

# Identifying Temporal Trends and Mechanisms for Successful Reforestation on Former Agricultural Land

A Case Study in Norfolk County, Ontario

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# Approval

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## **Abstract**

This study investigates the outcomes of restoration efforts completed on retired agricultural land in Southwest Ontario. Sites acquired by the Nature Conservancy of Canada were planted to kickstart succession to native deciduous forests, but the results of the plantings are mixed. Analysis of soil conditions indicated that low levels of soil organic carbon were correlated to low water content and high density unfavourable for plant growth. Analysis of remotely sensed imagery was done to assess and compare vegetation cover to reference conditions at Walpole Island First Nation. Analysis revealed that successful restoration was dependent on multiple soil characteristics, but conditions correlated to higher total organic carbon favoured greater vegetation cover. Remote sensing data revealed that succession towards tree canopy development was accelerated compared to passive restoration, and a shaded understory was established approximately 8-12 years following restoration. Future work can expand on succession and the effects of other restoration treatments.

**Keywords:** Secondary Succession; Soil; Reforestation; NDVI; Agriculture; Restoration

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During a field course at Walpole Island First Nation, I was introduced to Clint Jacobs and Torey Day who were members of the Walpole Island Heritage Committee. After approaching Clint with my project idea, he identified two sites that would be suitable to determine reference conditions, and Torey took me to those sites to collect samples. In all the time I've spent in Southwest Ontario I've never seen ecosystems like those I was fortunate enough to study at Walpole Island, and Torey opened my eyes to cultural connections with the landscape that I was studying. I would like to extend my sincerest thanks to Torey, Clint, and the rest of the community for the opportunity to learn from the unceded traditional territory of the Bkejwanong First Nation.

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## **List of Acronyms**

ARD: Analysis Ready Data

GPS: Global Positioning System

NCC: Nature Conservancy of Canada

NDVI: Normalized Difference Vegetation Index

UR: Unrestored Sites

WP: Walpole Island (Reference Sites)

## **Chapter 1: Introduction and Background**

Evaluating the results of restoration efforts on former agricultural land in Norfolk County, Ontario is a key step towards the long term and large-scale success of a Carolinian ecosystem in Southwest Ontario. This ecosystem is characterized by unique deciduous forest, meadow and prairies, which each host rare and endangered species. However, only a small portion of these ecosystems remain making them priority for restoration efforts.

The Nature Conservancy of Canada (NCC) has played a fundamental role in restoring of these ecosystems. The efforts so far have led to variable success and understanding the mechanisms behind these results will contribute to more effective future restoration. This project assesses the state of restored agricultural lands to determine the feasibility and time required to return retired farms to an ecosystem state representative of pre-development conditions. This will inform decisions in holistic management of crop and pasture lands, as well improve restoration methods of the Carolinian ecosystem.

The following sections provide an overview of the restoration strategies implemented by NCC in the area, the ecological characteristics of the Carolinian Ecosystem and conclude with the goal and objectives proposed for this research.

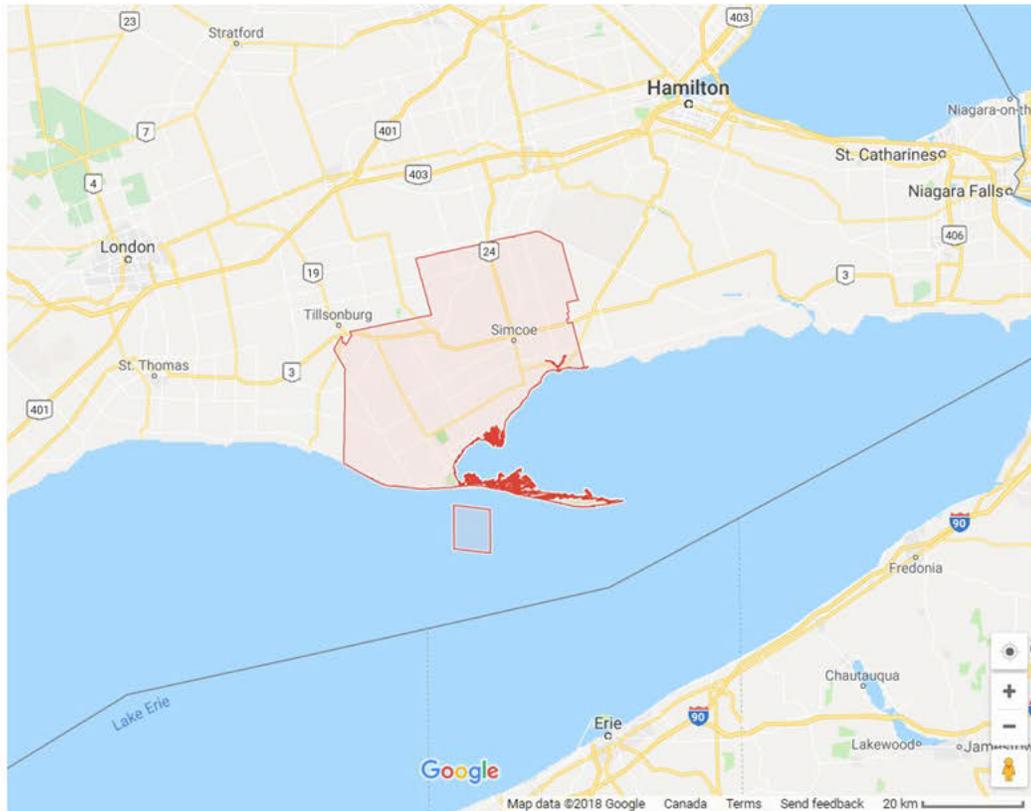
### **1.1 Nature Conservancy of Canada Restoration Strategies in Norfolk County**

Over the last 21 years, the NCC has been acquiring and restoring agricultural land in Norfolk County, Ontario (Figure 1). These restoration efforts have involved seeding a mix of native grasses, perennial herbs and trees to direct and fast-track the succession of these old fields into functional ecosystems representative of the Carolinian ecozone found in Southwest Ontario. It is the objective that these restoration efforts will accelerate the progress of unassisted colonization by local native plant species. This work is similar to other efforts that have been made to use active restoration to accelerate the path of succession using species typical of later successional stages, such as trees (Benayas et al., 2008). Since site conditions can be highly variable across agricultural landscapes, passive restoration can lead to multiple alternative stable states (Keever 1983). On these agricultural landscapes, soil compaction results in increased runoff and erosion, resulting in a positive feedback loop in which plant colonization is inhibited by dry conditions (Suding et al., 2004). It is therefore possible that soil conditions that exist as a legacy of the agricultural history will not be conducive to supporting a desirable native ecosystem and could therefore benefit from intervention. Evaluation of these

restoration efforts and a comparison to soil and vegetation characteristics observed in unassisted secondary succession remains unquantified.

Once acquired by the NCC, fields that are designated for restoration receive spot treatment of herbicides to remove known invasive species and are tilled prior to seeding. Seed mixes mainly consisted of a variety of native herbaceous species including goldenrods (*Solidago spp.*), asters (*Aster spp.*), meadow grasses, and woody species such as sumac (*Rhus spp.*) and oak (*Quercus spp.*). While there may be some variation in diversity and abundance of seed species, the mixes used for restoration in Norfolk County are largely similar and represent a diverse range of species found in Carolinian ecosystems. In many cases these fields previously included clay tiles to aid drainage for farming. Wherever possible these tiles were removed prior to restoration, but there is a chance that some tiles were missed.

The annual restoration of retired agricultural land presents the opportunity to study the temporal trends associated with the restoration efforts in a space-for-time substitution. Rather than observing individual sites for many years, multiple sites restored over several years can display different stages of growth simultaneously. With many fields in various stages of regrowth, landscape level sampling efforts can be deployed to assess the current characteristics. This space for time substitution assumes that field conditions at the time of restoration are the same across all sites, and that restoration methods were consistent across all sites and years. Results from this work uses site-specific information to develop a thorough understanding of spatial and temporal soil and floral characteristics and variability.



**Figure 1:** Norfolk County (highlighted red) on the North shore of Lake Erie, Ontario, Canada (Google Maps, 2018).

## 1.2 Norfolk County Ecological Description

Norfolk County is a particularly valuable target for ecological restoration because of its unique context on the Canadian landscape. Despite intense agriculture and high population density, Ontario’s Carolinian ecozone is the most biologically diverse in Canada and hosts 125 species (59 plants, 66 wildlife) that are of special concern or greater at the federal or provincial level (Carolinian Canada 2004a). Within this ecozone, Norfolk County has the greatest forest cover in Southwest Ontario, maintains significant natural connectivity on a landscape scale, and contains a variety of ecosystems representative of the broader ecozone (NCC 2018). It is therefore a priority for further restoration efforts to reduce habitat fragmentation and improve habitat quality across the wide variety of ecosystems found in this ecozone.

Deciduous forest historically dominated the Southern Ontario landscape prior to the rise of large-scale agriculture (Carolinian Canada 2004b). These forests were unique in their Canadian context, and their restoration is a priority for restoration efforts by the NCC (NCC 2018). Approximately 70 species of trees are known to occur in Ontario’s Carolinian forests, as well as roughly 2200 species of herbaceous plants (Carolinian Canada 2004a). Southwest Ontario’s

highly diverse and productive landscape, also known as the “Banana Belt,” was a major draw for farmers and ranchers who saw great potential in the rich soils, flat landscape and proximity to major shipping hubs such as Hamilton (Unterman-McPhail 2007).

### **1.3 Intensive Agriculture and Impact on Ecological Health**

The arrival of industrialized agriculture along with urban development across the landscape led to the demise of a vast majority of the natural landscape beginning in the late 1700's (Unterman-McPhail 2007). Logging of pine and oak forests from 1790 to 1880 reduced the deciduous forest land cover from 80% to about 11% in the Carolinian ecosystem of Southwest Ontario (Carolinian Canada 2004b). By 1880, agriculture, particularly wheat, corn and oats, had taken over as the primary industry in the region (Unterman-McPhail 2007). Tobacco, fruit orchards and ginseng later became the dominant crops. In addition to the loss of forests in the region, wetlands were reduced from 28% of land cover to 3%, while tallgrass prairie and savannah ecosystems have been reduced to 3% of their original extent (Carolinian Canada 2004c).

