Lifecycle Assessment Of Shrub Willow Evapotranspiration Cover Versus Conventional Clay And Geosynthetic Covers

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LIFECYCLE ASSESSMENT OF SHRUB WILLOW EVAPOTRANSPIRATION
COVER VERSUS CONVENTIONAL CLAY AND GEOSYNTHETIC COVERS

by

Zainab Tariq

A thesis
submitted in partial fulfillment
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In loving memory of
my late mother
Talat Tariq
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Abstract


The establishment of the landfill covers consumes substantial amounts of fuels and materials that in turn contribute to greenhouse gas emissions and fuel depletion, the impacts of which are less explored. This study conducts lifecycle assessments of a willow ET cover, a conventional clay cover and a geosynthetic cover for Solvay settling basins to assess their global warming impact (GWI) and fossil fuel depletion (FFD) for 30 years at Camillus, NY. The study suggests that willow ET is a carbon negative system with the total GWI of -13,206 kgCO$_2$eq ha$^{-1}$, while the clay (194,916 kgCO$_2$eq ha$^{-1}$) and geosynthetic scenarios (260,212 kgCO$_2$eq ha$^{-1}$) have large positive carbon impacts. Similarly, for FFD, the impact of willow ET cover (75,303 MJ Surplus ha$^{-1}$) is the lowest and is 4.7 times lower than the clay cover and 7.7 times lower than the geosynthetic cover. Sensitivity and uncertainty analyses indicated that in all scenarios the GWI of the willow ET cover was less than zero and the GWI of the geosynthetic cover was greater than the clay covers.

Keywords: landfill covers, lifecycle assessment, evapotranspiration, shrub willow, clay cover, geosynthetic cover.

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1. Introduction

1.1 Background

In the early 1980s, the United States introduced regulations to control waste disposal in landfills. The guidelines presented a set of requirements for sealing and covering landfills to prevent waste exposure. Initially, the main components for sealing and closing landfills were clay and gravel or sand layers. The clay was used as a sealing layer and gravel (or sand) as water seepage and gas drainage layers. Currently, landfill covers are regulated under the guidelines developed by the United States Environmental Protection Agency (USEPA) for hazardous waste and solid waste landfills or under the Toxic Substances Control Act (US EPA, n.d.). The hazardous waste landfills fall under the Resource Conservation and Recovery Act (RCRA) Subtitle C while non-hazardous industrial solid waste is covered under RCRA Subtitle D landfills that are mostly constructed with resistive barrier layers (Albright et. al., 2004; USEPA, 2011).

At most sites where closure or sealing activities are required, the regulators recommend a final cover design based on the resistive principle (Benson, Albright, Roesler, & Abichou, 2002). Final landfill covers minimize the volume of percolating water through low saturated hydraulic conductivity layers to avoid the leachate generation and flow that contaminate underground water. The final covers recommended under RCRA Subtitle D are categorized based on the type of conventional landfill covers to control percolation into underlying waste and are often referred to as RCRA covers (USEPA, 2011). Although these covers are RCRA recommended, they are expensive to install, require ongoing maintenance due to short-term durability, develop frequent cracks and holes that impairs their ability to reduce percolation (Albright et. al., 2004; USEPA, 2006). The RCRA, thus, has a provision that permits alternative final covers that are capable of...
controlling percolation less than or equivalent to that of the conventional covers (Albright et. al., 2004; Benson et. al., 2002). Another factor that contributes to its faulty performance of conventional covers are their unnatural design that prevents downward water flow thus opposing nature’s force (Hauser, 2009). When disruptions to their system such as cracks or tears occur, it results in outflows into the surrounding environment (Foye et. al., 2017; Sin Nathamby Â, Phillips Â, Sivakumar, & Paksy, 2014).

One of the alternatives to the conventional landfill covers are evapotranspiration (ET) covers. ET covers are designed to modify components of the water budget (Rock et. al., 2017) such as soil water storage capacity, surface runoff, precipitation, evapotranspiration, and infiltration. ET cover systems use one or more soil layers and vegetation to store water until it is either evaporated from the soil surface or transpired through vegetation (USEPA, 2011). The covers control percolation by water storage in periods of high precipitation and evapotranspiration in periods of low precipitation (Albright et. al., 2004). Consequently, the higher the storage and evapotranspiration capacity of the cover system, the lower the risk of leachate flow from the system (Dwyer, 2003).

A variety of plants have been used for ET covers in different regions of the country. Short rotation woody crops (SRWC) like poplar (Populus spp.) and willow (Salix spp.) have been used in various situations where they can grow effectively (Mirek & Volk, 2010b; Volk, Heavey, & Townsend, 2018; Zalesny & Bauer, 2007). For instance, Zalesny and Bauer found that Populus and Salix genotypes have the characteristics and potential that are required for use as landfill covers (Zalesny & Bauer, 2007). When these genera have been irrigated with landfill leachate, studies have reported their remediation ability with positive growth responses (Dimitriou et. al., 2011; Pandey, Bajpai, & Singh, 2016). Similarly, the performance and remediation potential of willow-based ET cover on a former industrial site in upstate NY have been assessed and tested in several
studies (Brown.W, 2007; Farber, 2006; Heavey & Volk, 2016; Mirck, 2008; Mirck & Volk, 2010a; Volk, Mirck, Purdy, Cameron, & Lawrence, 2006). It was found that shrub willow and poplar have many features that contribute to their performance as landfill covers and apply to many locations across the country.

Honeywell International Inc. and State University of New York College of Environmental Science and Forestry (SUNY-ESF) have established an ET cover system at the Solvay settling basins using different willow varieties including *Salix miyabeana* (SX64), *S. purpurea* (9882-34), *S. sachalinensis* (SX61), and *S. sachalinensis* x *S. miyabeana* (9870-23) (Mirck & Volk, 2010a). Following the incorporation of organic amendments, standard willow site preparation techniques were followed to determine the potential of willow ET cover to reduce deep percolation from the site. Willows were able to grow effectively in high pH and salty substrate at the settling basins as well as effective at controlling the water balance of the site (Heavey & Volk, 2016; Mirck, 2008).

### 1.2 Landfill cover site: Solvay settling basins

The site under consideration for this study is located in the town of Camillus at Syracuse, New York (NY) and is known as Solvay settling basins (Figure 1) (Qiu, 2017). The settling basins were created back in the 1940s (numbered 1 to 8) and 1950s (numbered 9 to 15) with the expansion of the Solvay waste operations into the Camillus town by the Solvay Process Company. The waste was generated because of soda ash manufactured from local natural deposits of calcium carbonate and brine using the Solvay process between 1881 and 1986. Initially, most of the generated Solvay waste was discharged directly into Onondaga Lake. Later in 1907, New York State Attorney General enforced the Solvay Process Company to cease discharging waste materials into the lake. Hence, in 1916, the waste byproducts from the Solvay process were discharged into the settling basins that covered a total area of 607 ha with a depth between 3 and 21 meters (Mirck, 2008).
The deposition of waste material into the settling basins primarily consisted of calcium chloride, calcium oxide, calcium carbonate, sodium chloride, and calcium sulfate ceased in 1986 (Michalenko, 1991). However, the discharge from settling basins became an environmental concern as elevated chloride concentrations were observed in the nearby water bodies such as Nine Mile Creek and Onondaga Lake. The discharge characterized by high alkaline (pH as high as 12) (Qiu, 2017) and saline materials (as high as 7,800 mg kg\(^{-1}\)) (Farber, 2006) attributes to the Solvay waste leaching from the settling basins. New York State Department of Environmental Conservation (NYSDEC) classified Solvay settling basins as Class III hazardous waste landfill that does not cause a significant threat to human health and the environment (NYSDEC, 2010). However, New York State Solid Waste & RCRA regulations require remedial action for Solvay settling basins through a final cover system as part of proper closure of the site. (N. Yang et. al., 2014).
In the case of landfill sites like the Solvay settling basins, the RCRA recommends conventional covers that commonly employ geomembrane or compacted clay covers, or a combination of these. However, their material and construction requirements are high, and there are concerns about their long term performance (Jaros, 1991). An alternative to conventional covers for site remediation is ET covers (Albright et. al., 2004; Rock et. al., 2017). Willows have among the fastest growth rates for woody species in temperate North-American climates and are well adapted to broad site conditions with varying degrees of stress tolerance (Frédette, Grebenshchikova, Comeau, & Brisson, 2019; Kuzovkina & Volk, 2009). Analysis of shrub willow ET covers at the Solvay site indicated that they offer equivalent reductions in percolation to conventional covers because of the higher ET rates (Brown.W, 2007; Mirck, 2008).

1.3 Conventional and ET cover

Generally, conventional covers are used to cap sites. These systems consist of unnatural resistive barriers to prevent water infiltration with low saturated hydraulic conductivity either \(10^{-7}\) cm sec\(^{-1}\) or \(10^{-5}\) cm sec\(^{-1}\) (Albright et. al., 2004; Goldenberg & Reddy, 2017). A typical conventional cover is constructed with a low-permeability layer underlying compacted fine-grained soil cover (typically 450 mm thick) (Albright et. al., 2004). The low-permeability layer(s) include geomembrane (1 or 1.5 mm thick), compacted clay liner (typically 0.6 m), polymeric liners (1 to 2 mm thick), or a geosynthetic clay liner (3.5 to 6.0 kg m\(^{-2}\) of bentonite clay layered between two geotextiles) (Benson et. al., 2002). Geotextiles are permeable fabrics that may be required above and below the low-permeability layer to separate the liner from under and overlain cover components. The soil covers may be thinner or thicker depending on the site-specific conditions. While the surface cover is typically designed to prevent soil erosion and cover deterioration (New Jersey Department of Environmental Protection, 2014).
ET covers consist of a layer of top and (fill) soil capped by native grasses or other native vegetation. It does not contain any resistive or impermeable layers (Figure 2) (Hauser et. al., 2005). They are usually constructed using a monolithic soil barrier, modified by adding a capillary break (USEPA, 2011), or vegetation such as grasses (wheatgrass and clover), trees and shrubs (rabbitbrush, sagebrush, willow, and hybrid poplar) (Madalinski, Gratton, & Weisman, 2003; Rock et. al., 2017). Unlike conventional covers that rely on the barrier layer, ET covers are designed to adapt the water storage of soil, surface water runoff, transpiration, evaporation, and water infiltration at the waste site (Hauser et. al., 2005). The soil component provides support and nutrients for the plants in the system and serves as a storage for water until it can be returned to the environment directly by soil evaporation or through plant transpiration (Volk et. al., 2018). However, the performance of these cover systems needs to be designed for site-specific soil conditions and natural plant processes to maintain a favorable water balance (Johnson, 2005). USEPA has encouraged site remediation through plant covers specifically in regions where potential evapotranspiration (PET) is higher than the received precipitation (USEPA, 2016). In areas such as upstate New York, actual evapotranspiration rates are often close to precipitation however, appropriate plant species with high ET rates can overcome this challenge (Mirck & Volk, 2010b).

![Figure 2. A cross-sectional comparison of conventional barriers and ET covers (Hauser et al., 2005)](image-url)
1.4 Shrub willow as ET cover

Shrub willow (*Salix*-based) ET covers can be used for site remediation (Benson et. al., 2002) in most locations with a temperate climate (Kuzovkina & Volk, 2009). Globally, there are about 330 to 500 species of shrub willow (*Salix spp*) (Argus, 1997). They are generally found in temperate and arctic regions, also found in subtropical and tropical zones. They are widely distributed in the Northern Hemisphere while a few native species exist in Southern Hemisphere. Although some species are adapted to harsh or arid conditions, they more often inhabit wet or humid climates (Frédette, Labrecque, Comeau, & Brisson, 2019).

Frédette et. al. emphasized the utilization of shrub willow for a range of environmental projects such as treatment of wetlands and leachate, phytoremediation of contaminated soils, and riparian buffers (Frédette, Labrecque, et al., 2019). For example, the application of a specific species of willow such as *S. amygdalina* L. has been proposed as a cheap and effective method of landfill leachate control marked by high transpiration ability of willows. They indicated that transpiration from three-month-old sprouts of *S. amygdalina* L. can range from 80% to 90% of full evapotranspiration potential. Their extensive root system and perennial nature enable them to transpire extensively as compared to other vegetative covers (Kuzovkina & Volk, 2009; Qiu, 2017). Białowiec et. al. (Białowiec, Wojnowska-Baryła, & Agopsowicz, 2007) found that ET from willows was on average about 3.5 times more than the evaporation from soil surface without a vegetative cover. The study demonstrated that cover shrub willow cover systems can be useful in landfill leachate treatment through vaporization.

Mirck and Volk assessed the potential of shrub willow ET covers on the Solvay settling basins to minimize infiltration, which would help address concerns with leaching of chloride from the site (Mirck & Volk, 2010b). They measured the ET potential of willow over an entire growing
season and found that the crop coefficient ($K_c$) ranged from 1.2 to 1.4, indicating the ET of the willow was 120 to 140% of a standard grass cover. This suggests that the shrub willows have the potential to function as an ET cover that can effectively manage the water budget on this site and minimize infiltration.

*Salix* species can be successfully grown on a wide variety of agricultural land due to a number of ecological and biological features (Manion, 2017). For example, they can be easily propagated from dormant stem cuttings and adapted into existing agricultural systems, can achieve maximum annual growth in few years of establishment (Keoleian & Volk, 2005), and have typically longer growing season than the other candidate species (e.g. *Populus*) (Tharakan, Volk, Nowak, & Ofezu, 2008). A particular feature of willow is that they can re-sprout after harvest that allows frequent harvesting at a comparatively affordable cost to conventional forestry operations (Keoleian & Volk, 2005). Finally, their light-use efficiency helps them to grow faster provided there is moderate water and nutrient supply (Dimitriou & Aronsson, 2010; Tharakan et. al., 2008). Other physiological characteristics of *Salix* such as efficient nutrient uptake, survival in flooded conditions, as well as high biomass yield are significant features of the shrub willow (Kuzovkina & Quigley, 2004).

Shrub willows can provide several other ecosystem services such as enhancing aesthetics, promoting wildlife habitat, a food source for pollinators. For centuries, willows have been used for a variety of applications such as streambank stabilization projects and by Native Americans. Shrub willow’s native habitat, flexible and fibrous root system, good coppicing ability and multiple-stem growth enhance its ability to occupy a site rapidly and successfully. Successful field trials between 2011 and 2017 resulted in over 50 ha at the Solvay site being established due to their tolerance of high planting density at saturated soils. Thanks to their high biomass yield per area of production, they can be utilized as a bioenergy crop that could help minimize the associated
energy and carbon footprints, which can utilized for revenue or to offset costs (Caputo et. al., 2014; Rytter, 2012; Rytter, Rytter, & Högbom, 2015).

1.5 Choice of landfill cover systems

In most cases, the drivers in choosing between the conventional and ET cover design are the cost and performance of the cover system. However, to achieve the core mission of protecting human health and environment, USEPA and other stakeholders recommended a more efficient and sustainable method of site remediation (USEPA, n.d.). This includes optimizing remedy performance of remedies while minimizing unnecessary use of resources and assuring the remedial adaptability to a changing climate. In the production of landfill covers, substantial quantities of material are required, and the final cover is transported to the landfill installation site that tends to result in a large amount of fuel consumption and emissions. In the context of this study, a sustainable and efficient cover is defined as the one that has the least impact to the environment in terms of emissions (greenhouse gases) and consumption of nonrenewable (fossil) resources.

Both conventional and ET cover systems have been used for site remediation in the United States (Albright et. al., 2004; Madalinski et. al., 2003; Rock et. al., 2017). However, the large-scale environmental impacts such as greenhouse gas (GHG) emissions and resource depletion associated with the production, use, and maintenance of these systems are barely addressed (Athanassopoulos & Vamos, 2011; Dillon, 2008a; Goldenberg & Reddy, 2017). A comprehensive study of the environmental impacts of various covers at different stages of their lifecycle from the production of materials and components, through the cover’s use and maintenance, is essential to evaluate an appropriate final cover system for the intended function. Lifecycle assessment (LCA) is a standard method used to assess the environmental impacts associated with the lifespan of a system (Dillon, 2008a). The overall objective of this study is to ascertain the global warming (GW) and fossil fuel
depletion (FFD) impact associated with willow ET and conventional clay and geosynthetic cover systems using the LCA method. The study will compare the GW and FFD impact of the willow ET, conventional clay and geosynthetic covers for 30 years using a comparative LCA.

1.6 Objectives

The specific objectives of this study are:

- Complete a lifecycle inventory (LCI) of the willow ET, conventional clay and geosynthetic covers based on the data obtained from the databases using Simapro 8.2 and the field trials at Solvay Settling basins and the literature.

- Use the LCI results and the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI 2.1) to assess the GW and FFD impact of the willow ET, conventional clay and geosynthetic covers.

