A Dissertation

entitled

Determining Preliminary Components for a Landfill Evapotranspiration Cover

by

Kristopher D. Barnswell

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requirements for the Doctor of Philosophy Degree in Biology (Ecology-track)

Dr. Daryl F. Dwyer, Committee Chair

Dr. Andrew Heydinger, Committee Member

Dr. Helen Michaels, Committee Member

Dr. Daryl Moorhead, Committee Member

Dr. Alison Spongberg, Committee Member

Dr. Patricia R. Komuniecki, Dean
College of Graduate Studies

The University of Toledo

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Evapotranspiration (ET) covers have gained considerable interest as an alternative to conventional covers for the final closure of landfills. Due to their apparent benefits (e.g. comparatively lower costs and longer life-span), ET covers are becoming ubiquitous in arid and semiarid regions. The goal of this project is to demonstrate, in part, how changes in the design of ET covers can be used to accommodate more humid regions, specifically northwest Ohio. In the initial stages of this project, we realized that an ET cover also could be designed to help ameliorate two issues of environmental concern in northwest Ohio: the management of dredged sediment from Lake Erie by its incorporation into the soil layer of a cover, and the restoration of native habitat by the judicious selection and incorporation of native plant species into the cover design.

The target value for the percolation of water through an ET cover in Ohio is less than 32 cm yr\(^{-1}\). We hypothesized that the changes needed to achieve this target and accommodate the wetter conditions of northwest Ohio include: (1) increasing the soil
water storage capacity, and (2) maximizing plant transpiration throughout the growing season. The experimental approach to test this hypothesis included:

- Create a manufactured soil that incorporates the dredged sediment. Organic materials (peat moss and sawdust) were added to increase the soil water storage capacity and the growth of native plant species.
- Select native plant species that are prevalent in the region with a functionality that spans the early, mid, and late months of the growing season (April through October). Ten candidate plant species were tested for their transpiration capacity.
- Combine the components into a model ET cover. Field lysimeters were watered at a rate to simulate a portion of the wettest year on record (66 cm from June through November).

The results from these experiments were encouraging.

- We found that adding peat moss and/or sawdust to dredged sediment increased the soil water storage capacity. Whereas the addition of peat moss increased plant growth, sawdust decreased plant growth.
- Of the ten candidate plants, we identified five species that in combination maximized transpiration throughout the growing season (*Elymus virginicus* and *Achillea millefolium* in the spring, *Panicum virgatum* in the summer, and *Andropogon gerardii* and *Solidago canadensis* into the fall).
- We found that model ET covers produced percolation at rates less than 32 cm yr⁻¹. The covers representing the mature restored tall-grass prairie produced considerably
less percolation (0.00 to 9.41 cm yr\textsuperscript{-1}) than immature plants (6.67 to 25.36 cm yr\textsuperscript{-1}). Thus, the percolation produced by ET covers decreased over time with plant maturation.

The findings of this project suggest (1) an ET cover would work for the final closure of landfills in humid regions, which should encourage the extension of the application to northwest Ohio. (2) By incorporating dredged sediment, the ET covers may provide a strategy to beneficially re-use significant amounts of sediment and further extend the lifespan of confined disposal facilities. (3) The ET covers also included a mixture of native plant species, indicating that an ET cover may facilitate the restoration of native habitat. (4) Based on our research findings, the Ohio Environmental Protection Agency has allowed for an Alternatives Array that includes a call out for designs for an ET cover as part of the remedial strategy for the King Road Landfill. This is the first time that an alternative cover will be used for a landfill in Ohio, and I will continue to be part of the ongoing research.
Acknowledgements

I thank my family and friends for all of their support, especially my wife Crystal, for taking care of me; my son Logan, for making me happy; my parents, for believing in me. I love you all.

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Chapter 1

Some Issues of Environmental Concern in Northwest Ohio –
Describing the Basis of my Dissertation Research

1.1 Loss of Natural Habitat

The Oak Openings Region (OOR) includes 84,000 acres of land that extends from northwest Ohio into southeast Michigan. The OOR was formed by the retreat of glaciers that left behind undulating prairies with wet depressions and poorly drained flats (Sears 1926). Sand dunes that have a relief up to 10 m were formed from wind-blown sand deposits from the former glacial Lake Warren (Sears 1926). Oak savannas developed on the sand dunes and wet prairies formed in the interdunal areas (Sears 1926; Moseley 1928). The unique combination of dry and wet habitat has produced an unusual flora, which includes more rare plant species than in any other area in Ohio of similar size (McCance and Burns 1984; ODNR 2002). However, drainage, agriculture, and urbanization have resulted in a significant loss of natural habitat where today, only a small percentage of natural green space remains (Green Ribbon Initiative 2004). This has led to the once forgotten brownfields and waste sites (e.g. dumps and landfills) to be considered as potential sites where significant areas may be restored to natural habitat.
1.2 King Road Landfill

Landfills are sites for the disposal of waste materials by burial and are the oldest form of waste treatment. However, regulations for landfill activities (including construction, operation, and closure) were not implemented until 1976 when the Resource Conservation and Recovery Act (RCRA) was passed. This means that there are many landfills located throughout the U.S. that fail to meet modern day regulations.

An example is the King Road Landfill (KRL), located in Sylvania Township in the OOR of northwest Ohio. The KRL was operated from 1954 to 1976, during which primarily municipal solid waste was placed onto approximately 85 of the 104-acre site and sandy soil was used as a cover. Fear that the KRL may adversely impact its surroundings led to the request for a Remedial Investigation / Feasibility Study (RIFS) by the Ohio Environmental Protection Agency (OEPA) in the 1990s, during which a leachate collection system was installed and a number of remedial/closure strategies were evaluated. The results of the investigation concluded that a conventional cover was the preferred closure strategy (Midwest Environmental Consultants 1997), which meant that all of the existing vegetation at the landfill would need to be removed for the construction of a barrier layer that consists of compacted clay and plastic sheets.

 Shortly after the RIFS was conducted, the University of Toledo was granted access to the KRL to conduct phytoremediation research. During this time, an extensive vegetation survey was made for the landfill (Barnswell 2005; Barnswell and Dwyer 2007) to evaluate plant succession and determine if the species composition of the plant community was similar to mature plant communities within the OOR. Plots were established in areas of the KRL where the time period of operation was known (Figure
so that changes in plant community development could be evaluated from a specific time. Plots also were established in regional plant communities (including deciduous forest floodplain, upland deciduous forest, savanna, and sand barren) in the Oak Openings Preserve, the largest of the metroparks in the Toledo area. All vascular plants were identified to species within the plots and the Jaccard index (Real and Vargas 1996) was used to measure the similarity in species composition between the KRL and the regional plant communities.

Figure 1.1: Locations of the plots (denoted by stars) used for the vegetation survey at the King Road Landfill. Time periods of operation for areas of the landfill are indicated by the months and years. See Barnswell (2005) for more details.
The results of the vegetation survey suggested that the species composition at the KRL differed considerably from the regional plant communities; however, the landfill contained several threatened and endangered plant species including, *Lupinus perennis* [wild lupine] and a species that once was presumed to be extirpated, *Digitaria filiformis* [slender finger grass]. In an effort to preserve these rare plant species and limit the percolation of water into the underlying waste (the same function of a conventional cover), we suggested that an evapotranspiration (ET) cover be employed.

ET covers consist of soil and plants and function to limit percolation by storing water in the soil layer until it can be evaporated from the surface or transpired by plants. Comparative cost estimates for an ET cover at the KRL are several times lower than for a conventional cover (Michael Momenee, personal communication 2005). When told of an ET cover, the representatives of Lucas County were very enthusiastic because it would ameliorate the problem of water percolation into the waste at a fraction of the cost of the suggested conventional cover and concurrently promote the restoration of habitat. In 2005, the results of the vegetation survey and the strategy of using an ET cover were presented to the OEPA, which in the following months issued Lucas County to submit an Alternatives Array that include an ET cover as the preferred plan for the closure of the KRL. This led to the current research project of designing an ET cover for the KRL, which would allow the University of Toledo to continue performing research at the landfill (Figure 1.2), and for the first time, extend the application of ET covers to northwest Ohio.
1.3 Management of Dredged Sediment from the Port of Toledo

Dredging sediment that has accumulated in the bottom of navigable waterways is necessary to provide an adequate depth of water for the safe passage of vessels. The U.S. Army Corps of Engineers (USACE) maintains 131 navigation related projects throughout the Great Lakes. In recent years, the Port of Toledo has become one of their largest projects, requiring more than 1,000,000 cubic yards of sediment to be dredged annually (Great Lakes Commission 2001). Most of the dredged sediment is discharged into open waters, but sediment that is considered unsuitable for open water disposal is placed into a confined disposal facility (CDF). Like many other CDFs, this facility is nearing its
volumetric storage capacity and has less than 10 years of capacity remaining (www.lre.usace.army.mil/greatlakes/navigation). This led the USACE to evaluate beneficial uses for the dredged sediment that could further extend the lifespan of the CDF by decreasing the volume added, because locating sites along the shoreline for a new CDF are difficult and construction costs would be high. Although the dredged sediment in this CDF contains contaminants (Table 1.1), the concentrations for these contaminants are below the maximum levels for land application in Ohio (OEPA 2002). Thus, the dredged sediment is suitable for projects in terrestrial habitats.

Table 1.1: The concentrations for the contaminants of concern in the dredged sediment in comparison to the Ohio land application standards. Source: Ohio land application standards – OAC 3745-40-05.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Dredged Sediment (ppm)</th>
<th>Ohio Land Application Standards (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>11.3</td>
<td>75</td>
</tr>
<tr>
<td>Cadmium</td>
<td>7.5</td>
<td>85</td>
</tr>
<tr>
<td>Copper</td>
<td>96.4</td>
<td>4300</td>
</tr>
<tr>
<td>Nickel</td>
<td>65.5</td>
<td>420</td>
</tr>
<tr>
<td>Selenium</td>
<td>11.4</td>
<td>100</td>
</tr>
<tr>
<td>Zinc</td>
<td>294.6</td>
<td>7500</td>
</tr>
</tbody>
</table>

A local company discovered that the sediment from the CDF could be amended with sewage sludge from a wastewater treatment plant and lime sludge from a drinking water treatment to form a nutrient-rich soil from what are considered ‘waste products’. This soil is referred to as ‘Nu-soil’ (Stanley Perry, personal communication 2006) and has been used for landscaping and the daily cover at the city’s active municipal solid
waste landfill, the Hoffman Road Landfill. Because ‘Nu-soil’ is readily available in significant volumes and has some characteristics that are favorable for an ET cover (e.g. high nutrient content to support plant growth and a fine texture to store large volumes of water) it is being evaluated for constructing the ET cover for the KRL.

1.4 Goals

The overall goal of this project is to design an ET cover for the KRL and other waste sites in northwest Ohio that limit percolation to a rate less than 32 cm yr$^{-1}$, the maximum allowable rate for landfill covers in Ohio (OEPA 2003). The sub-goals are to beneficially re-use the dredged sediment from the Port of Toledo CDF and facilitate restoration of habitat at the KRL.

1.5 Objectives

To achieve the goals of this project, I conducted a series of greenhouse and field experiments with the following objectives:

1. Increase the soil water storage (Chapter 3).
2. Maximize plant transpiration throughout the growing season (Chapter 4).
3. Test these modifications using field lysimeters (Chapter 5).

The objectives were addressed by:

1. Adding organic material to the dredged sediment.
2. Selecting native plant species with highest rates of transpiration and a functionality that spanned the early, mid, and late months of the growing season.
3. Applying water to constructed ET covers at a rate that simulated a portion of the region’s wettest year on record.
References


Chapter 2

Designing Landfill Evapotranspiration Covers for Humid Regions

Abstract:

Evapotranspiration (ET) covers have gained considerable interest as an alternative to conventional covers because they are less costly to construct and have a longer lifespan. ET covers consist of soil and plants that function to limit the percolation of water into the underlying waste by storing water in the soil layer until it is either evaporated from the surface or transpired by the plants. ET covers have been successfully used in arid and semiarid regions where the precipitation (P) to potential evapotranspiration (PET) ratio is less than 0.75. The research discussed in this chapter details attempts to extend their use to regions denoted as humid (P:PET > 0.75) specifically to northwest Ohio (P:PET 1.29) where the allowable rate of water percolation is < 32 cm yr\(^{-1}\). As part of this goal, dredged sediment from the Port of Toledo was used in the soil layer of the ET covers as a beneficial use, and native plant species were selected to concurrently attempt to restore native habitat.

To achieve the target rate of percolation and determine the suitability of ET covers in northwest Ohio, the following was necessary:
• Increase the soil water storage capacity (Chapter 3)
• Maximize transpiration throughout the growing season (Chapter 4)
• Test these modifications using field lysimeters (Chapter 5).

During a 173-day monitoring period, model ET covers all produced acceptable rates of percolation (0.00 to 25.36 cm yr\(^{-1}\)). The findings of this study suggest that ET covers are (i) suitable for humid regions, which should encourage the extension of application to northwest Ohio; (ii) a strategy to beneficially re-use considerable volumes of dredged sediment; and (iii) an approach to restore native habitat at landfill. Currently, the Ohio Environmental Protection Agency is allowing for an ET cover as part of the remedial plan for an inactive landfill in northwest Ohio, which is the first of its kind in the state.
2.1 Introduction

There are more than 3,500 active municipal solid waste landfills throughout the U.S. (www.epa.gov) that eventually will require a final cover system to control the percolation of water into the underlying waste. Currently, final covers consist of a barrier layer composed of compacted clay and/or a geosynthetic membrane that promote surface runoff and reduce the downward movement of water. These are often referred to as conventional covers and in most cases function adequately to meet material specifications (e.g. a maximum hydraulic conductivity ranging $10^{-5}$ to $10^{-7}$ cm sec$^{-1}$, USEPA 1993), but are not subjected to a performance criterion such as maximum rate of percolation (Albright et al. 2004). These conventional covers are expensive to construct, ranging from $97,000 to $360,000 per acre (Dwyer 1998$^A$; Hauser et al. 2001$^A$; Licht et al. 2001), and their performance decreases over time with the natural deterioration of materials. For example, cracking of compacted clay is common following freeze-thaw cycling (Albright et al. 2006$^A$) and prolonged dry periods when the soil becomes desiccated (Albrecht and Benson 2001; Albright et al. 2006$^B$). These problems have led to the evaluation of alternative designs for final covers that are less expensive to construct than conventional covers and function for longer time periods.

The Resource Conservation and Recovery Act (RCRA) and many state regulations permit landfills to use alternative covers when they demonstrate comparable performance to conventional covers, i.e. the rate of percolation produced by the alternative cover is less than or equal to the rate produced by a conventional cover (USEPA 1993). Evapotranspiration (ET) covers have gained considerable interest as an alternative strategy for the final closure of landfills. They consist of soil and plants, and
function to limit percolation using water storage principles, which include soil water storage during periods of inactive plant growth and the combination of evaporation from the soil surface and transpiration during the growing season. In contrast to conventional covers, ET covers are less expensive to construct, costs range from $80,300 to $299,000 per acre (Dwyer 1998; Hauser et al. 2001; Licht et al. 2001), their performance is expected to increase over time as plants mature (Albright et al. 2004), and require low maintenance since they are self-renewing (Hauser 2009). Many field studies made for ET covers acknowledge that they are suitable in arid and semi-arid regions (Nyhan et al. 1990; Dwyer 1998; Albright and Benson 2002; Fayer and Gee 2006) while only a few studies indicate effectiveness in humid regions (Albright et al. 2004; Abichou et al. 2005). To extend the application of ET covers to humid regions, the following is necessary: (i) increase soil water storage and (ii) maximize transpiration throughout the growing season. This article synthesizes the results of recent studies made for ET covers and reports on the approach taken to design an ET cover for an inactive landfill in Ohio, a humid region with little experience in design for ET covers (Albright and Benson 2002).