In addition to this habitat loss, conventional western agriculture has led to soil degradation through nutrient depletion (Tan et al., 2005), reduced capacity for moisture retention (Bot & Benites 2005), and soil erosion (Montgomery 2007). The impact of unsustainable agriculture can be observed across the landscape, as large river networks carry fertilizer and sediment runoff downstream to Lake Erie where algal blooms are common and increasing in severity (Michalak et al., 2013). On land, environmental and socioeconomic factors have led to many farms going out of business following the collapse of various crop industries such as tobacco (Ramsey et al., 2003). Once farmland ceases to produce food or other crops, it no longer has economic or social value. Additionally, the environmental value decreases significantly since much of this derelict land is left abandoned which often enables invasive/weedy species to establish, preventing the reestablishment of natural ecosystems (Cramer et al., 2008). Instead, action must be taken to repurpose this land. Options for alternative land use in these areas include restoration of the natural ecosystems and associated services, regenerative agriculture which can rekindle the productivity of the land, or a combination of the two in the form of holistic management. These methods, particularly restoration, could enable the return of natural ecosystem residents and processes while simultaneously sequestering atmospheric carbon dioxide on a large scale (Spiesman et al., 2017; Johnston et al., 1996).

## **1.4 Restoration of Agricultural Land through Old Field Succession**

Old field succession, or secondary succession, describes the transitional process from bare or near bare soil following a disturbance to a mature ecosystem (Keever 1950). In Southern Ontario and the Northeastern United States, secondary succession generally follows a pathway from open meadows to deciduous forests representative of the Carolinian ecozone (Vankat & Carson, 1991). For this transition to occur, local species pools from the surrounding region must colonize the site. From there, site conditions and climate dictate the rate and success of this colonization (Fridley & Wright 2012). Over time, herbaceous species that are typically dominant early on are gradually outcompeted by woody species. The rate of this takeover varies considerably, but herbaceous communities can dominant old fields for 50 or more years in the Northeast USA (Mellinger & McNaughton 1975).

In denuded land or bare rock, primary succession drives community changes. As soil develops through physical and chemical erosion, pioneer species begin to colonize. In primary succession, community composition is driven by the resource ratio hypothesis (Tilman 1985). During the early establishment of plant communities, these pioneer species can capitalize on limited soil nutrients. However, over time these plants facilitate the arrival of others, and are eventually outcompeted. As these sites age, the development of a canopy and the shading effect it has on the understory is the main driver of competition.

Secondary succession follows a similar trajectory, but the early growth may not be exclusive to conventional early successional species due to the persistence of 'late successional' species through the disturbance (Blatt et al., 2005) and the immediate availability of soil nutrients. Inouye et al. (1987) observed that many herbaceous species had already colonized abandoned sandy fields in Minnesota when they began studying them approximately 10 years after abandonment. The percent cover of these herbaceous species changed little as time went on. This may indicate that soil nutrients were not a limiting factor early on, but instead they were eventually limited by competition after reaching their near maximum percent cover in the first 10 years. In contrast, the authors did not observe any trees or sedges until approximately 15 years after abandonment, after which their cover increased significantly. In this case, species establishment may have been limited by the absence of necessary conditions created by the early community, physical or chemical properties of the soil, or the rate of colonization from the local species pool was slow. Fridley and Wright (2012) noted that nearby species and soil properties are more significant drivers of woody species establishment than climate, supporting

the theory that the rate of succession towards a woody community can be highly variable if nearby species are able to colonize quickly.

### **1.5 Accelerating Old Field Succession**

Instead of waiting for the local species pool to colonize an abandoned field, or in cases where there is no local species pool, planting the desired species may lead to the establishment of the desired community (Benayas et al., 2008). In this project I describe this as accelerated old field succession or accelerated secondary succession. Unlike primary succession, pioneer species may not be necessary to create the soil conditions that later-stage communities require since the right conditions may exist as a relic from the site prior to disturbance. However, it is also possible that the disturbance created conditions that are not suitable for the late successional community. In the case of intensive agriculture, the depletion of soil nutrients and organic material may hinder the success of planted species (Suding et al., 2004). In restrictive soils such as this, time since abandonment plays a very minor role in determining community variability but is instead controlled by soil conditions (Martínez-Duro et al., 2010). Many sites in Norfolk County have been planted to accelerate the secondary succession towards a deciduous forest. Once planted, the local species pool and their ability to colonize matters little in the short-term establishment of a plant community. However, with variable success in the regrowth among sites, analysis of the soil conditions and quantification of the percent vegetation cover may indicate which variables are facilitating successful restoration. By measuring change in vegetation cover on restored sites, the rate and quality of restoration can be compared and potentially attributed to soil conditions.

### **1.6 Research Goal and Objectives**

This project assesses the state of restored agricultural lands in the Norfolk County to determine the soil conditions and time required to return retired farms to an ecosystem state representative of pre-development conditions. This will inform decisions in holistic management of crop and pasture lands, as well improve restoration methods of the Carolinian ecosystem. This goal will be achieved through three primary objectives:

1. Determine changes in soil characteristics following restoration.
2. Assess changes of vegetation cover over time on restored sites using remote sensing methods.
3. Identify timelines and mechanisms driving success of restored sites based on observed characteristics.

## **Chapter 2: Selected Soil and Vegetation Parameters to Monitor Restoration Success**

### **2.1 Indicators of Soil Conditions**

Several variables are considered when assessing the state of healthy, restored and degraded soils. Assessment of these variables across multiple ecosystem states ranging from degraded to intact enables assessment of restoration effectiveness. Additionally, this information informs predictions of temporal changes in soil characteristics beyond the scope of this assessment. Soil pH, bulk density moisture, and particle size distribution were all measured because of their influence on plant growth. In contrast, total organic carbon is largely a product of plant growth, added to the soil through photosynthesis (Hungate et al., 1997). Although plant growth is necessary to add organic matter to the soil, existing organic carbon that is present as a result of the natural or industrial history of the site may also play a role in fostering conditions that facilitate further growth (Loveland & Webb, 2003). In addition to their contribution to abiotic and biotic soil qualities, the following soil and vegetation parameters were included in this ARP due to available analytical and resource capabilities.

#### **2.1.1 Particle Size Distribution**

The range of particles that make up the soil structure dictate the space in which roots can grow, water and air can fill, and how easily organisms can move (Dexter, 2003). Different proportions of sand, silt and clay in the soil have different water retention and infiltration rates. Particle size distribution also has a large influence on soil structure, in which primary sand, silt and clay particles are held together by moisture and organic material (Díaz-Zorita et al., 2002). Erosion associated with tillage on agricultural land results in the loss of fine particles and organic matter (Ruiz-Colmenero et al., 2013), but organic matter on and in the soil help stabilize the material, reducing erosion and increasing soil organic carbon.

#### **2.1.2 Bulk Density**

A common side effect of intensive agriculture and especially livestock is soil compaction (Savory & Butterfield, 2016). Poorly managed livestock can spend too much time in one location on a pasture, which results in dense, compact soil in that area. On cropland, shallow roots common among most cash crops do little to penetrate and break up the soil, while heavy machinery compacts it further. This compaction can initiate a positive feedback loop; where water cannot penetrate the soil, more runoff occurs and with it increased erosion of the

remaining loose soil material (Suding et al., 2004). The result is an impermeable surface layer and minimal open space below the surface for water to occupy.

To combat this problem on retired agricultural land, the NCC tilled the topsoil using a tiller behind a tractor to reduce surface compaction before planting. The seed mix would then have a greater likelihood of successful propagation, and the healthy roots would continue the work of reducing soil compaction.

### **2.1.3 Soil Water Content**

Soil water content and the ability to retain moisture is critical for soil health. Plant communities can tolerate some degree of variability in water content but will experience water stress when exposed to too much or too little water (Rezaei et al., 2016). Healthy soil in the terrestrial ecosystems of the Carolinian ecozone need adequate moisture to support plant growth but also effective drainage to prevent oversaturation. On agricultural land, the organic layer has often been removed from the soil surface, and with it the protection it provides to the soil surface (Savory & Butterfield, 2016). Exposed soil will lose moisture to evaporation much more rapidly than soil that has a protective organic layer, resulting in increased runoff and compaction (Mitchell et al., 2012). It is therefore essential that soil water content is monitored on restored sites, as it could likely be an inhibiting factor in plant growth.

### **2.1.4 Soil pH**

Soil pH alters plants' ability to uptake nutrients (Gazey, 2018). The loss of organic matter combined with the addition of fertilizers can change soil pH over time (USDA, 1998). If changes in soil pH are large enough, plant growth can be inhibited. Soil pH is considered a fundamental indicator of soil health because it changes biological, physical and chemical processes (Gazey, 2018). A neutral pH from 5.5 to 8 is optimal for plant growth, while lower values indicate acidic conditions that lead to nutrient deficiencies and high values indicating alkalinity result in salt accumulation (Havlin et al., 1999)

### **2.1.5 Total Organic Carbon**

Different land use and land cover types result in various rates of carbon sequestration in soil (Guo & Gifford, 2002). Plants, through photosynthesis, pull carbon dioxide from the atmosphere. Oxygen is expelled through respiration, while the carbon is converted into tissue in the various parts of the plant (Johnson, 2016). This plant material at the base of the trophic pyramid supports all other life through upwards energy flow; more biomass at the bottom supports more biomass at the top (Savory & Butterfield 2016). Other studies on secondary

succession have indicated that total soil organic content increases very slowly, on the order of decades or centuries, and is therefore not a strong predictor for field age (Inouye et al., 1987; Dormaar et al., 1990). Because of this slow rate of change, it is reasonable to conclude that soil carbon measured within 25 years of the start of the study window is similar initial soil carbon levels (Blatt et al., 2005). In the case of this study, the 12-year sample window is not likely to experience any noticeable changes in total organic carbon following restoration, so total organic carbon measured in soil analysis is assumed to be similar to pre-restoration values.