- Determine the factors for each of the willow ET, conventional clay and geosynthetic covers that contribute the most to the GW and FFD impact and variability of the LCA results using sensitivity and uncertainty analyses.
2. Literature Review

2.1 Landfill cover systems and associated environmental impacts

Landfill cover systems are widely used to prevent the physical contact, infiltration, and exposure to waste throughout the United States, however, a limited number of studies have explored problems and environmental impacts associated with these systems (Bonaparte, Daniel, & Koerner, 2002; Dwyer, 2003; Foye et al., 2017; Keoleian & Volk, 2005). For instance, Bonaparte et. al. discussed problems associated with the functioning of conventional cover systems as they develop major fissures with the time that promotes rodent intrusion, increased risk of holes and contamination through existing holes (Bonaparte, Daniel, & Koerner, 2002). These problems result in soil erosion, bad odor, clogging of drainage layers, soil and groundwater contamination, that adversely impact human and environmental well-being (Bonaparte, Daniel, & Koerner, 2002; Kim & Owens, 2010). Closure with an appropriate final cover system, thus, became essential as per USEPA performance standards to minimize the impacts associated with landfill covers.

Under the provision of closure criteria of USEPA, a final cover system must comply with federal (Title 40 Protection of Environment, subchapter 1, part 258) or equivalent state regulations (Albright et al., 2004; USEPA, 2011). As per regulations, the minimum requirement of a landfill cover system is to limit the infiltration less than or equal to the permeability rate of $1 \times 10^{-5}$ cm sec$^{-1}$ (Albright et. al., 2004; Rock et. al., 2017; USEPA, 2011). Typically, this minimum requirement is met by major components of a conventional cover system that includes geomembrane, geotextiles, geonets, compacted clay, geosynthetic clay or a combination of these resistive barriers. However, they are susceptible to failure, particularly, in the arid or semi-arid environment; and prone to desiccation, cracking, freezing/thawing cycles, and biointrusion. These
factors can result in waste exposure and potential environmental impacts (Albright et. al., 2004; USDOE, 2000).

Several researchers have investigated the potential impacts associated with the degradation of landfill covers that lead to waste exposure to the surrounding environment (Bonaparte et. al., 2002; Dwyer, 2003; Zornberg, LaFountain, & Caldwell, 2003). Dwyer (Dwyer, 2003) and Zornberg et. al. (Zornberg et. al., 2003) stated that in the long term, conventional covers are more susceptible to degradation than the ET covers, specifically in arid conditions. A study by the California EPA found that conventional clay covers desiccate irrespective of geology or climatic conditions (Dwyer, 2003). Other studies (Foye, 2011; Foye, Asce, & Soong, n.d.; Sin Nathamby et. al., 2014) have also observed desiccation damage associated with geomembrane covers. Considering the research findings (Dwyer, 2003; McGuire, Andraski, & Archibald, 2009; USEPA, 2011), the EPA permits the use of ET covers with natural soil cover in place of the conventional covers as long as they offer equivalent control on erosion and infiltration.

Although several environmental benefits are associated with the ET covers, the plant cultivation, transportation of system inputs, and field operations result in emissions to air, soil, and water that may have adverse effects on the environment (Murphy, Devlin, & Mcdonnell, 2014). Several LCA studies have evaluated the environmental footprint of producing willows for bioenergy systems (Buonocore, Franzese, & Ulgiati, 2012; Caputo et. al., 2014; González-Garcia, Mola-Yudego, & Murphy, 2013; Heller, Keoleian, & Volk, 2003a; Parajuli et. al., 2017). It was found that the willow biomass for energy purposes can offer environmental benefits in terms of avoided GHG emissions and FFD. However, potential improvement in certain processes e.g., fertilization (reduction of the dose of N-based fertilizer) or addition of organic amendments can reduce or negate the contributions from willow systems. It is, therefore, important to investigate
both positive and negative effects holistically to present a comprehensive lifecycle assessment of willow as the ET cover system in comparison to the conventional methods.

In contrast, some studies (Bonaparte et al., 2002; Na et al., 2014) in the literature reported negligible environmental impacts associated with the conventional covers that are constructed particularly with geomembrane cover. For example, Bonaparte et al. reported that the environmental impacts from the potential increased liner leakage are presumably insignificant given that the landfill is constructed with geomembrane cover (Bonaparte et al., 2002). The authors further emphasized that the liner leakage from side slope holes is less detrimental in impact than the base slope holes. Assuming minimal environmental impacts, the regulators required no remedial action at the field regardless of cover’s faulty field performance reported in several other studies (Albright et. al., 2004; Dwyer, 2003; Foye et. al., 2017; Sin Nathamby Â et. al., 2014). Additionally, the maintenance of geomembrane covers is difficult as well as expensive. For example, an electrical leak survey typically costs between $3,700 and $6,200 per hectare (Darilek & Laine, 2001). Considering negligible environmental impacts from the leakage, the regulators continue to rely on the conventional cover systems (Bonaparte et. al., 2002).

Although landfills cover systems are used to protect from various environmental impacts and problems associated with landfills, their production, establishment, and care consume materials and energy at various stages of their lifecycle. Moreover, the production and utilization of these materials and energy resources lead to additional environmental impacts such as global warming, resource depletion, and others. The quantification of these environmental impacts through LCA modeling is essential to evaluate the relative estimates of associated impacts and material used so that a view of their environmental trade-offs can be presented.
2.2 Assessment of environmental impacts using LCA

LCA is one of the most commonly used methods to assess the environmental performance of the systems (Dotro, Molle, Nivala, Puigagut, & Stein, 2017). LCA is unique as it includes all processes and environmental releases beginning with the extraction of raw material and the production of energy used to create products through the use and its final disposal. When deciding between two or more alternatives, LCA can help decision-makers compare all main environmental impacts from by-products, processes, or services (Environment Protection Agency (EPA)., 2008).

In site remediation LCA, generally, two types of associated environmental impacts are reported (Morais & Delerue-Matos, 2010). The impacts from the physical state of the site are termed as primary impacts, whereas, the impacts related to the remedial action are referred to as secondary impacts. Lesage et. al. introduced tertiary environmental impacts that are associated with the effects of post-restoration fate of the site (Lesage, Ekvall, Deschênes, & Samson, 2007). Whereas, the primary and secondary environmental impacts of landfill covers are entirely associated with the utilization of materials and energy resources (N. Yang et. al., 2014).

The LCA of remediation services (e.g., landfill covers) mostly consider only the primary and secondary environmental impacts of the remediation technologies (Sparrevik et. al., 2011), while avoiding the effects of the remediation on other stages of the site’s lifecycle (N. Yang et. al., 2014). Tertiary impacts are often omitted even when the compared remediation technologies generate different physical states of the site (e.g., soil covering versus decontamination) that later may lead to different site uses (Page, Diamond, Campbell, & McKenna, 1999; Volkwein, Hurtig, & Klopffer, 1999). Furthermore, the inclusion of tertiary impacts could introduce a greater complexity in LCA models.
Non-comparative LCA studies have reported potential environmental impacts of landfills using simplified approaches suitable for waste management systems (Turner, Beaven, & Woodman, 2017; Zarea, Moazed, Ahmadmoazzam, Malekghasemi, & Jaafarzadeh, 2019). For example, a study by Sandia National Laboratories (Turner et al., 2017) found that most LCA models could not perform comparative impact assessment associated with landfill cover systems due to design complexity and unavailability of data on long term life (over 30-50 years) of the conventional landfill covers. Whereas, some argue that LCAs of plant-based systems usually cover only selected natural material and energy flow due to complexity, undeveloped methodology, and missing data (Schweinle et al., 2015). The LCA practitioner, therefore, must define the processes within the LCA system's boundary where the most significant consequences in the lifecycle of landfill cover system could occur to assess the environmental impact of such consequences.

2.3 Comparative studies of Conventional and ET cover systems

2.3.1 Field performance

Numerous studies have compared the field performance of conventional and ET covers (Albright et al., 2004; Benson et al., 2002; E.McGuire et al., 2009; Zhang & Sun, 2014). The principle field performance metric for conventional covers conventional cover is determined by the rate of infiltration. On the other hand, the rate of evapotranspiration determines the field performance of ET covers. An EPA study in California (Bonaparte et al., 2002) compared the field performance of conventional compacted clay covers using a database of 89 large-scale field hydraulic conductivity tests. According to the results, 25% of the 89 field tests of compacted clay covers constructed without an overlain geomembrane tended to desiccate and fail to perform within one or two years. Whereas, geomembrane covers could achieve impermeability in 90 to 99% range for years, with better field performance relative to compacted clay covers.
Albright et. al. analyzed 24 sites from the Alternative Cover Assessment Project (ACAP) to assess performance equivalence of ET covers to the conventional covers (Albright et. al., 2004). The author reported cases that demonstrated the performance equivalency as the rate of percolation from ET covers was less than that of conventional covers or below a minimum threshold (e.g., 3 mm yr\(^{-1}\)). The sites included in the project had diverse climates, rainfall, altitude, temperature, and length of the growing season. The performance of the ET covers in arid, semi-arid, and semi-humid climates was observed equivalent or better than that of the conventional covers as low percolation rates (less than 1.5 mm y\(^{-1}\)) were noted for seven of the ten ET covers. Other studies (Benson et. al., 2002; Kavazanjian & Dobrowolski, n.d.) also supported the performance standard of ET covers equivalent or superior to that of conventional covers, especially in humid conditions. However, the criteria for acceptable percolation rates may vary with the regulations for different locations (Johnson, 2005).

2.3.2 Lifecycle assessment

A few LCA studies have compared and evaluated the GHG emissions and fossil fuel depletion of conventional covers. One of the reasons could be that it is difficult to conduct their LCA due to the proprietary nature of polymers and combinations of polymers used (Katherine D. Chulski, 2015; Stucki, Büsser, Itten, & Frischknecht, 2011). Also, the formulations are irretraceable without the manufacturer’s consent. Chulski compared the amount of embodied carbon within geosynthetic materials utilized for traditional soil remediation with three other alternative designs. These were concrete gravity walls, mechanically stabilized earth walls, geotextile wrap around the walls and gabion walls. The author found the highest contribution of embodied carbon from the manufacturing of both gravity and the geotextile wrap around walls due to the nature of their fuel-based materials. However, the study didn’t include the lifecycle impact assessment (Katherine D. Chulski, 2015).
Another LCA study in Switzerland (Stucki et. al., 2011) compared the environmental performance of conventional geosynthetic covers to that of traditional construction materials that are equivalent in performance to conventional covers. The study followed ISO 14040 and 14044 standards and assessed environmental performance using eight impact category indicators. The geosynthetic filter layer caused lower environmental impacts compared to conventional gravel-based filter layer in all impact categories studied. For example, the cumulative GHG emissions of 7.8 kgCO$_{2}$eq m$^{-2}$ in the case of conventional gravel-based filter layer were ten times higher than the geosynthetic filter layer (0.81 kgCO$_{2}$eq m$^{-2}$). The main factor for higher environmental impacts associated with lifecycle of gravel-based filter layer is the extraction and transportation of gravel which were higher than the burdens associated with lifecycle of geosynthetics. Overall, geosynthetics had a 25% lower integrated environmental impact than that of a conventional gravel-based filter layer.

In a study of different cover types at the Solvay settling basins, Patel found that the energy input establishing a geomembrane cover is 9.4 times higher and incurred 88% more GHG emissions than that of the willow ET cover (Patel, 2014). However, this study was an initial estimate using a Greenhouse Protocol rather than LCA protocols. Also, it was a deterministic analysis and did not include a sensitivity or uncertainty analysis to investigate the robustness of the results. Another study (Dillon, 2008b) supported site remediation using tree covers such as willow and poplars compared to conventional landfill covers. With a tree based phytoremediation system they found a reduction in global warming potential (GWP) of 1.4E11 kgCO$_{2}$eq and energy use of 1.8E11 MJ per 10 ha of the landfill compared to conventional covers, but did not specify the type of tree and system used. Moreover, the lifecycle interpretation through the sensitivity and uncertainty analyses were not conducted in the study.
Other LCA studies on conventional and ET covers investigated overall carbon footprint and results for several other impact categories (Athanassopoulos & Vamos, 2011; Goldenberg & Reddy, 2017). The results of Athanassopoulos and Vamos indicated that the carbon footprint of compacted clay and geosynthetic clay liners depends on the difference of distance from the location of either clay borrow source or geosynthetic manufacturing plant to the installation site (Athanassopoulos & Vamos, 2011). They found the carbon footprint of clay liners 1.4 times higher than the geosynthetics due to the long hauling distance of the clay borrow source and the study suggested a fewer number of trucks hauling clay from borrow source can reduce the associated carbon footprint with clay covers.

Similarly, Goldenberg and Reddy (Goldenberg & Reddy, 2017) performed a sustainability assessment of ET covers, compacted clay and geosynthetics liners for lifecycle GHG emissions and other impact categories such as natural resource depletion, water intake, etc. Their study found that compacted clay liners had higher GWP than geosynthetic and ET covers, specifically approx. 2.5 times higher than the geosynthetics, while 7.2 times than that of the ET covers. The authors further emphasized that the factor of soil transportation is the single most influential parameter that had major contributions to the total carbon footprint. The study, however, did not specify the type of ET cover used and the models for each cover approach were based on assumptions for a hypothetical landfill.

The relevant assessment studies (Athanassopoulos & Vamos, 2011; Goldenberg & Reddy, 2017) that compared geosynthetics, compacted clay, and ET covers, neither specified the type of compared ET covers (e.g., grasses, tree or shrub) and they are not site-specific analyses. Moreover, their study lacked compliance with the International Organization for Standardization (ISO 14040 and 14044) framework of LCA. According to the ISO framework, a typical LCA study consists of four elements, (1) goal and scope, (2) the inventory analysis, (3) the impact assessment, and (4)
the interpretation. To the best of our knowledge, no other LCA has comparatively assessed shrub willow as ET cover to the clay and geosynthetic conventional covers for their potential environmental impacts using LCA complaint to the ISO standards. To fill this knowledge gap, the current LCA study conducts a lifecycle impact assessment of these three covers using standard LCA methodology in compliance with ISO requirements.
3. Methodology

The study includes four phases of LCA as per ISO 14040 and 14044 series of standards. The first phase in the LCA framework is the definition of the goal and scope in which the objective of the study, function of the system, functional unit, system boundaries, assumptions, and limitations are laid out. The second phase is lifecycle inventory analysis (LCI) that consists of the collection and calculation of all the necessary, qualitative, and quantitative input and output data to meet the goal of the study. The third phase is the lifecycle impact assessment (LCIA) that assesses the potential environmental impacts of all inputs and outputs of the systems, collected and modeled in the LCI by using impact category indicators. Finally, the fourth phase of LCA is the lifecycle interpretation in which findings from the LCI and LCIA results are summarized and analyzed for sensitivity and uncertainty (ISO 14040, 2006; ISO 14044, 2006). These phases are described below in the context of this study.

3. Phase I: Goal and scope definition

3.1.1 Goal

The purpose of this LCA study has been discussed earlier in introduction section. The cover systems considered in this study are land-based, hence, GW and FFD are the most relevant impact categories in this context. The research questions of the study are:

1. Does willow ET cover system impact higher GW and FFD than the conventional clay and geosynthetic covers?

2. Which input parameter is contributing the most to the GW and FFD impact of the cover systems?

The proposed willow ET cover is analyzed from an environmental lifecycle perspective to see if willow ET cover can be recommended at other potential industrial waste sites. Furthermore,
the willow research group at SUNY ESF is also very interested in the LCA results because one of their focus is to see if the proposed willow ET cover system has lower GHG emissions and resource use than other technologies for site closure at Solvay settling basins. This analysis would help obtain information about potential impacts of landfill cover systems used commercially for site closure in New York. Also, this study can be considered as a decision basis to industrial site owners, New York State regulators and authorities about how to regulate the management of waste industrial sites by minimal use of resources and energy. Actors within the waste management industry as well as the containment system design will also have an interest in this LCA.

3.1.2 Scope

The scope of this study includes four main lifecycle stages of willow ET, clay and geosynthetic cover from preinstallation and installation stages to maintenance and natural for 30 years. A comprehensive list of activities as well as the detail of the individual process, equipment used, application rates, material and fuel consumption, and data sources, are discussed in the lifecycle inventory section. Other items considered in the scope of the study are discussed below.

System description

The cover design and soil profiles of the willow ET, clay and geosynthetic covers are adapted from O’Brien & Gere predesign study for Solvay settling basins (Figure 3). The thickness of conventional clay cover is modeled from top to bottom as 0.15 m of topsoil, 0.60 m of cover soil also known as a barrier protection layer, 0.45 m of low permeability clay soil (saturated hydraulic conductivity of $1.0 \times 10^{-7}$ cm s$^{-1}$), and Solvay waste to a total depth of 4.0 m. The willow ET cover soil profile is designed as 0.45 m of amended Solvay waste or cover soil underlain by Solvay waste to a total depth of 4.0 m. The soil profile of conventional geosynthetic cover is like
a clay cover except for the addition of two other polymer-based layers to provide improved performance to prevent infiltration compared to the conventional clay cover. One of them is polypropylene (PP) based geosynthetic liner (0.0075 m thick) that lies between the topsoil and cover soil, while others are typically high-density polyethylene (HDPE) geomembrane (0.0015 m thick) sandwiched between cover soil and clay lining underlay by Solvay waste.

