.61	127.93	175

Appendix I   Raw Soil Texture Data

Raw soil texture data. Sample ID according to site number and soil depth (A = A horizon, B = B horizon).

SAMPLE ID	CLAY CONTENT (%)	SILT CONTENT (%)	SAND CONTENT (%)	USDA CLASSIFICATION
1A	18	0.02	81.98	SANDY LOAM
2A	14	0	86	LOAMY SAND
3A	17	0	83	SANDY LOAM
4A	22	0.01	77.99	SANDY CLAY LOAM
5A	16	0	84	SANDY LOAM
6A	23	0	77	SANDY CLAY LOAM
7A	17	0.01	82.99	SANDY LOAM
8A	16	0.03	83.97	SANDY LOAM
9A	16	0	84	SANDY LOAM
10A	19	0.01	80.99	SANDY LOAM
11A	20	0	80	SANDY CLAY LOAM
12A	17	0.02	82.98	SANDY LOAM
13A	21	0.01	78.99	SANDY CLAY LOAM
14A	18	0	82	SANDY LOAM
15A	19	0	81	SANDY CLAY LOAM
16A	21	0	79	SANDY CLAY LOAM
17A	22	0.03	77.97	SANDY CLAY LOAM
18A	19	0	81	SANDY LOAM
19A	19	0.04	80.96	SANDY LOAM
20A	20	0.02	79.98	SANDY CLAY LOAM
21A	18	0	82	SANDY LOAM
22A	15	0.03	84.97	SANDY LOAM
23A	20	0	80	SANDY CLAY LOAM
24A	17	0.01	82.99	SANDY LOAM
25A	19	0.02	80.98	SANDY LOAM
26A	18	0.01	81.99	SANDY LOAM
27A	18	0	82	SANDY LOAM
28A	18	0.04	81.96	SANDY LOAM
29A	17	0.02	82.98	SANDY LOAM
30A	19	0	81	SANDY LOAM
31A	17	0	83	SANDY LOAM
32A	19	0.01	80.99	SANDY LOAM
33A	20	0	80	SANDY CLAY LOAM

34A	18	0	82	SANDY LOAM
35A	18	0.01	81.99	SANDY LOAM
36A	22	0	78	SANDY CLAY LOAM
37A	19	0.01	80.99	SANDY LOAM
38A	19	0.01	80.99	SANDY LOAM
39A	25	0	75	SANDY CLAY LOAM
40A	18	0.01	81.99	SANDY LOAM
41A	18	0.01	81.99	SANDY LOAM
42A	19	0	81	SANDY LOAM
43A	21	0.01	78.99	SANDY CLAY LOAM
44A	21	0	79	SANDY CLAY LOAM
45A	12	0.01	87.99	LOAMY SAND
46A	16	0	84	SANDY LOAM
47A	19	0	81	SANDY LOAM
48A	24	0.01	75.99	SANDY CLAY LOAM
49A	20	0.01	79.99	SANDY CLAY LOAM
50A	19	0.02	80.98	SANDY LOAM
51A	20	0.01	79.99	SANDY CLAY LOAM
52A	20	0.04	79.96	SANDY CLAY LOAM
53A	21	0.02	78.98	SANDY CLAY LOAM
54A	21	0.01	78.99	SANDY CLAY LOAM
55A	20	0.01	79.99	SANDY CLAY LOAM
56A	19	0.01	80.99	SANDY LOAM
57A	18	0	82	SANDY LOAM
58A	21	0.01	78.99	SANDY CLAY LOAM
59A	20	0	80	SANDY CLAY LOAM
60A	19	0	81	SANDY LOAM
61A	20	0.03	79.97	SANDY CLAY LOAM
62A	20	0	80	SANDY CLAY LOAM
63A	21	0.02	78.98	SANDY CLAY LOAM
64A	26	0	74	SANDY CLAY LOAM
65A	17	0.04	82.96	SANDY LOAM
66A	18	0.01	81.99	SANDY LOAM
67A	17	0	83	SANDY LOAM
68A	18	0	82	SANDY LOAM
69A	22	0.01	77.99	SANDY CLAY LOAM
70A	12	0.01	87.99	LOAMY SAND
71A	21	0.01	78.99	SANDY CLAY LOAM
72A	22	0.01	77.99	SANDY CLAY LOAM
73A	18	0	82	SANDY LOAM