2.2 Research Site

The research described here was conducted in northwest Ohio, which has a continental climate with typical air temperatures ranging from 27.39 °C (mean summer high) to -7.11 °C (mean winter low). The mean annual precipitation (P) is 83.45 cm and the most precipitation received in a year was 116 cm in 2006 (www.ncdc.noaa.gov); the mean annual potential evapotranspiration (PET) is 64.7 cm (Martin-Hayden et al. 1999).
The region is classified as humid because the ratio of P to PET is 1.29, far exceeding the value of 0.75 that defines a region as humid (UNESCO 1979).

The ET cover is being designed for the King Road Landfill (KRL) located in Sylvania Township, Ohio that received primarily municipal solid waste from 1954 to 1976. The waste was placed onto approximately 85 of the 104 acre landfill and was covered with sandy soil excavated from an onsite borrow pit. Fear that the KRL may adversely impact the surrounding areas led to the Ohio Environmental Protection Agency (OEPA) to issue a Remedial Investigation / Feasibility Study (RIFS) that suggested a conventional cover be used for the final closure of the landfill. Shortly after the RIFS, the University of Toledo initiated phytoremediation research at the landfill, which included a vegetation survey that identified threatened and endangered plant species (Barnswell and Dwyer 2007). The results of the vegetation survey were presented to the OEPA, and it was at that time, that the application of an ET cover for the landfill was introduced, which led to the current investigation.

Model ET covers were constructed, tested, and monitored at the Environmental Remediation and Restoration Experimental Park at the University of Toledo’s Stranahan Arboretum located in Toledo, OH that includes 12 cylindrical lysimeters (six that are 1.22 m in diameter x 0.61 m depth; six that are 1.52 m in diameter x 1.52 m in depth) with a conical bottom (0.30 m in depth). The six larger lysimeters were used for testing ET covers. The lysimeters were constructed using sheet metal (5 mm) and were placed in-ground and covered by translucent roof constructed with a corrugated fiberglass panel to maintain in-situ soil temperatures, natural sunlight, and control of precipitation inputs (www.utoledo.edu/as/lec/research/errl/ERREP.html).
2.3 Design Concepts

Precipitation (P) and air temperature are the main factors that affect the performance of ET covers and are the first considerations in the design procedure. The annual rate of P is used to determine the amount of water that must be managed by the cover system (Benson 2004) and the air temperature is one factor indicating the evapotranspiration potential. In general, ET covers are considered effective in regions with a P:PET less than 0.75 but not in regions with a value greater than 0.75 (Benson 2006). This is because PET may greatly exceed P in arid and semiarid regions, and percolation is less likely to occur, which is in contrast to humid regions where P may greatly exceed PET and percolation is more likely to occur. As a result, it is challenging to design ET covers for cold humid regions, such as Ohio. However, the performance requirements for landfill covers in Ohio are not as stringent as other regions. For example, the OEPA requires landfill covers to produce a rate of percolation that is less than 32 cm yr\(^{-1}\), equivalent to a hydraulic conductivity of \(10^{-6}\) cm sec\(^{-1}\) (OEPA 2003), while many states located in drier regions (e.g. California, Montana, and Oregon) require landfill covers to produce a rate of percolation that is less than 0.3 cm yr\(^{-1}\), equivalent to a hydraulic conductivity of \(10^{-8}\) cm sec\(^{-1}\) (Albright et al. 2004). Thus, it may be feasible to construct ET covers for landfills in Ohio able to meet the performance requirements even though the region receives high rates of precipitation.

There are two basic choices of design for ET covers (Figure 2.1), monolithic covers and capillary barriers (Albright et al. 2004). Monolithic covers consist of a single soil layer used to store water. Capillary barriers consist two soil layers: a fine-grained soil overlying a coarser grained soil. At the interface of the two contrasting soils in the
capillary barrier, a capillary break is formed, which allows the fine-grained soil to store greater amounts of water than an identical soil of the same thickness not overlying a coarser grained soil (Khire et al. 2000).

Figure 2.1: Soil profiles for monolithic and capillary barrier ET covers.

Soil and plants are the basic components for constructing ET covers. The soil functions to store water and support the growth of plants, which prevent soil erosion and transpire water that is stored in the soil layer. The two processes, soil water storage (SWS) and plant transpiration, work concurrently to limit percolation, but the importance of each one varies by season (Figure 2.2). For example, SWS is critical during periods of inactive plant growth, such as late fall through early spring, and ET is needed throughout
the growing season to maximize the water storage capacity of the soil so that it once again can store the precipitation received when plants are dormant.

Figure 2.2: The seasonal cycle for evapotranspiration and soil water storage in an ET cover. Soil water storage is required during periods of inactive plant growth and evapotranspiration is needed during the growing season to maximize the water storage capacity of the soil for the non-growing season.

This continuous cycle is in theory demonstrated for an ET cover in northwest Ohio during a two-year period using mean seasonal P and PET (Table 2.1). The P (www.ncdc.noaa.gov) that is received in northwest Ohio includes 22.16 cm in spring (March – May), 25.14 cm in summer (June – August), 19.66 cm in fall (September – November), 16.29 cm in winter (December – February); PET rates for the seasons include 13.4 cm in Spring, 28.8 cm in Summer, 22.5 cm in Fall, and 0.0 cm in Winter (Martin-Hayden et al. 1999). Indeed, the SWS increases when P exceeds PET during the winter and spring, and decreases when PET exceeds P during the summer and fall. This
implies that over time the SWS of the cover will to continue to increase until it reaches capacity (depending on the thickness of the soil), at which percolation will then be produced. However, this example does not include surface runoff from the soil layer, which may reduce the downward movement of water, and thus percolation. For example, Albright et al. (2004) observed that surface runoff accounted for up to 10% of P.

Table 2.1:  Seasonal variations in the soil water storage for an ET cover in northwest Ohio.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Year 1</th>
<th>Year 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>PET (cm)</td>
<td>13.4</td>
<td>28.8</td>
</tr>
<tr>
<td>Cumulative SWS (cm)</td>
<td>8.76</td>
<td>5.1</td>
</tr>
</tbody>
</table>

In order to maximize the performance of ET covers, a judicious selection of soil and plants is needed. The following factors are considered for the selection and placement of the soil:

- Grain size: Fine-grained soils (e.g. loams, silt loams, or silt clays) are primarily used (Gurdal et al. 2003) because they have a greater water storage capacity than coarse-grained soils (Saxton et al. 2005). Although clayey soils have a higher water storage capacity compared to other fine-grained soils, they are not recommended for constructing ET covers because they are prone to cracking due to desiccation (Albrecht and Benson 2001) and freeze-thaw cycling (Albright et al. 2006), which may result in an increase in the rate of percolation.
- **Nutrients:** The soil should have sufficient nutrient content to support plant growth and a pH within the tolerable range for the plants. Essential nutrients for plants include (Marschner 1995; Barker et al. 2005) nitrogen, phosphorus, potassium, sulfur, magnesium, and calcium (optimal concentrations for these nutrients are species specific), and the optimum pH range for many plant species is between 6.0 and 7.5 (Marschner 1995).

- **Thickness:** The thickness of the soil is selected based on the water storage capacity of the soil and the amount of water that needs to be stored to prevent percolation. The soil layer should store a volume of water that is equivalent to the amount of water that was received during the region’s wettest year on record (Benson 2006), but this may not be feasible in all locations because of the significant volume of soil that may be needed or due to cost restraints. This suggests that ET covers in humid regions will need to be greater in thickness than ET covers in arid and semi-arid regions (Albright et al. 2004).

- **Compaction:** When placing the soil during construction, it is often compacted to a bulk density between 1.10 and 1.50 g cm$^{-3}$ (Hauser et al. 2001$^\text{A}$). Increasing the soil bulk density results in decreasing the hydraulic conductivity and water storage capacity (Radford et al. 2001; Mooney and Nipattasuk 2003), and increasing the bulk density greater than 1.55 g cm$^{-3}$ significantly impedes plant root growth (Kuchenbuch and Ingram 2004), and water uptake by plants.
(Arvidsson 1999). Thus, it is necessary to attain an adequate bulk density so that maximum root growth and transpiration can be attained.

These factors were addressed during the construction of the ET covers in northwest Ohio. The soil was attained from a confined disposal facility (CDF) located in the Toledo Harbor where sediment dredged from the Port of Toledo shipping channel was placed. On the CDF, the sediment was amended with sewage sludge (12% DWT) from a wastewater treatment plant and lime sludge (3% DWT) from a drinking water treatment plant. Referred to as ‘Nu-soil’ (Stanly Perry, personal communication 2006), this formulated loamy soil (45.3% sand, 40.0% silt, 14.3% clay) is low in clay content but high in nutrients (56 ppm nitrogen as NO₃⁻, 354 ppm phosphorus as P₂O₅, and 251 ppm potassium as K₂O).

Since the water storage capacity affects the thickness of the soil layer(s) for an ET cover, with a greater thickness required for soils that have a lower capacity, it is necessary to maximize the water storage capacity of the soil so that less soil is used and construction costs remain low. Organic materials are commonly used to increase the water storage capacity of agricultural soils (Averett et al. 2004; Li et al. 2004). In Chapter 3, I noted that peat moss and sawdust increased the soil water storage capacity (Table 3.1), but the sawdust reduced plant biomass production (Figure 3.1). Plant growth (biomass and leaf area development) is a major factor affecting transpiration, and therefore should at least be maintained when applying organic materials to increase the soil water storage. For this reason, peat moss was considered more appropriate than sawdust. However, peat moss may be very costly when it is not locally available and
thus may not be suitable for all locations. Therefore, additional organic materials should be evaluated for their ability to increase soil water storage and plant growth in a similar manner as peat moss, but at a lower cost.

The soil profiles for the test ET covers are shown in Figure 5.1. Capillary barriers were used for two reasons, (1) the capillary break promoted greater water storage in the overlying fine-grained soil layers and (2) the coarse sand in the conical bottom assisted in the collection of percolation. The soils were compacted to a low bulk density (1.0 g cm\(^{-3}\)) to provide adequate porosity and facilitate root growth. Peat moss was applied only to the upper 0.6 m because it is costly (approximately $5.00 for 2 ft\(^3\) at many home gardening stores) and the majority of plant root biomass extends to this depth. Topsoil and sod were used for different types of vegetation (discussed in the following paragraphs), and the top 12 cm was left open to prevent the surface runoff of applied water.

Plants commonly used for ET covers consist of species native to the region that are adapted to the climate. The types of plants that have been previously used for ET covers include annual and perennial grasses, forbs, shrubs, and hybrid poplars (Bolen et al. 2001; Roesler et al. 2002; Rock 2003; Albright et al. 2004). In most cases, herbaceous plants are preferred because they form dense root systems that prevent soil erosion from wind or water (Hauser et al. 2001\(^\text{A}\); Hauser 2009). A mixture of native plants with the following characteristics has been suggested for the ET covers:

- Annual: providing erosion control and water uptake in a short amount of time (Hauser et al. 2001\(^\text{A}\); Hauser 2009).
• Perennial: able to survive for many years (Hauser et al. 2001\textsuperscript{A}; Hauser 2009).

• Adapted to a variety of soil conditions such as those at landfills and waste sites (Venkatraman and Ashwath 2007).

• Extensive root systems: a mixture of sod-forming and bunch grasses able to provide erosion control and water uptake from shallow and deep soil layers (Hauser et al. 2001\textsuperscript{A}; Rock 2003; Hauser 2009).

• Function throughout the growing season: a mixture of warm and cool season plants (Hauser et al. 2001\textsuperscript{B}; Albright and Benson 2002).

In part of the major goal of this project, to design an ET cover for the KRL that produces allowable rates of percolation, it was realized that an ET cover might concurrently facilitate habitat restoration. Therefore, when designing the ET cover for the KRL, restoration was acknowledged as a beneficial extension and played a major role in the selection of the plant species. Thus, it is believed that ET covers are a new paradigm for the restoration of habitat on landfills.

Since the KRL is located in an area that used to be forested, as indicated by the remnant trees on site (primarily \textit{Quercus}, Barnswell 2005), the long-term restoration goal is to establish native woodlands. However, this may take several decades to develop, therefore, we are using a trajectory that allows plant succession to be directed into a native forest. This includes using the native plants that are dominant in the earlier plant
communities that develop along the successional pathway to a forest: the herbaceous species of the tall-grass prairies. The plant species for the ET cover were selected based on the characteristics mentioned above as well as their establishment in regional plant communities (Easterly 1973) and the KRL (Barnswell and Dwyer 2007).

One feature that has been overlooked when selecting plants for an ET cover is the transpiration potential of the species. In Chapter 4, I addressed this issue by estimating the rate of transpiration for candidate plants and observed that the rate of transpiration (i) is highly variable between species and with time (Figure 4.2), (ii) corresponded to the biomass of the species (Figure 4.3), and (iii) was highly variable during the growing-season as weather conditions changed (Figure 4.4). Phenotypic traits, such biomass and leaf area were considered useful indicators for conservatively predicting the transpiration potential of a plant species. Thus, evaluating the phenotypic traits of a plant may be a general tool used when selecting species for an ET cover.

The results in Chapter 4 suggest that the selection of plants for an ET cover use a multi-step approach that includes: (i) vegetation surveys at the landfill of interest and in regional plant communities to identify native species that may facilitate habitat restoration; (ii) evaluation of the phenotypic traits of these plants to identify the most appropriate candidate species; and (iii) determination of the transpiration potential of the plants to identify the species that will maximize transpiration throughout the growing season.

Based on the findings in Chapter 4 and recommendations made for the restoration of tall-grass prairies by Packard and Mutel (1997), the following seeding densities (individuals per m²) were used in the model ET covers: cool-season species: 0.09
Rudbeckia hirta [black-eyed susan], 0.09 Danthonia spicata [poverty grass], 0.19 Achillea millefolium [yarrow]; and 0.33 Elymus virginicus [Virginia wildrye], warm-season species: 0.19 Andropogon gerardii [big bluestem], 0.19 Eupatorium altissimum [tall boneset], 0.23 Solidago canadensis [Canada goldenrod], 0.46 Sorghastrum nutans [Indian grass], 0.46 Panicum virgatum [switch grass], and 0.56 Schizachyrium scoparium [little bluestem]. Because the seeds of S. canadensis in our collection were no longer viable, the ecological equivalent Solidago rigida [stiff goldenrod] was used in place. This mixture includes plants that will promote soil water uptake throughout the entire growing: spring – E. virginicus and A. millefolium, summer – P. virgatum, and fall – A. gerardii and S. nutans, with greater seeding densities for the species that attained greater rates of transpiration in the experiments in Chapter 4. In addition, a second plant mixture was used to predict the performance of ET covers over time the vegetation matures. This plant mixture consisted of two native species (A. gerardii and S. canadensis) that were transplanted from a nearby tall-grass prairie that has been restored for more than 10 years.

2.4 Application of ET Covers

ET covers have been tested at many locations in arid and semiarid regions (Nyhan et al. 1990; Chichester and Hauser 1991; Anderson et al. 1993; Waugh et al. 1994; Dwyer 1998B, 2003; Albright et al. 2004; Nyhan 2005; Fayer and Gee 2006), but at few locations in humid regions (Albright and Benson 2002; Albright et al. 2004; Abichou et al. 2005). Two demonstration projects were funded by agencies in the U.S. to evaluate the performance of ET covers: (1) the Alternative Cover Assessment Program (ACAP)
was introduced by the U.S. Environmental Protection Agency (USEPA) in 1998 and has testing sites located throughout the U.S. in climatic regions that range from arid to humid (Albright et al. 2001). At several of the sites ET covers and conventional covers are constructed in adjacent lysimeters so that side-by-side comparisons could be made. (2) The Alternative Landfill Cover Demonstration (ALCD) was initiated by the U.S. Department of Energy (DOE) in 1995 (Dwyer 1998A,B) and has a central testing site in Albuquerque, NM where six landfill cover designs (Subtitle C, Subtitle D, geosynthetic clay liner (GCL), capillary barrier, anisotropic barrier, and ET cover) were constructed in adjacent large-scale lysimeters. In both programs, the landfill covers were tested under ambient conditions in lysimeters that were fabricated to allow the quantification of surface runoff, soil water storage, and percolation. Data from these demonstration projects and field studies that used lysimeters to monitor the performance of the ET are summarized in Table 2.2.