![Functional unit](image)

**Functional unit**

The functional unit is the key element in a comparative LCA to assure a fair comparison of the systems at an equivalent level of function. The primary function of the closure systems is to cover the underlying waste from exposure to the surrounding environment and to reduce rainwater infiltration and soil erosion. Based on the primary function 1 hectare covered of the systems, the selected functional unit for these systems is 1 hectare covered for 30 years. Since, the
preinstallation and installation processes occur once during this period, while maintenance and natural processes vary during the 30 years, thus, all the processes are scaled to a per hectare basis.

System boundaries

This comparative LCA is based on a cradle-to-gate approach. The unit processes included in the system boundaries of the compared cover systems include preinstallation, installation, maintenance, and natural phases (Figure 4). The system boundary of the willow ET cover includes the establishment of willow from preparation the site to planting and harvesting of willow to seven four-year rotations and then transportation of willow chips to the edge of the field. Moreover, the underground carbon sequestration in root systems and the GHG emissions associated with leaf decomposition of willow ET cover are included in the system boundary. The use of fuel such as diesel and material inputs including oil lubricants, herbicides, fertilizer, rye seeds, and transport and mixing of organic amendments are inside the boundary.

For the conventional clay cover, the system boundary starts with preinstallation and installation of the bottom (clay and sand drainage layers) and ends with the site closure procedures of grass seed sowing and mowing within the 30-years. The processes of mining, transportation, spreading and compaction of top and bottom liners are included in the system boundary. The conventional geosynthetic cover scenario comprises of same processes and materials used as in the system boundary of clay cover. However, the geosynthetic cover scenario, in addition to site preparation and closure procedures, include layering of geomembrane and geosynthetic liners. Also, the processes of production, transportation, and sealing the seams of the liners are included in the system boundary. Additional processes such as mining and transport of bentonite, use of energy sources such as a generator for welding of geomembrane seams, as well as electricity and fuels required for bentonite processing that are used in production of geosynthetic liners are inside
the system boundary. The processes of carbon sequestration and grass decay in lifecycle of conventional covers are small components of the overall GWI and data is lacking for landfill cover so these processes were not included in this analysis. As far as possible, the impact of the resources and equipment used along with the inputs of their manufacturing and infrastructure are also covered in the boundary. However, in the few cases, when information is unavailable, the impacts are excluded based on their small impact over the lifetime of the clay and geosynthetic cover.
Figure 4. Flow diagram of the three cover systems (willow ET, clay, and geosynthetic) with unit processes and system boundary for a 30-year period. Foreground processes of the three cover systems shown side by side with their preinstallation (PH1), installation (PH2), maintenance phases (PH3), and natural phase (PH4). Preinstallation and installation phases occur once, however, maintenance phase continues as per requirement over the 30-year period. The processes in dashed boxes indicate the impact is small and literature-based data is lacking so they not included in the analysis. All foreground processes are scaled to 1 ha covered.
As per the scope of this LCA, the post closure care phase of the three cover systems has been excluded as the considered lifecycle of three cover systems is 30-year in which willow ET cover is left to regrow after seven harvest rotations. While, the conventional covers are maintained for at least 30 years after the site closure is completed (USEPA Office of Resource Conservation, 2016).

**Allocation procedures**

An allocation problem arises when one process generates more than one product. In such cases, the problem can be avoided by increasing the levels of details in the analysis or by performing system expansion as per the recommendation of the International Standardization Organization (ISO) (ISO 14044, 2006). This study considers the conservative approach since the relative clay and geosynthetic systems have no by-products or co-products since no gas collection systems are considered for the type of waste at Solvay settling basins. Whereas, willow ET cover system produces willow chips that could serve as an alternative bioenergy source. However, in this study the harvested chips are delivered to short term storage so their use to generate energy is not considered. Hence, all the impacts associated with willow have been accounted for the willow ET cover system.

**Type of LCA**

There are two lifecycle inventory approaches: attributional and consequential. An attributional approach refers to a way of accounting the environmental impact over a product or systems lifecycle with factual and measurable data. Whereas, a consequential modeling approach is based on changes and effects a decision has on the studied product or system. Since the purpose of the study is to compare and assess the lifecycle of willow ET cover versus clay and geosynthetic systems based on factual and measurable data, an attributional modeling approach is chosen.
Hence, this LCA does not assess any change-oriented effects which would be more suited with a consequential lifecycle inventory approach (Ekvall et. al., 2016).

Data quality and requirements

The three cover systems are comparatively assessed based on a typical landfill cover requirement for the type III hazardous Solvay settling basins in NY (NYSDEC, 2010). The data required for the modeling of the willow ET cover system are based on the cultivation and harvest of shrub willow in years from 2012 to 2017 (Therasme, 2019; Yang, 2017). Specifically, the lifecycle inventory data for willow ET cover is obtained from field studies performed at Solvay settling basins on Plots 14-2 through 14-5 at Camillus in Syracuse, NY and other locations in the region (Caputo et. al., 2014; O’Brien & Gere, 2018; Patel, 2014; Nathan J. Sleight et. al., 2016; Therasme, 2019; S. Yang, 2017) and discussion with site experts. While, the data for conventional clay and geosynthetic scenarios are based on the assumptions, field reports, and peer-reviewed literature. The lifecycle inventory data for the use of resources, equipment, as well as material distribution and transport are obtained from Ecoinvent 3.3, DK & EU Input-Output Database, and USLCI Database using the SimaPro software (version 8.2.3).

Modeling software

A wide variety of LCA software is fully compliant with the ISO 14040 and 14044 standards e.g. SimaPro and GaBi. SimaPro libraries support multiple LCI databases and LCIA methods for impact evaluation. The choice of software can have substantial effect on the outcome of a study, hence, it is imperative to select the most suited software in each case (Henriksson, 2017). The LCA software used for modeling the three cover systems is SimaPro 8.2.3 that comprises of libraries of peer reviewed literature.
Limitations

As per the goal and scope of the study, the willow ET cover model is compared with the conventional clay and geosynthetic models for GW and FFD impacts for 30 years. However, the difference in emissions over the years cannot be modeled precisely as LCA has issues when dealing with the temporal scales. Hence, the difference in emissions over the years is an uncertain scenario in these models as the results are given per area covered across the entire lifetime of the landfill covers i.e., GW or FFD impact per hectare covered as opposed to emissions or resource depletion per hectare in a year.

The lifecycle inventory data for the willow ET cover is obtained from the Solvay site and other locations in the region (Nathan J. Sleight et. al., 2016; Therasme, 2019; S. Yang, 2017) which is used to compare the willow ET cover with clay and the geosynthetic cover as hypothetical scenarios. The comparison of the systems could have been more precise if the data for all three models are obtained from the Solvay settling basins.

The SimaPro software has a comprehensive number of built-in libraries and databases for processes and systems in Europe but lacks the same amount of information available for the US lifecycle inventories. Moreover, SimaPro lacks information for extrusion and thermoforming of HDPE geomembrane and PP geosynthetics. Hence, generic data for a plastic thermoforming and extrusion process of HDPE resins is used to complete the LCI. Also, the local availability of geomembrane and geosynthetic liners is another challenge that adds estimation of long transportation distances and associated uncertainty in installation procedures of both the clay cover and geosynthetic cover. Hence, generic data as well as the data from European, Danish, and global databases has been obtained to fill the gap of US LCI datasets assuming similar processes, standards, and technologies in these regions.
The design of the three cover systems is modeled based on the common regulatory requirements of NYDEC (NYSDEC, 2010) and pre-design study by O’Brien and Gere (O’Brien & Gere, 2018), suitable for class III hazardous waste landfills that do not pose threat to human health and environment. Thus, this model may not apply to municipal solid waste or hazardous waste landfills that require double to several layers of polymer-based liners and other components such as leachate collection systems as standard landfill requirements (USEPA Office of Resource Conservation, 2016).

The boundary for clay and geosynthetic models only includes the preinstallation, installation, maintenance, and natural processes of the cover system for 30 years and does not include the aftercare period or disposal phase. One of the reasons for this exclusion is a lack of data on the evaluation and monitoring procedures of the conventional cover systems. Since these systems are installed under long term contracts by private installation companies, the data for the aftercare and disposal phase are not readily accessible.

Carbon sequestration in lifecycle of willow ET cover includes the sequestration in permanent parts of the plants (coarse roots, above- and below ground stool) that are not removed over the lifespan of the cover and excludes the fine roots. This is the case because studies have shown that willow fine roots turn over 4.9 and 5.8 times per year (Rytter & Rytter, 1998) so are very short term carbon pools. An earlier study showed that that net carbon balance between the fine roots sequestration and soil carbon dioxide efflux amounts to zero (Pacaldo, Volk, & Briggs, 2013). A portion of the litter and fine roots is probably incorporated as soil organic matter, however, data is lacking for the soil organic carbon dynamics at this site so changes in soil organic carbon are not included.
Root systems of grasses are primarily made up of fine roots and carbon sequestration in this portion of the plants on conventional clay and geosynthetic cover systems is not available in the literature so it is not included in this analysis. Moreover, carbon sinks and the annual decay of the above ground part of the grass is not analyzed due to a lack of data on grass production in these systems.

3.2 Phase II: Lifecycle inventory

The quantitative data is collected per the goal and scope definition of the study that includes datasets from the databases, inputs and output data from the energy and mass balance, as well as, calculations based on estimates and assumptions (Table 1). Lifecycle inventories obtained from the databases and peer-reviewed literature are listed in the supplemental information (Table 4).

3.2.1 Description of the lifecycle inventory

The major difference between the three cover systems is the cover design and processes involved in preinstallation, installation, maintenance, and natural phases. The first step in preinstallation phase (PH1) is site clearing which is similar for all three systems where site soil is excavated up to 1.6 ft using a hydraulic digger to clear any existing vegetation, roots, or debris at the site (Agru America Inc., 2015; O’Brien & Gere, 2018). However, based on the requirements of each system, all other processes of these systems differ distinctly in each phase (Figure 4). For example, for the willow ET system, the site is plowed followed by post-emergent herbicide application. Whereas, in the case of the clay and geosynthetic covers, the site is further smoothed and refined by preparing subgrade that breaks and remolds clumps of graded material before low permeability clay is installed and compacted (USEPA Office of Resource Conservation, 2016).

The installation phase includes the main processes of the establishment of willow ET, clay, and geosynthetic cover system. The organic amendments (a blended mixture of Stable Peat, an
organic mulch and soil amendment composted from horse stable bedding) are transported by combination trucks to the Solvay site. The amendments are incorporated in soil (0.45 m thick) at the rate of 2.5 hr ha\(^{-1}\) and disked (large and small @ 1 hr ha\(^{-1}\)) before planting a cover crop (rye seed, *Secale cereale* L.). After the cover crop is mowed using 1.8 m rotary mower, the willow cuttings from the nursery are planted at a density of 13,500 plants ha\(^{-1}\) on the site (Caputo et. al., 2014). The emerging willow is coppiced at the end of 1st growing season to stimulate the growth, followed by pre- and post-emergent herbicide and tillage application.

The installation of conventional clay and the geosynthetic cover is, however, the hypothetical scenarios for Solvay settling basins (Figure 3). The installation process of these covers is based on the field study by O’Brien & Gere (O’Brien & Gere, 2018) that gives guidelines for the installation of a final cover on Solvay waste beds. Based on the common regulatory requirement and data obtained from O’Brien & Gere, it is assumed that the thickness and bulk density of the bottom and top liners (clay, sand, soil) for both the conventional covers is the same (O’Brien & Gere, 2018; USDA Natural Resources Conservation Service, 2008). Also, based on the previous study and personal communication with field experts, it is assumed that the clay soil and sand are available from local quarries at 20 km from the Solvay site (Patel, 2014). Thus, a low permeability clay soil from the quarry are transported and installed at the prepared subgrade with a high-speed dozer by spreading (hp 220) and compacting the clay (hp 248) at the rate of 2.5 hr ha\(^{-1}\). The considered bulk density of the clay is 1,470 kg m\(^{-3}\) (USDA Natural Resources Conservation Service, 2008), while the thickness is 0.45 m. Similarly, the clay liner is further protected by installing cover soil layer, which is loamy sand and has bulk density of 1,809 kg m\(^{-3}\) and thickness of 0.60 m. A compost mixed topsoil of bulk density 1,650 kg m\(^{-3}\) and thickness 0.15 m is finally installed and compacted over the cover soil that functions as an erosion control layer. All these installation processes include the lifecycle impact of mining, excavation, and
transportation of the clay, cover soil, and topsoil as well as the input rates by the dozers, tractors, and dump trucks.

Table 1. List of major and ancillary activities as well as inputs during the process of establishment of willow ET, conventional clay and geosynthetic covers.

<table>
<thead>
<tr>
<th>Inputs and activities</th>
<th>Units</th>
<th>Willow ET cover</th>
<th>Clay cover</th>
<th>Geosynthetic cover</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Willow cuttings</td>
<td>cuttings</td>
<td>13,500</td>
<td>n/a</td>
<td>n/a</td>
<td>(Caputo et. al., 2014)</td>
</tr>
<tr>
<td>Organic amendments</td>
<td>Mg ha(^{-1})</td>
<td>1,741</td>
<td>n/a</td>
<td>n/a</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Post-emergent herbicide</td>
<td>hr ha(^{-1})</td>
<td>2.24 kg</td>
<td>n/a</td>
<td>n/a</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Plowing</td>
<td>hr ha(^{-1})</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Disking</td>
<td>hr ha(^{-1})</td>
<td>1.4</td>
<td>n/a</td>
<td>n/a</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Sowing cover crop</td>
<td>hr ha(^{-1})</td>
<td>5 bushels @ 0.3</td>
<td>n/a</td>
<td>n/a</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Mowing cover crop</td>
<td>hr ha(^{-1})</td>
<td>1.5</td>
<td>n/a</td>
<td>n/a</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Pre-emergent herbicide</td>
<td>hr ha(^{-1})</td>
<td>1.12 kg</td>
<td>n/a</td>
<td>n/a</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Coppicing willow</td>
<td>hr ha(^{-1})</td>
<td>1.5</td>
<td>n/a</td>
<td>n/a</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Fertilizer application</td>
<td>hr ha(^{-1})</td>
<td>100 kg urea @ 0.5</td>
<td>n/a</td>
<td>n/a</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Mowing headlands</td>
<td>hr ha(^{-1})</td>
<td>1.5</td>
<td>n/a</td>
<td>n/a</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Clay, cover soil, topsoil spreading and compaction rate</td>
<td>hr ha(^{-1})</td>
<td>n/a</td>
<td>2.5</td>
<td>2.5</td>
<td>Field expert, Karl Halen</td>
</tr>
<tr>
<td>Mass compost</td>
<td>Mg ha(^{-1})</td>
<td>n/a</td>
<td>632.13</td>
<td>632.13</td>
<td>(New York State Department Of Environmental Conservation, 2005)</td>
</tr>
<tr>
<td>Grass seed and compost small disk rate</td>
<td>hr ha(^{-1})</td>
<td>n/a</td>
<td>1</td>
<td>1</td>
<td>Field expert, Karl Halen</td>
</tr>
<tr>
<td>Dozer efficiency for spreading and compaction (hp 220 &amp; 248)</td>
<td>-</td>
<td>n/a</td>
<td>0.20</td>
<td>0.20</td>
<td>(“Caterpillar Performance Handbook,” 2018)</td>
</tr>
<tr>
<td>Tractor energy efficiency (hp 140)</td>
<td>-</td>
<td>n/a</td>
<td>0.15</td>
<td>0.15</td>
<td>(“Caterpillar Performance Handbook,” 2018)</td>
</tr>
<tr>
<td>Mass of geomembrane roll</td>
<td>kg ha(^{-1})</td>
<td>n/a</td>
<td>n/a</td>
<td>17,145</td>
<td>(Agru America Inc., 2015)</td>
</tr>
<tr>
<td>Mass of geosynthetic roll</td>
<td>kg ha(^{-1})</td>
<td>n/a</td>
<td>n/a</td>
<td>54,250</td>
<td>(Agru America Inc., 2015)</td>
</tr>
</tbody>
</table>
In addition to clay, cover soil, and topsoil layering, the geosynthetic cover is installed with two other polymer-based layers i.e., sheets of HDPE geomembrane and PP processed with bentonite clay aka geosynthetic liner (Athanassopoulos & Vamos, 2011; Goldenberg & Reddy, 2017). The HDPE geomembrane (1.5 mm thick) is thermoformed and extruded liners from polymer resins (Müller, 2007) are rolled into panels, each with average roll mass of 1,905 kg (Agru America Inc., 2015). Whereas, geosynthetic liners are factory-manufactured clay liners (5-10 mm thick) that consist of a thin layer of bentonite clay-lined between the two layers of polypropylene-based geotextiles and reinforced by needle punching or stitching (Koerner, 1994; Sobti & Singh, 2017).