## **2.2 Indicators of Aboveground Vegetation Cover**

### **2.2.1 Normalized Difference Vegetation Index**

Remote sensing techniques can be used to assess landscape level changes in biomass and productivity. The Normalized Difference Vegetation Index, or NDVI, uses the reflective characteristics of chlorophyll in plant leaf material to produce a simple ratio describing productivity (Jensen, 2016). Since chlorophyll within healthy plant material reflects near infrared (NIR) wavelengths very effectively, and simultaneously absorbs (visible) red wavelengths, they can be used to create an index representing biomass or productivity. The formula is as follows:

$$NDVI = (NIR - Red)/(NIR + Red)$$

The result is a value ranging from -1 to 1, where higher values indicates healthy, productive plant material and lower values indicate a high portion of unproductive material (Jensen, 2016). Bare soil is characterized an NDVI value of approximately 0.1, while grasslands are closer to 0.3 (NASA, 2000). Tropical forests would have NDVI values from 0.6 to 0.8. When paired with ground-truthing, NDVI can serve as a metric for biomass or percent cover of vegetation (Purevdorj et al., 2010). Additionally, change in NDVI between two dates is an indicator of productivity; an increase in NDVI relative to an earlier date implies that there is greater biomass or vegetative cover.

### **2.2.2 Vegetation Percent Cover**

While NDVI serves as a landscape level assessment tool for vegetation, local monitoring is needed to ‘ground truth’ the results, providing a practical interpretation of NDVI values in the form of biomass or percent cover. Collecting plant material within a quadrat of a constant size enables measurement of biomass per unit area, which can be correlated to NDVI values to estimate biomass or biomass changes on a landscape scale (Santin-Janin et al., 2009). Alternatively, estimating percent vegetation cover can serve a similar purpose, enabling prediction of percent vegetation cover and percent cover changes over space and time. Percent

vegetation cover can be calculated in the field through quadrat sampling, or through digital photography and analysis of standardized images (Chen et al., 2010).

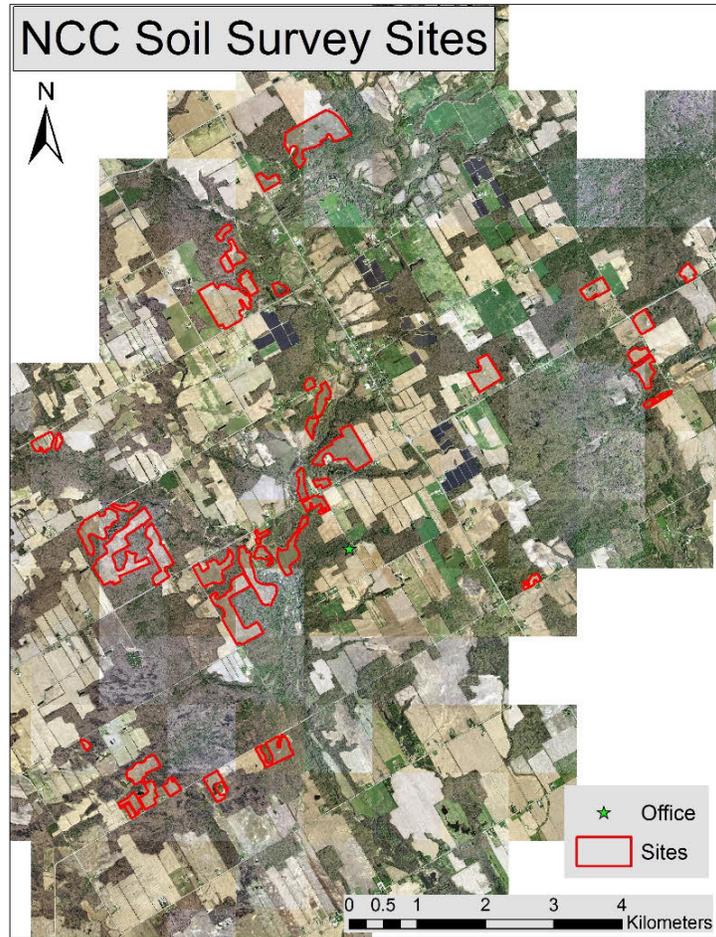
## Chapter 3: Methods

To determine how the timeline of succession occurring on NCC restored sites differs from unassisted old-field succession, all Norfolk County restored sites were identified and grouped by age after restoration. This chronosequence method would then be used to identify changes over time in soil and floral characteristics, and if/when major shifts in ecosystem states occurred.

### 3.1 Site Selection

Sites were organized based on their first year of growth following fall seeding. The number of sites (referring to the entire field as a site) was based on the number of available sites previously restored by the NCC (Figure 2). The number of years since restoration was inclusive of the sampling year, 2018. These selected years represent roughly the first decade of growth following restoration efforts. Undisturbed tallgrass prairie sites were selected for reference conditions since the early growth included grassland and meadow species typical of Carolinian prairie ecosystems. In total, 49 unique suites were studied. Year classes are as follows:

- 2014 (10 sites) – 5 years of growth
- 2013 (9 sites) – 6 years of growth
- 2012 (8 sites) – 7 years of growth
- 2011 (8 sites) – 8 years of growth
- 2007 (5 sites) – 12 years of growth
- Baseline conditions – retired but unrestored fields (7 sites)
- Reference conditions (2 sites) – undisturbed (Walpole Island First Nation meadow and tallgrass prairie)



**Figure 2:** Sample sites (in red) are scattered across the Walsingham region of Norfolk County. These sites are both unrestored and in various stages of regrowth following restoration.

## 3.2 Soil Characterization

### 3.2.1 Soil Sampling Design

To determine soil characteristics of a site, individual soil cores were collected from across the site. The number of samples per site was determined by field size, with 1 core collected per hectare, with a minimum of 5 samples and maximum of 10 per site/field. Core locations were randomly selected using the Random Points tool in ArcGIS 10.5 (ESRI, 2018), with an additional specification that samples had to be at least 50 m apart to ensure adequate coverage. Although most tiles were removed from restoration sites prior to planting, there is a chance that some tiles were missed. Due to the low probability of encountering a tiled area, the chance of sampling over a tile was an acceptable risk in this random sample design. Any

variability caused by soil cores collected over tiles is expected to be negligible in the context of the broader sample design.

To establish reference conditions, two geographically distinct sites were sampled at Walpole Island. Since Walpole Island is home to some of the only pristine tallgrass prairie left in Ontario, there were not multiple sites to choose from. The reference sites surveyed in this project were designated by the Walpole Island First Nation Heritage Committee. These sites were similar in that they hosted primarily meadow and grass species, with *Quercus* (oak) species dotted around the sites (I expect that these were black oak (*Quercus velutina*), but this is unconfirmed). Selection of these two reference sites was done to compare restored and unrestored sites to a pristine ecosystem with mature soils. Since early years following restoration efforts are expected to be more like meadow and prairie habitats than deciduous forest, these reference conditions were established to serve as a goal for restoration efforts.

Unrestored sites, used to determine baseline conditions prior to restoration, were selected at the request of the NCC. Although there are a variety of unrestored sites that are designated for restoration in the coming years, the NCC requested that these be surveyed because they were scheduled for planting in the Fall of 2018. Collecting data on these sites would then enable future surveys to be compared to site-specific baseline data.

### **3.2.2 Core Sampling**

At each site, samples were collected in a random order that minimized the walking distance between sample sites. Navigation was done using Avenza Maps (Avenza Systems, 2018), on which the randomly generated points were transferred.

Once at a sample site, the soil core was collected. The top 15 cm of the core (OMAFRA, n.d.) were separated using a finger or edge of a pen, measured in between two notches on the soil probe. The 15 cm core was then collected in a bag, while the rest was discarded. Bags used to collect and store soil samples were labelled in advance of the site visit in order to streamline the sampling process.

The sample was then thoroughly mixed by shaking the bag, and a pH reading was taken using a Field Scout SoilStik. The bag was then sealed before taking a moisture reading from the soil surface. Due to technical difficulties with the probe, the percent moisture data was not usable and discarded from the study. Percent moisture could be determined later during lab analysis. Details were recorded on the sample bag itself, as well as recorded as a GPS point along with the sample site photos (Figure 3).

Samples were stored in a cooler backpack with an ice pack while the remaining cores were collected. Following the completion of each site (field), the cores were transferred to a cooler with additional ice packs in order to maintain a temperature at or below 4°C. Although this specification is for nitrate sampling (OMAFRA, n.d.), I aimed to maintain this standard throughout the sampling. If nitrate sampling is not an objective, storage at room temperature is adequate. Samples were stored in coolers no longer than 3 days, after which they were transferred to a freezer and stored at -4°C.



**Figure 3:** Sample sites were determined randomly to reduce user bias. Once a sample was collected, the position was marked on a GPS (Avenza Systems, 2018) and the relevant information recorded.

### 3.2.3 Soil Sample Analysis

*Soil Sample Processing:* During the 6-week analysis window, samples were stored at 4°C in a walk-in fridge, and cores were analyzed in groups of approximately 30 based on limited furnace capacity. Each complete sample was weighed, and a subsample collected. Subsamples were collected to mostly fill a 1g aluminum tray, with weights ranging from 18 g to 21 g (Hoogsteen et al., 2015). Subsamples used as much of the original sample as possible to ensure the subsample was as representative as possible, without overfilling the tray. Each subsample was weighed to determine a wet weight. Subsamples were then dried at 40°C for 48 hours, after which no further weight loss was observed. The dry samples were weighed again,

and then baked for 1 hour at 400°C (Konare et al., 2010). Higher combustion temperatures could lead to combustion of inorganic carbon such as carbonates and were therefore not used.

*Soil Water Content:* Percent soil water content by mass was determined based on the difference between the wet and dry subsample temperature. Bulk density could then be determined by subtracting the percent moisture mass from the total of the original sample and dividing by the volume of the soil probe. Total organic carbon, expressed as a percent of the total mass, was determined based on the difference between the dry and baked temperatures over the original weight (Konare et al., 2010).