### 2.5 Extending the Application of ET Covers to Northwest Ohio

Model ET covers were monitored at the Environmental Remediation and Restoration Experimental Park from 11 June through 30 November 2009. During construction, a leachate collection system was placed to collect the percolation that drained through the ET covers; moisture sensors were placed in the soil at two depths (0.30 m and 1.12 m) to quantify the volumetric water storage of the soil layers. The ET covers in northwest Ohio were tested in ambient conditions, but water was manually applied at a rate to simulate the months of the wettest year on record. In 2006 the region received 116 cm of precipitation: June 9.93 cm, July 23.34 cm, August 8.20 cm,
September 5.97 cm, October 10.90 cm, November 7.70 cm (www.ncdc.noaa.gov). Twenty-four hour 100-year rainstorm events were applied on 21 July and 6 October to evaluate the influence that the season, i.e. summer or fall, has on the rate of percolation produced by ET covers. During each 100-year rainstorm event, a total of 11.7 cm was applied onto the ET covers during a 14 hr period. The preliminary findings of this project are presented in Table 2.2.

2.6 General Considerations

There was a precipitation threshold when comparing the rates of percolation produced by ET covers to conventional covers. ET covers produced higher rates of percolation than conventional covers at testing sites that received precipitation at a rate of 32 cm yr$^{-1}$ or more. However, there was an indication of effectiveness from an ET cover that received more than 100 cm of precipitation per year. At Albany, GA the ET cover produced less percolation than the adjacent conventional cover, even after receiving a greater amount of water (additional water was applied to the ET cover to assist in vegetation establishment) (Albright et al. 2004; Abichou et al. 2005). This ET cover was constructed using a mixture of clayey sand amended with peanut-hull compost and vegetated with a combination of Bermuda grass and hybrid poplars (Abichou et al. 2005). Hybrid poplars have gained considerable interest as tools to control percolation into landfills and filter sediments and pollutants into aquatic systems (www.ecolotree.com) because they grow fast and attain high rates of transpiration. For example, Hinckley et al. (1994) indicated that a mature hybrid poplar plantation has the potential to remove between 87 and 107 cm of water from the soil per year. Thus, it is apparent that the
Table 2.2: Summarized performance data for ET covers. Data for conventional covers are given for locations where side-by-side comparison was made to an ET cover.

<table>
<thead>
<tr>
<th>Location</th>
<th>P:PET</th>
<th>Climate</th>
<th>Cover type and Thickness (cm)</th>
<th>Monitoring period</th>
<th>Precipitation (cm yr(^{-1}))</th>
<th>Percolation (cm yr(^{-1}))</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td></td>
<td>Arid</td>
<td>Conventional – composite (90) ET – monolithic (105)</td>
<td>1997 - 2001</td>
<td>28.76</td>
<td>0.06</td>
<td>Dwyer 2003</td>
</tr>
<tr>
<td>Apple Valley, CA</td>
<td>0.06</td>
<td>Arid</td>
<td>Conventional – composite (120) Conventional – soil barrier (90) ET – monolithic (112.5)</td>
<td>2002 – 2003</td>
<td>14.8</td>
<td>0.0</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Altamont, CA</td>
<td>0.31</td>
<td>Semiarid</td>
<td>Conventional - composite (120) ET – monolithic (127.5)</td>
<td>2001 - 2003</td>
<td>34.27</td>
<td>0.2</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Boardman, OR</td>
<td>0.23</td>
<td>Semiarid</td>
<td>Conventional – composite (120) ET – monolithic (210)</td>
<td>2001 - 2003</td>
<td>13.0</td>
<td>0.0</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Helena, MT</td>
<td>0.44</td>
<td>Semiarid</td>
<td>ET – capillary (180)</td>
<td>2000 - 2003</td>
<td>23.27</td>
<td>0.0</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Marina, CA</td>
<td>0.46</td>
<td>Semiarid</td>
<td>Conventional – composite (120) ET – capillary (150)</td>
<td>2000 - 2003</td>
<td>32.22</td>
<td>2.35</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Monticello, UT</td>
<td>0.34</td>
<td>Semiarid</td>
<td>ET – capillary (202.5)</td>
<td>2000 - 2003</td>
<td>29.8</td>
<td>0.0</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Location</td>
<td>P:PET</td>
<td>Climate</td>
<td>Cover type and Thickness (cm)</td>
<td>Monitoring period</td>
<td>Precipitation (cm yr⁻¹)</td>
<td>Percolation (cm yr⁻¹)</td>
<td>Source</td>
</tr>
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<td>-------------------</td>
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</tr>
<tr>
<td>Richland, WA</td>
<td>29.0</td>
<td>Semi-arid</td>
<td>ET – capillary (293)</td>
<td>1987 - 2004</td>
<td>18.1</td>
<td>0.0</td>
<td>Fayer and Gee 2006</td>
</tr>
<tr>
<td>Sacramento, CA</td>
<td>0.33</td>
<td>Semi-arid</td>
<td>ET – monolithic (150)</td>
<td>1999 - 2003</td>
<td>34.91</td>
<td>2.54</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Polson, MT</td>
<td>0.58</td>
<td>Sub-humid</td>
<td>Conventional – composite (150)</td>
<td>2000 - 2003</td>
<td>31.09</td>
<td>0.04</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Albany, GA</td>
<td>1.10</td>
<td>Humid</td>
<td>Conventional – soil barrier (75)</td>
<td>2000 - 2002</td>
<td>95.78</td>
<td>2.59</td>
<td>Abichou et al. 2005</td>
</tr>
<tr>
<td>Albany, GA</td>
<td>1.10</td>
<td>Humid</td>
<td>Conventional - soil barrier (75)</td>
<td>2000 - 2003</td>
<td>115.51</td>
<td>19.52</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Cedar Rapids, IA</td>
<td>1.03</td>
<td>Humid</td>
<td>Conventional - composite (105)</td>
<td>2002 - 2003</td>
<td>79.12</td>
<td>2.1</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Omaha, NE</td>
<td>0.75</td>
<td>Humid</td>
<td>Conventional - composite (120)</td>
<td>2001 - 2003</td>
<td>51.79</td>
<td>0.51</td>
<td>Albright et al. 2004</td>
</tr>
<tr>
<td>Toledo, OH</td>
<td>1.29</td>
<td>Humid</td>
<td>ET – capillary (170)</td>
<td>2009 (175 days)</td>
<td>116</td>
<td>0.0</td>
<td>Barnswell and Dwyer (in review)</td>
</tr>
</tbody>
</table>

Note: The data includes monitoring periods, precipitation, and percolation rates for different locations and cover types.
Note: Composite conventional covers consist of a geomembrane underlain by fine-grained soil, soil barrier conventional covers consist of compacted clay soils, monolithic ET covers consist of a single type of soil, and capillary ET covers consist of coarse-grained soil overlain by fine-grained soil. Superscript M = mature plants (5 – 10 yrs old); Superscript I = immature plants (seeds). P = precipitation (P), (PET) = potential evapotranspiration. Climatic zones, arid (0.03 < P:PET < 0.2); semiarid (0.2 < P:PET < 0.5); sub-humid (0.05 < P:PET < 0.75); humid (P:PET > 0.75).

hybrid poplars may have led to lower rates of percolation produced by the Albany ET cover, which suggests they should be used for ET covers in regions that receive high rates of precipitation. However, when habitat restoration is intended for the landfill, hybrid poplars may not be suitable because they might hinder establishment of the desired native plant species. For that reason, hybrid poplars were not considered for the model ET covers in northwest Ohio.

The model ET covers in Toledo, OH produced higher rates of percolation than ET covers at the other testing site (Table 2.2). Several factors are suggested for this: (1) no surface runoff, the ET covers were constructed in cylindrical lysimeters that restricted the movement of water to only downward direction; (2) significant amounts of water were applied, the ET covers received watered at a rate that simulated a portion of the wettest year on record and additional 100-year rainfall events; and (3) transpiration rates were low, the ET covers were monitored only during the first growing season of plant growth. It’s worth noting that no conventional covers were constructed in the lysimeters adjacent to the ET covers, so side-by-side comparisons were not made. In order to determine whether the ET covers were suitable for Ohio, the rates of percolation produced by them were compared to a value (32 cm yr\(^{-1}\)) that was extrapolated from the specifications for construction materials for landfills in Ohio (hydraulic conductivity 10\(^{-6}\) cm sec\(^{-1}\), OEPA
2003). Using this extrapolated value, all six of the ET covers were considered suitable for Ohio (Table 2.2; Table 5.1; Figure 5.2); ET covers using mature plants produced considerably less percolation than ET covers using immature plants, which suggests that performance may increase over time with plant maturation.

Although no data are available to contrast the rates of percolation produced by monolithic ET covers to capillary barrier ET covers at the same testing site, comparisons can be made between the two types of ET covers within similar climatic regions (Table 2.2). A review of published data suggests that the rates of percolation produced by both types of ET covers were similar in arid and semiarid regions, and capillary barriers produced lower rates of percolation in humid regions. For example, the monolithic ET cover in Cedar Rapids, IA produced percolation at a rate of 15.71 cm yr\(^{-1}\) while receiving precipitation at a rate of 79.21 cm yr\(^{-1}\); and the capillary barriers in Omaha, NE produced percolation at rates of 1.64 and 2.72 cm yr\(^{-1}\) while receiving precipitation at a rate of 51.79 cm yr\(^{-1}\).

An overview of the published studies made for ET covers indicated that the rates of percolation increased with the precipitation (Table 2.2), and high rates of percolation may have been produced because of the following factors:

1. Insufficient water storage: The soil layer(s) did not store an adequate volume of water to prevent percolation. Although the water storage capacity for many of the ET covers was determined from the average annual precipitation of the region, above average and seasonal patterns in the precipitation were not considered. For example, percolation was produced by an ET cover in Albany, GA that received
precipitation at a rate 30% higher than the annual average; the water storage capacity for two ET covers in Omaha, NE was exceeded during intense spring rainfalls (Albright et al. 2004). The investigators from this study suggest that the storage capacity of the soils at the field sites were conservatively estimated to be 30% less than the storage capacity measured in the laboratory.

2. Formation of cracks: Soils with high clay content are susceptible to forming cracks following a drying period. This was demonstrated by the soil used to construct the ET cover in Albany, GA, which had 24% clay content (Gurdal et al. 2003). Following an extensive drying period, percolation was produced shortly after precipitation events, suggesting that cracks had penetrated through the soil profile (Albright et al. 2004).

3. Insufficient transpiration capacity: Transpiration is the primary mechanism to remove the water stored in the soil, especially from the deeper layers. Although the plants for the ET covers were selected based on their establishment in the region, the transpiration potential of the species was not evaluated. Thus, it was uncertain as to whether the most appropriate plants were used for an ET cover. The rate of percolation produced by the ET covers at Omaha significantly decreased from first growing season to the second growing season, by 97.5% and 94.7% (Albright et al. 2004). This indicates that the plant species had become established by the second growing season and suggests that a mixture of species
with faster growth rates may reduce the rate of percolation during the initial months following construction.

2.7 Conclusion

An indication of effectiveness by model ET covers in northwest Ohio suggests the extension of their application to humid regions. These successful model covers incorporated sediment dredged from the Port of Toledo. Thus, construction of ET covers may provide a strategy to beneficially re-use significant amounts of dredged sediment. The successful model covers also included a mixture of native plant species with a functionality that spanned the early, mid, and late months of the growing season. Thus, a judicious selection of plant species for an ET cover can maximize transpiration throughout the growing season and facilitate the restoration of native habitat. Currently, the OEPA is allowing for an ET cover as part of the remedial strategy for an inactive landfill in northwest Ohio, the first of kind; this project may play a major role in amending the regulations for the final closure of landfills in Ohio.
References


Chapter 3

The Effects of Organic Materials on Water Storage and Available Nitrogen in a Nutrient-Rich Soil for Constructing Evaptranspiration Covers to Restore Habitat on Landfills

Abstract:

The suitability of using evapotranspiration (ET) covers for landfills located in northwest Ohio is being evaluated with respect to limiting water percolation to allowable rates (< 32 cm yr<sup>−1</sup>), while restoring habitat through the use of native plant species. As part of this process, dredged sediment from the Port of Toledo, which is located in Lake Erie and the Maumee River, is being incorporated into the soil used to construct model ET covers. This sediment is favorable for ET covers because it is has a fine grain size, which is indicative of a high water storage capacity and is necessary for covers in northwest Ohio to store the high rates of precipitation that are received (83 cm, annual mean). However, this sediment has a high level of available nitrogen (NO<sub>3</sub>N, 56 ppm), which could promote the growth of weeds in the proposed ET covers and limit the establishment of native plants, thus hindering the restoration of native habitat. For this reason peat moss and sawdust were incorporated into the soil (0, 6.5, and 13% fresh weight and in combination as 0, 3.25, and 6.5% fresh weight, each) and their effect on
available-N, soil water storage (SWS), and plant growth were assessed over time. Two native grass species, *Panicum virgatum* and *Sorghastrum nutans*, that attained favorable rates of transpiration in a previous greenhouse experiment were grown in the soil treatments to determine whether the organic materials affected biomass and leaf area. All of the treatments that used the organic materials increased SWS. When compared to the control, the treatments using sawdust had significantly (p < 0.05) lower levels of available N, total biomass, and leaf area; the treatments using peat moss had increased levels of available N, total biomass, and leaf area. The findings suggest that (i) peat moss and sawdust are suitable amendments to increase the SWS, (ii) sawdust had the potential to decrease available N, and (iii) peat moss had the potential to increase plant growth. Currently, we are evaluating the ability of dredged sediment that has been amended with peat moss (6.5% fresh weight) to limit percolation through model ET covers in field lysimeters. Utilizing this manufactured soil to construct an ET cover that is 1.4 m in depth at a landfill that is 85 acres would use approximately 62% of the volume that is annually dredged from the Port of Toledo.
3.1 Introduction

Landfills represent potential sites where significant areas of land may be restored to native habitat. However, the closure requirements for landfills usually include a final cover system that consists of (i) a barrier layer using materials with low permeability (e.g. compacted clay and plastic liner) to limit the percolation of water into the underlying waste and (ii) a mixture of grasses to prevent soil erosion (USEPA 1993). This type of cover, known as a conventional cover, may restrict the downward extension of plant roots due to high soil compaction, an occurrence that occurs in agricultural fields (Hussan et al. 2007; Whalley et al. 1995). Conventional covers may also alter the soil hydrology in order to enhance surface runoff (USEPA 1993), thus, making habitat restoration difficult to achieve.