The finished geosynthetic liners are packed in rolls with an average roll mass of 1,179 kg (Agru America Inc., 2015). For this LCA, it is assumed that both the conventional covers are manufactured at the same production site, from where the finished geosynthetic and geomembrane rolls are transported to the job site via either 28 metric ton dump trucks or closed vans (Athanassopoulos & Vamos, 2011). The geomembrane and geosynthetic landfill liners are not manufactured locally in Syracuse, New York. Hence, this study assumes that these liner rolls are

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
<th>Source</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Bentonite</td>
<td>kg m²</td>
<td>n/a</td>
<td>4.49 (Athanassopoulos &amp; Vamos, 2011)</td>
</tr>
<tr>
<td>Diesel use for bentonite</td>
<td>l t⁻¹</td>
<td>n/a</td>
<td>1.26 Adapted from (Athanassopoulos &amp; Vamos, 2011)</td>
</tr>
<tr>
<td>Gasoline use for bentonite</td>
<td>l t⁻¹</td>
<td>n/a</td>
<td>0.14 Adapted from (Athanassopoulos &amp; Vamos, 2011)</td>
</tr>
<tr>
<td>Natural gas for bentonite</td>
<td>l t⁻¹</td>
<td>n/a</td>
<td>0.43 Adapted from (Athanassopoulos &amp; Vamos, 2011)</td>
</tr>
<tr>
<td>Propane for bentonite</td>
<td>GJ t⁻¹</td>
<td>n/a</td>
<td>51.89 Adapted from (Athanassopoulos &amp; Vamos, 2011)</td>
</tr>
<tr>
<td>Electricity for bentonite</td>
<td>MWh t⁻¹</td>
<td>n/a</td>
<td>0.034 Adapted from (Athanassopoulos &amp; Vamos, 2011)</td>
</tr>
<tr>
<td>Coal for bentonite</td>
<td>Mg t⁻¹</td>
<td>n/a</td>
<td>17.04 Adapted from (Athanassopoulos &amp; Vamos, 2011)</td>
</tr>
</tbody>
</table>
transported from the manufacturers in South Carolina to the distributors in Maryland via rail and from Maryland to Solvay via dump trucks. Considering the mass of each geomembrane (1,905 kg) and geosynthetic roll (1,179 kg), an average 28 metric ton truck can carry 16 geomembrane and 17 geosynthetic rolls.

The organization procedures of conventional covers are typically specified by the cover manufacturers (Environmental Protection Agency, 2001). The individual roll of geomembrane and geosynthetic can be deployed using dozers with spreader or stinger bar with extendable boom forklift and a group of laborers pulling the sheet off the roll. However, this LCA does not include the unloading process and assumes the basic procedures of rolling out the individual sheets onto the graded site. After spreading the sheets with minimum one-inch overlap, the liner should be seamed and secured by the end of each workday (Müller, 2007; USDA Natural Resources Conservation Service, 2016). The seaming of both geomembrane and geosynthetic sheets is performed by different methods. The geomembranes are seamed using hot wedge welding powered by a low load factor generator (<18.64KW). The welding machine is pulled between the overlapping upper and lower geomembranes at an average weld speed of 6.5 ft per min along the 183 m long and 7 m wide liners (LEISTER Process Technologies, 2005). The geosynthetic liners are seamed by spreading loose bentonite between the overlapped 46 m long and 5 m wide sheets that will seal off the seaming area with its high swelling and low permeability potential upon hydration (Agri America Inc., 2015; Gleason, Daniel, & Eykholt, 1997).

Finally, after the installation procedures, the site closure is performed by seeding and disking the topsoil with grass seed using a TV tractor (hp 140) for the maintenance of clay and geosynthetic covers. The willow stems are harvested, using New Holland FR9080 forage harvester equipped with a New Holland 130FB coppice header, at the end of each four-year rotation and fertilized at the beginning of the new growing season following each harvest until seven
consecutive rotations are completed. The harvested willow chips are transported and piled at the edge of the field, while headlands around the field are mowed annually (Therasme, 2019; Yang, 2017). Since this LCA does not include the end-of-life phase, it is assumed that the willow is left to regrow after seven harvest rotations. In the case of the clay and geosynthetic covers, it is assumed that the grass is mowed once every three years to suppress the weed growth and maintain the grass's survival for 30 years or even longer (50 years) (U.S. Department of Agriculture Soil Conservation Service, n.d.).

3.2.2 Data collection

The model for willow ET cover is based on data collected from northeast New York State (Nathan J. Sleight et. al., 2016; Therasme, 2019; S. Yang, 2017) field studies, however, this LCA considers seven four-year rotations of willow establishment and harvest. Both summer and winter harvest data are considered in this LCA as they have different harvesting dynamics that affect the mass and energy balance of the system (Therasme, 2019). The fuel consumption by harvester is based on data collected during large scale harvesting operations for leaf-on and leaf-off harvest as a function of standing biomass (Eisenbies, Volk, de Souza, & Hallen, 2020).

Willow ET cover system sequesters carbon in foliage, stem, fine roots for a short term, while in coarse roots, above ground stool, and below ground for a long duration. The sequestration in roots and stool is based on root-to-shoot ratios i.e., a root-to-biomass yield, is determined from trials in central and northern NY (Yang, 2017). The data for the root-to-shoot ratio is obtained from Sleight’s study that considered three-year seven harvest rotations (Sleight, Volk, Fandrich, & Eisenbies, 2015). Since the relationship between willow biomass allocation and underground biomass is uncertain (Cunniff et. al., 2015), it is assumed that the root-to-shoot ratio is constant (Therasme, 2019) and would remain the same after three years. Thus, the root-to-shoot ratio is 0.6 at the end of the 3rd-year (Yang, 2017). The average of 460 g of carbon per kilogram of material
in the stool and coarse roots is the carbon dioxide equivalent sequestered by willow ET cover, which results in storage of 1,687 g of carbon dioxide per kilogram (Nathan J. Sleight et. al., 2016). The leaf decomposition emissions are determined based on the International Panel on Climate Change (IPCC) 2006 assuming an emission factor of 1% of the released nitrogen (Therasme, 2019; Yang, 2017). The amount of leaf litter, leaf nitrogen content and nitrous oxide emissions are converted to carbon dioxide equivalent emissions during growth years of willow ET cover.

The configuration and thickness of layers of clay and geosynthetic cover models are based on the data obtained from O’Brien & Gere field study (O’Brien & Gere, 2018) (Figure 1). Soil density data is retrieved from USDA (USDA Natural Resources Conservation Service, 2008), while the model for both covers followed the installation guidelines of AGRU manufacturers, USDA, and EPA (Agru America Inc., 2015; U.S. Department of Agriculture Soil Conservation Service, n.d.; USEPA Office of Resource Conservation, 2016). The transportation distance from the manufacturers in South Carolina to the distributors in Maryland and from the distributors to the Solvay site is computed using GPS. The results from all three models are generated using Python programming.

3.3 Phase III: Lifecycle impact assessment

The impact assessment method chosen for all the three landfill covers is based on the U.S Environmental Protection Agency’s Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts Version 2.1 (EPA TRACI) using SimaPro. TRACI is an integrated set of LCIA methods that intends to provide the latest possible treatment of impact categories from the North American perspective (Bare, Norris, & Pennington, 2003). Also, the methods are operational within a public domain software (available from EPA) that transforms LCI data and applies the methods to produce LCIA results. There is a total of eight impact categories in the EPA
TRACI. However, the study analyzes only two of these indicators namely GW and FFD as determined in the goal of this LCA.

The production of landfill covers requires large quantities of material and energy resources, as well as the final covers, which are transported to the installation site that tends to result in a large amount of resource consumption and emissions (Goldenberg & Reddy, 2017). Thus, this analysis intends to determine a sustainable and efficient cover approach that has the least impact on the environment in terms of emissions (GHG) and consumption of nonrenewable (fossil) resources. Based on the mean values of parameters, the baseline estimates of GW and FFD impact, expressed in kgCO$_2$eq and MJ surplus, respectively, for each cover scenario are calculated.

3.4 Phase IV: Lifecycle Interpretation

Sensitivity and uncertainty analyses for each cover scenario are conducted to investigate the variability of the GW and FFD impact associated with the establishment of willow ET, clay, and geosynthetic cover under a range of probable circumstances. The sensitivity analysis is conducted using python programming by changing an input parameter from its baseline value to its minimum and maximum values while keeping all other variable parameters at their baseline values. The minimum, baseline, and maximum values of variable input parameters for all three cover models are presented in Table 2. To assess the variability associated with the data, 90% and 110% of baseline values are chosen as a minimum value and maximum value, respectively to analyze which variables have largest impact with a set amount of change applied to them. The uncertainty analysis is conducted by Monte Carlo simulation that selects random values from an assigned probability distribution for each variable input parameter and quantifies the uncertainty of the GW and FFD impact. Different combinations of input values are generated running the Monte Carlo code in Python for 10,000 simulations.
<table>
<thead>
<tr>
<th>Parameters of willow ET</th>
<th>units</th>
<th>minimum</th>
<th>baseline</th>
<th>maximum</th>
<th>sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass herbicide used</td>
<td>kg ha(^{-1})</td>
<td>2.25</td>
<td>2.5</td>
<td>2.75</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Willow biomass yield</td>
<td>Mg ha(^{-1}) yr</td>
<td>10.44</td>
<td>11.6</td>
<td>12.76</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Soil excavated</td>
<td>m(^3) ha(^{-1})</td>
<td>4,389</td>
<td>4,877</td>
<td>5,365</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Distance transport truck mixing gate to the site</td>
<td>km</td>
<td>8.6</td>
<td>9.6</td>
<td>10.6</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>%</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Headland proportion</td>
<td>%</td>
<td>0.09</td>
<td>0.1</td>
<td>0.11</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Moisture content</td>
<td>%</td>
<td>0.40</td>
<td>0.44</td>
<td>0.48</td>
<td>(Eisenbies, Volk, Posselius, Shi, &amp; Patel, 2015)</td>
</tr>
<tr>
<td>Leaf Nitrogen</td>
<td>%</td>
<td>0.021</td>
<td>0.023</td>
<td>0.025</td>
<td>(Nathan J. Sleight et al., 2016; S. Yang, 2017)</td>
</tr>
<tr>
<td>Root shoot ratio</td>
<td>%</td>
<td>0.55</td>
<td>0.61</td>
<td>0.67</td>
<td>(Nathan J. Sleight et al., 2016)</td>
</tr>
<tr>
<td>Wagon count</td>
<td>-</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
<td>(Yang, 2017)</td>
</tr>
<tr>
<td>Distance truck planting site to storage site</td>
<td>km</td>
<td>0.23</td>
<td>0.25</td>
<td>0.28</td>
<td>(Patel, 2014)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters of clay</th>
<th>units</th>
<th>minimum</th>
<th>baseline</th>
<th>maximum</th>
<th>sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavated topsoil</td>
<td>m(^3) ha(^{-1})</td>
<td>1,372</td>
<td>1,524</td>
<td>1,676</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Excavated coversoil</td>
<td>m(^3) ha(^{-1})</td>
<td>5,486</td>
<td>6,096</td>
<td>6,706</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Excavated clay</td>
<td>m(^3) ha(^{-1})</td>
<td>4,115</td>
<td>4,572</td>
<td>5,029</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Soil excavated at site</td>
<td>m(^3) ha(^{-1})</td>
<td>4,389</td>
<td>4,877</td>
<td>5,365</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Mass grass seed</td>
<td>kg ha(^{-1})</td>
<td>176</td>
<td>195</td>
<td>215</td>
<td>(New York State Department Of Environmental Conservation, 2005) Communication with field expert (Karl Halen)</td>
</tr>
</tbody>
</table>

| Distance truck compost to Solvay site | km | 117 | 130 | 143 |
| Distance truck mined clay, cover soil, topsoil to Solvay site | km | 18 | 20 | 22 |

<table>
<thead>
<tr>
<th>Parameters of geosynthetic</th>
<th>units</th>
<th>minimum</th>
<th>baseline</th>
<th>maximum</th>
<th>sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavated topsoil</td>
<td>m(^3) ha(^{-1})</td>
<td>1,372</td>
<td>1,524</td>
<td>1,676</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Excavated coversoil</td>
<td>m(^3) ha(^{-1})</td>
<td>5,486</td>
<td>6,096</td>
<td>6,706</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Excavated clay</td>
<td>m(^3) ha(^{-1})</td>
<td>4,115</td>
<td>4,572</td>
<td>5,029</td>
<td>(O’Brien &amp; Gere, 2018)</td>
</tr>
<tr>
<td>Soil excavated at site</td>
<td>kg ha(^{-1})</td>
<td>4,389</td>
<td>4,877</td>
<td>5,365</td>
<td>(New York State Department Of Environmental Conservation, 2005)</td>
</tr>
<tr>
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<td>kg ha(^{-1})</td>
<td>176</td>
<td>195</td>
<td>215</td>
<td>(New York State Department Of Environmental Conservation, 2005) Communication with field expert (Karl Halen)</td>
</tr>
</tbody>
</table>

| Distance truck compost to Solvay site | km | 117 | 130 | 143 |
| Distance truck mined clay, cover soil, topsoil to Solvay site | km | 18 | 20 | 22 |

<p>| Distance truck mined bentonite | km | 27 | 30 | 33 | Assumption based on the location of a nearby quarry |</p>
<table>
<thead>
<tr>
<th>Distance</th>
<th>Unit</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance rail geomembrane</td>
<td>km</td>
<td>806</td>
<td>895</td>
<td>985</td>
</tr>
<tr>
<td>manufacturing plant to distributor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance truck geomembrane</td>
<td>km</td>
<td>494</td>
<td>549</td>
<td>604</td>
</tr>
<tr>
<td>distributor to Solvay site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance rail geosynthetic</td>
<td>km</td>
<td>806</td>
<td>895</td>
<td>985</td>
</tr>
<tr>
<td>manufacturing plant to distributor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance truck geosynthetic</td>
<td>km</td>
<td>494</td>
<td>549</td>
<td>604</td>
</tr>
<tr>
<td>distributor to Solvay site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weld average speed</td>
<td>ft min⁻¹</td>
<td>5.85</td>
<td>6.5</td>
<td>7.15</td>
</tr>
</tbody>
</table>

The assumption, based on distance from Agru manufacturers in SC to Hallaton distributor in MD, calculated using GPS.

The assumption, based on distance from Hallaton distributor in MD to Solvay site NY, calculated using GPS.

The assumption, based on distance from Hallaton distributor in MD to Solvay site NY, calculated using GPS.

(LEISTER Process Technologies, 2005)
4. Results and Discussion

4.1 LCIA results for GWI

4.1.1 The overall comparison

The GWI of the willow ET cover is substantially lower than the conventional clay and geosynthetic covers (Figure 5). Specifically, the greenhouse gas emissions associated with the 30-year lifecycle of willow ET cover incur a net negative GWI (-13,206 kgCO$_{2}$eq ha$^{-1}$), while both the clay (194,916 kgCO$_{2}$eq ha$^{-1}$) and geosynthetic (260,212 kgCO$_{2}$eq ha$^{-1}$) cover have large positive emissions. Although the preinstallation, installation, maintenance, and natural phases of willow ET cover incur 22,378 kgCO$_{2}$eq ha$^{-1}$ of GHG emissions, the impact of carbon sequestration in natural phase (-35,583 kgCO$_{2}$eq ha$^{-1}$) of the willow ET overshadow the positive values of GHG emissions. Thus, the net impact is negative.