*Particle Size Distribution:* After processing the soil, subsamples from the same site were mixed together and sieved to determine particle size distribution on each site. Sieve sizes were selected following the international standard on soil identification and classification (ISO 2017). Sieve sizes included:

- Coarse sand and larger material (>600 µm)
- Medium sand (600-250 µm)
- Fine sand (250-63 µm)
- Fines, including silt and clay (<63 µm)

Weights of each category were recorded and determined as a percent of the total mass, based on the combined initial mass of each subsample included.

### **3.2.4 Soil Data Analysis**

Particle size distribution was first calculated to determine if all sampled fields in Norfolk County and Walpole Island exhibited similar sandy soils. Since all restored sites are within a similar geographic region dominated by post-glacial sandy soil, it is reasonable to assume that particle size distribution would be similar across all sites in Norfolk County. However, comparison of Norfolk County sites to reference sites at Walpole Island was necessary to confirm reference conditions from the unmodified ecosystem are not a product of different soils.

Analysis of soil data was completed prior to satellite image analysis to determine whether changes in soil characteristics over time could be attributed to time lapsed following restoration. While literature suggests changes in soil carbon occur slowly during herbaceous succession (Johnston et al., 1996), assessment of soil variables across restoration sites could reveal detectable changes in other variables such as bulk density or pH. In order to test for these differences, a single factor ANOVA was run for each soil variable across all year classes,

followed by post-hoc tests to identify significantly different pairs of groupings if the ANOVA revealed significant difference. Significant differences were set at  $p < 0.05$ .

Regression analyses were used to determine the relationship between soil variables, which would inform discussion on potential mechanisms behind different soil characteristics observed across restored sites. Linear regression comparing total organic carbon and bulk density was completed to determine whether organic matter was correlated to less compact soil. Linear regression comparing total organic carbon to soil water content was also completed to confirm the effect that organic material has on water retention, which is particularly important in sandy soils that typically drain quickly.

### **3.3 Changes in Vegetation Cover**

#### **3.3.1 Normalized Difference Vegetation Index (NDVI) Calculation**

LandSat Analysis Ready Data (ARD) tiles were acquired from the USGS EarthExplorer platform. Images came from the LandSat 5, 7 and 8 series depending on date and data availability. ARD tiles were selected to avoid the need for further atmospheric correction of the original images, and while this reduced the frequency of available images it was more in line with the scope of this project. Annual images were collected beginning in 2006 and up to 2018. Image dates were as close to June 15<sup>th</sup> of each year as possible, corresponding to the same time of year that the field sampling took place. All images included the complete spatial extent of the Norfolk County study area and stitching multiple images together to ensure complete coverage each year was not required. Due to a lack of cloud-free observations in spring of 2012, no data was obtained for that year.

#### **3.3.2 Digital Photograph Analysis**

Using SamplePoint software (Booth et al., 2015), digital photographs taken at each sample location from chest height were assessed to determine percent cover of vegetation. Classification was done using four distinct classes: vegetation, litter, bare soil, and unknown. For each image, 49 training pixels were manually classified into one of the four classes, from which the rest of the image pixels were assigned. No attempt was made to distinguish between different vegetation types or species in order to minimize classification uncertainty. Each of the four classes used in the analysis was visibly distinct, and the 'unknown' class used for shadows in which the true ground cover could not be identified from the image. Percent vegetation cover for an entire field was calculated as an average of the individual sample locations that each had an associated photograph.

### 3.3.3 Digital Image Processing

Red and near infrared bands 3 and 4 for Landsat 5 and 7 and bands 4 and 5 for Landsat 8 (USGS, n.d.) were selected for analysis in ArcMap 10.5 (ESRI, 2018). Using the NDVI function within the Image Analysis tool, red and infrared bands were applied to the NDVI equation, resulting in an 8-bit unsigned raster image, with discrete pixel values ranging from 0-255. Using the following equation in the Raster Calculator tool, the output 8-bit images were converted from discrete values (0-255) to float values, resulting in a 32-bit image that expressed NDVI values from 0-255 on a continuous scale.

$$32BitImage = Float(8BitImage)$$

Next, the Raster Calculator tool was used again to express the NDVI values in a scientific format from -1 to 1. The following equation was applied to reclassify the original values ranging from 0-255:

$$NDVI\ Raster = \left( \frac{32BitImage}{256} \right) * 2 - 1$$

The result was an identical 32-bit raster, with NDVI values ranging continuously between -1 and 1.

Using the Extract Values to Points tool, NDVI values were assigned to each sample location for each year, and an average annual NDVI calculated on a per-field bases using the zonal statistics tool.

Annual LandSat images spanning 12 years (2006-2018) were used in the analysis, using the images available from dates as close as possible to June 15<sup>th</sup> of each year. This date was chosen as it was when the 2018 field work took place. However, limited data or the presence of clouds resulted in a range of images from different dates. While most images were collected in June of each respective year, imagery for 2010 had a sample date of July 7<sup>th</sup>, while 2009 had a sample date of May 17<sup>th</sup>. These samples represent extreme ends of potential seasonal variability in the data because more growth is expected and detected in July compared to May. Since vegetation cover is expected to be higher as the growing season progresses, consistent image dates are important to ensure that observed vegetation cover is comparable to that of other years. However, even annual observations with the same sample date in different years are subject to seasonal variability, as year to year spring weather may fluctuate considerably and appear in the image as more or less vegetated than the previous year. In order to account for this variability, NDVI values were standardized based on their relative difference from the

NDVI values detected on unrestored sites of that same year. Unrestored sites will still exhibit seasonal variability in NDVI values, and the difference between the unrestored NDVI and the restored NDVI serves as a better indicator of relative percent vegetation cover for that year. By subtracting the average unrestored NDVI value from the NDVI value of each restored site, the amount of growth attributed to natural season variability is removed from the observation. This assigns an NDVI value of zero to unrestored sites and results an NDVI value for each restored site that has had within-season growth removed. All annual NDVI values are thus expressed as a difference from average NDVI of unrestored sites, minimizing seasonal noise and better reflecting vegetation cover as a result of restoration rather than natural variability. For example, if a restored site had an observed NDVI value of 0.35, while the unrestored sites had an NDVI value of 0.05, the unrestored value would be subtracted from that of the restored site, resulting in an NDVI value of 0.3. This removes growth attributed to natural seasonal variability that is observed on the unrestored site, giving a better representation of growth as an outcome of restoration efforts.

### **3.3.4 Vegetation Cover Data Analyses**

In order to determine the project-specific reliability of NDVI as a predictor for vegetation cover of restored sites in Norfolk County, a linear regression was used to compare NDVI values from June 2018 to the percent vegetation cover established from digital images through SamplePoint software (Booth et al., 2015). This method compared site-specific observations with remotely sensed values as a method of ground-truthing, from which percent vegetation cover of other sites can be predicted. A statistically significant linear relationship between NDVI values and observed percent vegetation cover would serve as a reliable metric to assess the changes in NDVI values of a site detected over multiple years following restoration.

Vegetation cover changes following restoration were quantified based on a 5-year difference in NDVI values, ranging from 1 year prior to restoration to 4 years after. A 5-year range was selected because it was the longest period that could be measured using satellite images across all restoration dates from 2007 (oldest restored site) to 2014 (newest restored site). For example, increase in vegetation cover on sites restored in 2007 would be calculated as the difference in NDVI values from 2006 to 2011, representing the range from one year before restoration to 4 years after. Sites restored in 2014 would be measured as the NDVI difference from 2013 to 2018. Because data was not available for 2012, relative change in NDVI for sites restored in 2013 were calculated based on the difference in NDVI values from 2011 to

2017. This is not expected to change the outcome significantly, since NDVI values of sites prior to restoration exhibited minimal variability across years.

Lastly, in order to determine if soil characteristics, specifically total organic carbon (as a measure of soil organic matter) was correlated to the increase in vegetation cover following restoration, a linear regression comparing total organic carbon with 5-year NDVI change as well as an ANOVA were performed on 5-year change in NDVI values grouped by total organic carbon. Total organic carbon group ranges included 1-2%, 2-3% and greater than 3% based on the observed normal distribution of the data.

## Chapter 4: Results

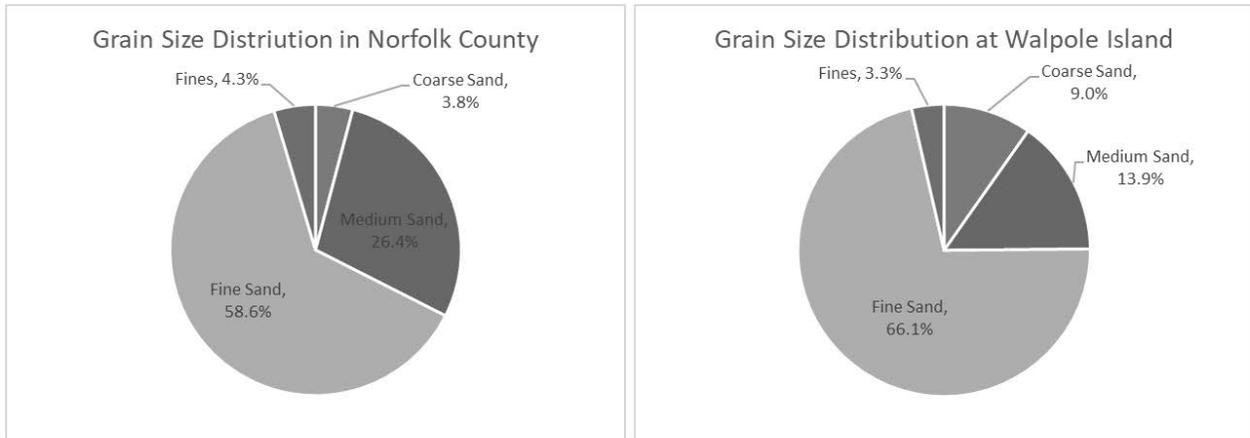
### 4.1 Soil Characteristics

All results are presented with  $\pm$  one standard deviation.

#### 4.1.1 Particle Size Distribution

Soil in the Norfolk County study area is sandy, with fine sand (250-63  $\mu$ m) accounting for an average of  $58.6 \pm 10.4\%$  of the material. Fines, which are less than 63  $\mu$ m and include silt and clay, account for only  $4.3 \pm 2.8\%$  of the material compared to coarse, medium and fine sand (Figure 4a).