74A	20	0.01	79.99	SANDY CLAY LOAM
75A	20	0.01	79.99	SANDY CLAY LOAM
76A	15	1	84	SANDY LOAM
77A	16	0.01	83.99	SANDY LOAM
78A	20	0.02	79.98	SANDY CLAY LOAM
79A	20	0.01	79.99	SANDY CLAY LOAM
80A	21	0	79	SANDY CLAY LOAM
81A	18	0	82	SANDY LOAM
82A	18	0.02	81.98	SANDY LOAM
83A	21	0	79	SANDY CLAY LOAM
84A	18	0	82	SANDY LOAM
85A	19	0	81	SANDY LOAM
86A	17	0.02	82.98	SANDY LOAM
87A	5	0.06	94.94	SAND
88A	19	0	81	SANDY LOAM
89A	20	0	80	SANDY CLAY LOAM
90A	6	0.04	93.96	SAND
91A	14	0.01	85.99	LOAMY SAND
92A	23	0	77	SANDY CLAY LOAM
93A	21	0	79	SANDY CLAY LOAM
94A	15	0.02	84.98	SANDY LOAM
95A	22	0.01	77.99	SANDY CLAY LOAM
96A	26	0	74	SANDY CLAY LOAM
97A	0	0.07	99.93	SAND
98A	21	0	79	SANDY CLAY LOAM
99A	20	0.01	79.99	SANDY CLAY LOAM
100A	19	0	81	SANDY LOAM
1C	15	0	85	SANDY LOAM
2C	17	0	83	SANDY LOAM
3C	24	0	76	SANDY CLAY LOAM
4C	20	0.01	79.99	SANDY CLAY LOAM
5C	19	0.02	80.98	SANDY LOAM
6C	22	0.02	77.98	SANDY CLAY LOAM
7C	19	0	81	SANDY LOAM
8C	18	0	82	SANDY LOAM
9C	19	0.01	80.99	SANDY LOAM
10C	17	0.02	82.98	SANDY LOAM
11C	20	0	80	SANDY CLAY LOAM
12C	23	0.01	76.99	SANDY CLAY LOAM
13C	20	0	80	SANDY CLAY LOAM

14C	14	0	86	LOAMY SAND
15C	20	0.01	79.99	SANDY CLAY LOAM
16C	20	0	80	SANDY CLAY LOAM
17C	20	0	80	SANDY CLAY LOAM
18C	16	0	84	SANDY LOAM
19C	19	0.01	80.99	SANDY LOAM
20C	20	0	80	SANDY CLAY LOAM
21C	16	0	84	SANDY LOAM
22C	20	0.01	79.99	SANDY CLAY LOAM
23C	20	0.01	79.99	SANDY CLAY LOAM
24C	8	0	92	SAND
25C	17	0	83	SANDY LOAM
26C	18	0.03	81.97	SANDY LOAM
27C	16	0.02	83.98	SANDY LOAM
28C	21	0.01	78.99	SANDY CLAY LOAM
29C	19	0	81	SANDY LOAM
30C	20	0	80	SANDY CLAY LOAM
31C	19	0	81	SANDY LOAM
32C	17	0	83	SANDY LOAM
33C	20	0.01	79.99	SANDY CLAY LOAM
34C	19	0.01	80.99	SANDY LOAM
35C	18	0.01	81.99	SANDY LOAM
36C	20	0	80	SANDY CLAY LOAM
37C	24	0	76	SANDY CLAY LOAM
38C	20	0	80	SANDY CLAY LOAM
39C	16	0.02	83.98	SANDY LOAM
40C	16	0.01	83.99	SANDY LOAM
41C	16	0.01	83.99	SANDY LOAM
42C	21	0	79	SANDY CLAY LOAM
43C	20	0.05	79.95	SANDY CLAY LOAM
44C	20	0.01	79.99	SANDY CLAY LOAM
45C	21	0	79	SANDY CLAY LOAM
46C	19	0	81	SANDY LOAM
47C	22	0	78	SANDY CLAY LOAM
48C	23	0	77	SANDY CLAY LOAM
49C	21	0	79	SANDY CLAY LOAM
50C	16	0.02	83.98	SANDY LOAM
51C	22	0.03	77.97	SANDY CLAY LOAM
52C	17	0.03	82.97	SANDY LOAM
53C	21	0.02	78.98	SANDY CLAY LOAM