My research has focused on the hypothesis that the restoration of native habitat on landfills may be achieved using evapotranspiration (ET) covers that simulate natural soil conditions. Recently, ET covers have gained considerable interest as an alternative to conventional covers, because they are less costly to construct (Dwyer 1998; Hauser et al. 2001) and have a longer lifespan (Hauser 2009). ET covers consist of soil and plants that function to limit percolation by storing water in the soil layer until it is either evaporated from the surface or transpired by plants. Fine-grained soils (e.g. loam, silt loam, silty clay) are used to construct ET covers (Gurdal et al. 2003), because they can store greater volumes of water than coarser-grained soils. The thickness of the soil layer(s) for the cover varies depending on the amount of water that must be stored. For example, ET covers in humid regions need to be thicker than covers in arid and semiarid regions (Albright et al. 2004) to accommodate the greater volumes of precipitation to be stored.
The types of plants used for ET covers may include native annual and perennial grasses, forbs, and shrubs (Bolen et al. 2001; Roesler et al. 2002; Rock 2003; Albright et al. 2004). Utilizing several types of plants (e.g. grasses, forbs, and legumes) increases diversity and stability (Tilman et al. 2006), which contrasts the conventional covers that commonly use a mixture of grasses.

The primary goal of my research is to assess the suitability of using ET covers for landfills in northwest Ohio to limit the rate of the percolation to less than 32 cm yr\(^{-1}\) (OEPA 2003). As part of this goal, I am attempting to use the ET covers to restore native habitat in the region, because there is only a small percentage of natural green space that remains today (Green Ribbon Initiative 2004).

Northwest Ohio receives high rates of precipitation (83 cm, annual mean), which means that large amounts of water will need to be stored in the soil layer of the cover. Sediment dredged from the Port of Toledo, which is located in Lake Erie and the Maumee River, is favorable to construct the ET covers because it is a loam, which suggests that it has a high soil water storage (SWS) capacity, and is readily available in significant volumes. The U.S. Army Corps of Engineers (USACE) annually removes 1,000,000 yd\(^3\) of sediment from the port, most of which is placed offshore in Lake Erie, and the rest into a confined disposal facility (CDF). Like many other CDFs, this one is nearing its volumetric capacity and beneficial re-uses for the sediment are needed to further extend its lifespan.

One approach that has successfully re-used a significant volume of the sediment from the CDF is the creation of a fertile soil for landscaping. On the CDF, the sediment is dewatered and amended with sewage sludge from a wastewater treatment plant (13%
dry weight) and lime sludge from a drinking water treatment plant (2% dry weight) to create a nutrient-rich soil (Stanley Perry, personal communication 2006). However, the high level of available nitrogen (N) (56 ppm NO$_3^-$) in the soil, in contrast to low levels of available N, such as that measured (2.55 ppm) in the field plots during 2004 at the University of Minnesota Cedar Ecosystem Science Reserve, Minnesota, USA, makes the soil vulnerable to weed invasion (Davis et al. 2000; Maron and Jeffries 2001; Blumenthal et al. 2003) thereby reducing the success of native species establishment and hindering restoration.

Organic materials have been used to effectively slow down the invasion of weeds and increase the success of native species in the restoration of prairies (Blumenthal et al. 2003; Averett et al. 2004). The addition of organic material to soil increases the soil C:N ratio, which induces soil microbes to immobilize plant-available N, in the forms of NO$_3^-$ and NH$_4^+$. This decrease in available N has been shown to reduce the growth of nitriphilic weeds and releases native species from competitive exclusion (Morgan 1994; Corbeels et al. 2000; Török et al. 2000). The addition of organic material also has been used to increase the SWS (Gupta et al. 1977; Gupta and Larson 1979; Saxton et al. 2005), which in turn is favorable for an ET cover. For example, Li et al. (2004) increased the SWS of a sandy soil nearly 300% by applying Sphagnum peat at rates of 48 and 68 Mg ha$^{-1}$; Averett et al. (2004) increased the moisture content of a silty clay loam by 27% using 6 kg m$^{-2}$ hardwood sawdust. Thus, organic amendments are a potential strategy to reduce the invasion of weedy plants, facilitate native species establishment, and increase the SWS for ET covers.
This paper reports the results of a greenhouse study used to quantify the effect of the addition of organic material, in the forms of peat moss (Sphagnum) and sawdust (Quercus), on the water storage, available N, and plant growth in a nutrient-rich soil for constructing ET covers. The effects were quantified by measuring the growth (biomass and leaf area) of two native plant species after seven weeks and the properties of the manufactured soils. The organic material(s) that increase both SWS and plant growth were preferred for an ET cover; the reduction in available N was considered a beneficial extension.
3.2 Materials and Methods

3.2.1 Plant species and growing materials

Seeds of *Panicum virgatum* [switch grass] and *Sorghstrum nutans* [Indian grass], two species that are native to northwest Ohio were purchased from the Ohio Prairie Nursery (Hiram, OH). These species were selected because they attained favorable rates of transpiration in a greenhouse study (see Chapter 4) and will be incorporated into the model ET covers. The soil created by S&L Fertilizer (Oregon, OH) using the dredged sediment was obtained from the Toledo Port Authority Facility 3 - Corps of Engineers Dredged Disposal Containment Area (41° 42’ 12” N, 83° 26’ 01” W). Peat moss (*Sphagnum*, The Scotts Company) was purchased from a commercial store, it has 79.48% organic matter content; sawdust (*Quercus*) was collected from a recently sanded hardwood floor, it has 96.57% organic matter content. These materials were air-dried and separately added to the created soil (0, 6.5, 13% fresh weight) and in combination (3.25, 6.5% fresh weight, each). Materials were weighed in plastic beakers and placed into buckets, mixed thoroughly, then packed into plastic pots (10.5 cm diameter, 9 cm tall) to a bulk density of 1.0 g cm\(^{-3}\).

3.2.2 Greenhouse procedures

In each of the seven manufactured soils (control, dredged sediment with peat moss 6.5%, dredged sediment with peat moss 13%, dredged sediment with sawdust 6.5%, dredged sediment with sawdust 13%, dredged sediment with peat moss 3.25% and sawdust 3.25%, and dredged sediment with peat moss 6.5% and sawdust 6.5%) two plant species that were seven weeks old (*P. virgatum* and *S. nutans*, one individual, each) were
transferred into the soil treatments (n = 5) and grown for seven weeks in a greenhouse; there were five replicates per treatment with no plants. All pots were randomly arranged on a table weekly and irrigated every other day with tap water (approximately 75 ml). During the experiment (7 January to 15 April 2009), the greenhouse temperature ranged from (18-25 ºC), with 16 hours of light (mean photosynthetic active radiation 350 µmol m⁻² sec⁻¹), and the relative humidity ranged from 25% - 50%.

3.2.3 Soil analyses

The effects of the organic materials on SWS and nutrient content were evaluated in pots without plants (three replications per treatment). This was done to prevent the plants from affecting the soil properties, such as increasing organic matter content from root growth or reducing nutrient content from acquisition. The soil in these pots was homogenized and approximately 500 g were sent to a soil testing laboratory (Spectrum Analytic, Washington Court House, OH) and analyzed for organic matter content (loss on ignition, 440°C), pH (1:1), extractable Ca as Ca²⁺, Mg as Mg²⁺, P as P₂O₅, K as K₂O (Mehlich 1984), CEC (summation of extractable cations from Mehlich 1984), and extractable N as NO₃⁻ (ion selective electrode). The soil water storage capacity was estimated using a pedotransfer function that required percentages for sand, silt, clay, and organic matter content (Saxton et al. 2005).

3.2.4 Quantification of Plant Growth

Plants were harvested after seven weeks (on 15 April 2009) and evaluated for height, biomass (total, root, and shoot), and leaf area (n = 5). These growth parameters
were measured because they influence transpiration, which is the essential process to remove water that is stored in the soil layer(s) of an ET cover. The shoots for each species was separated into stems and leaves, but the roots for each species could not be distinguished from one another, therefore sorted roots represented the whole pot. Leaves were photographed using a digital camera (Powershot 10.0-Megapixel, Canon, USA, Inc.) and the leaf area was measured using Assess: Image Analysis Software for Plant Disease Quantification (APS Press, St. Paul, MN). All plant material was oven dried at 60°C for 48 hours and weighed.

### 3.2.5 Statistical analysis

The effects of the organic materials on soil properties and plant growth were analyzed by performing one-way ANOVA with a Tukey posttest. (SAS, Statistical Analysis System, North Carolina); p < 0.05 was used to determine a significant difference between treatments.
3.3 Results and Discussion

3.3.1 Organic material effect on organic matter and soil water storage

As expected, each of the organic materials increased the soil organic matter (SOM). Significant (p < 0.05) increases were observed for the treatments using the low and high additions of sawdust, the high addition of peat moss, and the combined treatment using the high addition of peat moss and sawdust (Table 3.1). Indeed, the effects of the organic materials on SWS were similar to those observed for SOM. The treatments using the high additions of sawdust had the greatest increases in SWS, followed by the treatments using the high addition of peat moss and low addition of sawdust (Table 3.1). These results were encouraging, and the addition of sawdust was considered more favorable than peat moss to increase the water storage of the soil for constructing ET covers.

3.3.2 Organic material effect on available nitrogen

There was variation in the effects of the organic materials on available N (NO$_3^-$), whereas peat moss increased N, sawdust decreased N; the high addition of peat moss was the only treatment to significantly increase N (Table 3.1). These results were in contrast to Li et al. (2004) that observed a decrease in available N from the incremental addition of peat moss (0 to 68 Mg ha$^{-1}$ 3-yr$^{-1}$) to a sandy soil. Significant decreases in N were observed for the treatments using the low and high addition of sawdust and the combined treatment using the addition of peat moss and sawdust. These results were similar to Blumenthal et al. (2003) that observed a decrease in available N from the addition of sucrose plus sawdust (3346 g C m$^{-2}$) to a silt loam and Averett et al. (2004) that observed
Table 3.1: Characteristics of the base soil (Nu-soil) and treatments. Values are the means ± SD, n = 3. Different superscript letters indicate a significant difference (p < 0.05) between soil treatments: control; PM6.5, dredged sediment with peat moss 6.5%; PM13 dredged sediment with peat moss 13%; SD6.5, dredged sediment with sawdust 6.5%; SD13, dredged sediment with sawdust 13%; PMSD6.5, dredged sediment with peat moss 3.25% and sawdust 3.25%; and PMSD13, dredged sediment with peat moss 6.5% and sawdust 6.5%.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Soil Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
</tr>
<tr>
<td>pH</td>
<td>7.27 (0.1)A</td>
</tr>
<tr>
<td>Organic Matter (%)</td>
<td>8.0 (0.2)C</td>
</tr>
<tr>
<td>CEC (meq/100g)</td>
<td>18.6 (0.5)BC</td>
</tr>
<tr>
<td>Extractable Nutrients</td>
<td></td>
</tr>
<tr>
<td>Ca²⁺ (ppm)</td>
<td>7106 (301)A</td>
</tr>
<tr>
<td>Mg²⁺ (ppm)</td>
<td>368 (11)A</td>
</tr>
<tr>
<td>NO₃⁻ (ppm)</td>
<td>56 (21)B</td>
</tr>
<tr>
<td>P₂O₅ (ppm)</td>
<td>354 (18)A</td>
</tr>
<tr>
<td>K₂O (ppm)</td>
<td>251 (14)A</td>
</tr>
<tr>
<td>Available Water (cm³/cm³)</td>
<td>0.17 (0)C</td>
</tr>
</tbody>
</table>
a decrease in available N from the addition of sawdust (6 kg m$^{-2}$) to a silty clay loam. These findings suggest that the type of organic material is a major factor that influences available N, and that the soil type may be an important factor that affects the ability of organic materials (especially peat moss) to decrease available N.

3.3.3 Organic material effect on soil properties

The treatment using the high addition of peat moss was the only treatment that had an effect on pH, in which it significantly decreased pH. All of the other treatments had no effect on pH. Each treatment using peat moss, including the combined treatments, increased CEC, while the treatments using sawdust decreased CEC. Each of the treatments using an organic material decreased Ca$^{2+}$; the treatments using sawdust and the combined treatment using the high addition of peat moss and sawdust significantly decreased Mg$^{2+}$. Each treatment, except the low addition of peat moss, significantly decreased P$_2$O$_5$, and all of the treatments using the organic materials significantly decreased K$_2$O. These findings suggest that the organic materials may have variable affects on many soil properties, including the essential nutrients for plant growth and pH.

3.3.4 Organic material effect on plant growth

The effects of the organic materials on plant growth were similar to their effects on available N. The treatments using peat moss increased plant growth (biomass and leaf area) and the treatments using sawdust decreased plant growth (Figure 3.1). The total biomass per pot increased from the treatments using peat moss and significantly decreased from the treatments using sawdust and the combination treatment using the
Figure 3.1: Effect of soil treatments on plant growth (total biomass and leaf area) per pot. Bars are means ± SD, n = 5. Different letters indicate a significant difference (p < 0.05) between soil treatments: control; PM6.5, dredged sediment with peat moss 6.5%; PM13, dredged sediment with peat moss 13%; SD6.5, dredged sediment with sawdust 6.5%; SD13, dredged sediment with sawdust 13%; PMSD6.5, dredged sediment with peat moss 3.25% and sawdust 3.25%; and PMSD13, dredged sediment with peat moss 6.5% and sawdust 6.5%.

High addition of peat moss and sawdust; the combined treatment using the low addition of peat moss and sawdust also decreased total biomass. As expected, the root biomass increased from the treatments using peat moss and decreased from the treatments using sawdust and the combined treatments (Table 3.2). Total leaf area increased from the treatments using peat moss, decreased from the combination treatments, and significantly decreased from the treatments using sawdust. There was variation in the effects of the
organic materials on the growth of the individual plant species: *P. virgatum* and *S. nutans* (Table 3.2). For *P. virgatum*, the shoot biomass and leaf area increased from the treatments using peat moss and significantly decreased from the treatments using sawdust; the combination treatments had no effect. Each of the organic materials had no effect on the height of the species. For *S. nutans*, the shoot biomass increased from treatments using peat moss, and deceased from the treatments using sawdust and from the combination treatment using the high addition of peat moss and sawdust. Each of the organic materials had no effect on height or leaf area of the species.