The two sites at Walpole Island had a similar content of fines, averaging  $3.3 \pm 0.25\%$ . Fine sand was the dominant material at  $66.1 \pm 4.6\%$ , while coarse and medium sands accounted for roughly a quarter of the material (Figure 4b).



**Figure 4:** Particle size distribution for Norfolk County on the left (a) shows a similar soil structure to that of Walpole Island on the right (b).

Both sites thus have sandy soils, which is resistant to compaction and allows for generally unimpeded root growth (Moody & Cong, 2008). However, the large particle sizes result in a high rate of water infiltration which leaves less water available for plant roots near the surface.

#### 4.1.2 Bulk Density

Bulk density ranged from  $0.69 \text{ g/cm}^3$  to  $1.66 \text{ g/cm}^3$ . Across all sites the average bulk density was  $1.22 \pm 0.08 \text{ g/cm}^3$ . Unrestored and restored sites had bulk density values averaging from  $1.2$  to  $1.27 \text{ g/cm}^3$ , while the reference sites at Walpole Island were lower with an average of  $0.94 \text{ g/cm}^3$  (Table 1). An ANOVA comparing bulk density across year classes indicated a

significant difference between the reference sites at Walpole Island and the restored and unrestored sites in Norfolk County ( $F=15.576$ ,  $p<0.0001$ ). No significant differences were detected between any of the restored year classes, or between the restored sites and unrestored sites.

**Table 1:** Mean values for soil properties for each site class (Restoration Year, UR-Unrestored, WP-Walpole Island). Values are displayed with  $\pm$  one standard deviation. N = 48.

Soil Properties	Site Class						
	2007	2011	2012	2013	2014	UR	WP
<b>Bulk Density</b> (g/cm <sup>3</sup> )	1.196 $\pm$ 0.095	1.249 $\pm$ 0.079	1.236 $\pm$ 0.071	1.218 $\pm$ 0.083	1.203 $\pm$ 0.071	1.267 $\pm$ 0.078	0.935 $\pm$ 0.091
<b>pH</b>	6.05 $\pm$ 0.34	6.16 $\pm$ 0.35	6.25 $\pm$ 0.38	6.30 $\pm$ 0.33	5.78 $\pm$ 0.34	5.85 $\pm$ 0.31	6.30 $\pm$ 0.36
<b>Water Content (%)</b>	5.67 $\pm$ 3.01	6.06 $\pm$ 2.28	7.71 $\pm$ 2.09	12.07 $\pm$ 4.88	6.92 $\pm$ 2.74	10.03 $\pm$ 1.96	17.49 $\pm$ 7.02
<b>TOC (%)</b>	2.31 $\pm$ 0.63	2.25 $\pm$ 0.68	2.45 $\pm$ 0.53	3.53 $\pm$ 1.15	2.46 $\pm$ 0.66	2.70 $\pm$ 0.68	7.53 $\pm$ 1.91

#### 4.1.3 Soil pH

Soil pH ranged from 4.38 to 7.33, with an average across all sites of  $6.07 \pm 0.49$ . An ANOVA revealed no significant differences between restored sites, reference sites and unrestored sites ( $F=1.459$ ,  $p=0.216$ ). Unrestored fields and those planted in 2014 had a pH less than 6 and therefore in the range of non-ideal conditions (Table 1).

#### 4.1.4 Soil Water Content

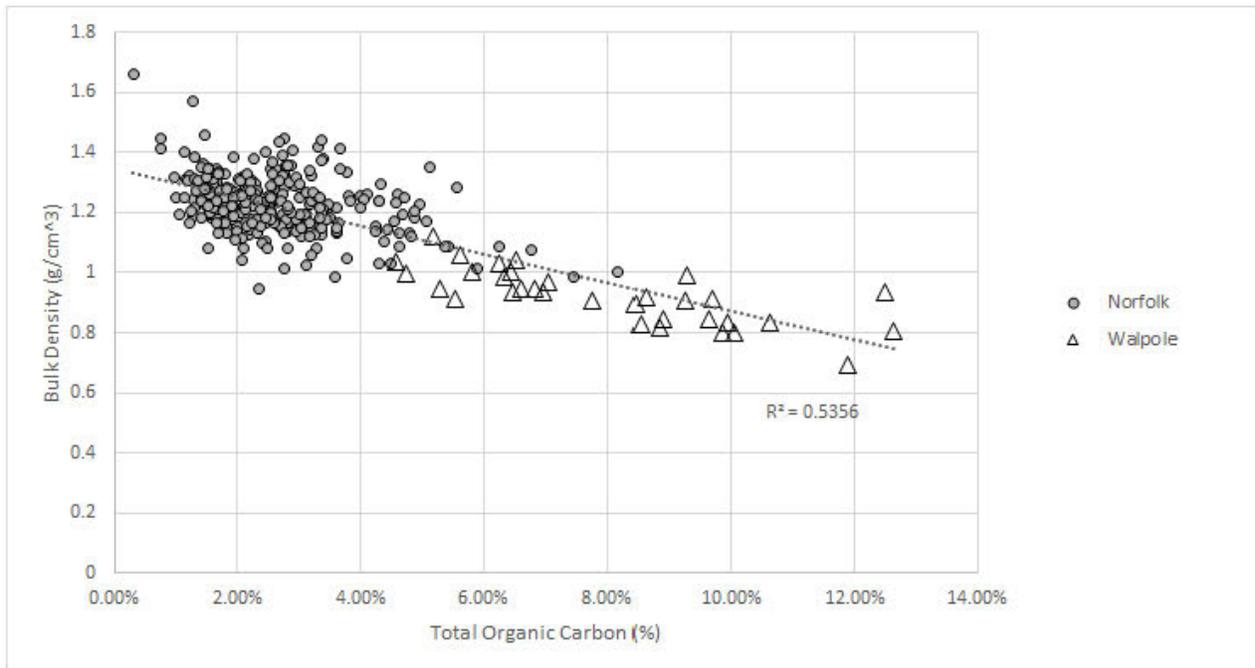
Soil water content was highly variable both within and between year classes (Table 1). While an ANOVA indicated significant differences between year classes ( $F=8.486$ ,  $p<0.0001$ ), there is no apparent trend in the data which would suggest time since restoration influences water content. Across all sites soil water content averaged  $8.62 \pm 3.96\%$ .

#### **4.1.5 Total Organic Carbon**

Across unrestored and restored sites, total organic carbon averaged  $2.62 \pm 0.80\%$ . In contrast, the sites at Walpole Island averaged  $7.53 \pm 0.29\%$  (Table 1). Once again, there was no indication that time since restoration resulted in increased total organic carbon, but significant difference between year classes were detected ( $F=16.386$ ,  $p > 0.0001$ ). Post hoc testing indicated that the reference sites at Walpole Island (WP) had significantly higher total organic carbon compared to all restored and unrestored sites, and sites restored in 2013 showed significantly higher total organic carbon than those restored in 2011. Besides the significant difference between sites restored in 2013 and 2011, no significant differences were detected among restored sites or between restored and unrestored sites.

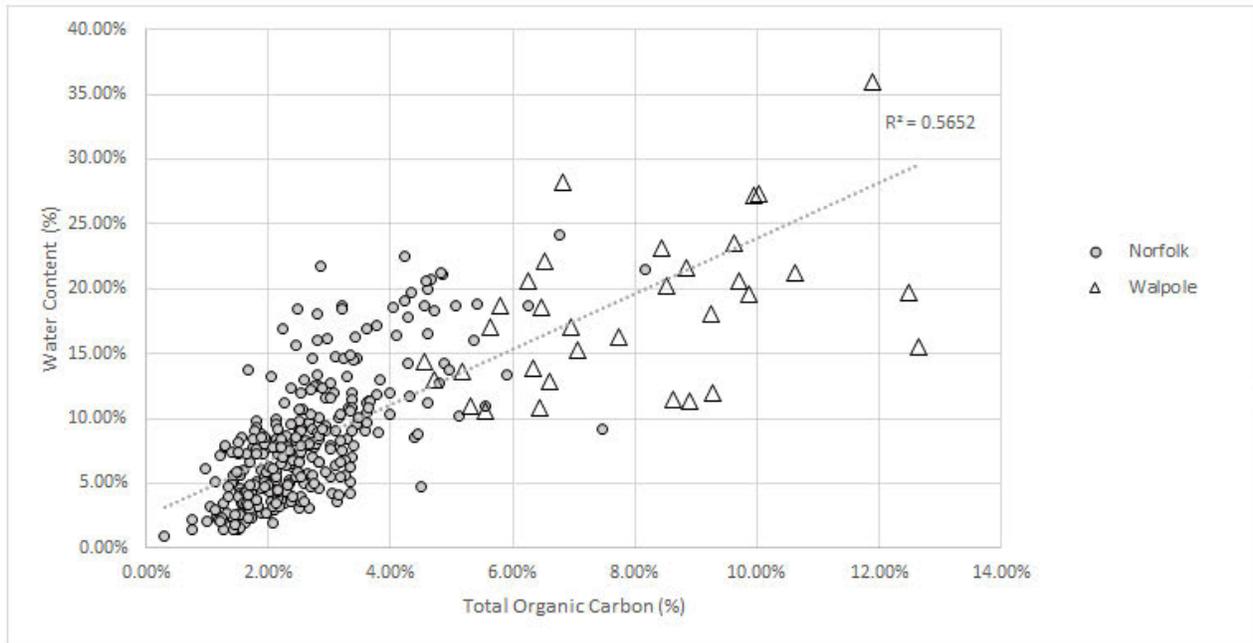
#### **4.1.6 Correlations between Soil Variables**

In order to understand the mechanisms enabling successful revegetation following restoration, correlations between soil variables were explored. Regression analysis comparing soil bulk density to total organic carbon was done to determine whether increased organic content in the soil was correlated with reduced density which would enable better root growth. The regression was done on all individual samples in the study in order to include extreme bulk density values that would otherwise get masked in site-based averages. The regression analysis revealed a significant negative correlation between total organic carbon and bulk density ( $R^2=0.54$ ,  $p < 0.0001$ ), indicating that low values of organic carbon in the soil are correlated to higher values of bulk density (Figure 5).