54C	19	0.02	80.98	SANDY LOAM
55C	21	0.02	78.98	SANDY CLAY LOAM
56C	20	0.01	79.99	SANDY CLAY LOAM
57C	18	0.04	81.96	SANDY LOAM
58C	19	0.02	80.98	SANDY LOAM
59C	22	0	78	SANDY CLAY LOAM
61C	17	0.01	82.99	SANDY LOAM
62C	14	0.03	85.97	LOAMY SAND
63C	22	0.03	77.97	SANDY CLAY LOAM
64C	20	0	80	SANDY CLAY LOAM
65C	18	0.02	81.98	SANDY LOAM
60C	17	0	83	SANDY LOAM
66C	14	0.04	85.96	LOAMY SAND
67C	21	0	79	SANDY CLAY LOAM
68C	20	0.02	79.98	SANDY CLAY LOAM
69C	21	0	79	SANDY CLAY LOAM
70C	20	0.01	79.99	SANDY CLAY LOAM
71C	20	0.01	79.99	SANDY CLAY LOAM
72C	22	0.01	77.99	SANDY CLAY LOAM
73C	18	0	82	SANDY LOAM
74C	20	0.02	79.98	SANDY CLAY LOAM
75C	19	0	81	SANDY LOAM
76C	21	0	79	SANDY CLAY LOAM
77C	18	0.02	81.98	SANDY LOAM
78C	20	0	80	SANDY CLAY LOAM
80C	18	0.02	81.98	SANDY LOAM
82C	22	0	78	SANDY CLAY LOAM
83C	20	0	80	SANDY CLAY LOAM
84C	19	0.01	80.99	SANDY LOAM
85C	21	0	79	SANDY CLAY LOAM
86C	21	0.02	78.98	SANDY CLAY LOAM
87C	5	0.06	94.94	SAND
88C	23	0	77	SANDY CLAY LOAM
89C	20	0	80	SANDY CLAY LOAM
90C	10	0.02	89.98	LOAMY SAND
92C	21	0	79	SANDY CLAY LOAM
93C	15	0	85	SANDY LOAM
94C	20	0	80	SANDY CLAY LOAM
95C	20	0	80	SANDY CLAY LOAM
96C	16	0.02	83.98	SANDY LOAM