### 3.3.5 Considerations for an ET cover

ET covers rely on SWS and plant transpiration to limit percolation to allowable rates. Thus, it is necessary that these processes be maximized for ET covers to effectively function in regions that receive high rates of precipitation, such as northwest Ohio. As expected, the organic materials used in this study all increased the SWS of the created soil that incorporated dredged sediment. However, the treatments using sawdust decreased available N, which was intended, but these treatments also decreased the growth of the native plants, which suggests that the rate of transpiration also would decrease from the addition of sawdust because it is a function of biomass (Ben-Gal et al. 2003) and leaf area (Vertessy et al. 1995; Cortina et al. 2008). In contrast to the sawdust, the peat moss increased available N and plant growth, which means that it also would increase transpiration. Based on these findings, peat moss was considered to be a suitable amendment for soil to construct an ET cover. However, peat moss is an expensive material (approximately $5.00 per 2 ft\(^3\) at many home gardening stores) when not readily
Table 3.2: Effect of soil treatments on plant growth per pot and per species. Values are the means + SD, n = 5. Different superscript letters indicate a significant difference (p < 0.05) between soil treatments: control; PM6.5, dredged sediment with peat moss 6.5%; PM13 dredged sediment with peat moss 13%; SD6.5, dredged sediment with sawdust 6.5%; SD13, dredged sediment with sawdust 13%; PMSD6.5, dredged sediment with peat moss 3.25% and sawdust 3.25%; and PMSD13, dredged sediment with peat moss 6.5% and sawdust 6.5%.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>PM6.5</th>
<th>PM13</th>
<th>SD6.5</th>
<th>SD13</th>
<th>PMSD6.5</th>
<th>PMSD13</th>
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<tbody>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root biomass (g)</td>
<td>0.13 (0)^AB</td>
<td>0.19 (0)^A</td>
<td>0.20 (0.1)^A</td>
<td>0.07 (0)^BC</td>
<td>0.04 (0)^C</td>
<td>0.13 (0)^AB</td>
<td>0.10 (0)^BC</td>
</tr>
<tr>
<td>Root : shoot</td>
<td>0.30 (0.1)^B</td>
<td>0.39 (0.1)^AB</td>
<td>0.33 (0.1)^B</td>
<td>0.52 (0.1)^AB</td>
<td>0.45 (0.2)^AB</td>
<td>0.40 (0.2)^AB</td>
<td>0.63 (0.1)^A</td>
</tr>
<tr>
<td><strong>Panicum virgatum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoot biomass (g)</td>
<td>0.27 (0.1)^ABC</td>
<td>0.36 (0.3)^AB</td>
<td>0.37 (0.2)^A</td>
<td>0.07 (0)^C</td>
<td>0.05 (0)^C</td>
<td>0.23 (0.2)^ABC</td>
<td>0.08 (0)^BC</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>40.51 (9.4)^AB</td>
<td>38.61 (21.1)^AB</td>
<td>44.71 (12.2)^A</td>
<td>23.50 (5.4)^AB</td>
<td>18.80 (3.9)^B</td>
<td>41.66 (7.6)^A</td>
<td>25.72 (9.1)^AB</td>
</tr>
<tr>
<td>Leaf area (cm²)</td>
<td>24.97 (12)^ABC</td>
<td>27.71 (19.1)^AB</td>
<td>39.61 (17.2)^A</td>
<td>3.60 (1.7)^C</td>
<td>3.48 (1.1)^C</td>
<td>15.78 (11.1)^BC</td>
<td>6.73 (3.7)^BC</td>
</tr>
<tr>
<td><strong>Sorghastrum nutans</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Shoot biomass (g)</td>
<td>0.14 (0.1)^AB</td>
<td>0.15 (0.1)^AB</td>
<td>0.23 (0.1)^A</td>
<td>0.06 (0)^B</td>
<td>0.04 (0)^B</td>
<td>0.14 (0.1)^AB</td>
<td>0.07 (0)^B</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>30.17 (10.5)^AB</td>
<td>35.94 (12.7)^A</td>
<td>34.80 (7.9)^AB</td>
<td>23.42 (6.6)^AB</td>
<td>17.08 (4.3)^C</td>
<td>27.94 (5.6)^AB</td>
<td>24.32 (10.7)^AB</td>
</tr>
<tr>
<td>Leaf area (cm²)</td>
<td>9.53 (6.7)^A</td>
<td>10.38 (8.3)^A</td>
<td>14.04 (7.7)^A</td>
<td>4.57 (2.8)^A</td>
<td>2.54 (1.1)^A</td>
<td>8.81 (7.1)^A</td>
<td>5.88 (4)^A</td>
</tr>
</tbody>
</table>
available, which suggests that it may not be feasible to incorporate into the construction of ET covers in many areas. Rather, additional types of organic material that are less costly should be assessed for their effect on SWS and plant growth, and available N as well. For example, *Phragmites australis* [common reed], an invasive plant that has taken over many areas along the coastline of Lake Erie may attain a high aboveground biomass (2 kg m\(^{-2}\), Windham 2001) and is readily available at a low cost.

Restoration of native habitat on landfills is a secondary goal for using the ET covers. Thus, the establishment of native plant species is desired. The fact that peat moss increased available N, which suggests that its incorporation into the soil used for constructing the covers may promote the invasion of weedy species, can be ameliorated by using it in the sub-soil. Applying a layer of topsoil over a soil that has been amended with peat moss would restrict the uptake of increased available N to those plant species that are able to extend their roots to the depths where it is located. Since, many weedy species are characterized by rapid growth rate, a short life span, and abundant seed production (MacArthur and Wilson 1967; Odum 1969; Grime 1977), they may not invest the energy in root growth that is necessary to obtain the available N in the deeper soil. As a result, the slower-growing native plants that invest their energy in future growth (Odum 1969) may acquire the available nutrients in the deeper depths of the soil and eventually exclude the weedy species that have established in the topsoil.

### 3.4 Extending the Lifespan of the Confined Disposal Facility

The construction of ET covers using dredged sediment is a potential strategy to beneficially re-use significant volumes of sediment that have been placed into the CDF
and further extend its lifespan. The CDF has a volumetric capacity of 16,400,000 yd$^3$ and it is expected that capacity will be reached within five to ten years (www.lre.usace.army.mil/greatlakes/navigation). Constructing an ET cover with the dredged sediment to a depth of 1.4 m (Barnswell and Dwyer in review) for a landfill that is 85 acres would use approximately 620,000 yd$^3$, which is about 4% of the capacity for the CDF and 62% of the volume that is annually dredged from the Port of Toledo. This would extend the lifespan of the CDF and in turn, save money that would have been spent on the construction of a new CDF.

3.5 Conclusion

After reviewing published studies on the beneficial re-use of dredged sediment, I can state that this study represents the first time that dredged sediment has been modified for the construction of ET covers. Since the dredged sediment is readily available on the CDF in significant volumes and has a relative low cost, ET covers may be constructed at landfills in the region at a fraction of the cost of conventional covers. In addition, utilizing considerable portions of the sediment from the CDF will extend its lifespan and save the additional costs that would be spent on the construction of a new facility.
References


Windham, L. (2001). Comparison of biomass production and decomposition between Phragmites australis (common reed) and Spartina patens (salt hay grass) in brackish tidal marashes of New Jersey, USA. Wetlands, 32: 179-188.
Chapter 4

Transpiration Rates of Candidate Plant Species for a Landfill Evapotranspiration Cover in Northwest Ohio

Abstract:

The overall goal is to design final covers for landfills that produce allowable rates of percolation and use native plants to restore habitat. Evapotranspiration (ET) covers may achieve this, but require a judicious mixture of native plant species to maximize transpiration \( (E) \) throughout the growing season. In this study, I evaluated the rate of \( E \) for 10 candidate plant species that are prevalent in northwest Ohio and make their growth during either the early, mid, or late months of the growing season. I conducted a greenhouse experiment to estimate \( E \) at the whole-plant level and identify relationships between \( E \) and plant phenotypic traits, and a field experiment to compare the effects of two soils that are suitable for constructing ET covers on \( E \) at the leaf-level and plant growth.

In the greenhouse, I grew *Achillea millefolium*, *Danthonia spicata*, *Eupatorium altissimum*, *Lespedeza capitata*, *Panicum virgatum*, *Rudbeckia hirta*, *Solidago canadensis*, and *Sorghastrum nutans*, and estimated \( E \) over three consecutive days during weeks 6, 10, and 14 from the time of seed germination by the change of pot mass from
the previous day; control pots containing no plants were used to measure evaporation. In the field, I grew *Andropogon gerardii*, *Elymus virginicus*, and *R. hirta* in a loam and clay loam and estimated $E$ on several sampling dates during the growing season from measured stomatal conductance and meteorological parameters.

In the greenhouse, *R. hirta* attained the highest $E$ (cm H$_2$O cm$^-2$ day$^-1$) during week 6 (0.12 ± 0.02), and *P. virgatum* attained the highest $E$ during weeks 10 and 14 (0.09 ± 0.04 and 0.31 ± 0.17, respectively). There were positive correlations between $E$ and total biomass ($r^2 = 0.59$) and green leaf area ($r^2 = 0.60$), which were greatest for *P. virgatum*. In the field, *A. gerardii* attained the highest $E$ (mmol m$^-2$ sec$^-1$) in the loam (7.78 ± 2.48) and *E. virginicus* attained the highest $E$ (9.95 ± 2.17) in clay loam. The highest $E$ recorded on a sampling date was for the individuals grown in the clay loam: *E. virginicus* (12.55 ± 3.27), *A. gerardii* (11.79 ± 2.96), and *R. hirta* (5.70 ± 0.38). The clay loam had a significant effect ($p < 0.05$) on the growth (total mass and green leaf area) of *A. gerardii* and the loam had a significant effect on the growth of *E. virginicus*; no differences were observed for *R. hirta*.

These experiments were an effective method to estimate $E$ and compare the suitability of candidate plant species for an ET cover. The results suggest that the following species be used to maximize transpiration throughout the growing season: *A. millefolium* and *E. virginicus* in the spring, *P. virgatum* in the summer, and *A. gerardii* and *S. canadensis* into the fall. Thus, it is possible to create a plant mixture that maximizes transpiration throughout the growing season and that may facilitate habitat restoration:
4.1. Introduction

Evapotranspiration (ET) covers may be used for the final closure of landfills when they demonstrate equivalent performance, in terms of percolation to conventional covers (USEPA 1993). They consist of soil and plants and function to minimize the percolation of water into underlying waste using two natural processes (Hauser 2009): soil water storage and the combination of surface evaporation and transpiration ($E$) by plants. ET covers produce percolation when the soil water storage capacity is exceeded, which results from constructing them with soil that has an insufficient water storage capacity and/or using a mixture of plant species that is unable to remove soil water at sufficient rates.

The maximum performances of ET covers may be attained when the $E$ potential is the greatest. This is because water may be removed from the soil layer at sufficient rates to provide adequate storage space for the forthcoming precipitation events. Several factors affect $E$ including plant species (Körner et al. 1979) and their physical characteristics such as biomass (Ben-Gal et al. 2003) and leaf area (Vertessy et al. 1995; Cortina et al. 2008), water availability (Turner et al. 1985; Tanguilig et al. 1987) and meteorological variables (e.g. humidity, solar radiation, temperature, and wind speed, Montero et al. 2001). Aside from precipitation, the most important factor that influences the amount of water available for plant uptake is the soil. In general, clayey soils have a greater water storage capacity than silty or sandy soils, but silty soils have the greatest water content that is available to plants (Brady and Well 2002). This is because clayey soils consist of very fine micropores that store large volumes of water, but plants are unable to draw water from these pores because it is held so strongly; sandy soils consist
of macropores that are unable to store water against the force of gravity, which results in the downward percolation of water at rates faster than plants are able to utilize the water. Silty soils consist of pore sizes in between the extremes of clayey and sandy soils so that water is retained against the force of gravity but not too strongly that plants are unable to draw the water from them.

A mixture of native plants that include cool- and warm-season species is commonly used for ET covers because the plants are adapted to the regional climate and will function throughout the growing season (Hauser et al. 2001; Albright and Benson 2002; Rock 2003). The types of plants that have been previously used for ET covers include annual and perennial graminoids, forbs, shrubs, and hybrid poplars (Bolen et al. 2001; Roesler et al. 2002; Albright et al. 2004). In general, herbaceous species, i.e. graminoids and forbs, are preferred to woody species because they provide optimum soil erosion control. However, a major factor that is often overlooked when selecting plants for an ET cover is the $E$ potential of the species. Transpiration affects the performance of an ET cover since it is the primary mechanism to remove water that is stored in the soil layer; the other mechanism is surface evaporation. Thus, it is uncertain as to whether the plant species that have previously been used for ET covers were the most appropriate in terms of removing soil water.

There is little information in the literature regarding the rates of $E$ by plant species. Estimating the $E$ potential of candidate plants for an ET cover may be an effective strategy to identify the most appropriate species to optimize soil water removal throughout the growing season. In this study, the $E$ potentials of 10 candidate herbaceous plant species for a landfill ET cover in northwest Ohio were evaluated. The native plants
included cool- and warm-season species that were selected based on their prevalence in regional plant communities (Easterly 1973; Brewer and Vankat 2004) and at the landfill where an ET cover is considered (Barnswell and Dwyer 2007). The first objective of this study was to gain information about which plant species had the greatest $E$ potential. The second objective was to identify relationships between $E$ and plant growth to determine if phenotypic traits may be an indicator of the $E$ potential of plants. The third objective was to evaluate $E$ and the plant growth for species grown in two soils (clay loam and loam) that are suitable for constructing an ET cover. Having identified the plant species with the highest rates of $E$ and the soil that promotes the greatest $E$ and plant growth, an ET cover can be designed and tested.
4.2 Materials and Methods

Two separate experiments were conducted in this study: a greenhouse experiment was used to evaluate the whole-plant transpiration ($E$) potential for eight species and to identify relationships between $E$ and plant growth, and a field study was used to evaluate the effects of two soils (clay loam and loam) that are suitable for an ET cover on $E$ and plant growth.

4.2.1 Greenhouse experiment

4.2.1.1 Plant species and growing conditions

Eight plant species were used in this experiment: *Achillea millefolium* [yarrow, cool-season forb], *Danthonia spicata* [poverty grass, cool-season graminoid], *Eupatorium altissimum* [tall boneset, warm-season forb], *Lespedeza capitata*, [round headed bush-clover, warm-season legume], *Panicum virgatum* [switch grass, warm-season graminoid], *Rubeckia hirta* [black-eyed susan, cool-season forb], *Solidago canadensis* [Canada goldenrod, warm-season forb], and *Sorghastrum nutans* [Indian grass, warm-season graminoid].

This experiment was conducted in a greenhouse from 5 May 2008 through 15 August 2008. Conditions were set at a 16:8 hr light:dark period, mean air temperature of 28 °C, mean relative humidity of 50%, and mean light level at 600 µmol m$^{-2}$ sec$^{-1}$ of photosynthetic active radiation (PAR) (Figure 4.1). The seeds of the plant species were sown into LC-1 Horticubes (Oasis Growing Medium, Smithers-Oasis, USA). When seeds germinated and roots were visible from the bottom of the growing medium (approximately three weeks after seeds were sown), twenty individuals of each plant
Figure 4.1: Greenhouse conditions. *Top,* photosynthetic active radiation (µmol m\(^{-2}\) sec\(^{-1}\)); *Middle,* temperature (°C); *Bottom,* relative humidity (%). Values are the mean and range for three measurements taken at midday during the weeks that transpiration was estimated.
species were transferred into plastic pots (10.5 cm diameter, 9.0 cm depth), one individual per pot, filled with Sunshine Mix 1, a growing medium containing 70-80% Canadian Sphagnum peat moss, perlite, dolomite limestone, and gypsum, but no added nutrients (Sun Gro, Canada). The pots were placed onto tables, randomized weekly, and irrigated (50 ml) every other day by alternating the use of tap water and a modified Hoagland nutrient solution (Rofkar et al. 2007).

4.2.1.2 Estimating rates of transpiration

Rates of transpiration were estimated for three consecutive days during weeks 6, 10, and 14 from the time the plant species were transferred into the pots (Table 4.1). The rates of \( E \) for many plant species were not estimated during the same calendar week, i.e. not on the same Julian days. This is because the time required for seed germination and root development varied between plant species and not all of the species were sown into the Horticubes on the same date. All pots containing plants and five control pots (containing Sunshine Mix 1 but no plants) were watered to soaking on the first day of the week that rates of \( E \) were to be estimated and were then weighed (to the nearest 0.2 g) 24 hrs later. At this time, all pots were considered to be at field capacity and no additional irrigation was applied. The control pots were used to determine evaporation. All pots were weighed daily between 1400 and 1600 hrs EST. The rate of \( E \) was calculated as the difference in mass from the previous day (Nable et al. 1999) while adjusting for the mass lost by evaporation from the control pots.
Table 4.1: Sampling dates that transpiration was estimated for the plant species grown in the greenhouse experiment.

<table>
<thead>
<tr>
<th>Plant Species</th>
<th>Week 6</th>
<th>Week 10</th>
<th>Week 14</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Solidago canadensis</em></td>
<td></td>
<td></td>
<td>8/13 – 8/15</td>
</tr>
</tbody>
</table>

4.2.1.3 Quantification of plant growth

After rates of $E$ were estimated, five random individuals of each plant species were selected for harvest. This resulted in the total number of individuals of each plant species to decrease in the following weeks that $E$ was estimated, while the number of control pots remained constant. Harvesting consisted of separating the selected plants into leaves, stems, and roots. The green leaf area was determined immediately to prevent wilting and rolling of leaves by photocopying the leaves on paper. The silhouette of the leaves on the paper was cut out and weighed, and values for leaf area were calculated by converting the paper mass of the leaf silhouette from a weighed reference area of the same paper material (Guo et al. 2002). Roots were separated from the bulk part of the growing medium then rinsed with tap water over a 0.5 mm sieve to remove any additional growing medium. All plant tissues were dried at 65 °C for 48 hrs and weighed to determine dry mass.
4.2.2 Field experiment

4.2.2.1 Plant species and growing conditions

Three plant species were used in this experiment: *Andropogon gerardii* [big bluestem, warm-season graminoid], *Elymus virginicus* [Virginia wildrye, cool-season graminoid], and *R. hirta*.