**Figure 5:** Total organic carbon showed a significant negative correlation with bulk density ( $R^2=0.54$ ,  $p \Rightarrow 0.0001$ ). All sample core data ( $N=345$ ) were used to explore this relationship so extreme high and low values were not masked by average total organic carbon and bulk density values of each site.

Another key relationship between soil properties that could impact vegetation growth following restoration is between total organic carbon and water content. Regression analysis between these two variables on restored sites was completed to determine whether organic content in the soil enabled a greater amount of water content to be retained. The regression revealed a positive correlation between the two variables ( $R^2=0.57$ ,  $p < 0.0001$ ), suggesting that higher total organic carbon in the soil could retain a greater amount of water as a portion of the total mass of the soil (Figure 6).



**Figure 6:** Across all restored, unrestored and reference sites, total organic carbon was positively correlated to soil water content ( $R^2=0.57$ ,  $p>0.0001$ ,  $N=345$ ).

## 4.2 Changes in Vegetation Cover

### 4.2.1 Normalized Difference Vegetation Index (NDVI)

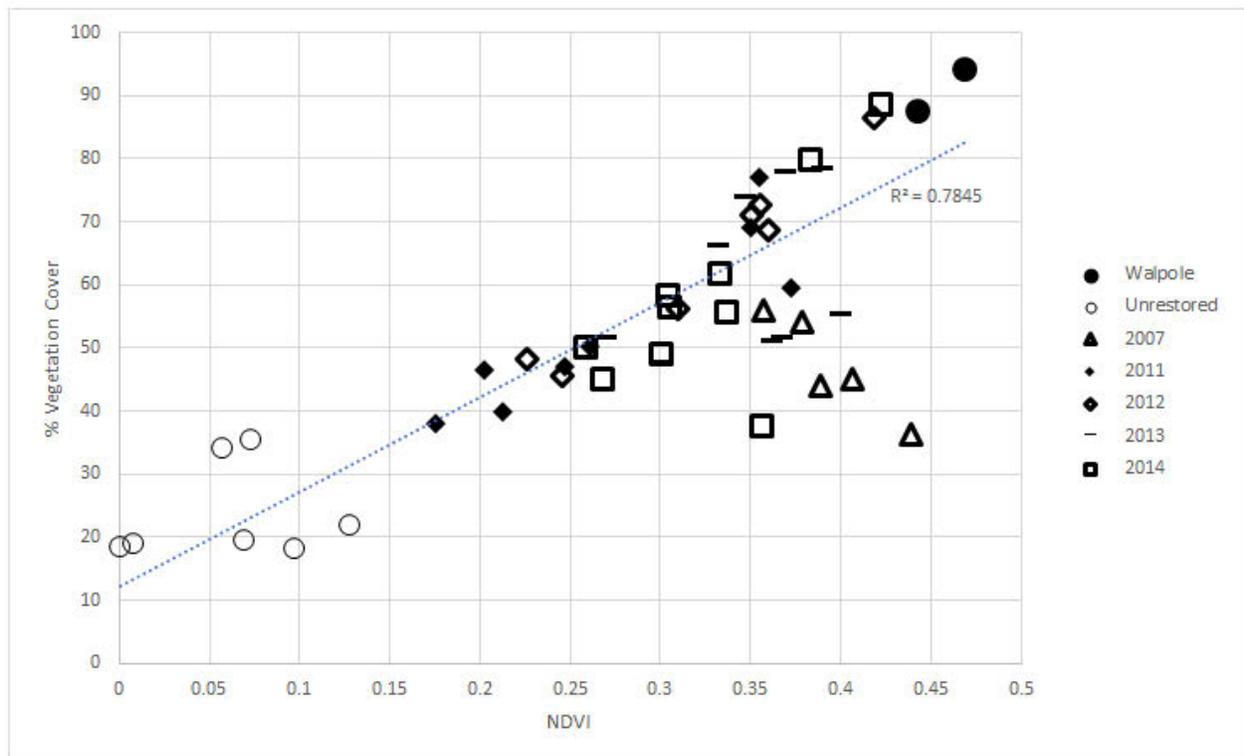
To determine temporal trends in vegetation cover following restoration, the 5-year change in NDVI was calculated, ranging from 1 year prior to restoration to 4 years post-restoration. Prior to restoration, unrestored fields exhibited an average NDVI value of  $0.098 \pm 0.14$ . To reduce the effect of seasonal variation in observed vegetation cover, NDVI values were calculated as a difference from the average NDVI value of unrestored sites for that year. Among restored sites, the 5-year change in NDVI ranged from -0.03 to 0.35, with an average 5-year change of  $0.199 \pm 0.09$ . In this case a negative minimum value suggests a net decrease in NDVI 4 years after restoration. An ANOVA of restored sites indicated that there was a significant difference detected between 5-year NDVI change group by year class ( $F=5.928$ ,  $p=0.001$ ), but a post hoc test indicated that the only significant difference was between sites restored in 2013 and 2014. No other significant differences in 5-year NDVI change were detected between year classes.

### 4.2.2 Correlations between Aboveground Vegetation Indicators

Vegetation percent cover results based on field photographs showed that unrestored sites had an average percent vegetation cover of  $23.54 \pm 7.65\%$ , while restored sites had an average percent vegetation cover of  $57.64 \pm 14.04\%$ . A linear regression showed no statistically

significant relationship between time since restoration and vegetation cover as measured in 2018 ( $R^2=0.09$ ,  $p=0.069$ ). In contrast, reference sites at Walpole Island had an average vegetation cover of  $90.67 \pm 4.80\%$ .

In order to interpret the NDVI values, a linear regression was completed comparing NDVI from June 2018 to percent cover data from digital photographs collected during field sampling. The linear regression showed a strong relationship between NDVI and percent cover ( $R^2=0.62$ ,  $p<0.0001$ ,  $N=49$ ). Higher NDVI values correlate to greater vegetation cover (Figure 7). There is a noticeable bifurcation in the data which can be mainly attributed to sites restored in 2007, as indicated by the hollow triangles in Figure 7. By performing another linear regression comparing NDVI to % cover but excluding the 2007 sites (Figure 7), the relationship between the two variables is improved ( $R^2=0.78$ ,  $p<0.0001$ ,  $N=44$ , 2007 sites excluded). Interpretation of Figure 7 shows that percent vegetation cover increases by approximately 15% for every 0.1 increase in NDVI.



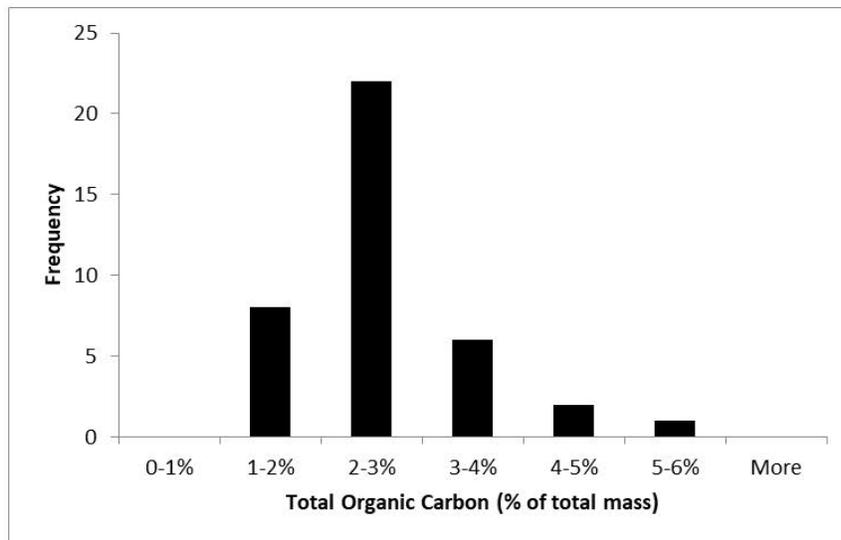
**Figure 7:** Comparing 2018 NDVI values to vegetation cover as observed in the field produced a linear regression that indicates a strong relationship between NDVI and % cover ( $R^2=0.78$ ,  $p<0.0001$ ,  $N=44$ , 2007 sites excluded). The five 2007 sites, indicated by hollow triangles, are excluded from the linear regression due to the presence of a young tree canopy that shades the

understory. These sites were excluded from the regression because the presence of a canopy alters the nature of the relationship between NDVI and % vegetation cover, however, they are included in the figure to show all collected data.

### 4.3 Relationship among Aboveground Vegetation Indicators and Soil Variables

With a statistically significant correlation between NDVI and % vegetation cover, change in vegetation cover could be quantified based on the observed 5-year change in NDVI among restored sites. Earlier analysis has shown that variables which contribute to plant growth, moisture and bulk density, are correlated to total organic carbon in the soil. The last step was to determine if total organic carbon could serve as a reliable predictor for vegetation growth following restoration.

A linear regression comparing total organic carbon to 5-year change in NDVI indicated a significant relationship between the variables, but also suggested that total organic carbon explains only a small portion of the total variability in 5-year growth ( $R^2=0.12$ ,  $p=0.028$ ). After grouping 5-year growth values based on their total organic carbon in 1% intervals, an ANOVA was run to determine if more total organic carbon in the soil was associated with greater observed changes in vegetation cover. Groupings for the ANOVA comparing 5-year NDVI change were based on the frequency distribution of total organic carbon values on restored sites (Figure 8). Groups included 1-2%, 2-3%, and greater than 3% TOC. Soils with total organic carbon values of 4% or greater were grouped in the '>3%' category to avoid small group sizes.



**Figure 8:** Frequency distribution of 5-year NDVI change values when grouped by total organic content. N=39, which includes all restored sites and excludes unrestored and reference sites.

The ANOVA indicated that there is a significant difference in 5-year growth based on the total organic content in the soil ( $F=3.96$ ,  $p=0.028$ ). A post hoc test revealed that there was no significant difference in 5-year NDVI change between soils with 1-2% total organic carbon and 2-3% TOC, but soils with greater than 3% TOC had a significantly greater increase in 5-year NDVI change. Since TOC changes occur very slowly, it is likely that sites with greater TOC values as measured in 2018 likely had had greater TOC at the time of restoration. These sites experienced a greater 5-year change in percent vegetation cover following restoration, suggesting that conditions associated with higher TOC values supported a faster rate of vegetation cover increase than those with low TOC values.