There are very few other LCA comparisons of different cover types in the literature (Dillon, 2008b; Goldenberg & Reddy, 2017; Patel, 2014), but this study is consistent with the Goldenberg and Reddy analysis as the ET cover in their study had lowest GWI than the conventional covers (Goldenberg & Reddy, 2017). Goldenberg and Reddy found that the GHG emission associated with their ET cover was 14% of the GHG emissions from the geomembrane-lined clay (114,772 kgCO$_{2}$ ha$^{-1}$) and 35% of the geosynthetic cover system (45,833 kgCO$_{2}$ ha$^{-1}$) (Goldenberg & Reddy, 2017). However, their study differs from this study because they their type of ET cover is unknown. Moreover, their assumptions were different than this study. For example, they assumed that their ET soil layers are available on-site, while the scenario in this study involves importing 1,741 Mg ha$^{-1}$ of organic amendments for the willow ET cover. Lastly, the covers considered in their study consisted of additional layers and materials that had different soil depths than considered in this LCA.
Another substantial difference between the results of Goldenberg and Reddy’s study and this study is the net GWI of their type of ET cover than the GWI of willow ET cover in this analysis. The net GWI of their ET cover was positive (15,947 kgCO$_{2eq}$ ha$^{-1}$) rather than negative (-13,206 kgCO$_{2eq}$ ha$^{-1}$) in case of willow ET cover system in this study. The net impact of willow ET cover is negative because of the carbon sequestration process in below ground and above ground portion of willow ET cover system. The carbon sequestration process is not accounted in the ET cover system of their study. Moreover, another process in natural phase is leaf decomposition process which has positive contributions (7,294 kgCO$_{2eq}$ ha$^{-1}$) to GWI associated with willow ET cover, has not been included in the ET cover of their study. Nevertheless, excluding the impact of carbon sequestration and leaf decay (-28,290 kgCO$_{2eq}$ ha$^{-1}$) from the GWI associated with willow ET cover in our study, the total GWI becomes 15,084 kgCO$_{2eq}$ ha$^{-1}$ which is close to the GWI (15,947 kgCO$_{2eq}$ ha$^{-1}$) of the ET cover estimated in their study.

The willow ET cover in this study has the lowest GWI of all three covers because of the much lower impact in the preinstallation and installation phases and the fact that the willow ET cover system sequesters carbon during its lifespan. The preinstallation phase of willow ET cover (2,653 kgCO$_{2eq}$ ha$^{-1}$) has a lower contribution to GHG emissions in comparison to clay (38,726 kgCO$_{2eq}$ ha$^{-1}$) and geosynthetic covers (38,726 kgCO$_{2eq}$ ha$^{-1}$). The preinstallation phase of willow ET cover, which is only 12.8% of the total positive emissions, involves the process of site clearing followed by post-emergent herbicide application. While the impact from the preinstallation phase contributes 19.9% for the clay and 14.8% for the geosynthetic cover of their total impact. This difference is most likely due to the additional processes of off-site mining and transport of materials required for the conventional covers. The willow ET cover has no such mining activities, which reduces the extent of emissions from the preinstallation of willow ET cover as compared to the clay and geosynthetic scenarios.
Similarly, the installation of the willow ET cover (3,473 kgCO$_{2}$eq ha$^{-1}$) has the lowest GWI followed by clay (155,285 kgCO$_{2}$eq ha$^{-1}$) and geosynthetic covers (220,582 kgCO$_{2}$eq ha$^{-1}$). The installation of clay incurs around 80% of the total, whereas the impact from geosynthetic cover installation is about 85% of the total. The clay and geosynthetic covers had the highest impact in this phase because their installation predominantly involves the impact of several activities and additional liners made from fossil fuels that have large emissions. In contrast, the installation phase of the willow ET cover incurs about 15.5% of the total positive emissions. The impact of individual
processes in the installation of willow ET cover in comparison to clay and geosynthetic scenarios is explained later in this section.

Contrary to the impact of preinstallation and installation of willow ET cover, the maintenance phase of willow ET cover has the largest contribution to the GWI (8,958 kgCO$_2$eq ha$^{-1}$) and it is an order of magnitude greater than the maintenance of clay (904 kgCO$_2$eq ha$^{-1}$) and geosynthetic cover (904 kgCO$_2$eq ha$^{-1}$). This is because the maintenance of willow ET cover included the emissions associated with N fertilizer applications and harvesting, which combined account for 40% of the total positive emissions. These processes occur every four years or seven times during the lifecycle of the cover. In contrast, the maintenance of clay and geosynthetic covers do not require major inputs once the cover is installed. Thus, the contribution to GWI from the maintenance of these covers is negligible compared to willow ET cover and less than 1% of the total GWI impact of the clay and geosynthetic covers (0.46% for clay and 0.34% for geosynthetic).

It is important to note that the clay and geosynthetic covers may require annual inspection and occasional cover repair depending upon the materials used in the construction of the cover as well as the end-use of the cover area (New Jersey Department of Environmental Protection, 2014). The repair potentially consumes soil, sand, clay, geomembrane, geotextile, and diesel inputs. Additionally, the repairing process includes transportation of the materials to the site via diesel-fueled trucks and vehicles during inspection and maintenance visits. Previous studies assumed 10% of the conventional cover materials are replaced during 30 years (Dillon, 2008b; North Carolina State University and Eastern Research Group Inc., 2011). Considering an assumption of a 10% replacement of cover materials, the impact estimated for the maintenance phase of the clay and geosynthetic covers could be higher than the 904 kgCO$_2$eq ha$^{-1}$ estimated in this study, depending on the type of materials used and need for maintenance. The cover repair or
replacement, however, is inconsistent across sites and there is truly little actual data available, so we chose not to include this estimate in our maintenance calculations.

The processes that are produced by nature and occur without human interaction are included in the natural phase. With the growth of the willow plant as ET cover, the roots and shoots of the willow grow as well as the stems shed leaves on the ground that decompose during the entire lifecycle. The natural phase of willow ET cover includes both positive (7,294 kgCO₂eq ha⁻¹) values associated with the decay of foliage and negative (-35,583 kgCO₂eq ha⁻¹) values for the process of carbon sequestration in permanent parts of the willow plants such as the coarse roots and stool. Consequently, the net GWI of this phase is negative (-28,290 kgCO₂eq ha⁻¹) and is the reason willow covers have an overall negative GWI. The carbon sequestration occurs in the below ground, long lived parts of the plant (coarse roots and below ground stool) as well as in the above-ground stool portion of the willow cover that is not harvested or removed over the lifetime of the cover (Sleight et al., 2015). In contrast, the carbon sequestered by grass cover in clay and geosynthetic covers is assumed to be small compared to the sequestration rate of willow ET cover due to its higher carbon storage capacity (Volk, Heavey, & Eisenbies, 2016).

4.1.2 Comparison of processes in each phase of willow ET, clay and geosynthetic covers

a) Willow ET cover

The processes in the lifecycle of willow ET cover have contributions to both GHG emissions and reductions in the entire lifespan. The main contributing process from the preinstallation is clearing vegetation (2,602 kgCO₂eq ha⁻¹), while a post-emergent herbicide application (51 kgCO₂eq ha⁻¹) have negligible impact. The key contributing process of installation phase is the transportation and mixing organic amendments (3,005 kgCO₂eq ha⁻¹) while planting willow (158 kgCO₂eq ha⁻¹), pre and post-emergent herbicide application and tillage (121 kgCO₂eq ha⁻¹)
ha\(^{-1}\)), and the remaining processes have a minor contribution (<0.5%) to the total impact (Figure 6). Activities like clearing vegetation and the addition of organic amendments are unique to the Solvay site as the case may vary for willow ET covers installed at other locations. For example, there are areas of the site where vegetation, including some trees like cottonwood (*Populus deltoides*) and herbaceous plants, are growing but they are not dense or rooted deeply enough to function as an ET cover. These plants need to be removed to plant the willow. Other sites may not have this type of vegetation so they would have a lower amount of activity and GWI in the preinstallation phase. The organic amendments applied at this site are based on a series of greenhouse and field trials and have supported high willow growth rates on the site for over 10 years (Townsend et al., 2018). Thus, due to site-specific conditions, other vegetation clearings, and amendment additions may likely be needed, and the impact of these activities would vary in that case.

The GWI associated with fertilizer application (4,486 kgCO\(_2\)eq ha\(^{-1}\)) and harvesting (4,378 kgCO\(_2\)eq ha\(^{-1}\)) shows a major contribution to the total positive impact from the maintenance phase. Previous LCA studies on shrub willow have reported that processes of fertilizer input and harvesting are the main contributors to the GWI (Krzyżaniak, Stolarski, Szczukowski, & Tworkowski, 2016; Krzyzaniak, Stolarski, Szczukowski, & Tworkowski, 2013; Whittaker, Macalpine, Yates, & Shield, 2016). It was suggested that improvement in harvester efficiency and replacement of synthetic fertilizer with organic amendments can contribute to reducing the extent of GWI (Yang, 2017). Also, harvest can be done during the summer or winter season, but the timing of harvest impacts the GWI associated with harvesting. This study uses data for harvests that were split evenly between summer and winter (Therasme, 2019). Eisenbies et al. and Therasme reported that GWI associated with harvest in summer is higher than the winter harvest as fuel consumed per unit of harvested willow biomass is 45% lower in the winter than the summer
harvest (Eisenbies et al., 2020; Therasme, 2019). Thus, the approach of harvest rotations in winter can reduce fuel consumption and resultantly contributions to GHG emissions.

Leaf decay and carbon sequestration have significant GWI with large positive emissions associated with leaf decomposition and negative values with carbon storage in the natural phase. The leaf decay process has the highest (32.5%) contribution to the total positive GWI and was reported as one of the major contributors to GHG emissions in the previous studies on shrub willow (Therasme, 2019; Yang, 2017). Willow plants drop between 2.6 to 4.1 Mg ha$^{-1}$ yr$^{-1}$ of foliage to the soil during the fall season with an N content of 0.3% to 2.6% of the harvested biomass on a CO$_{2eq}$ basis (Heller et al., 2003). As the leaves decompose, NO$_x$ are released and contribute to the GWI.
This study shows that willow ET cover is a carbon sink and corroborate the finding of previous studies where shrub willow systems sequester carbon when grown on mineral soils (Caputo et. al., 2014; Pacaldo, Volk, & Briggs, 2013; Rytter, 2012; N. J. Sleight et. al., 2015). For example, Rytter estimated 76,600 to 80,100 kgCO$_2$eq ha$^{-1}$ of carbon sequestered in above and below ground willow grown for biomass production on arable lands. Sleight et. al. have found that 45,000 to 46,000 kgCO$_2$eq ha$^{-1}$ are accumulated in shrub willow systems by the time they are 10 to 14 years old (Sleight et al., 2016). The difference in the level of carbon sequestration suggests that carbon storage is site-specific and depends on various other factors (e.g., management practices) (Keoleian & Volk, 2005). In this LCA, the data for root to shoot data biomass is obtained from 10-year-old willow from two different sites to determine belowground biomass yield (Nathan J. Sleight et. al., 2016) which are supported by other studies (Rytter et. al., 2015).
b) Clay cover

The total result of all phases in the lifecycle of the clay cover indicates the cover significantly contributes to the GWI (Figure 7). In the preinstallation phase, 90% of the total preinstallation impact (38,726 kg CO$_2$eq ha$^{-1}$), is contributed by the mining and transport of clay. Mined clay with a clay density of 1,470 kg m$^{-3}$ is excavated (4,572 m$^3$ ha$^{-1}$) from the nearby quarries and transported (20 km) via diesel-powered combination trucks to the installation site. The impact of all these activities amounts to 20% of the total GWI (194,916 kg CO$_2$eq ha$^{-1}$). The rest of the activities in the phase are less than 2% of the total GWI.

The installation phase has the highest GWI (155,285 kg CO$_2$eq ha$^{-1}$) than any other phase in the lifecycle of the cover system. It is evident from the graph that mining and transport of coversoil have the major contributions (54%) to the total GWI. This process includes the impact of sand, stone, and gravel (coversoil) mining, excavation of 6,096 m$^3$ ha$^{-1}$ coversoil with soil density of 1,809 kg m$^{-3}$ and its transportation from quarries (20 km) to the installation site. The other major contributing process in this phase is mining and transport of topsoil to the site which is 20% of the total GWI. Topsoil is also mined from the nearby soil borrow source to excavate 1,650 m$^3$ ha$^{-1}$ of soil with a density of 1,524 kg m$^{-3}$ carried (20 km) via trucks to the installation site. Topsoil is then mixed with compost, the impact of which is not more than 5% of the total GWI. The processes that impact less than 0.5% are categorized in the minor.

Past researchers have found that the distance to which excavated soil liners are transported from quarries to the installation site should be minimized to reduce the associated impacts with transportation. For example, Athanassopoulos & Vamos (Athanassopoulos & Vamos, 2011) conducted a carbon footprint analysis over a range of different transport distances from soil borrow source to the installation site. They found transportation as the only largest factor that contributed
57% of the total GHG emissions for the clay liner. Specifically, they observed a 36% higher carbon footprint of the clay cover constructed with a clay lining (mined and transported only 16 km from the installation site) than a factory manufactured geosynthetic liner (located 1,610 km away from the site).

In contrast to Athanassopoulos & Vamos study (Athanassopoulos & Vamos, 2011), the clay cover mined and transported in this LCA, resulted in 28% fewer emissions than the factory manufactured geosynthetic cover. Since this LCA is based on a hypothetical clay landfill scenario,
it was assumed that clay borrow source is within 20 km, while the geosynthetic plant is located 1,444 km from the Solvay site. Even though the transportation distances considered in our study are not substantially different than that of the Athanassopoulos & Vamos study, the results of our study are different. This is because of the difference in the cover composition of the two individual studies that suit the requirement of the individual landfill site. For example, the amount of clay transported in their study is $8,280 \text{ m}^3 \text{ ha}^{-1}$ which is 1.8 times greater than that of clay ($4,572 \text{ m}^3 \text{ ha}$) in this study. Under both impact categories reduces the impact (63%) due to fewer truck loads. Moreover, their type of landfill requires additional layering of geomembrane liners which is not required in the case of Solvay landfill site. Thus, the results of our analysis imply that the factor of mass transportation has higher GWI than just the single transportation unit in the overall impact.

Another factor that contributes to the higher GWI is the availability of soil borrow sources near the installation site. The relative transportation distances from the soil borrow to the installation site should be minimized to reduce the emissions associated with the long haul. For instance, in our analysis, the impact of the installation of coversoil (54%) is higher than the impact of topsoil (20%) on the overall GWI. Although it was assumed that the soil borrow source for both cover soil and topsoil were available within 20 km from the site, the greater mass of the coversoil impacted the overall impact substantially greater than the topsoil. In certain cases, the borrow source for coversoil and topsoil may not be available close to the installation site due to challenging geology of the surrounding region (Goldenberg & Reddy, 2017).

Previous studies suggested that the excavated soils should be in the closer distance to the installation site to reduce the impacts associated with the number of truckloads to haul soils from the borrow source to the installation site (Athanassopoulos & Vamos, 2011; Goldenberg & Reddy, 2017). The authors added that the availability of soil source onsite that is of superior quality can further reduce the cost of borrowing soil from the offsite source. Thus, based on past sustainability
assessments as well as the results of this LCA, the availability of the soil borrow source (for both liners) close to the installation site and in the ideal case on the site is of critical importance to minimize GWI associated with transportation.

The contribution of the impact associated with each soil liner (coversoil and topsoil) to the total emissions was not explicitly discussed in the previous studies. Our study takes a step further in analyzing this difference. Moreover, the information obtained in previous studies is inconsistent due to information obtained from various LCI inventories. The results of this LCA are consistent largely due to information obtained from SimaPro databases that mostly used Ecoinvent 3 and USLCI libraries. These databases are relevant to conditions in the US. While other relevant studies (Athanassopoulos & Vamos, 2011; Goldenberg & Reddy, 2017) used the Inventory of Carbon and Energy (ICE) databases that mostly consist of information relevant to the United Kingdom. For instance, the impact of coversoil (26,004 kgCO$_{2eq}$ ha$^{-1}$) calculated in their study is based on information obtained from ICE databases that lack information regarding the impact from mining and transportation of sand/gravel from the borrow source or the quarries. Our study filled this knowledge gap by calculating the impact of sand mining and transportation (106,184 kgCO$_{2eq}$ ha$^{-1}$) from Ecoinvent 3 libraries that are suitable for US-based conditions.

The contribution of the impact of the maintenance phase of clay cover is small (0.5%) as compared to the preinstallation (20%) and installation phases (80%) on the total GWI. This phase has the lowest impact than the previous phases because it includes only two activities. Specifically, this phase has 533 kgCO$_{2eq}$ ha$^{-1}$ GWI of plowing and disking of grass seed followed by the process of mowing grass (371 kgCO$_{2eq}$ ha$^{-1}$), each of which has not more than 0.2% impact, overall.
c) Geosynthetic cover

The baseline results for GWI associated are greatest for the installation phase and smaller for the preinstallation, with a minimal impact associated with maintenance (Figure 8). The major contribution (90%) from the preinstallation phase is from the process of mining and transportation of clay to the site which contributes 14.8% of the total GWI (260,212 kgCO$_{2}$eq per ha$^{-1}$). This includes the impact of clay mining with a soil density of 1,470 kg m$^{-3}$ and excavation of 4,572 m$^{3}$ ha$^{-1}$ clay from the nearby clay and soil quarries that are hauled 20 km via diesel-fueled combination trucks to the site. The remaining activities (clear vegetation and subgrade preparation) have less than a 1% impact on the total GWI.