Two soils (clay loam and loam) that are representative of soils that have been used for ET covers (Gurdal et al. 2003) were used in this experiment. The soils were obtained from field sites within the region. The clay loam was collected from the surface (0 – 10 cm) of a mesic forest (41° 41’ 16” N, 83° 23’ 47” W) dominated by *Acer saccharinum* [silver maple]. The loam was collected from the Toledo Port Authority Facility 3 – Corps of Engineers Dredged Disposal Containment Area (41° 42’ 12” N, 83° 26’ 01” W) and consists of dredged sediment (85% DWT), sewage sludge (13% DWT), and lime sludge (2% DWT). Approximately 500 g (n=3) of each soil were sent to a soil-testing laboratory (Spectrum Analytic, Washington Court House, OH) and analyzed for particle size (Day 1965), pH (1:1), organic matter content (loss on ignition, 360 °C), and extractable nutrients (Mehlich 1984): Ca, P, Mg, and K (Table 4.2).

4.2.2.2 Field procedure

The soils were loosely packed into pipes (PVC, 8.9 cm diameter x 55.6 cm depth) to a depth of 51 cm at a bulk density of 1.1 g cm$^{-3}$ (fresh weight). The pipes were placed side by side into trenches (51 cm depth) in a systematic block design, and then backfilled with the sandy soil excavated to dig the trenches so they would remain in a vertical
position. By placing the pipes into the ground, natural microclimate (e.g. air temperature, solar radiation and wind speed) was maintained.

Table 4.2: Chemical and physical properties of the soil treatments in the field experiment. Values are the means + SD; n=3.

<table>
<thead>
<tr>
<th>Property</th>
<th>Loam</th>
<th>Clay loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.7 (0.0)</td>
<td>6.9 (0.1)</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td>3.8 (0.4)</td>
<td>2.6 (0.3)</td>
</tr>
<tr>
<td>P as P$_2$O$_5$ (ppm)</td>
<td>162 (7.0)</td>
<td>23 (1.0)</td>
</tr>
<tr>
<td>Mg as Mg$^{2+}$ (ppm)</td>
<td>2624 (104)</td>
<td>658 (44)</td>
</tr>
<tr>
<td>Ca as Ca$^{2+}$ (ppm)</td>
<td>16167 (582)</td>
<td>4391 (277)</td>
</tr>
<tr>
<td>K as K$_2$O (ppm)</td>
<td>132 (24)</td>
<td>194 (16)</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>45 (5.8)</td>
<td>32 (3.6)</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>40 (1.0)</td>
<td>33 (2.8)</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>15 (4.6)</td>
<td>35 (1.4)</td>
</tr>
<tr>
<td>Wilting point (cm$^3$ cm$^{-3}$)</td>
<td>12</td>
<td>22</td>
</tr>
<tr>
<td>Field capacity (cm$^3$ cm$^{-3}$)</td>
<td>26</td>
<td>36</td>
</tr>
<tr>
<td>Available water (cm$^3$ cm$^{-3}$)</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

On 6 June 2009, several seeds of the plant species were sown into the soils of the pipes and covered with 1 cm of peat moss to prevent desiccation. The pipes were thinned to one individual plant approximately three weeks later to eliminate competition for nutrients, water, and sunlight. Plants were grown under ambient conditions in northwest Ohio and approximately 50 ml of tap water was applied to each pipe during periods of drought when there was no precipitation received for more than three days.
4.2.2.3 **Estimating rates of transpiration**

Transpiration was calculated using a series of equations that required the measurement of stomatal conductance ($g_s$) and several meteorological parameters (Decagon Devices 2008). A portable steady state diffusion porometer (Model SC-1 Leaf Porometer, Decagon Devices, Pullman, WA) was used to measure $g_s$ on fully expanded leaves of the plant species several times during the growing season, beginning once the leaves of the plant species were of adequate size (6 mm) for the leaf porometer. Measurements were made on clear days at ambient light and temperature between 1200 and 1500 hr EST. Air temperature, relative humidity (Digital Sling Psychrometer, AMPROBE, Columbus, OH), and solar radiation (Quantum Meter, Model BQM, Apogee Instruments, Logan, UT), were also recorded during the time that $g_s$ was measured; wind speed was assumed to be 0.001 m sec$^{-1}$ due to the leaf being enclosed within the chamber of the leaf porometer.

4.2.2.4 **Quantification of plant growth**

Plant species were harvested on 2 September 2009 and 3 November 2009. During the harvests, plants were separated into leaves, stems, and roots. Green leaf area was determined for each plant from digital photographs of detached leaves using Assess: Image Analysis Software for Plant Disease Quantification (APS Press, St. Paul, MN); root depth was measured. Plant tissues were then dried at 60 °C for 72 hrs and weighed to determine dry root and shoot biomass.
4.2.2.5 Quantification of soil water content

The gravimetric soil water content was determined at the time that plants were harvested. Approximately 10 grams of soil were collected from two depths - 15 cm and 38 cm – then weighed and dried at 105 °C for 24 hrs, and re-weighed.

4.2.3 Statistical analyses

In the greenhouse experiment, one-way analysis of variance (ANOVA) with a Tukey posttest (GraphPad Prism Version 5.0a, Graphpad Software, Inc., La Jolla, CA, USA) was used to test for significant differences between the plant species for growth: total mass and leaf area, whole-plant $E$, $E$ per gram of total mass, and $E$ per cm$^2$ of green leaf area. Spearman correlation analyses were made to test for relationships between $E$ and total biomass and green leaf area. In the field experiment, an analysis was conducted for each species to determine whether leaf gas exchange and growth differed as a function of the soil treatments. One-way ANOVA with a Tukey posttest was used to test for significant effects of soil type on $g_s$, $E$, and growth: shoot mass, root mass, total mass, root:shoot, green leaf area, root depth, and gravimetric water content.
4.3 Results

4.3.1 Greenhouse experiment

There was considerable variation in the transpiration \((E, \text{ cm H}_2\text{O cm}^{-2} \text{ day}^{-1})\) between the species at each sampling period (weeks 6, 10, and 14). \(R. \text{ hirta}\) attained the highest \(E\) during week 6 and \(P. \text{ virgatum}\) attained the highest \(E\) during weeks 10 and 14. \(E\) was expected to increase from week 6 to week 14 since it is a function of plant growth. Indeed, this was the trend for most of the plant species (Figure 4.2). However, some of the species attained their highest \(E\) during week 6 (\(L. \text{ capitata}\)) or week 10 (\(A. \text{ millefolium}\) and \(E. \text{ altissimum}\)); two species (\(D. \text{ spicata}\) and \(R. \text{ hirta}\)) had a decrease in \(E\) from week 6 to week 10, but attained their highest \(E\) during week 14. The inconsistency with the general trend between \(E\) and plant growth was due to fluctuations in the greenhouse conditions (e.g. relative humidity, solar radiation, and temperature) (Figure 4.1). Since the greenhouse conditions were not controlled, \(E\) was susceptible to being higher when air temperature and solar radiation increased and lower when air temperature and solar radiation decreased.

All of the plants increased in total mass and leaf area from week 6 to week 14 and there was a considerable variation between species (Table 4.3). \(P. \text{ virgatum}\) produced the greatest total mass and leaf area at each sampling period, while \(L. \text{ capitata}\) produced the least. There were positive correlations between \(E\) and total mass \((r^2 = 0.5897)\) and leaf area \((r^2 = 0.6027)\) and the highest \(E\) corresponded to the greatest total mass and leaf area (Figure 4.3). However, when comparing \(E\) per unit plant (e.g. gram of dry weight or cm\(^2\) of leaf surface area) the highest values were not attained from the species with greater total mass or leaf area. Rather, the \(E\) per gram of dry weight was highest for \(A.\)
*millefolium* during week 6, *L. capitata* during week 10, and *D. spicata* during week 14; 
$E$ per cm$^2$ leaf surface was highest for *R. hirta* during week 6 and *L. capitata* during weeks 10 and 14 (Table 4.3).

Figure 4.2: Rates of transpiration for plant species evaluated in the greenhouse experiment. Transpiration was estimated for three consecutive days during weeks 6, 10, and 14 from the time that plants were transplanted to pots. Values are the means + SD; n=3-20.

### 4.3.2 Field experiment

In general, *R. hirta* had higher stomatal conductance ($g_s$) than *A. gerardii* and *E. virginicus* on all of the sampling dates (Figure 4.4). There was no significant difference ($p < 0.05$) between the soil treatments for the $g_s$ of *A. gerardii*, but significant differences were observed for *E. virginicus* on two sampling dates and for *R. hirta* on one sampling date. During the growing season, $g_s$ increased for *A. gerardii*, but no trends were apparent for *E. virginicus* or *R. hirta*. The plants varied in $E$ (mmol H$_2$O m$^{-2}$ sec$^{-1}$).
Table 4.3: Plant growth at the time transpiration was estimated. Plants were harvested after transpiration was estimated for three consecutive days during the weeks 6, 10, and 14. Values are the means ± SD; n=3-5.

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Week 6</th>
<th></th>
<th></th>
<th>Week 10</th>
<th></th>
<th></th>
<th>Week 14</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Leaf</td>
<td>E per g</td>
<td>Total</td>
<td>Leaf</td>
<td>E per g</td>
<td>Total</td>
<td>Leaf</td>
<td>E per g</td>
</tr>
<tr>
<td></td>
<td>mass (g)</td>
<td>area (cm²)</td>
<td>(dwt)</td>
<td>mass (g)</td>
<td>area (cm²)</td>
<td>(dwt)</td>
<td>mass (g)</td>
<td>area (cm²)</td>
<td>(dwt)</td>
</tr>
<tr>
<td>Achillea millefolium</td>
<td>0.0047</td>
<td>2.86</td>
<td>0.0263</td>
<td>0.1909</td>
<td>46.05</td>
<td>0.1404</td>
<td>1.0419</td>
<td>104.15</td>
<td>0.1212</td>
</tr>
<tr>
<td></td>
<td>(0.0036)</td>
<td>(0.36)</td>
<td></td>
<td>(0.1238)</td>
<td>(24.42)</td>
<td></td>
<td>(0.4612)</td>
<td>(25.89)</td>
<td></td>
</tr>
<tr>
<td>Danthonia spicata</td>
<td>0.0217</td>
<td>4.10</td>
<td>0.0071</td>
<td>0.1134</td>
<td>23.56</td>
<td>0.1270</td>
<td>0.1753</td>
<td>20.97</td>
<td>0.1409</td>
</tr>
<tr>
<td></td>
<td>(0.0002)</td>
<td>(2.44)</td>
<td></td>
<td>(0.0934)</td>
<td>(18.54)</td>
<td></td>
<td>(0.0470)</td>
<td>(4.98)</td>
<td></td>
</tr>
<tr>
<td>Eupatorium altissimum</td>
<td>0.0337</td>
<td>2.50</td>
<td>0.0093</td>
<td>0.3628</td>
<td>61.47</td>
<td>0.2051</td>
<td>1.1143</td>
<td>105.55</td>
<td>0.0578</td>
</tr>
<tr>
<td></td>
<td>(0.0424)</td>
<td>(2.26)</td>
<td></td>
<td>(0.2041)</td>
<td>(37.70)</td>
<td></td>
<td>(0.0371)</td>
<td>(38.21)</td>
<td></td>
</tr>
<tr>
<td>Lespedeza capitata</td>
<td>0.0105</td>
<td>1.75</td>
<td>0.0136</td>
<td>0.0508</td>
<td>6.59</td>
<td>0.7047</td>
<td>0.0891</td>
<td>7.61</td>
<td>0.1639</td>
</tr>
<tr>
<td></td>
<td>(0.0049)</td>
<td>(0.75)</td>
<td></td>
<td>(0.0266)</td>
<td>(3.15)</td>
<td></td>
<td>(0.0309)</td>
<td>(3.00)</td>
<td></td>
</tr>
<tr>
<td>Panicum virgatum</td>
<td>0.1774</td>
<td>29.68</td>
<td>0.0023</td>
<td>1.7889</td>
<td>190.43</td>
<td>0.0514</td>
<td>5.4901</td>
<td>325.90</td>
<td>0.0561</td>
</tr>
<tr>
<td></td>
<td>(0.0805)</td>
<td>(12.58)</td>
<td></td>
<td>(0.4223)</td>
<td>(37.20)</td>
<td></td>
<td>(1.4780)</td>
<td>(42.66)</td>
<td></td>
</tr>
<tr>
<td>Rhus hirta</td>
<td>0.0077</td>
<td>1.52</td>
<td>0.0790</td>
<td>0.2633</td>
<td>48.34</td>
<td>0.1747</td>
<td>0.9084</td>
<td>107.29</td>
<td>0.1322</td>
</tr>
<tr>
<td></td>
<td>(0.0005)</td>
<td>(0.30)</td>
<td></td>
<td>(0.1682)</td>
<td>(41.51)</td>
<td></td>
<td>(0.2892)</td>
<td>(35.11)</td>
<td></td>
</tr>
<tr>
<td>Solidago canadensis</td>
<td>0.1321</td>
<td>21.48</td>
<td>0.0030</td>
<td>1.1744</td>
<td>117.79</td>
<td>0.0452</td>
<td>2.0768</td>
<td>142.72</td>
<td>0.0687</td>
</tr>
<tr>
<td></td>
<td>(0.0441)</td>
<td>(7.63)</td>
<td></td>
<td>(0.3844)</td>
<td>(36.55)</td>
<td></td>
<td>(0.8175)</td>
<td>(108.67)</td>
<td></td>
</tr>
<tr>
<td>Sorghastrum nutans</td>
<td>0.1321</td>
<td>21.48</td>
<td>0.0030</td>
<td>1.1744</td>
<td>117.79</td>
<td>0.0452</td>
<td>2.2947</td>
<td>149.77</td>
<td>0.0638</td>
</tr>
<tr>
<td></td>
<td>(0.0441)</td>
<td>(7.63)</td>
<td></td>
<td>(0.3844)</td>
<td>(36.55)</td>
<td></td>
<td>(0.3093)</td>
<td>(13.84)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.3: Spearman correlation analyses between transpiration and plant growth per species. Total biomass (top), leaf area (bottom).

throughout the growing season (Figure 4.4) and *A. gerardii* and *E. virginicus* consistently attained higher $E$ than *R. hirta*. *A. gerardii* attained the highest $E$ (7.78 ± 2.48) in the loam and *E. virginicus* attained the highest $E$ (9.95 ± 2.17) in the clay loam. The highest
E on one sampling date was attained by the individuals grown in the clay loam: 12.55 ± 3.27 by *E. virgnicus* on 19 August, 11.79 ± 2.96 by *A. gerardii* on 31 July, and 5.70 ± 0.38 by *R. hirta* on 25 August. There were small differences in E for the plant species grown in the two soils. For example, there was a significant difference in E between the soil treatments for *A. gerardii* and *E. virginicus* only on one of the sampling dates, and there were no significant difference in E attained by *R. hirta* between the soil treatments. Transpiration increased during the growing season for *E. virginicus*, but no trends were observed for *A. gerardii* and *R. hirta*.