## **Chapter 5: Discussion**

### **5.1 Soil Characteristics at NCC Restored Sites in Norfolk County and Walpole Island**

#### **5.1.1 Implication of Sandy Soils at Restored Sites**

Soils at all the study sites were sandy, with greater than 90% sand particles and less than 10% silt and clay. Soils with high sand content generally experience high rates of soil drainage (Moody & Cong, 2008). Across the project study area, high soil drainage partnered with low organic content following agriculture will restrict the ability of plants to access water (USDA, n.d). On restored sites, the absence of adequate organic matter to store water may be limiting plant growth, leading to the variability in the rate of vegetation cover change across restoration sites.

Although sandy soil does not effectively retain water, the reference sites at Walpole Island show that increased levels of organic matter in the soil do result in higher moisture content. Higher total organic carbon likely holds more moisture, which in turn enables further plant growth. The result is a feedback loop that accelerates the sequestration of carbon into the soil material. This trend is also observed across restored sites (Figure 6), suggesting that sites with greater organic content in the soil are better able to retain moisture.

Since sites in Norfolk County have similar sandy soils compared to reference sites at Walpole Island, the reference sites likely indicate a benchmark of organic content that the degraded sandy soils in Norfolk County may aim to achieve over time. The meadows and oak savannahs of Walpole Island have persisted through many generations, and it is reasonable to assume that the persistence of these natural areas has surpassed the timeline which is necessary to sequester a significant amount of carbon through photosynthesis. This study observed no significant increase in total organic carbon across a 12-year study window, while Inouye et al. (1987) determined no significant temporal increase in total organic carbon over 56 years in similar sandy soils experiencing secondary succession.

#### **5.1.2 Comparing Soil from Different Year Classes After Restoration**

Soil pH remains similar across all treatments, although pH from the unrestored sites and those growing since 2014 show lower values than the other year classes. There was no significant trend in pH based on time since restoration. Soil pH either changes very slowly, or under a mechanism not influenced by restoration. Since no significant difference was detected between reference sites and those in Norfolk County, it would appear as though soil pH remains

unchanged from levels characteristic to the Carolinian ecosystem of Southwest Ontario. Inouye et al. (1987) also detected no significant correlation between field age and pH over 56 years but did detect a weak correlation between pH and soil nitrogen.

Referring to Figure 5, bulk density also showed no significant difference between restored and unrestored sites. Sites at Walpole Island exhibit a much lower bulk density, corresponding to the significantly higher level of organic content in the soil and the lack of disturbance by mechanized agricultural practices. Such high organic content contributes to more porous, aerated soil that has better water storage capacity and ability to support plant life. With no history of disturbance, it is likely that the soil below the organic horizon at Walpole Island is at or near a saturation of organic content. With a history extending back far earlier than European colonization, the time necessary for restored fields to reach similar total organic carbon levels through natural carbon sequestration and accumulation is unknown. Norfolk sites likely experienced a long history of compaction because of their common industrial legacy. In addition to mechanical compaction, the depletion of soil nutrients would have altered soil structure, limiting space for air and water to penetrate (Suding et al., 2004).

The total organic content of the restored sites follows a similar pattern to that of the soil water content. While no temporal trend is noticeable, significant differences do exist between year classes. Further analysis will seek to interpret the mechanism behind those differences. As with moisture, total organic content at the Walpole Island sites is 2 to 3 times that of the restored and unrestored sites in Norfolk County.

### **5.1.3 Correlations between Soil Characteristics**

Figure 5 shows a moderate negative correlation between total organic carbon and bulk density. The lowest bulk density values are likely a result of high organic content and root penetration from the surface, as well as the activity of a healthy microbial community (Lowenfels and Lewis 2010). However, bulk density greater than 1.6 g/cm<sup>3</sup> tends to inhibit root growth (McKenzie et al., 2002). The results shown in Figure 5 verify this result, as the general trend indicates that the samples with the lowest organic carbon occur just below this threshold. It is unlikely that the bulk density of the soil on these sites is a limiting factor in plant growth, since even the sites that are unrestored do not pass this threshold. This can likely be attributed to the soil texture. Sandy soils usually have lower bulk density than finer textured soils since they have fewer, larger pore spaces, but are not as easily compacted (Moody & Cong, 2008).

Soil water content also shows a significant correlation to total organic carbon (Figure 6). This positive relationship indicates that soils with lower organic content have a reduced ability to retain water than those with higher total organic content. As previously mentioned, sandy soils already experience a high rate of infiltration, so it is therefore likely that soil water content may be a limiting factor in plant growth on restored sites. Variability in water content of the soil appears to increase with total organic carbon. Most observations with total organic carbon values less than 2% were associated with low water content, but despite variability, water content increased dramatically for observations with total organic carbon greater than 2%. Despite the high variability, there are practically no instances of water content less than 10% for observations with greater than 4% total organic carbon. This suggests that more organic content in the soil is necessary for retaining greater water content necessary for plant growth.

## **5.2 Aboveground Vegetation Cover**

### **5.2.1 Assessing 5-Year Change in NDVI**

Restored sites exhibited an average NDVI increase of  $0.199 \pm 0.09$  over 5 years ranging from 1 year before restoration to 4 years after. A significant difference was detected between 2013 and 2014 sites, which is likely attributed to the fact that some 2014 sites had above average NDVI values prior to restoration, which may have existed due to the persistence of perennial cover crops after farming has ceased. The elevated NDVI values prior to restoration could easily reduce the observed 5-year change, since the initial value was higher than that of the other fields. This may also explain why the minimum 5-year NDVI change was a negative value, -0.03. Growth that was a relic of the agricultural history of the site prior to restoration, and minimal growth following restoration due to soil limitations could feasibly result in an overall decrease in detected vegetation cover.

### **5.2.2 NDVI as an Indicator for Changes in Vegetation Cover**

Figure 7 showed a strong positive correlation between NDVI and percent vegetation cover that was observed during field observations in June 2018. Based on the correlation between the data, an NDVI increase of 0.1 represents an approximate 15% increase in percent vegetation cover on open meadow and grassy sites in Southwest Ontario. The strength of this correlation shows that NDVI does serve as a strong predictive tool for assessing vegetation cover on a landscape scale, if the analysis starts from minimal vegetation cover and remains reliable until a significant tree canopy is present. Once a tree canopy exists, the nature of the relationship between percent vegetation cover on the ground surface as measured by LandSat imagery is altered, invalidating the comparison. As expected, unrestored sites exhibited the

lowest combination of NDVI/vegetation cover values, as well as the greatest variability about the mean. As previously discussed, this variability could be a result of the agricultural legacy on these sites, which could result in varying degrees of cover crops or other perennial plants persisting beyond the lifetime of the agriculture.

Restored sites showed high variability between age classes, suggesting that time since restoration is only one of several variables that likely influences vegetation growth. In a study of secondary succession on sandy fields in Spain, Martinez-Duro et al. (2010) determined that time since abandonment accounted for only 3% of variation in community composition, while soil chemical characteristics played a much more significant role. No significant relationship between time since restoration and percent vegetation cover was detected in this study. Inouye et al. (1987) determined that organic matter in the soil was strongly correlated to total nitrogen on a site-specific basis, which also suggests that existing soil characteristics will determine the outcome of restoration. The absence of a relationship between time since restoration and observed vegetation cover is highlighted by the two sites that are closest to NDVI and vegetation cover characteristics of the Walpole Island sites, which were restored in 2014 and 2012. In contrast, the three sites most like unrestored conditions were all restored in 2011. Despite having 1-3 years of additional time since restoration, they exhibit significantly lower growth.

Although time since restoration does not play a significant role in determining vegetation cover, the bifurcation in the data beginning at an NDVI value of approximately 0.35 does imply that time since restoration may have an influence on tree canopy development and its influence on ground cover. The bifurcation in the data can be mainly attributed to the five sites restored in 2007, indicated in Figure 7 by the hollow triangles. While these sites show high NDVI values, the vegetation cover of the ground was considerably lower than other, younger restored sites. While conducting fieldwork, I noticed that the 2007 sites had developed a significant tree canopy, consisting mainly of oak and sumac species, as well as an occasional conifer (Figure 9a). Under this canopy there was a clear absence of understory vegetation, likely due to the shade created by the young trees. Younger sites that were restored in 2011 and later did not show the same degree of canopy development (Figure 9b), and as a result the understory had not yet been shaded and reduced.



**Figure 9:** Sites restored in 2007 had developed a considerable canopy that shaded the understory below (Figure 9a, left). As a result, the ground cover of the understory was reduced, leaving sparse vegetation, litter and bare soil. Figure 9b (right) shows a site planted in 2012, which exhibits considerably less tree and canopy development, allowing the herbaceous ground vegetation to receive direct sunlight.

Because of this canopy, NDVI calculated from satellite images maintained higher values, while photos taken from chest height to determine vegetation cover resulted in measurements lower than other sites. This shading effect and the reduction of the understory is dependent on trees being included in the seed mix initially. Some sites did not have any trees at all, and other had trees concentrated in certain areas. If no trees are included in the seed mix, the rate of colonization by woody species will be almost entirely dependent on distance to and composition of nearby species pools, as observed by Fridley and Wright (2012). All 2007 sites had tree growth and based on my field observations. Oak trees on these sites had grown about 4.5-6 m tall in the 12 years since restoration. In comparison, oaks observed across sites restored in 2011 were only about 2 m tall, 1.5 m tall on sites restored in 2012, 1 m tall on sites restored in 2013, and only 0.5 m tall on sites restored in 2014. A small portion of sites restored between

2011 and 2014 did not have any trees, likely as a result of trees being excluded from the planting mix at the time of restoration.