97C	20	0	80	SANDY CLAY LOAM
98C	21	0.01	78.99	SANDY CLAY LOAM
99C	18	0	82	SANDY LOAM
100C	23	0	77	SANDY CLAY LOAM

Appendix J Normal Transformation Methods

SOIL CHARACTERISTIC & DEPTH	TREND ORDER	SKEW	TRANSFORMATION
CHEMICAL			
pH (OM)	Second	-0.65263	box-cox
pH (A)	Second	0.1836	log
pH (B)	Second	-0.17476	box-cox
Electroconductivity (OM)	Second	3.2591	log
Electroconductivity (A)	Second	1.2653	log
Electroconductivity (B)	Second	4.1073	log
Organic Matter (OM)	Second	1.1266	log
Organic Matter (A)	Second	1.2	log
Nitrate (OM)	Second	3.5893	log
Nitrate (A)	Second	3.5115	log
Ammonium (OM)	Second	8.3781	log
Ammonium (A)	Second	5.6539	log
Phosphorus (OM)	Second	4.3043	log
Phosphorus (A)	Second	2.2717	log
Potassium (OM)	Second	3.7665	log
Potassium (A)	Second	2.173	log
Calcium (OM)	Second	0.69531	log
Calcium (A)	Second	-0.60849	box-cox
Magnesium (OM)	Second	1.1266	log
Magnesium (A)	Second	0.015923	log
Cation Exchange Capacity (OM)	Second	1.8706	log
Cation Exchange Capacity (A)	Second	-0.61377	box-cox
PHYSICAL			
Compaction (5 cm)	Second	1.5116	log
Compaction (12.5 cm)	Second	2.9552	log
Compaction (30 cm)	Second	1.6344	log

Appendix K   Raw Vegetation Data – Tree Species

Family	Betulaceae / Birch				Willow						Soapberry		Dogwood	Cashew	Pine		Unknown
	Paper Birch	European White Birch	Ironwood	European Alder	Eastern cottonwood	Trembling Aspen	Bebb's Willow	Sandbar willow	Peachleaf willow	Heartleaf Willow	Manitoba Maple	Silver Maple	Red-Osier Dogwood	Staghorn Sumac	White Spruce	Eastern White Pine	Tree Trunk
ID																	
Latin name	*Betula papyrifera*	*Betula pendula*	*Ostrya virginiana*	*Alnus glutinosa*	*Populus deltoides*	*Polulus tremuloides*	*Salix bebbiana*	*Salix exigua*	*Salix amygdaloides*	*Salix cordata*	*Acer negundo*	*Acer saccharinum*	*Cornus sericea*	*Rhus typhina*	*Picea glauca*	*Pinus strobus*	
1					12								1				
2		1			2								1				
3					1								1				
4					1					1			1				
5		1		2	3								1				
6					11								1				
7		1		2	11								1				
8					1			10				2	1				
9				6	1								1				
10				10	6								1				
11					9												
12					2								1				
13		8			3								1				
14		1		2	3							2	1				
15	1			5	2								1				
16		5		6	2	1							1				

#	1	2	3	4	5	6	7	8	9	10	11	12	13
17			3	3							1		
18		4									1		
19	3			2 DEAD							1		
20				3		1			3		1		
21			3	3					1		1		
22		1		1	4						1		
23		20		3							1		1
24											1	1, 5 DEAD	1
25		2		7							1		
26				4, 1 DEAD							1		
27				1		35					1		
28				6							1		
29			1	5			1				1		
30				9							1		
31	2			4									
32		5		6							1		
33		3						1			1		
34		1						1			1		
35						50				1			
36		5		3									
37		2		5							14		
38											1		
39		2					1				30		
40		2									18		
41							1				29		
42				5 DEAD					1, 4 DEAD				

#									
43		1		4			1	1	
44		2		5			1		
45			8				1		
46							1		
47					17				
48				14 DEAD					
49				19 DEAD		2			
50				8 DEAD					2
51		1					1		
52						2			4
53									3
54									
55				1, 4 DEAD					
56	1 DEAD						1		
57				4 DEAD					
58									1
59									1
60				1					
61				2 DEAD		8			
62									
63				1					
64									2
65									
66									
67				1					

68						
69						
70						
71						
72						
73						
74						
75						
76						
77						
78			27			
79						
80						
81						
82		1				
83						
84			1			
85						2
86						2
87						
88						
89						
90						
91						1
92	1					
93		1 dead			1	
94				1		
95						
96						
97						
98						3