The soil treatments had a significant effect on the growth of *A. gerardii* and *E. virginicus*, but not on *R. hirta*. Root mass, shoot mass, total mass, and green leaf area were greater for the *A. gerardii* individuals grown in the clay loam; this was shown only for the September harvest. In contrast to *A. gerardii*, the root mass and total mass of *E. virginicus* were significantly greater for individuals grown in the loam, and this was shown for both harvests (Table 4.4). The water content (%) was similar in the soil treatments, loam (28.31 ± 8.23) and clay loam (26.83 ± 3.48), and there was a small difference between the soil collected from the two depths (15 cm and 38 cm): loam – 15 cm 27.38 ± 8.08, 38 cm 29.32 ± 8.21 and clay loam – 15 cm 25.97 ± 3.23, 38 cm 27.81 ± 3.6. There were no trends observed between $g_s$ and $E$ to soil water content (data not shown).
Figure 4.4: Effect of soil treatment on leaf gas exchange measurements. * indicates a significant difference (p < 0.05) between soil treatments. Values are means ± SD; n=3-15 (except for *E. virginicus* on 5-Aug., n=1).
4.4 Discussion

Transpiration ($E$) was influenced by plant species and the greenhouse conditions. The greatest variation in whole-plant $E$ and plant growth occurred between $P. virgatum$ and $L. capitata$ during week 14 (21-fold variation for $E$, 61-fold variation for total mass, and 42-fold variation for leaf area). Total mass and leaf area production were important factors affecting whole-plant $E$, which was apparent in all of the plant species, but most noticeable in $P. virgatum$ that attained the highest whole-plant $E$ and as well as total mass and leaf area (Figure 4.2, Table 4.3). This suggests that observing the phenotypic traits of plants may be a useful strategy to make a priori assertion of the whole-plant $E$ potential for a species. Thus, one could reduce the number of candidate plant species for an ET cover to those that attain a relatively higher total mass and leaf area.

The plant species with the highest $E$ per gram of dry weight (week 6, $A. millefolium$; weeks 10 and 14, $L. capitata$) and per cm$^2$ of leaf surface (week 6, $R. hirta$; weeks 10 and 14, $L. capitata$) did not attain the highest total mass or leaf area (Table 4.3). Although this measurement was useful to indicate the $E$ rate for a species per unit of growth, the most effective plants for ET covers are those species with the ability to remove the greatest volume of water from the soil. Thus, measurements that quantify the removal of soil water at the whole-plant level should be used to evaluate the suitability of candidate plant species for an ET cover.
Table 4.4: The effect of soil treatment on plant growth. Harvests were made on 2 September and 3 November 2009. Different superscript letters indicate a significant difference (p < 0.05) between soil treatments. Values are the means ± SD; n=3-10.

<table>
<thead>
<tr>
<th>Plant species / Parameter</th>
<th>September</th>
<th>November</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loam</td>
<td>Clay loam</td>
</tr>
<tr>
<td><strong>Andropogon gerardii</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root mass (g)</td>
<td>0.63 (0.23)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.61 (1.56)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Shoot mass (g)</td>
<td>0.76 (0.35)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.70 (0.73)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total mass (g)</td>
<td>1.38 (0.58)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4.31 (2.22)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Root:shoot</td>
<td>0.87 (0.15)</td>
<td>1.48 (0.40)</td>
</tr>
<tr>
<td>Green leaf area (cm²)</td>
<td>71.85 (27.55)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>180.79 (55.60)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Root depth (cm)</td>
<td>51.64 (5.29)</td>
<td>53.98 (0.96)</td>
</tr>
<tr>
<td><strong>Elymus virginicus</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root mass (g)</td>
<td>3.85 (1.96)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.10 (1.06)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Shoot mass (g)</td>
<td>4.12 (2.41)</td>
<td>2.07 (1.22)</td>
</tr>
<tr>
<td>Total mass (g)</td>
<td>7.98 (2.93)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.16 (1.75)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Root:shoot</td>
<td>2.18 (3.43)</td>
<td>1.43 (1.27)</td>
</tr>
<tr>
<td>Green leaf area (cm²)</td>
<td>339.45 (186.31)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>132.64 (113.42)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Root depth (cm)</td>
<td>54.45 (1.26)</td>
<td>51.22 (5.37)</td>
</tr>
<tr>
<td><strong>Rudbeckia hirta</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root mass (g)</td>
<td>1.15 (0.90)</td>
<td>NA</td>
</tr>
<tr>
<td>Shoot mass (g)</td>
<td>6.97 (4.51)</td>
<td>NA</td>
</tr>
<tr>
<td>Total mass (g)</td>
<td>8.12 (5.16)</td>
<td>NA</td>
</tr>
<tr>
<td>Root:shoot</td>
<td>0.17 (0.08)</td>
<td>NA</td>
</tr>
<tr>
<td>Green leaf area (cm²)</td>
<td>727.25 (446.80)</td>
<td>NA</td>
</tr>
<tr>
<td>Root depth (cm)</td>
<td>47.63 (16.51)</td>
<td>NA</td>
</tr>
</tbody>
</table>
The condition of the greenhouse is a major factor influencing \( E \). There was a decrease in the highest \( E \) recorded among the species in week 6 to week 10, despite the plants attaining greater total mass and leaf area in week 10 (Figure 4.2, Table 4.3). Air temperature was the major factor responsible for the decrease in \( E \), which is shown for the species \( R. \) hirta and \( E. \) altissimum. Air temperature and \( E \) decreased (8.78 °C and 62%, respectively) for \( R. \) hirta from week 6 to week 10 as well as for \( E. \) altissimum (3.87 °C and 14%, respectively) from week 10 to week 14 (Figure 4.1, 4.2). The rate of \( E \) attained by these species also was affected by the relative humidity. For example, \( E \) increased at lower levels of relative humidity and \( E \) decreased at higher levels of humidity (Figure 4.1, 4.2). This suggests that the \( E \) potential for plant species may vary depending on the growing conditions; it also suggests multiple sampling dates should be used to evaluate the \( E \) potential of a species, especially if the plant is being evaluated in field conditions.

The plant species grown in the field varied considerably in \( E \) between species and these rates fluctuated during the growing season. This was expected since \( E \) is affected by meteorological variables that change daily. \( A. \) gerardii and \( E. \) virginicus attained higher \( E \) than \( R. \) hirta throughout the experiment, and the ranking of species with the highest \( E \) on a single sampling date was: \( A. \) gerardii (31 July), \( E. \) virginicus (19 August), and \( R. \) hirta (25 August). These data suggest that the maximum \( E \) potential for the species occurs at different times of the growing season.

There was no significant difference in water content between the soil treatments, which resulted in a general similarity in the stomatal conductance (\( g_s \)) and \( E \) for a species (Figures 4.3, 4.4). However, there were significant differences in the growth of the plants
between the loam and clay loam. The total mass and leaf area of *A. gerardii* was significantly greater for the individuals in the clay loam for the harvest made in September, but no differences were observed for the harvest made in November, and the *E. virginicus* individuals grown in the loam had a significantly greater total mass and leaf area (Table 4.3). These data indicate that the two soils are comparable in terms of water storage and facilitating water uptake by plants, but are species-specific in terms of promoting total mass and leaf area production.

In summary, the experiments performed in this study were effective methods for comparing the *E* potential and growth of candidate plant species for an ET cover in northwest Ohio. I was successful in identifying appropriate species that together represent a mixture of plants that will function throughout the entire growing season. For example, species can be combined that transpire predominately in the spring (*A. millefolium* and *E. virginicus*), summer (*A. gerardii* and *P. virgatum*) and into the fall (*S. canadensis* and *S. nutans*). Relationships were present between *E* and the phenotypic traits of the plant species, which indicates that visual observations of candidate plants for an ET cover should be made prior to evaluating their *E* potential so that only the most appropriate species are tested. Both of the soils evaluated in this study are suitable for constructing an ET cover, in terms of water storage and facilitating soil water removal. However, based on plant growth, the most appropriate soil for an ET cover is species-specific, this is because *A. gerardii* grew significantly greater in the clay loam, whereas *E. virginicus* grew significantly greater in the loam. Therefore, the most appropriate soil for constructing the ET cover should be selected based on the ability to support the growth of the species that will comprise the greatest density in the plant mixture.
References


Chapter 5

Assessing the Field Performance of Evapotranspiration covers in Northwest Ohio

Abstract:

Evapotranspiration (ET) covers have gained considerable interest as an alternative to conventional covers for the final closure of landfills, but often produce unfavorable rates of percolation in regions that receive more than 32 cm yr\(^{-1}\) of precipitation. Our goal is to design ET covers for landfills in northwest Ohio (83 cm yr\(^{-1}\)) that produce acceptable rates of percolation (< 32 cm yr\(^{-1}\)) and restore habitat. To attain this goal, the soil water storage capacity and plant transpiration were maximized using dredged sediment and native plant mixtures: immature (seeds) and mature (sod transplanted from a restored tall-grass prairie that is more than 10 years old). ET covers were constructed in field lysimeters (1.52 m diameter, 1.52 m depth) and watered at a rate to simulate the region’s wettest year on record (116 cm) while also receiving 100-yr rain events (11.7 cm over 24 hrs). During the 173-day monitoring period, mature plant mixtures produced considerably less percolation (0.00 to 9.41 cm yr\(^{-1}\)) than immature plant mixtures (6.67 to 25.36 cm yr\(^{-1}\)). Thus far, all ET covers have produced acceptable rates of percolation and will continue to be monitored.
5.1 Introduction

Landfills represent a significant threat to human health and the environment because of their potential to form leachate that may contaminate groundwater and the surrounding areas. The current approach to limit the percolation of precipitation into the deposited waste utilizes a final cover that employs a resistive barrier layer, often referred to as a conventional cover. The barrier layer in a conventional cover may consist of compacted clay or a geomembrane underlain by compacted clay (USEPA 1993) and functions to promote surface runoff. However, the high costs associated with the construction of conventional covers and their deterioration with time (Albrecht and Benson 2001; Albright et al. 2006) has resulted in alternative cover designs that need to be evaluated.

In the U.S., the Resource Conservation and Recovery Act (RCRA) of 1976 and comparable state regulations permit the use of alternative covers when they demonstrate equivalent performance to conventional covers (USEPA 1993). The evapotranspiration (ET) cover has gained considerable interest (USEPA 2003) as an alternative to the conventional cover because (i) it is less costly to construct (Dwyer 2000; Hauser et al. 2001), (ii) the overall performance is expected to increase with time (Albright et al. 2004; Hauser 2009), and (iii) it may be used to promote habitat restoration, but this is yet to be evaluated. ET covers consist of soil and plants and function to prevent the formation of leachate using water storage principles, which include soil water storage during periods of inactive plant growth and the combination of evaporation from the soil surface and plant transpiration, i.e. evapotranspiration, during the growing season (Hauser 2009). Fine-grained soils are mostly used (Gurdal et al. 2003) because they have a greater water
storage capacity than coarse-grained soils (Hausenbuiller 1978), and native plants are used since they are adapted to the regional climate (Rock 2003).

ET covers have been tested in many regions of the U.S. (Albright and Benson 2002; Albright et al. 2004; Nyhan 2005; Scanlon et al. 2005), with success being limited to regions that receive less than 32 cm yr$^{-1}$ of precipitation. In these drier areas (e.g. Apple Valley, CA; Boardman, OR; Helena, MT) the annual precipitation is less than the annual evapotranspiration, which is favorable for ET covers because water may be lost from the soil rather than accumulated as it occurs when precipitation is greater than the evapotranspiration. In the wetter areas (e.g. Albany, GA; Cedar Rapids, IA; Omaha, NE), unfavorable rates of percolation were produced from the soil water storage capacity being exceeded because the plants were not effective at removing the water stored in the soil layer. It has been suggested that the rates of percolation produced by the ET covers in these wetter areas will decrease with time as the plants mature and increase their transpiration potential, or if the soil water storage capacity is increased (Albright et al. 2004). There has been indication of effectiveness by an ET cover in Albany that receives 130 cm yr$^{-1}$ of precipitation. Abichou et al. (2005) performed a side-by-side comparison of an ET cover to a conventional cover in lysimeters (10 m by 20 m, for each cover) and observed that the ET cover produced a lower rate of percolation (40.1 cm over a 32 month period) than a conventional cover (69.8 cm), even when the ET cover received a greater amount of precipitation (additional water was applied to aid the establishment of vegetation). In their study, organic material was used to increase the soil water storage capacity of the ET cover and the combination of grasses and trees were used to increase transpiration. This study demonstrates that ET covers are effective in wetter areas when
constructed to accommodate the climate and that more field studies should be performed in such areas to evaluate their suitability.

The overall goal of our research is to design ET covers for landfills in northwest Ohio (average annual precipitation, 83 cm) that produce acceptable rates of percolation. This means the rate of percolation produced by the ET covers must no greater than 32 cm yr\(^{-1}\), which is the maximum allowable rate of percolation for landfill covers in Ohio (OEPA 2003). In order to attain this goal, the ET covers will need to be constructed with a soil that is able to store the amounts of precipitation received during periods when rates of transpiration are low, and a plant mixture consisting of cool and warm-season species that functions throughout the growing season. It is worth noting that ET covers represent a cost-effective strategy to ameliorate two largely concerned issues in northwest Ohio: (i) dredged sediment management, recently the Toledo Harbor Project has become one of the largest projects in the Great Lakes by the U.S. Army Corps of Engineers; and (ii) habitat restoration, only a small proportion of the region’s natural habitat remains (Green Ribbon Initiative 2004). Thus, constructing the ET covers with dredged sediment and native plants may produce acceptable rates of percolation as well as provide a long-term management strategy for dredged sediment and promote habitat restoration.

In this technical note, we assess the field performance of ET covers in northwest Ohio. The ET covers were constructed in field lysimeters (1.52 m diameter x 1.52 m depth, with a conical bottom 0.30 m depth) with dredged sediment and planted with either an immature (seeds) mixture of native plant species that would be used to restore a tall-grass prairie or a mature mixture of native plant species that were excavated from a nearby restored tall-grass prairie that is more than 10 years old. Plants in different stages
of development were evaluated to determine whether ET covers could be effective immediately following construction, or if several years may be required. We expected that ET covers with both plant mixtures would produce acceptable rates of percolation, but the covers using the sod from the tall-grass prairie would produce lower rates. The data are reported for the initial growing season (a period of 173 days, 11 June through 30 November 2009) and the ET covers will be monitored through the 2010 spring, at that time modifications will be made to improve the performance.
5.2 Materials and Methods

5.2.1 Plant species

Eleven herbaceous plants that consist of cool- and warm-season species were used in this study. The species in the immature plant mixture and their seeding densities (individuals per m$^2$) were: cool-season species – 0.19 *Achillia millefolium* [yarrow], 0.09 *Danthonia spicata* [poverty grass], 0.33 *Elymus virginicus* [Virginia wildrye], and 0.09 *Rudbeckia hirta* [black-eyed susan]; warm-season species – 0.19 *Andropogon gerardii* [big bluestem], 0.19 *Eupatorium altissimum* [tall thoroughwort], 0.46 *Panicum virgatum* [switch grass], 0.56 *Schizachyrium scoparium* [little bluestem], 0.23 *Solidago rigida* [rigid goldenrod], 0.46 *Sorghastrum nutans* [Indian grass]; and The seeding densities were based on the rates of transpiration attained by the species in Chapter 4, and from suggested rates for establishing a tall-grass prairie (Packard and Mutel 1997). The species in the mature plant mixture (sod excavated from a nearby tall-grass prairie that is more than 10 years old) was dominated by two warm-season species – *A. gerardii* and *Solidago candensis* [Canada goldenrod] that had densities of 0.19 and 0.37 individuals per m$^2$, respectively. The plants in the immature mixture represent potential species that would be used to restore tall-grass prairies in northwest Ohio, and the plants in the mature mixture are in fact the species that remain dominant in a tall-grass prairie after more than ten years since restoration was initiated.