The transition to a canopied understory represents a major shift along the successional pathway, fundamentally altering the understory as a result of shading (Lebrija-Trejos et al., 2011). The development of a canopy will change a variety of site conditions, including microclimate, light penetration, interception of water, and relative humidity. The canopy represents a major step in successional progress towards reforestation, enabling shade-tolerant species to establish (van Breugel et al., 2007). In comparison, Inouye et al. (1987) did not observe tree species on sites experiencing passive old field succession until 15 years after abandonment. Assuming the same rate of growth following the establishment of tree species, sites progressing through secondary succession unassisted by planting would not have a canopy until approximately 27 years after abandonment. By including tree species and accelerating secondary succession on abandoned agricultural land, the successional step of canopy development is accelerated considerably. Because the succession to a canopied ecosystem was accelerated, the rate of tree growth is perhaps faster than the rate of colonization by shade-tolerant species, resulting in an unvegetated understory as seen in Figure 9a.

### **5.3 Predicting Revegetation based on Soil Characteristics**

Based on the strong linear correlation observed in Figure 7, an NDVI increase of 0.1 represents an approximate 15% increase in percent vegetation cover in the context of the Carolinian Ecosystem of Southwest Ontario. Additionally, the results of an ANOVA comparing total organic carbon in the soil to 5-year change in NDVI values showed that sites with total organic carbon greater than 3% experienced a significantly greater 5-year NDVI change than sites with less than 3% organic carbon. Based on these findings, greater amounts of total organic carbon appear to be associated with better growth following restoration. Since regression analysis indicated that total organic carbon accounts for only a small portion of variance in 5-year NDVI change, the predictive power of this relationship at higher levels of total organic carbon is low. It is assumed that greater portions of total organic content would accelerate growth further, but the lack of observations in this survey of values between 3-7% total organic carbon limit interpretation. However, for retired agriculture that is designated for restoration, a simple combustion test to determine total organic carbon can help restoration practitioners create goals for revegetating these sites.

It is important to note that while sites with 1-2% or 2-3% total organic carbon grew less than sites with more than 3% total organic carbon, they still grew considerably. The variability of these results suggests that the mechanisms driving growth are much more complex and the ability to predict growth based on total organic carbon alone is limited. Other studies, however, have observed biologically significant thresholds of total organic carbon that influence crop growth (Musinguzi et al., 2016). They observed significant differences crop growth above and below 2.2% total organic carbon. In comparison, this study revealed no significant differences in 5-year NDVI change on sites with more or less than 2.2% total organic carbon. This suggests that while biologically relevant thresholds may exist for some plant types, the ability to predict growth as a function of soil fertility is complex and varies between ecosystem types. Increased levels of organic carbon in soil are clearly correlated to lower bulk density and increased water content, both of which are expected to contribute to better plant growth. Further research would benefit from including soil chemistry variables such as nitrogen, phosphorus and potassium to predict vegetation growth.

## **Chapter 6: Conclusions**

### **6.1 Summary of Findings**

Analysis of soil variables revealed that pH remained constant across all groups, suggesting that neither the agricultural legacy or restoration efforts had a significant effect on pH. For this reason, soil pH was excluded as a factor that was contributing to variability in vegetation growth on restored sites at Norfolk County. ANOVAs indicated that soil bulk density and moisture of restored sites were significantly different than reference sites, implying that the agricultural legacy of the restored sites contributed to soil compaction and reduced moisture retention. While both moisture and bulk density are known to influence plant growth, linear regressions showed that both were significantly correlated to total organic content. This relationship indicated that reduction in total organic content from agricultural activity would contribute to more compact soil with less water retention capacity, and therefore indirectly inhibit plant growth following restoration.

Using annual NDVI values and on-site plant cover values estimated from photographs, I identified a relationship by which 5-year NDVI change values could be interpreted as a relative change in percent vegetation cover. Sites restored in 2007 had developed a tree canopy which resulted in relatively high NDVI values as measured in LandSat imagery, but also shaded the understory vegetation. Through shading, the vegetative community had clearly been reduced, and measurement of percent vegetation cover was significantly lower than other sites with a similar NDVI value. This split suggests that a major successional shift occurs from 8-12 years following restoration, as sites restored in 2011 had not developed a canopy and subsequent loss of ground vegetation.

Total organic carbon accounted for about 12% of variability detected in 5-year growth, suggesting that other variables play a more significant role in growth outcomes following restoration. Additionally, comparing 5-year NDVI change to total organic carbon showed sites with greater total organic carbon experienced a significantly greater increase in vegetation cover than sites with lower total organic carbon. While the linear regression between these variables suggests that total organic carbon is responsible for only a small portion of this difference, it can still serve as a reliable indicator for estimating relative growth between sites.

### **6.2 Implications of Findings on Restoration Efforts**

Since soil conditions associated with greater total organic carbon have shown to be associated with significantly more vegetation cover than sites with lower total organic carbon,

soil sampling prior to seeding could inform restoration practitioners at the NCC or in other organizations on how to obtain the best results from restoration. If pre-restoration sampling indicates that soil has low levels of total organic carbon, restoration goals could be adjusted accordingly. Soil amendments such as biochar or green manure could be used to increase soil carbon (Kimetu & Lehmann, 2010) and litter cover, which could aid in the establishment of vegetation following planting. However, various soil amendments have different impacts on nutrient ratios and uptake in soil and should be considered to achieve suitable nutrient ratios (Helgason et al., 2007). Sites with low total organic carbon could be seeded at a greater rate or density to compensate for the lesser expected growth. These sites may also benefit from planting saplings or young shrubs to increase the growth and facilitate seedling establishment and growth.

Tilling the soil prior to seeding likely contributes to the loss of soil organic carbon (Savory & Butterfield 2016), therefore alternative measures could be used to clear existing vegetation on the site prior to seeding. Prescribed burning could be a viable alternative to tilling which may increase soil organic carbon, resulting in the early development of an O-horizon which was noticeably absent from all unrestored sites. Tilling would not contribute to an O-horizon and may inhibit growth in the years after seeding.

## Chapter 7: Future Work

In Norfolk County, this research has provided a variety of baseline data from which long-term trends in soil conditions could be measured. Repetition of soil surveying in 10- to 20-year intervals could provide information on the regenerative effects of restoration on soil health, while continued vegetation monitoring could be valuable for understanding growth trends beyond the 12-year study window of this survey. Further work should aim to include more recent restoration sites and include monitoring of baseline conditions prior to restoration. The NCC has also completed prescribed burns on some sites in Norfolk County. Comparison of soil conditions and growth rate on burned sites to unburned sites could provide valuable information on the effects of burning on restoration, particularly its contribution to soil carbon. Additionally, further monitoring should aim to include soil characteristics of forested sites in or near Norfolk County. Some of the forests and historic woodlots in the area are undisturbed, and soil conditions and vegetation characteristics on these sites would contribute to a much more complete database on alternative stable states that can exist in the region.

This study only monitored vegetation cover and rate of change but did not include any monitoring of community composition or turnover between year classes. In this case the decision to exclude compositional monitoring and metrics of beta diversity was due to resource and time limitations, but future studies could expand significantly on this. Monitoring the vegetation community that establishes following restoration would likely result in key finding about which plants or plant types prefer certain soil conditions. If significant differences in composition or compositional change over time are correlated to soil characteristics, further restoration could be modified to use the optimal plant community to rehabilitate a site, rather than a general seed composition. With new information on the timing of the first major successional shift occurring after about 10 years, additional planting on these sites could further accelerate the successional trajectory. For sites restored in 2007, the understory had been largely shaded out, but few shade-tolerant species were observed. This may indicate that the rate of growth for tree species on planted fields is faster than the rate of colonization by shade-tolerant plants. In passive secondary succession, the timing of tree colonization on the site is significantly slower and may better correspond to the natural establishment of shade-tolerant species. Once a canopy is established, additional seeding or planting could add plants typical of a shade tolerant understory in the Carolinian ecozone. This would likely accelerate succession significantly, since it would not depend on natural recruitment. Further research could

investigate the natural rate of colonization by shade tolerant species or study the outcomes of additional restoration efforts in the understory.

A key component missing from this study was the inclusion of soil chemistry, particularly soil nitrogen. Total organic carbon was shown to contribute to only a small portion of variability in 5-year growth, suggesting alternative mechanisms behind restoration success. Inouye et al. (1987) observed that plant cover and biomass were strongly correlated to soil nitrogen, and that soil nitrogen increased significantly with field age. This relationship indicates that the short-term mechanism responsible for plant growth is likely soil nitrogen, as no significant changes in soil carbon were observed between year classes. Further research on restored sites in Norfolk County should aim to include soil nitrogen as part of soil analysis to address this relationship. Since nitrogen fertilizers are so prevalent in conventional agriculture, variation in soil nitrogen that exists as a legacy of the agricultural land use may contribute significantly to restoration success.

Future work could expand on the effects of various restoration treatments. With baseline data available from this study representing 'no-treatment' restoration besides planting, comparison could be made to alternatives to determine the most effective and economical approach to agricultural restoration on a landscape scale. Burning represents one of these treatment alternatives, but others may include application of organic litter, grazing regimes or fertilizer applications. Monitoring these treatments could expand on nutrient ratios and their role on restored sites. Restoration is possible on fields that have been retired from agricultural production, but a sustainable agricultural industry may depend on integration of partial restoration regimes with continued food or livestock production. Restoration that enables continued food production while simultaneously supporting ecosystems and associated services could prevent the degradation of soil and habitat in the first place. Further research should expand on the effectiveness of restoration alternatives, as well as the integration of food sources into the restoration efforts. Examples of this may include the addition of fruit trees or perennial crops to planting mixes, or retroactive addition of food crops to sites in partially restored states. Additionally, there is a growing body of literature on the importance of coexistence between grasslands and ungulates, emphasizing the role that grazing plays in facilitating plant growth and carbon sequestration through root growth (Savory & Butterfield 2016). In addition to habitat restoration, the NCC may benefit from exploring these "working restorations" to integrate ecological knowledge into food production as the income from these sites will offset the cost of land and restoration efforts. Including both habitat restoration and

partial restoration of agriculturally active sites will be necessary to ensure that landscape-level restoration efforts are not just resulting in fragmented segments of habitat that are disconnected by crop monocultures that continue to degrade soil conditions and habitat loss.

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