99	
100	

Appendix L   Raw Vegetation Data – Understory Species pt. 1

Family	Daisy									Nettle	Amaranth
ID	Cocklebur	Canada fleabane	Common tansy	New England aster	Dandelion	Boneset	Canadian thistle	Woodland Sunflower	Canada Goldenrod	Stinging Nettle	Lamb's Quarters
Latin name	*Xanthium strumarium*	*Erigeron canadensis*	*Tanacetum vulgare*	*Symphyotrichum novae-angliae*	*Taraxacum*	*Eupatorium perfoliatum*	*Cirsium arvense*	*Helianthus divaricatus*	*Solidago canadensis*	*Urtica dioica*	*Chenopodium album*
1									1		
2									1		
3									1		
4									1		
5											
6									1		
7									1		
8	1	1								1	
9									1		
10											
11									1		
12									1		
13									1		
14											
15							1				
16									1		
17						1			1		
18									1		
19									1		
20									1		
21											
22			1						1		
23									1		

	1	2	3	4	5	6	7	8
24						1		
25						1		
26						1		
27				1	1			
28						1		
29					1	1		
30			1			1		
31						1		
32	1					1		
33						1		
34						1		
35					1	1	1	
36								
37						1		
38						1		
39			1			1		
40						1		
41						1		
42								1
43			1			1	1	1
44								
45				1		1	1	
46								
47		1	1			1	1	1
48								1
49								
50								
51					1		1	
52								1
53								1
54					1			1

55			1	
56			1	
57			1	1
58			1	1
59				1
60			1	
61				
62				1
63			1	
64			1	1
65			1	
66			1	1
67		1	1	
68		1	1	
69			1	
70	1			1
71				
72			1	1
73			1	
74			1	
75				1
76			1	
77		1	1	
78				
79				
80			1	1
81			1	
82			1	1
83			1	
84			1	
85				1

86					1	1
87				1	1	
88					1	1
89					1	
90					1	1
91					1	1
92	1				1	1
93					1	
94						
95			1		1	
96						
97						
98		1	1		1	1
99						
100						

Appendix M   Raw Vegetation Data – Understory Species pt. 2

Family	Bindweed	Grasses	Rose		Purslane	Cabbage	Mint	Loosestrife	Horsetail	Legumes		Dogbane	Moonseed	Grape	Carrot	Buttercup	Bindweed
ID	Hedge Bindweed	Common Reed	Wild strawberry	Silverweed	Purslane	Garlic Mustard	Wild mint	Purple loosestrife	Scouring Rush	White sweet clover	Cow vetch	Swamp milkweed	Canada moonseed	Virginia creeper	Wild carrot	Buttercup	Morning Glory
Latin name	Calystegia sepium	Phragmites australis	Fragaria virginiana	Argentina anserina	Portulaca oleracea	Alliaria petiolata	Mentha arvensis	Lythrum salicaria	Equisetum hyemale	Melilotus albus	Vicia cracca	Asclepias incarnata	Menispermum canadense	Parthenocissus quinquefolia	Daucus carota	Ranunculaceae spp.	Malva sylvestris
1		1															
2		1					1				1						
3		1															
4		1															
5									1		1						
6											1						
7									1					1			
8	1												1				
9									1								1
10									1								1
11									1								
12									1		1						
13									1		1						
14									1								
15			1						1								
16							1		1				1				

17							1							
18							1							
19			1				1		1					
20	1						1							
21							1							
22							1							
23														
24			1					1						
25							1							
26							1							
27	1	1								1	1			
28		1				1	1		1					
29						1	1		1			1		
30	1		1					1		1				
31			1					1					1	1
32							1							
33						1	1		1					
34							1							
35		1	1	1						1				
36		1				1	1							
37						1	1							
38						1	1							
39	1					1	1		1					
40						1	1							
41														
42														
43					1									
44														
45														
46						1								
47														

48					
49					
50					
51	1				
52					
53					
54					
55					
56	1				
57					
58					
59					
60					
61					
62					
63					
64					
65	1	1	1	1	
66					
67					
68					
69					
70					1
71	1				
72					
73					
74					
75					
76					
77					
78	1				

79		
80		
81		
82		
83		
84	1	
85		
86	1	
87		
88		
89		
90	1	
91	1	
92	1	
93	1	
94		
95	1	
96	1	
97	1	1
98		
99	1	1
100	1	1

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