A previous study on sustainability assessment of conventional geosynthetic systems mentioned that the availability of clay mines is dependent on the earth material of the location and the supply may be limited in some areas (Goldenberg & Reddy, 2017). Also, obtaining clay soil from quarries may not be a sustainable approach since mining and transportation of clay contribute to the emission of GHGs (Krishna & Dey, 2018). In that case, an alternative to a mined clay liner is a factory manufactured geosynthetic clay liner (Athanassopoulos & Vamos, 2011; Goldenberg & Reddy, 2017). However, there is a tradeoff between hauling geosynthetic clay liner from the manufacturing plants and transportation of the mined clay soil from the clay quarries to minimize the associated GWI. For instance, according to Athanassopoulos & Vamos, a clay borrow source providing clay soils should be located within 9 km from the installation site compared to its factory manufactured geosynthetic clay liner alternative, provided the factory of the latter is 1,610 km away. Similarly, the authors repeated their carbon footprint analysis over the range of different hauling distances. Considering their data, for the clay cover to produce lower impact than the geosynthetic clay liner, the clay mines should be within 20 km from the site if the factory plants of geosynthetic clay liner are 4,459 km away from the site. In other words, a hauling distance of
clay soils more than 20 km would increase the GWI of mining and transporting clay soils than the geosynthetic clay liner hauled from 4,459 km. The number of km for geosynthetic clay liner was computed using the following linear model¹:

\[ y = 251.20 \times x - 565 \]

Where \( y \) is the distance from a landfill site to the manufacturing plant of geosynthetic clay liner and \( x \) is the distance from a landfill site to clay mines.

The installation phase of the geosynthetic cover has the highest impact (84.7%) among all phases because this phase consists of several high impact activities. The mining and transport of cover soil (48.1%) is the largest impact in this phase and it alone is greater than the entire process in the installation phase. Besides, the manufacture and distribution of geomembrane (23.7%) and mining and transport of topsoil (17.4%) are other big contributors to the total GWI.

This phase includes the impact of additional polymer-based liners such as geomembrane and geosynthetic cover in addition to the mined soil liners. It was observed that the impact of transportation of geomembrane and geosynthetic liners from the manufacturer to distributor and then to the installation site is significantly different and each influence the total GWI with different proportions. Specifically, the impact of transport of geomembrane liners from producer to distributor (52,230 kg CO₂eq per ha⁻¹) via rail is 5.4% of the impact of the geosynthetic liner (2,806 kg CO₂eq per ha⁻¹). Although these liners are assumed to be transported from the same manufacturer, their impact is different mainly due to the difference in weight that is transported to the distributor. For example, an average roll mass of geomembrane liner is 1,905 kg (Agru America Inc., 2015) which is almost twice the average roll mass (1,179 kg) of the geosynthetic roll. While the impact of transport from distributor to the site via truck for the geosynthetic liner (6,640

¹ https://www.socscistatistics.com/tests/regression/default.aspx
kgCO$_{2eq}$ per ha$^{-1}$) is 3.2 times the impact of geomembrane liner (2,098 kgCO$_{2eq}$ per ha$^{-1}$). In this case, the carrying capacity of one 28 metric ton truck is 17 rolls for geosynthetic whereas 16 rolls for geomembrane. As the amount of geosynthetic rolls required to cover one hectare is 46 as compared to 9 for geomembrane, the number of truck trips to haul geosynthetic rolls will be greater than that of the geomembrane rolls which contribute to higher emissions.

![Global warming impact (GWI) (kgCO$_{2eq}$ per ha) associated with processes in preinstallation, installation, maintenance, and other phases of geosynthetic cover.](image)

Figure 8. The other most impactful process in the installation phase is mining and transport of topsoil (17.4% of the total) which is followed by transport and mixing of compost (4.6% of the total). These soil layers are typically installed in a conventional cover system (Goldenberg & Reddy,
The compost is mixed to support the growth of the grass as the landfill sites because these are typically nutrient-limited sites that will not support plant growth (New York State Department Of Environmental Conservation, 2005). This process includes the impact of 632.13 Mg ha\(^{-1}\) of compost transported (130 km) to the installation site and fuel consumed to transport and mix the compost. The impact of processes such as bentonite processing (0.7%) and coversoil installation (0.3%) is relatively low.

Comparing the results of this LCA with prior landfill cover assessment studies, a very few studies in the literature address the comparison of GHG emissions associated with conventional cover systems (Athanassopoulos & Vamos, 2011; Dillon, 2008a; Goldenberg & Reddy, 2017; Stucki et. al., 2011). These studies address the cumulative GHG emissions associated with soil liners and relevant materials but are not site and cover type specific.

Stucki et. al. compared the environmental impacts of geosynthetics with the most common conventional construction materials in four different applications (Stucki et. al., 2011). One of the cases was an assessment of the environmental impacts associated with the geosynthetic liner that can be used as an alternate to the gravel-based liner (identified as coversoil in our study) in landfill construction. Specifically, the study estimates that the geosynthetic liners in landfill construction cause 67% lower cumulative GHG emissions than the gravel-based liner. The cumulative GHG emissions associated with gravel-based liner in their study are 99,790 kgCO\(_2\)eq per ha\(^{-1}\) compared to 106,184 kgCO\(_2\)eq per ha\(^{-1}\) in our study. The difference is only 6%, which may be related to differences in transportation distances for materials and specific composition of the layers. Although the authors distinctly identify the cumulative impact of liner used in landfill construction, the study did not specify the type of landfill or cover system. Moreover, the cumulative impact did not include the total GWI of their cover system with either of these liners used. Thus, the findings of our study would be a crucial step to fill this knowledge gap.
4.2 LCIA results for FFD

4.2.1 The overall comparison

The baseline results of the willow ET cover show significantly lower contributions to FFD impact compared to the clay and geosynthetic cover scenarios (Figure 9). The total FFD impact of willow ET cover (75,303 MJ Surplus ha\(^{-1}\)) is 4.7 times lower than the impact of the clay cover (356,053 MJ Surplus ha\(^{-1}\)) and 7.7 times than that of the geosynthetic cover (583,417 MJ Surplus ha\(^{-1}\)). It was observed that all three landfill covers show large positive values for FFD impact. This shows that the preinstallation, installation, and maintenance phases of these covers require significant consumption of fossil fuels and resources. The natural phase for the FFD impact category is not included as there is no fossil fuel depletion associated with the natural processes of the willow ET, clay and geosynthetic covers.

The LCIA results for FFD in this study are in line with the relevant sustainability assessment study of conventional and ET covers by Goldenberg and Reddy (Goldenberg & Reddy, 2017). Despite the differences in assumptions and the components of cover systems, the findings for the FFD associated with the conventional covers in their study are surprisingly close to the ones in this LCA. In their analysis, the FFD impact of the geosynthetic cover (242,123 MJ Surplus ha\(^{-1}\)) is 1.6 times the impact of the geomembrane-lined clay cover (154,848 MJ Surplus ha\(^{-1}\)). In this LCA, the FFD impact of the geosynthetic cover (583,417 MJ Surplus ha\(^{-1}\)) is 1.5 times the impact of clay cover (356,053 MJ Surplus ha\(^{-1}\)). The similarity in results for conventional covers could be because the LCI data for these scenarios is obtained from the SimaPro databases, the use of which is common in both studies.
The results for the ET cover, however, in Goldenberg and Reddy assessment (Goldenberg & Reddy, 2017), are different than the FFD impact estimated for the willow ET cover in this study. The FFD impact associated with the ET cover (1,365 MJ Surplus ha\(^{-1}\)) in their study is 1.8% of the impact of the willow ET cover (75,303 MJ Surplus ha\(^{-1}\)). The main factor contributing to this difference is the inclusion of a maintenance phase in this willow ET cover, which included harvesting and fertilizing willow every four years, compared to the Goldenberg and Reddy study that did not include maintenance activities.

Additionally, the FFD impact of ET cover (1,365 MJ Surplus ha\(^{-1}\)) in Goldenberg and Reddy assessment (Goldenberg & Reddy, 2017) is considerably lower than the impact associated
with clay (113 times) and geosynthetic (177 times) covers in their analysis. Moreover, the LCI data of willow ET cover in our analysis is obtained from the field study at the Solvay site. Whereas, their assessments are based on a hypothetical model of an ET cover. Another reason for the difference is likely due to a different type of ET cover used in their study, as mentioned previously. Our study compared three specific covers (willow ET, clay, and geosynthetic) from two broad cover categories (vegetative and conventional). The Goldenberg and Reddy's study although specified the type of conventional covers compared with an ET cover, the authors did not clarify the type of analyzed ET cover (Goldenberg & Reddy, 2017) and is the reason why the results of willow ET cover vary in this study.

The proportion of the FFD impact associated with preinstallation, installation and maintenance phases varied between the willow ET and conventional covers. For the willow ET cover, the maintenance phase contributed 75% of the total FFD index followed by the maintenance impact of clay (2.3%) and the geosynthetic covers (1.4%). In contrast, the installation phase dominated the FFD impact for both the geosynthetic (84.4%) and clay (74.5%) covers than the lower impact (16.7%) of installation of willow ET cover. Preinstallation is the second largest contributor to FFD for the clay (23.2%) and geosynthetic (14.2%) covers while for the willow ET cover, the impact is lowest (8.2%) as compared to the conventional covers. The impact of each phase is discussed in detail in order of its magnitude on the total FFD impact.

The maintenance phase made the largest contribution (75%) to the total FFD impact for the willow ET cover and this was dominated by N fertilizer applications (56.9%) followed by harvesting operations (16.9%), both of which occur every three to four years at Solvay site. In comparison, the maintenance of clay and geosynthetic covers do not involve such recurring processes. The maintenance of these covers only includes cultivation and mowing of grass cover, the impact of which is not more than 2% of the total in each case. As mentioned in section 4.1,
other processes such as annual inspection and occasional cover repair, however, may be required for the maintenance of clay and geosynthetic covers. The impact associated with the consumption of resources and fossil fuels used in these processes is not accounted for geosynthetic and clay covers. Hence, the total impact of the maintenance phase can be considered conservatively estimated. With a 10% default value for cover repair, assumed in previous studies (Dillon, 2008a; North Carolina State University and Eastern Research Group Inc., 2011), the estimation of FFD impact for the maintenance phase of the clay and geosynthetic covers might result in a little higher impact than estimated (8,131 MJ Surplus ha\(^{-1}\)) in this LCA. The estimates, however, may vary as per requirement for maintenance. Since there are different requirements for cover repair or replacement across various locations, the consumption of resources and fossil fuels may vary. In that case, an assumption of a default 10% for cover repair may not be appropriate.

Contrary to the maintenance phase, the preinstallation and installation phases of willow ET cover have the minimum FFD impact as compared to the clay and geosynthetic counterparts. The preinstallation of willow ET cover has 13 times lower impact (6,198 MJ Surplus ha\(^{-1}\)) than that of clay (82,746 MJ Surplus ha\(^{-1}\)) and geosynthetic covers (82,746 MJ Surplus ha\(^{-1}\)). The preinstallation of willow ET cover, which is only 8.2% of the total FFD impact, involves site clearing with the impact of a hydraulic excavator to clear existing vegetation followed by spraying of post-emergent herbicide. On the other hand, the impact of the preinstallation of the conventional covers, which is 23.2% for the clay cover and 14.2% for the geosynthetic cover of their total impact. The preinstallation of clay and geosynthetic covers, in addition to vegetation clearing that occurs onsite, involves processes of mining of clay from quarries that are offsite and their transportation to the Solvay site. The mining and transportation processes consume a considerable amount of fossil fuels which leads to higher FFD impact. Thus, the preinstallation impact of willow ET cover is noticeably lower as there are no mining and transportation operations.
The installation phase of geosynthetic covers has the highest FFD impact as compared to the willow ET and clay cover. The FFD impact of the installation of the geosynthetic cover (492,540 MJ Surplus ha\(^{-1}\)) is almost twice the impact of clay cover (265,176 MJ Surplus ha\(^{-1}\)). The installation of both conventional covers requires mining and transportation of clay, sand, and compost soils, however, the installation of geosynthetic cover includes several polymer-based layers. The impact of these additional activities in the installation of geosynthetic cover (227,364 MJ Surplus ha\(^{-1}\)) made up 46% of the total installation impact (492,540 MJ Surplus ha\(^{-1}\)) and 40% of the total FFD impact (583,417 MJ Surplus ha\(^{-1}\)). Thus, the difference between the FFD impact of the clay and geosynthetic covers is due to additional processes and materials used in the installation of the geosynthetic cover that involves additional fuel consumption for production and transportation.

In contrast, the impact of the installation of willow ET cover (12,546 MJ Surplus ha\(^{-1}\)) is 21 times lower than the impact of clay cover (265,176 MJ Surplus ha\(^{-1}\)), whereas 39 times lower than the impact of geosynthetic cover (492,540 MJ Surplus ha\(^{-1}\)). Although the installation of willow ET cover involves transportation operations such as transport of organic amendments and willow cuttings to the Solvay site, the impact of these operations is only 11% of the total FFD impact. Other than transportation, all other operations such as sowing and mowing of cover crop, herbicide application and coppicing are onsite activities that impact the total impact relatively minimally (5%).

4.2.2 Comparison of processes in each phase of willow ET, clay and geosynthetic covers

a) Willow ET cover

The total FFD impact is more distributed in the maintenance phase among preinstallation and installation phases in the lifecycle of willow ET cover (Figure 10). The main contributing
processes from the maintenance are fertilizer application (42,848 MJ Surplus ha\(^{-1}\)) and willow harvest (12,750 MJ Surplus ha\(^{-1}\)), both of which made up 73% of the total FFD impact. The impact of these two processes includes application of urea as nitrogen fertilizer (100 kg N ha\(^{-1}\)) once every four years at the start of each growing season followed by harvest rotation. Since this process is repeated seven times in a 30-year lifecycle of willow ET cover, the impact associated with the amount of resources and fuel consumed in fertilizer and harvest operations amplifies seven times. Other processes such as mowing headlands annually and transport of chips after every harvest to the edge of the field are minor (≤1%) components of the total.

Fertilizer applications and harvest operations that occur every three years as part of the willow ET cover system made up a large proportion of the total GW and FFD impacts. Past studies analyzing the energy input of shrub willow systems had similar findings (Heller et al., 2003; Patel, 2014; Yang, 2017). Manufacturing of nitrogen fertilizers is an energy intensive process that impacts the energy input into the system because N fertilizer is applied once every three to four years following harvesting operations. For example, Heller et. al states that manufacture of fertilizer itself is 91% of the energy required to fertilize willow, whereas nitrogen fertilizer (urea) inputs accounts for 37% of the total fossil fuel consumed in the lifecycle of willow biomass crops (Heller et al., 2003). Studies have suggested substituting the synthetic fertilizers with organic amendments or biosolids (Heller et al., 2003; Yang, 2017). Field trials have shown willow yields are maintained when organic amendments are used in place of synthetic fertilizers (Quaye and Volk 2013) and adds organic matter to the soil (Adegbidi, Briggs, Volk, White, & Abrahamson, 2003). The energy required to prepare and transport the organic amendments are lower than the energy and resources required to produce fertilizers (Patel, 2014), so substituting organic amendments for synthetic fertilizer can lower the total impact of the willow ET system.
Similarly, the impact associated with harvest operations can be reduced by harvesting willow in dry weather conditions, as fuel consumed per unit of harvested willow biomass is 45% lower during the dormant season than the summer harvest (Eisenbies et al., 2020; Therasme, 2019). Typically, when willow is harvested during the summer when leaves are present, the material flow into the harvester is slower and variable. This slows down the harvester ground speed to maintain the flow of material into the throat of the harvester and requires more power from the engine to pull in the biomass, chip it and blow it into a wagon (Eisenbies et al., 2020). When ground conditions are wet fuel consumption per Mg of biomass increases because more power is needed to keep the harvester moving. The leaf on wet weather harvests consume about 2.5 time more fuel per Mg of biomass produced than leaf off harvests in dry conditions (Eisenbies et al. 2020). Based on this information the impact of harvesting can be reduced if conditions allow harvesting to be limited to the dormant season when ground conditions are dry.
The process contributing the most in the installation phase is the transportation and mixing of organic amendments (6,262 MJ Surplus ha\(^{-1}\)) which is 8% of the total impact. The quantity of organic amendments applied at this site is based on data from field trials that supported fast growth rates of willow for 10 years (Townsend et. al., 2018). However, the requirement for other locations may vary due to site-specific conditions thus the associated impact would vary in that case. Other processes in the installation including planting willow (2,281 MJ Surplus ha\(^{-1}\)) and pre- and post-emergent herbicide application and tillage (830 MJ Surplus ha\(^{-1}\)) made up 5.4% of the total. The remaining processes have a minor contribution (<2%), overall. The activities in the installation of willow ET cover are a relatively smaller component of the total impact because they occur only once in the 30-year life span of the system.