5.2.2 Dredged sediment

The principal soil used for this study was dredged sediment obtained from the Toledo Port Authority Facility 3 – Corps of Engineers Dredged Disposal Containment
Area (41° 42’ 12” N, 83° 26’ 01” W). This soil consists of sediment dredged from the Maumee River and Lake Erie shipping channel (85% DWT), sewage sludge (12% DWT), and lime sludge (3% DWT); it is referred to as ‘Nu-soil’ (NS) and has been used for landscaping and daily cover at a local municipal solid waste landfill (Stanley Perry, personal communication August 2007). It is classified as a loam (45% sand, 40% silt, 15% clay) and contains adequate nutrients to support native plant growth (in ppm): 162 P as P$_2$O$_5$, 132 K as K$_2$O, 2624 Mg as Mg$^{2+}$, and 16167 Ca as Ca$^{2+}$. The NS was amended with peat moss at a rate of 6.5% FWT (NSPM) to increase the soil water storage capacity and enhance plant biomass production (see Chapter 3).

5.2.3 Lysimeters

Six lysimeters were used in this study (Figure 5.1). In each lysimeter, coarse sand and a deep percolation collection system were installed first in the conical bottom. NS was placed to a thickness of 60 cm at 10 cm layers and compacted to a bulk density of 1.0 g cm$^{-3}$. NSPM was then similarly placed to a thickness of 60 cm and compacted to a bulk density of 0.85 g cm$^{-3}$. The remaining 32 cm of each lysimeter was then filled with 20 cm of topsoil (bulk density of 1.20 g cm$^{-3}$) for the ET covers using the immature plant mixture, or 20 cm of sod (bulk density of 1.30 g cm$^{-3}$) from the tall-grass prairie for the ET covers using the mature plant mixture; 12 cm remained unfilled in each lysimeter to prevent the runoff of surface water from the lysimeter. The layering of the soils in the lysimeters resulted in the ET covers using the immature plant mixture to have a water storage capacity of 51.82 cm, and the ET covers using the mature plant mixture to have a water storage capacity of 50.22 cm.
Moisture sensors (ECH₂O EC-5, Decagon Devices, Inc. Pullman, WA) were used to measure the spatial distribution of soil water in the lysimeters. They were positioned at two depths from the soil surface (0.30 m and 1.12 m) in a triangular array and connected to data loggers (Em5b, Decagon Devices, Inc. Pullman, WA) programmed to record at one-hour intervals. The moisture sensors were calibrated in the soils in which they were placed using the method of Campbell (2002).

Figure 5.1: Field lysimeters. *Left*, plan view of the six lysimeters with the experimental treatments, M = mature plant mixture, I = immature plant mixture; *Right*, details of the in-ground lysimeter, the conical bottom contained coarse sand to facilitate leachate collection in the system, which consisted of PVC (5.0 cm inside diameter) that extended downward along the sidewall to the base of the conical bottom. The PVC enclosed rubber tubing (0.6 cm inside diameter) that attached to a peristaltic pump (E/S Portable Sampler, Cole-Parmer Instrument Company, Vernon Hills, IL) for leachate removal. Figure prepared by Deanna Bobak.
5.2.4 Application of water

Lysimeters were watered with groundwater immediately following the sowing of seeds for the immature plant mixture and transplanting of the sod for the mature plant mixture. Lysimeters were three times weekly at rates equivalent to the wettest year on record, 2006 received 116 cm of precipitation (June 9.93 cm, July 23.34 cm, August 8.20 cm, September 5.97 cm, October 10.90, and November 7.70 (www.ncdc.noaa.gov). In addition to the monthly rates of water application, 100-year rain events (11.7 cm per 24 hrs) were simulated on 21 July to the mature plant mixture M-2 and the immature plant mixture I-2, and on 4 October to the mature plant mixture M-3 and the immature plant mixture I-3 (Figure 5.1).

5.2.5 Monitoring

The volumetric water content was downloaded weekly from the data loggers. When the values indicated the soil was at field capacity, a peristaltic pump was activated to collect water that had percolated to the bottom of each lysimeter. Evapotranspiration was calculated using the water balance equation from Hauser et al. (2005). Plant species not originally included in the plant mixtures were eliminated.

5.2.6 Statistical analysis

T-tests (GraphPad Prism Version 5.0a, Graphpad Software, Inc., La Jolla, CA, USA) wers used to test for significant (p < 0.05) differences between the quantities of percolation that were produced from the two treatments, i.e. types of plant mixtures (seeds and sod). I made two separate analyses based on the total percolation and the annual rate of percolation.
5.3 Results and Discussion

Water balance data for the ET covers are summarized in Table 5.1. The mature plant mixture M-1 was compared to the immature plant mixture I-1, the mature plant mixture M-2 was compared to the immature plant mixture I-2, and the mature plant mixture M-3 was compared to the immature plant mixture I-3. This allowed us to make a comparison between the performance of ET covers with mature and immature plant mixtures that received a similar amount of water, and to evaluate the effects of extreme precipitation events during the middle and late stages of the growing season.

The dredged sediment was suitable for constructing ET covers in northwest Ohio as all six of the ET covers produced acceptable rates of percolation (Table 5.1). Percolation from the ET covers was related to the status of the soil water storage (Figure 5.2); percolation was produced by most of the covers after their soil water storage capacity was exceeded. The 100-yr rain events significantly increased the soil water storage of the covers, indicated by the steep rise in the soil water storage for the covers M-2, M-3, I-2, and I-3, and this resulted in the production of percolation by all of these covers except for M-3. In the M-3 cover, the soil water storage decreased during the growing season, indicating that water was being removed from the soil by evapotranspiration at a rate greater than applied water. This proved to be favorable for the cover because it allowed all of the water from the 100-yr rain event on 4 October to be stored in the soil without exceeding the water storage capacity.

Both plant mixtures (mature and immature) removed the stored water from the soil layer, but the mature plant mixture removed greater amounts of water. This is demonstrated in Figure 5.2 where the soil water storage is decreased to lower values by
Table 5.1: Summary of water balance data for model ET covers.

<table>
<thead>
<tr>
<th>Model Evapotranspiration Covers</th>
<th>M-1</th>
<th>I-1</th>
<th>M-2</th>
<th>I-2</th>
<th>M-3</th>
<th>I-3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>June</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied water (cm)</td>
<td>4.96</td>
<td>5.51</td>
<td>4.74</td>
<td>5.51</td>
<td>4.96</td>
<td>5.51</td>
</tr>
<tr>
<td>Percolation (cm)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ET (cm)</td>
<td>4.96</td>
<td>4.91</td>
<td>3.10</td>
<td>4.91</td>
<td>3.76</td>
<td>4.31</td>
</tr>
<tr>
<td><strong>July</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied water (cm)</td>
<td>25.81</td>
<td>25.59</td>
<td>29.98</td>
<td>29.54</td>
<td>25.81</td>
<td>25.59</td>
</tr>
<tr>
<td>Percolation (cm)</td>
<td>0.00</td>
<td>0.26</td>
<td>4.01</td>
<td>7.45</td>
<td>0.00</td>
<td>1.0</td>
</tr>
<tr>
<td>ET (cm)</td>
<td>18.61</td>
<td>13.34</td>
<td>16.66</td>
<td>7.22</td>
<td>17.41</td>
<td>12.29</td>
</tr>
<tr>
<td><strong>August</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied water (cm)</td>
<td>8.88</td>
<td>8.88</td>
<td>8.88</td>
<td>8.88</td>
<td>8.88</td>
<td>8.88</td>
</tr>
<tr>
<td>Percolation (cm)</td>
<td>0.00</td>
<td>1.9</td>
<td>0.26</td>
<td>1.04</td>
<td>0.00</td>
<td>2.39</td>
</tr>
<tr>
<td>ET (cm)</td>
<td>17.88</td>
<td>10.93</td>
<td>16.40</td>
<td>10.54</td>
<td>17.41</td>
<td>12.12</td>
</tr>
<tr>
<td><strong>September</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied water (cm)</td>
<td>6.45</td>
<td>6.46</td>
<td>6.45</td>
<td>6.44</td>
<td>6.45</td>
<td>6.46</td>
</tr>
<tr>
<td>Percolation (cm)</td>
<td>0.00</td>
<td>0.42</td>
<td>0.19</td>
<td>0.11</td>
<td>0.00</td>
<td>0.04</td>
</tr>
<tr>
<td>ET (cm)</td>
<td>9.45</td>
<td>9.12</td>
<td>10.43</td>
<td>8.74</td>
<td>3.89</td>
<td>10.62</td>
</tr>
<tr>
<td><strong>October</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied water (cm)</td>
<td>10.87</td>
<td>10.86</td>
<td>10.89</td>
<td>10.9</td>
<td>12.62</td>
<td>12.61</td>
</tr>
<tr>
<td>Percolation (cm)</td>
<td>0.00</td>
<td>0.24</td>
<td>0.00</td>
<td>0.57</td>
<td>0.11</td>
<td>3.75</td>
</tr>
<tr>
<td>ET (cm)</td>
<td>4.35</td>
<td>4.62</td>
<td>4.95</td>
<td>3.83</td>
<td>4.25</td>
<td>5.60</td>
</tr>
<tr>
<td><strong>November</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied water (cm)</td>
<td>7.67</td>
<td>7.67</td>
<td>7.67</td>
<td>7.67</td>
<td>7.67</td>
<td>7.67</td>
</tr>
<tr>
<td>Percolation (cm)</td>
<td>0.00</td>
<td>0.34</td>
<td>0.00</td>
<td>2.96</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ET (cm)</td>
<td>2.85</td>
<td>4.21</td>
<td>1.01</td>
<td>3.23</td>
<td>2.82</td>
<td>5.28</td>
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<tr>
<td><strong>Totals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied water (cm)</td>
<td>64.64</td>
<td>64.97</td>
<td>68.81</td>
<td>68.94</td>
<td>66.39</td>
<td>66.72</td>
</tr>
<tr>
<td>Percolation (cm)</td>
<td>0.00</td>
<td>3.16</td>
<td>4.46</td>
<td>12.02</td>
<td>0.11</td>
<td>7.18</td>
</tr>
<tr>
<td>ET (cm)</td>
<td>58.10</td>
<td>47.22</td>
<td>52.55</td>
<td>38.47</td>
<td>55.41</td>
<td>50.22</td>
</tr>
<tr>
<td>Percolation (cm yr⁻¹)</td>
<td>0.00</td>
<td>6.67</td>
<td>9.41</td>
<td>25.36</td>
<td>0.23</td>
<td>15.15</td>
</tr>
</tbody>
</table>

Note: M = mature plant mixture; I = immature plant mixture. M-1 and I-1 received water at a rate equivalent to the months during the region’s wettest year on record (116 cm in 2006); M-2 and I-2 received water at the same rate and a 100-yr rain event on 20 July; M-3 and I-3 received water at the same rate and a 100-yr rain event on 4 October.

the ET covers with mature plant mixtures. This was expected because transpiration is influenced by biomass production (Hanks 1974), root depth and density (Ehlers et al. 1991), and leaf area (Vertessy et al. 1995), which increase in time with plant development.
development. The mature plant mixtures attained rates of ET similar to the rates of water application (Table 5.1), which resulted in a decrease or maintenance of soil water storage (Figure 5.2). In contrast to the mature plant mixtures, the rates of ET for the immature plant mixtures were considerably less than the rates of water application and the soil water storage increased following the watering events.

Overall, the ET covers with a mature plant mixture produced considerably less percolation than covers with an immature plant mixture, but there was no significant differences between the plant mixtures with respect to total percolation ($p = 0.1150$) and annual rate of percolation ($p = 0.1149$). The average total percolation for the mature plant mixtures was 2.22% of the applied water, whereas the percolation of the immature plant mixtures was 11.02% of the applied water. This suggests that with time, the rates of percolation produced by ET covers that are designed for the restoration of tall-grass prairies will decrease due to the maturation of vegetation. Rates of percolation for the mature plant mixtures ranged from 0.00 cm yr$^{-1}$ to 9.41 cm yr$^{-1}$, with the greatest rate being produced by the M-2 cover that received the 100-yr rain event in July. During this time, the species (*A. gerardii* and *S. canadensis*) in the plant mixture had not yet reached their maximum growth for the season, which occurs in August. Rates of percolation for the immature plant mixtures ranged from 6.67 cm yr$^{-1}$ to 25.36 cm yr$^{-1}$, and the I-2 cover that received the 100-yr rain event in July also produced the greatest rate; this was likely due to the species in the plant mixture being in early stages of development (6 weeks from the time seeds were sown into the soil). The percolation that resulted from the 100-yr rain event in October was much lower than the percolation that resulted from the rain
event in July (Figure 5.2). There was no percolation produced from the M-3 cover, and the I-3 cover produced half as much as the I-2 cover that

![Water balance data for model ET covers. Mature plant mixtures (M-1, M-2, M-3) are in the left column and immature plant mixtures (I-1, I-2, I-3) are in the right column. AW = applied water; ET = evapotranspiration; P = percolation; SWS = soil water storage; and WSC = water storage capacity.](image)

Figure 5.2: Water balance data for model ET covers. Mature plant mixtures (M-1, M-2, M-3) are in the left column and immature plant mixtures (I-1, I-2, I-3) are in the right column. AW = applied water; ET = evapotranspiration; P = percolation; SWS = soil water storage; and WSC = water storage capacity.
received the rain event in July. This suggests that the time period within the growing season is an important factor that may affect the production of percolation from extreme rain events, and it appears that rain events that occur during the later stages of the growing season will have less of a detrimental impact on ET covers than the rain events that occur during the early or mid stages.

5.4 Conclusion

Most of the field studies of ET covers indicate they are not suitable for regions that receive more than 32 cm yr$^{-1}$ of precipitation. However, the preliminary results of this study suggest that ET covers may be effective in wetter regions, such as northwest Ohio. During the 173-day monitoring period, all of the ET covers produced percolation rates that meet the standards for landfill covers in Ohio (32 cm yr$^{-1}$; OEPA 2003). As expected, the ET covers with the mature plant mixture had lower rates of percolation than the covers with the immature plant mixture (Table 5.1, Figure 5.2). The dredged sediment provided sufficient water storage and supported plant growth, which demonstrates that ET covers are a potential long-term management strategy for dredged sediment. The ET covers will be monitored through the 2010 spring at which modifications will be made to the soil and plants to improve the overall performance.
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References


Chapter 6

Conclusion

The findings detailed in this thesis can be used to suggest the following:

1. Our model ET covers all produced percolation at rates less than 32 cm yr$^{-1}$, the maximum allowable rate for landfill covers in Ohio. Thus, an ET cover would work for the final closure of landfills in humid regions, which should encourage the extension of application to northwest Ohio.

2. The successful model covers incorporated sediment dredged from the Port of Toledo. Thus, construction of ET covers may provide a strategy to beneficially re-use significant amounts of dredged sediment. Constructing an ET cover for the KRL (84 acres) to a depth of 1.4 m would use 620,000 yd$^3$ of dredged sediment, approximately 4% of the volumetric capacity of the CDF and 62% of the volume that is annually dredged from the Port of Toledo.

3. The successful model covers also included a mixture of native plant species with a functionality that spanned early, mid, and late months of the growing season. Thus, an ET cover may facilitate the restoration of native habitat at the
KRL. The mature plant mixture produced considerably less percolation than the immature mixture, implying not surprisingly that the performance of ET covers may improve over time with plant maturation.

4. The overall goal is to use the research herein to demonstrate the suitability of using an ET cover for the King Road Landfill, with the specific goals of limiting percolation and restoring native habitat. Based on our research findings, the OEPA has allowed for an Alternatives Array, which includes a call out for designs for an ET cover as part of the remedial strategy for the landfill. The University of Toledo will be involved in this, and once proven to be effective, this project may play a major role in amending the regulations for the final closure of landfills in Ohio.