Figure 10. Fossil fuel depletion impact (FFD) associated with processes in preinstallation, installation, and maintenance of the willow ET cover.
The key contributing process in preinstallation is clearing vegetation which contributes 7% of the total FFD impact. As mentioned previously, site clearing and the mixing of organic amendments may vary from site to site which depends on the need for growing plant and soil quality (Volk et. al., 2018). Since, every location may or may not require removing existing vegetation, site clearing, in that case, would vary or have fewer operations and associated FFD impact in the preinstallation.

b) Clay cover

The total FFD result of the clay cover indicates significant contributions from the installation phase followed by preinstallation and maintenance (Figure 11). In the preinstallation phase, the process with the highest impact on the total preinstallation phase (82,746 MJ Surplus ha\(^{-1}\)) is mining and transport of clay (74,054 MJ Surplus ha\(^{-1}\)). The clay soils with soil density of 1,470 kg m\(^{-3}\) are mined (4,572 m\(^{3}\) ha\(^{-1}\)) and transported (20 km) from clay quarries via diesel-powered combination trucks to the installation site. The impact of all these activities amounts to 21% of the total FFD (356,053 MJ Surplus ha\(^{-1}\)). The rest of the activities in the phase are less than 3% of the total FFD.

The installation phase has the highest FFD impact due to several energy-intensive activities involved, specifically in this phase. It can be observed that the impact of mining and transport of coversoil (178,233 MJ Surplus ha\(^{-1}\)) has the greatest contribution to the total installation impact (265,176 MJ Surplus ha\(^{-1}\)) and incurs 50% of the total FFD. Mining and transport of coversoil involve the excavation of sand, stone, and gravel (coversoil) (6,096 m\(^{3}\) ha\(^{-1}\) with a density of 1,809 kg m\(^{-3}\)) from mines, which are transported (1,809 kg m\(^{-3}\)) 20 km to the Solvay site. The other dominating process in this phase is mining and transport of topsoil to the site which is 18% of the total FFD. Topsoil is also mined from the nearby soil borrow source to obtain 1,650 m\(^{3}\) ha\(^{-1}\) of
organic soil and soil density of 1,524 kg m\(^{-3}\) that are carried (20 km) via trucks to the installation site. Additionally, topsoil is mixed with compost, the impact of which is not more than 6% of the total FFD. The processes that impact less than 0.5% are categorized in the minor.

![Figure 11. Fossil fuel depletion (FFD) impact associated with processes in preinstallation, installation, and maintenance, of clay cover.](image)

Previous studies have determined that transportation distance can be reduced to minimize the fuel depletion associated with transportation. For instance, Patel’s study reported transportation distances as one of the major contributors accounting for 27% of the overall energy input (Patel, 2014). Goldenberg and Reddy’s sustainability assessment also supported the idea of reducing transportation of soils from long distances, as consumption of resources and associated fuel depletion with long transportation distances is not a sustainable approach (Goldenberg & Reddy, 2017).
Another associated factor with transporting soils that contributes to the FFD is the availability of soil borrow source near the installation site or in an ideal case on the site. As mentioned previously, the borrow source for coversoil and topsoil, in some cases, may not be accessible near the installation site due to the unavailability of earth materials in the adjacent area (Goldenberg & Reddy, 2017). In that case, mining, and transportation of clay soils from distant locations would not be a viable approach in terms of consumption of fuel and depletion of natural resources as the impact of these processes is huge, even in small distances. Thus, to minimize the associated impact, studies in past assumed that the soils are available onsite or within 10-20 km of distance from the installation site (Goldenberg & Reddy, 2017; Patel, 2014).

The maintenance phase of clay cover has comparatively lower (2.3%) FFD impact than the preinstallation (23.2%) and installation phases (74.5%). This is due to fewer activities in maintenance than the preinstallation and installation phases. This phase has 2,952 MJ Surplus ha\(^{-1}\) of FFD associated with plowing and disking of grass seed that occurs once in lifetime followed by the impact of mowing grass (5,178 MJ Surplus ha\(^{-1}\)) that happens once in every three years. Each of these processes has not more than 1.5% impact, overall.

c) Geosynthetic cover

As in the case of clay cover, the installation phase accounts for the largest portion of the FFD impact followed by the preinstallation and maintenance. The largest share in total FFD impact (583,417 MJ surplus ha\(^{-1}\)) is due to the process of manufacture and transport of geomembrane that incurs 35% of the total FFD (Figure 12). The process of production of geomembrane is largely dependent on fossil fuel resources that are used to convert polymer-based resins into geomembrane sheets (Müller, 2007) that are transported in rolls to the installation site. Other major contributing activity is the impact of mining and transportation of the coversoil (178,233 MJ surplus ha\(^{-1}\)) and
topsoil (64,516 MJ surplus ha\(^{-1}\)) used during installation combined accounted for 49% of the installation phase impact while 42% of the total FFD. The remaining processes in this phase such as transport and mixing of compost and others made up 8% of the total installation impact, each of which has less than a 5% impact on the total FFD.

The impact of the preinstallation phase for both the clay and geosynthetic covers was the same (82,746 MJ surplus ha\(^{-1}\)) because they both included the same steps and were based on the same set of assumptions. As noted above with the GWI, the FFD impact of the maintenance phase for both cover types is low (8,130 MJ surplus ha\(^{-1}\)) because only regular sowing, plowing, and mowing of grass is included in this category.

Figure 12. Fossil fuel depletion (FFD) impact associated with processes in preinstallation, installation, and maintenance, of geosynthetic cover.
4.3 Sensitivity analyses

The response variables i.e. GW and FFD impact are sensitive to input parameters to varying degrees (Figure 13). The GWI associated with willow ET cover is most sensitive to root to shoot ratio and willow biomass yield with the largest relative differences in the impact (Figure 13a). The root to shoot ratio is inversely proportional to the GWI as a 10% increase in the root to shoot ratio decreases the GWI by 28%. The root shoot ratio estimates the amount of biomass stored in coarse roots belowground and the permanent part of the plant, the stool, which remains on the site and is the source of sprouts for the next willow crop. A relatively minor change in this ratio can contribute to a substantial change in the amount of biomass in these permanent plots and has shown to be a key factor in other recent LCA studies (Yang 2018, Caputo et. al. 2014). Root to shoot ratios in this study are based on data from three cultivars from two sites with 10-year-old root systems. Other studies suggest that the coarse root and stool biomass levels off at 12 – 14 years old so the estimates here may be a slight underestimate (Pacaldo et. al., 2013). Because of the importance of this parameter, there is a need for additional studies to understand this variable with the spatial and temporal variability (Rytter, 2012; N. J. Sleight et. al., 2015).

Willow biomass yield also has an inverse relationship with the GWI as a 10% increase in the willow biomass yield decreases the GWI by 21%. The inverse relationship between willow biomass yield and GWI can be associated with the higher carbon sequestration in coarse roots and stool that are not removed over their lifetime (Pacaldo, Volk, & Briggs, 2014). Because this relationship the GWI associated with a willow ET cover can be reduced by improving the biomass yield.

The amount of N fertilizer added to the system and leaf nitrogen concentration have a positive relationship with GWI and a change of ±10% in these parameters affect the GWI by ±3.5%
for N fertilizer and ±5.7% for leaf N concentration. The rest of the input parameters have a direct relationship with GWP, but their impact is nominal (<±2%).

In the case of FFD impact associated with the willow ET cover, the most sensitive input parameter is the N fertilizer percentage (Figure 13b). A change of ±10% in the N fertilizer rate has a ±5.3% change in the FFD impact. In this study, we used N fertilizer that is made from natural gas but other organic waste materials such as organic biosolids and composted manure have shown to be effective (Quaye & Volk, 2013) and would lower the FFD (Heller et. al., 2003b). The impact of directly replacing commercially produced N fertilizer with organic waste streams has not been assessed in this study because of the lack of trials to assess their impact at this location. The rest of the input parameters have an insignificant (<±1%) influence on the FFD impact.

The sensitivity analyses of GWI and FFD impact associated with clay cover indicate that all the input parameters exhibit a positive relationship with both impact categories (Figure 13 (c, d)). Moreover, in both cases, the results varied in almost similar proportions. For example, excavated cover soil is the most influential parameter for GWI (Figure 13c) and FFD impact (Figure 13d) and a ±10% change in the parameter alters GWI by ±5.5% and FFD impact by ±5.0%. The shifts for these two impact categories are similar because GWI is directly proportional to fuel depletion in the context of cover soil excavation. In other words, the major component responsible for GWI associated with the excavation of cover soil is fossil fuel consumption. Similarly, a ±10% change in excavated topsoil did not increase (or decrease) the GW results by more than 2.0% and FFD results by 1.8%. Also, the change in the excavated clay parameter influences GWI by ±1.8% and FFD impact by ±2.1% only.
Figure 13. Sensitivity analyses for the input parameters of the willow ET cover for (a) global warming impact and (b) fossil fuel depletion impact, followed by clay cover (c) global warming and (d) fossil fuel depletion impact, and geosynthetic cover (e) global warming and (f) fossil fuel depletion impact. The horizontal bars represent global warming (kgCO$_2$ eq ha$^{-1}$) and fossil fuel depletion impact (MJ Surplus ha$^{-1}$) when a parameter is altered from its minimum to its maximum value.
The remaining input parameters including distance cover soil (≤±1.5%) and distance clay to the site (≤±1.0%) have a nominal impact on both GW and FFD impact categories. Past studies on sustainability assessment of clay cover conducted sensitivity on the distance to clay borrow source as it was the only component analyzed for impact on carbon footprint. They found a positive relationship between distance to soil borrow source and carbon footprint as with greater distance more truck trips would be required to transport the clay soils from the quarries (Goldenberg & Reddy, 2017). The study, however, did not analyze other factors that could influence the carbon footprint, overall. Moreover, their study did not perform a sensitivity analysis for FFD associated with clay cover. Our study is a major step forward on that front.

For the geosynthetic cover, GW (Figure 13e) and FFD (Figure 13f) result varied in a similar trend as observed in the case of clay cover. Although the geosynthetic cover scenario has additional input parameters compared to the clay cover scenario, the response of both the impact categories to change in input parameters is less variable. For example, the excavated cover soil is the most influential parameter to both GWI and FFD impact for the geosynthetic and clay covers. For the geosynthetic cover, a change of ±10% in the excavated cover soil increases GWI by ±3.9%, whereas FFD increases by ±2.9%. Correspondingly, a ±10% change in the excavated topsoil and the excavated clay alters the GWI and FFD impact each by less than ±2%. Other parameters show minimal sensitivity (≤±1%) to both impact categories.

4.4 Uncertainty analyses

The results from the Monte Carlo analysis show that the average GWI associated with willow ET cover is negative (-12,873 ± 2,610 kgCO\textsubscript{2eq} ha\textsuperscript{-1}), while the average impact of both the clay (194,700 ± 7,292 kgCO\textsubscript{2eq} ha\textsuperscript{-1}) and geosynthetic scenarios (269,066 ± 7,587 kgCO\textsubscript{2eq} ha\textsuperscript{-1}) are positive and significantly higher (Figure 8). With all the variables included in this analysis,
there are no scenarios where the ET willow cover has a GWI greater than 0. Basically, over the life of this system, it can protect human health and the environment while sequestering a small amount of CO₂. The boundary of this study is at the edge of the ET willow cover field and does not include transportation and conversion of the biomass to heat, power, biofuels and/or bioproducts, which would likely shift the impact of the system.

Based on other studies transportation of willow biomass to an end-user can be an important contributor to GWI. Yang’s analysis for willow grown in northern NY showed that among crop and biomass management activities, transportation to different end users had the largest GWI at around 35 kgCO₂eq Mg⁻¹. With a baseline yield of 260 Mg ha⁻¹ this equates to 9,100 kgCO₂eq ha⁻¹, which means that more than 75% of the ET willow cover scenarios would still have a negative GWI (Yang, 2017).

The simulations for FFD impact indicate that willow ET cover has the minimum contribution (80,612 ± 2,706 MJ Surplus ha⁻¹) to FFD which is 23% of the impact of clay (354,221 ± 12,913 MJ Surplus ha⁻¹) and 14% of the impact of geosynthetic scenario (604,525 ± 13,844 MJ Surplus ha⁻¹). These estimates show that the willow ET cover has a significantly lower contribution to FFD impact than the clay and geosynthetic cover scenarios. The willow ET cover is a biological approach to protecting human health and the environment at the site and makes use of solar energy to both grow the crop and drive evapotranspiration that is central to managing the water budget. This system works with natural forces while the geosynthetic and clay barriers are creating a system to resist the natural water flow patterns and processes. This barrier approach requires a significantly larger investment of energy in the form of fossil fuels to make the system functional.
Table 3. Statistical data of the Monte Carlo results for GW and FFD impact associated with the lifecycle of willow ET cover, clay, and geosynthetic covers.

<table>
<thead>
<tr>
<th></th>
<th>Willow ET cover</th>
<th>Clay cover</th>
<th>Geosynthetic cover</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GWI (MgCO₂eq ha⁻¹)</td>
<td>FFD Surplus (MJ ha⁻¹)</td>
<td>GWI (MgCO₂eq ha⁻¹)</td>
</tr>
<tr>
<td>Mean</td>
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<td>194.7</td>
</tr>
<tr>
<td>Stdev</td>
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<td>2,706</td>
<td>7.3</td>
</tr>
<tr>
<td>Min</td>
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<td>Q2 (Median)</td>
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<td>194.7</td>
</tr>
<tr>
<td>Q3 (upper quartile)</td>
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<td>200.1</td>
</tr>
<tr>
<td>Max</td>
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<td>86,960</td>
<td>213.6</td>
</tr>
<tr>
<td>Range</td>
<td>13.9</td>
<td>12,652</td>
<td>37.9</td>
</tr>
</tbody>
</table>

Under both impact categories, the willow ET cover have a smaller variance than either the clay and geosynthetic covers (Figure 14 (a, b)). This indicates that the estimates for willow ET cover are less variable than the clay and geosynthetic covers. The shapes of the probability distribution curve and corresponding descriptive statistics suggest that the estimated values for GWI and FFD impact are normally distributed (Table 3), which concludes that the results of this LCA are dependable. The uncertainty analysis in this LCA would be an important advancement to previous LCA studies on landfill covers as to best of our knowledge no other comparative LCA’s on willow ET, clay and geosynthetic covers in the past have performed this analysis.
Figure 14. Monte Carlo analysis for (a) global warming (kgCO$_{2eq}$ ha$^{-1}$) and (b) fossil fuel depletion impact (MJ Surplus ha$^{-1}$) associated with the lifecycle of willow ET cover, clay and geosynthetic covers from 10,000 simulations. Probability distribution curve for all three scenarios represent normal distribution (Bell curve) with different means and standard deviations.
5. Conclusions

In this case study, shrub willow as ET cover has the lowest GW and FFD impact compared to clay and geosynthetic conventional covers. The processes in preinstallation, installation, maintenance and natural phases of willow ET cover incur 22,378 kgCO$_2$eq ha$^{-1}$ of GHG emissions, however, the impact of carbon sequestration in the natural phase (-35,583 kgCO$_2$eq ha$^{-1}$) was large enough that offsets (-13,206 kgCO$_2$eq ha$^{-1}$) the positive contributions. In other words, more GHGs were sequestered than emitted during the lifecycle of willow ET cover. Of these positive emissions, fertilizer input and harvest operations from the maintenance phase were the major contributors. In contrast to the GWI of willow ET cover, both the clay cover (194,916 kgCO$_2$eq ha$^{-1}$) and geosynthetic (260,212 kgCO$_2$eq ha$^{-1}$) cover contributed to large positive emissions. The key process contributing to GWI, for both clay cover and the geosynthetic cover was from the installation phase, which was mining and transport of coversoil for the clay cover whereas, for the geosynthetic cover, the production and transportation of geomembrane contributed the most.

For FFD impact, the willow ET cover (75,303 MJ Surplus ha$^{-1}$) resulted in the lowest impact than the clay cover (356,053 MJ Surplus ha$^{-1}$) and the geosynthetic cover (583,417 MJ Surplus ha$^{-1}$). The processes and phases for major impact on the total FFD emissions remain the same as in the case of total GWI because these processes and phases had major activities, as well as had higher impact consistently in terms of fuel and resource consumption.

Both sensitivity and uncertainty analyses indicated that the estimates for willow ET cover are less variable than for the clay and geosynthetic covers. The analyses demonstrated that root to shoot ratio, willow biomass yield, and fertilizer percentage were among the most influential input parameters for the willow ET cover. While, for the clay and geosynthetic covers, most of the input parameters remained insensitive, except for excavated coversoil, clay, and topsoil variables.
The results of the GW and FFD analyses suggest that the willow ET cover is relatively sustainable cover approach in terms of minimum contributions to GHGs and fuel consumption compared to clay and geosynthetic conventional covers. Further reduction in contributions to the impact of GW and FFD could be accomplished by optimizing the use of fertilizers and maximizing energy efficiency in terms of harvest operations.
6. Future Work

This study analyzed landfill covers from two broad categories i.e., vegetative, and conventional covers. Willow ET cover is one type of ET cover that is compared for GW and FFD impacts with two types of commonly used conventional covers (clay and geosynthetic covers). Comparing other types of ET covers with conventional alternatives would help to develop a broader knowledge of the differences between the two categories.

The lifecycle of landfill covers in this study is divided into separate phases depending upon the associated processes in the 30-year lifecycle of each cover system. Among these separate phases, the impacts associated with the maintenance of the clay and geosynthetic cover only included regular processes of cover care. Further research can be done gathering the field data on inspection and repair for the clay and geosynthetic covers. Similarly, field studies and information on the natural processes that occur in lifecycle of conventional landfill covers would be useful.

The LCI data for all phases of the willow ET cover was obtained from field data on the Solvay site, whereas, the data for clay and geosynthetic cover alternatives are based on hypothetical scenarios. The comparison of the three models could be further improved if the foreground information for all three covers is obtained from the Solvay site.


https://doi.org/10.1201/9781420086522


https://doi.org/10.1021/es0620181


Mirek, J. (2008). PERFORMANCE OF SHRUB WILLOWS (SALIX SPP.) AS AN EVAPOTRANSPIRATION COVER ON SOLVAY.


Patel, A. (2014). LIFE CYCLE ANALYSIS OF SHRUB WILLOW EVAPOTRANSPIRATION COVERS COMPARED TO TRADITIONAL GEOMEMBRANE COVERS.


Table 4. Supplemental information of lifecycle inventories obtained from the databases and peer-reviewed literature.

<table>
<thead>
<tr>
<th>Inventory</th>
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<tr>
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</tr>
<tr>
<td>Clay and soil Mining</td>
<td>EU &amp; DK Input Output Database</td>
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<tr>
<td>Clay mining</td>
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<td>Diesel at US refinery</td>
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<tr>
<td>Diesel industrial equipment use</td>
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Supplemental Information
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<td>Willow cuttings</td>
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Table 5. LCI baseline results of willow ET, clay and geosynthetic cover scenarios using GW and FFD impact categories of EPA TRACI.

<table>
<thead>
<tr>
<th>Phases</th>
<th>Cover scenarios</th>
<th>Processes</th>
<th>GWI (kg CO$_{2}$eq per ha)</th>
<th>FFD (MJ Surplus per ha)</th>
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<tbody>
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<td>718</td>
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<td></td>
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<td>3,213</td>
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<tr>
<td></td>
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<td>Clearing vegetation</td>
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<td>5,479</td>
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<td>Willow ET</td>
<td>Transport &amp; mix Organic amendment</td>
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<tr>
<td></td>
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<td>64,516</td>
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<td>12,750</td>
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<tr>
<td></td>
<td></td>
<td>Apply fertilizer</td>
<td>4,486</td>
<td>42,848</td>
</tr>
<tr>
<td></td>
<td>Geosynthetic</td>
<td>Transport willow chips to storage site</td>
<td>9.06</td>
<td>19.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plow, sow, and disk grass seed</td>
<td>533</td>
<td>2,952</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mow grass</td>
<td>371</td>
<td>5,178</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plow, sow, and disk grass seed</td>
<td>533</td>
<td>2,952</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mow grass</td>
<td>371</td>
<td>5,178</td>
</tr>
<tr>
<td></td>
<td>Willow ET</td>
<td>Carbon sequestration</td>
<td><em>(35,583)</em></td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Clay</td>
<td>Leaf decay</td>
<td>7,294</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Geosynthetic</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Total</td>
<td>Willow ET</td>
<td><em>(13,206)</em></td>
<td>75,303</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clay</td>
<td>194,916</td>
<td>356,053</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geosynthetic</td>
<td>260,212</td>
<td>583,417</td>
<td></td>
</tr>
</tbody>
</table>

*Note: The impact for each category may not add up to total due to round off
Equations for sensitivity and uncertainty analyses for willow ET cover, clay and geosynthetic conventional covers

Willow ET cover

Pr_01_clearing_vegetation=
LCI_impact_hydraulic_excavation_digger*Soil_excavated#kg CO2eq/ha*30

Pr_02_contact_Weedcontr=
LCI_impact_first_post_emergent_herbicide_used#kg CO2eq/ha

Pr_03_organic_amendment=
LCI_impact_transport_truck*Mass_org_amend_per_ha*distance_transport_truck_mixinggate_to_site
+LCI_impact_diesel*fuel_consumption_amend_spreading+LCI_impact_diesel*(fuel_consumption_amend_largedisk+fuel_consumption_amend_smalldisk)#kg CO2eq/ha*30,[kg Co2/t/km][t or Mg/ha][km],[kg Co2/m3] [m3/ha]

Pr_04_sow_covercrop=LCI_impact_covercrop+LCI_impact_rye_seed#kg CO2eq/ha*30

Pr_05_mow_covercrop=LCI_impact_mow_rake#kg CO2eq/ha

Pr_06_planting=LCI_impact_planting + LCI_impact_cuttings * 13500.0

Pr_07_preemer_herbi_appl= LCI_impact_pre_emergent_herb#kg CO2eq/ha*30

Pr_08_1stherbi_n_tillage_appl= LCI_impact_second_post_emergent_herbicide+ LCI_impact_roller_crimper#kg CO2eq/ha*30

Pr_09_coppicing=LCI_impact_coppice#kg CO2eq/ha

Pr_10_2ndherbi_n_tillage_appl=LCI_impact_third_post_emergent_herbicide+ LCI_impact_roller_crimper#kg CO2eq/ha*30

Pr_11_mowing_headland=LCI_impact_mow_headlands*area_headland*30#kg CO2eq/ha*30

Pr_12_harvesting=
((harvester_fuel_cons_ha*LCI_impact_diesel*1.0/1000)+lubricant_cons_ha*(LCI_lubricant/1000) + LCI_impact_wagon* Wagon_count )* 7.0#kg CO2/ha, 1 m³ = 1000 L, scaled to 30 years or 7 rotation, #kg CO2eq/ha

Pr_13_fertilizer_appl=LCI_impact_fertilizer_used#kg CO2eq

Pr_14_transport_chips_storagesite=
(LCI_impact_transport_truck*Distance_truck_planting_site_to_storage_site*Willow_biomass_yield_perha_yr*number_grow_year)#kg CO2eq

Pr_15_belowground_carbon= -1.0*(Willow_biomass_yield_perha_yr*3.0*1000) *Root_shoot_ratio*(0.25*0.466908+0.36*0.459453+0.39*0.447721) *3.67#kg CO2eq/ha

Pr_16_leafdecay=(Willow_biomass_yield_perha_yr*3.0*1000)/50.8*5.5*Leaf_Nitrogen*0.01*number_grow_year*298.0#kg CO2eq/ha
Clay cover

Pr_01_clearing_vegetation=LCI_impact_hydraulic_excavation_digger*
Soil_excavated_at_site# kg CO2eq/ha*30

Pr_02_mine_trans_clay_to_site=LCI_impact_clay_mining*
Excavated_clay_per_ha*Density_clay+LCI_impact_transport_truck_short_haul_NE*Distance_truck_mined_clay_to_solvay_site*Excavated_clay_per_ha*
Density_clay / 1000 # kg CO2eq/ha, [kg CO2eq/kg] [kg/ha] [kg Co2/t/km] [km] [Mg/ha]

Pr_03_clay_installation=LCI_impact_diesel*(fuel_consumption_clay_spreading + fuel_consumption_clay_compaction) + LCI_impact_roller_crimper
#kg CO2eq/ha, [kg CO2eq/m3] [m3/ha] [kg CO2eq/ha]

Pr_04_mine_trans_coversoil_to_site=LCI_impact_sandstonegravel_mining*
Excavated_coversoil_per_ha*Density_cover_soil+LCI_impact_transport_truck_short_haul_NE*Distance_truck_mined_coversoil_to_solvay_site*
Excavated_coversoil_per_ha * Density_cover_soil / 1000 # kg CO2eq/ha, [kg CO2eq/kg] [kg/ha] [kg Co2/t/km] [km] [Mg/ha]

Pr_05_coversoil_installation=LCI_impact_diesel*fuel_consumption_sandstone_and_gravel_spreading# kg CO2eq/ha, [kg CO2eq/m3] [m3/ha]

Pr_06_mine_trans_topsoil_to_site=LCI_impact_clay_and_soil_mining*
Excavated_topsoil_per_ha*Density_top_soil+LCI_impact_transport_truck_short_haul_NE*Distance_truck_mined_topsoil_to_solvay_site*
Excavated_topsoil_pr_ha * Density_top_soil / 1000 # kg CO2eq/ha, [kg CO2eq/kg] [kg/ha] [kg Co2/t/km] [km] [Mg/ha]

Pr_07_trans_and_mix_compost=LCI_impact_transport_truck_short_haul_NE*Mass_compost_per_ha*distance_truck_compost_to_solvay_site+
LCI_impact_diesel*fuel_consumption_compost_spreading+LCI_impact_diesel*(fuel_consumption_compost_largedisk+fuel_consumption_compost_smalldisk)#kg CO2eq/ha*30,[kg Co2/t/km][t or Mg/ha][km],[kg Co2/m3] [m3/ha]

Pr_08_sow_and_disk_grass_seed = LCI_impact_grass_seed * Mass_grass_seed + LCI_impact_disk # kg CO2eq/ha*30, [kg CO2eq/kg] [kg] [kg CO2eq/ha]

Pr_09_mowing=LCI_impact_mow_rake *10# kg CO2eq/ha

Geosynthetic cover

Pr_01_clearing_vegetation=LCI_impact_hydraulic_excavation_digger*
Soil_excavated_at_site# kg CO2eq/ha*30

Pr_02_mine_trans_clay_to_site=LCI_impact_clay_mining*
Excavated_clay_per_ha*Density_clay+
LCI_impact_transport_truck_short_haul_NE*
Distance_truck_mined_clay_to_solvay_site*Excavated_clay_per_ha*
Density_clay / 1000 # kg CO2eq/ha, [kg CO2eq/kg] [kg/ha] [kg Co2/t/km] [km] [Mg/ha]

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Pr_03_clay_installation=LCI_impact_diesel*(fuel_consumption_clay_spreading+fuel_consumption_clay_compaction)+LCI_impact_roller_crimper #kg CO2eq/ha, [kg CO2eq/m3] [m3/ha] + [m3/ha]

Pr_04_trans_geo_manufac_to_distr=(LCI_impact_geomembrane_manufacture + LCI_impact_extrusion_geomembrane)*Geomembrane_roll_weight_perha+LCI_impact_rail_transportation*
Distance_rail_geomembrane_manufacturing_plant_to_distributor*Geomembrane_roll_weight_perha / 1000 # [kg CO2eq/kg] + [kg CO2eq/kg] [kg Co2/t/km] [km] [Mg] [kg/ ha]

Pr_05_trans_geo_distr_to_solv_site=LCI_impact_transport_truck_geomembrane_rolls*Distance_truck_geomembrane_distributor_to_solvay_site*Geomembrane_roll_weight_perha / 1000# kg CO2eq/ha, [kg Co2/t/km] [km] [Mg]

Pr_06_bentonite_processing=LCI_impact_bentonite_mining*mass_bentonite*10000+LCI_impact_transport_truck_short_haul_SE*Distance_truck_mined_bentonite*44.860285+(LCI_impact_diesel*(1/1000)*amount_diesel+LCI_impact_Gasoline*(1/1000)*amount_gasoline+LCI_impact_natural_gas*(amount_natural_gas/1000000*hhv_natural_gas)+LCI_impact_propane*0.0254*amount_propane*1000+LCI_impact_transport_truck_short_haul_SE*Distance_truck_mined_bentonite*44.860285)* mass_bentonite*10000*(1/1000) # kg CO2eq/MJ#kg co2/kg x [kg/m2] x [m2/ha]x[kg co2/m3] x [m3/L] *[L/Mg bentonite] [kg co2/kg nat]/([kJ/kg])x [GJ/kJ] x [ GJ/Mg bentonite]

Pr_07_trans_geosyn_manufac_to_distr=(LCI_impact_PP_manufacture+LCI_impact_extrusion_PP)\*mass_PP_ha+LCI_impact_rail_transportation*
Distance_rail_geosynthetic_manufacturing_plant_to_distributor*Geosynthetic_roll_weight_perha/1000# [kg CO2eq/kg] + [kg CO2eq/kg] [kg Co2/t/km] [km] [Mg] [kg/ ha]

Pr_08_trans_geosyn_distr_to_solv_site=LCI_impact_transport_truck_geosynthetic_rolls*Distance_truck_geosynthetic_distributor_to_solvay_site *Geosynthetic_roll_weight_perha/1000 # kg CO2eq/ha, [kg Co2/t/km] [km] [Mg]

Pr_09_geo_welding=LCI_impact_machine_operation_low_loadfactor/((len_geom + wid_geom) * 9 * weld_average_speed * 18.288 / 10000)# 9 is the number of geom roll per ha, 18.288 m/hr~1ft/min #kg CO2eq/ha, 18.28800 meters per hour, [kg CO2eq/h], hours to weld geomembrane per hectare

Pr_10_mine_trans_coversoil_to_site=LCI_impact_sandstonegravel_mining
*Excavated_coversoil_per_ha*Density_cover_soil+LCI_impact_transport_truck_short_haul_NE*Distance_truck_mined_coversoil_to_solvay_site*
Excavated_coversoil_per_ha * Density_cover_soil /1000 # kg CO2eq/ha, [kg CO2eq/kg] [kg/ha] [kg Co2/t/km] [km] [Mg/ha]

Pr_11_coversoilInstallation=LCI_impact_diesel*
fuel_consumption_sand_stone_and_gravel_spreading# kg CO2eq/ha, [kg CO2eq/m3] [m3/ha]

Pr_12_mine_trans_topsoil_to_site=LCI_impact_clay_and_soil_mining
Excavated_topsoil_per_ha*Density_top_soil+LCI_impact_transport_truck_short_haul_NE*Distance_truck_mined_topsoil_to_solvay_site*
Excavated_topsoil_per_ha*Density_top_soil/1000# kg CO2eq/ha, [kg CO2eq/kg] [kg/ha] [kg Co2/t/km] [km] [Mg/ha]

Pr_13_trans_and_mix_compost=LCI_impact_transport_truck_short_haul_NE*M ass_compost_per_ha*distance_truck_compost_to_solvay_site+
LCI_impact_diesel*fuel_consumption_compost_spreading+LCI_impact_diesel
*(fuel_consumption_compost_largedisk+fuel_consumption_compost_smalldisk)#kg CO2eq/ha*30,[kg Co2/t/km][t or Mg/ha][km],[kg Co2/m3] [m3/ha]

Pr_14_plow_sow_and_disk_grass_seed=LCI_impact_plow+LCI_impact_grass_se ed * Mass_grass_seed + LCI_impact_disk # kg CO2eq/ha*30, [kg CO2eq/ha] [kgCO2eq/kg][kg][kgCO2eq/ha]Distance_rail_geosynthetic_manufacturing_pl ant_to_distributor

Pr_15_mowing = LCI_impact_mow_rake *10 # kg CO2eq/ha
Vita

Zainab Tariq

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Education:

- M.S. in Environmental Science (2020), GPA: 3.5/4.0
  State University of New York, College of Environmental Science and Forestry (SUNY-ESF), Syracuse, New York
- M.Phil Environmental Science (2012), GPA: 3.7/4.0
  International Islamic University, Islamabad, Pakistan
- M.Sc Environmental Science (2005), GPA: 3.0/4.0
  Fatima Jinnah Women University, Rawalpindi, Pakistan
- B.Sc. Biological Science (2001), GPA: 3.4/4.0
  University of Peshawar, Peshawar, Pakistan

Work experience:

Research (2016 - 2020): SUNY-ESF

- Applied lifecycle assessment to conventional and plant-based landfill cover systems to estimate potential environmental impacts by these systems
- Conducted scenario-based analysis of the role of renewables in current and future energy mix of Pakistan using environmental, economic, and social indicators
- Investigated the individual as well as combined interaction effect of transesterification parameters on the biodiesel yield using three-way ANOVA

Teaching (2016 - 2019): Assisted Professors at SUNY-ESF in teaching the following courses:

- SRE 454: Renewable Energy Finance and Analysis
- FOR 416: Sustainable Energy Policy
- FOR 207: Introduction to Economics
- FCH 151: General Chemistry
- EFB 120: The Global Environment and Evolution of Human Society
- Major responsibilities: deliver class lectures, develop, and grade homework, labs, exams, projects, review sessions and substitute my professors whenever required.

Environmental Scientist (2007-2008):

- Coordinated in public hearings and conducted social impact assessment using the interpretative approach in road extension and infrastructure development projects at Project Procurement International.

Publications: