REVIEWING COMPOST USE IN CONSTRUCTION AND MODELING THE HYDROLOGIC RESPONSE OF VEGETATED COMPOST BLANKETS

by

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Abstract

The objective of this independent study is to evaluate the use of compost in large scale earthwork projects such as those conducted by Departments of Transportation. A literature review outlining how compost can be used for soil stabilization, runoff reduction, and vegetation establishment in construction sites shows that compost is viable for these purposes. Important design parameters related to compost were taken from scientific literature, as well as from recommendations by the American Association of State Highway and Transportation Officials and the U.S. Composting council, the authority on composting in the U.S.

Then each state's latest DOT design specification document was assessed for if/how compost use is prescribed. Most states had some mention of compost, but specifications varied widely in scope. The particle size distribution requirements differed from state to state significantly. Many of the requirements outlined by the U.S. Composting Council and the American Association of State Highway and Transportation Officials were not incorporated design specifications for each state.

Modeling of the hydrology of vegetated compost blankets explored different vegetation scenarios, depths of compost, and types of compost in the one-dimensional domain. Fully established vegetation represents a significant sink of soil water from the root zone as transpiration or root water uptake. Since fully established vegetation covers exposed soil, it limited evaporation as well. Varying the depth of the compost layer had less of an effect on the change in soil water storage, evaporation and transpiration than changing the vegetation or type of compost. Different depths of compost did, however, affect the runoff depth more than changing the vegetation. Changing the hydraulic properties of the surface layer, based on hydraulic testing of various composts, had the greatest effect on runoff. While modeling different types of compost, we found the evaporation from the surface is not necessarily an indicator of the hydrologic effectiveness of a surface compost layer, as more water can infiltrate but is subject to evaporation, leading to similar cumulative evaporation.

Overall, the positive effects of compost have been demonstrated while DOTs and other construction companies would benefit from expanded understanding of how to use compost effectively on site. A way to model vegetated compost blankets is presented, which can help engineers determine how to best incorporate compost into design.

Acknowledgements

I would like to thank Professor Steven Loheide for deepening my understanding of vadose zone hydrology and hydroecology, and for his guidance throughout my graduate degree. He has spent many hours teaching me about hydrology and about life, both in his coursework and otherwise. This project would not have been possible without him. I would also like to thank my committee members, Professor Anita Thompson whose insights into this topic first piqued my research interest in it, and Professor William Likos who taught me the fundamentals of unsaturated flow. The other professors in the water resources engineering department at University of Wisconsin, Madison have inspired me along the way as well, especially Professor Paul Block, whose real-world experience and teaching approach I admired greatly. Thank you, also, to the other members of our research group who helped me solve problems, especially Carolyn Voter and Eric Booth. Finally, my family and friends have supported me and never had any doubt that I could complete this degree. Specifically, Steph Herbst supported me through my long hours of coursework, teaching, and research, which I am very grateful for.

Funding for lab work and a vote of confidence were also given to me by the Sustainability, Environmental Achievement and Leadership (SEAL) award. I am very grateful to have been given the opportunity to work with this organization.

When I lived in Minneapolis, many of my housemates were keen to compost our food scraps and yard waste. This always seemed like extra work as we would need to take our them outside to the compost bin each night and had to contend with pests such as fruit flies and families of rats. However, early one spring I took it upon myself to turn the compost. It was mesmerizing to see how all our old food waste turned into rich organic soil that we applied directly to our garden. Furthermore, while working in Saint Paul, MN inspecting construction sites for erosion control, I noted the need for an environmentally friendly way to stabilize soils and nurture vegetation establishment. My experience working on organic farms in Minnesota, Australia, New Zealand, and Japan, helped me to gain an appreciation for and technical expertise about compost. I became passionate and the cyclical nature of how waste can be turned into a usable product and sought to further my knowledge about how compost can be used on larger scales. As municipalities seek to divert more organic waste from landfills, I expect this area of research to expand considerably and am excited to see what the future holds for composting systems and supply chains.

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Chapter 1

Introduction

This paper examines a possible solution to two problems. First, a significant amount of valuable material is landfilled each year. In the United States, federal, state, and local governments, as well as waste handlers, have ambitious goals of diverting waste from landfills. These entities seek ways of recycling waste into usable products. The diversion of waste must be economically viable and environmentally sound. Composting organic waste is one way to divert organic material from landfills. The other problem addressed in this paper is that large construction companies and state Departments of Transportation (DOTs) require materials to stabilize construction site soils and to aid in vegetation establishment. Using compost for these purposes can help drive demand for compost, encouraging composting of organic waste.

In the next two chapters, compost as a means for erosion control, runoff reduction, and vegetation establishment is assessed. Relevant literature and design documents are examined in Chapter 2. How these findings can be applied to DOT projects is addressed in Chapter 3. The fourth chapter focuses on a different, but related problem: how a compost blanket layer affects the water balance and fluxes such as runoff, evaporation, and change in soil moisture. The main focus is the examination the effect of seeding the compost, allowing vegetation to establish, known as a vegetated compost blanket.

1.1 Compost feedstocks

Any organic material can be composted. Composting can be defined as "the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land" (Haug, 1993). Possible feedstocks, or parent materials, that can be used in the composting process are discussed below.

Most states banned green waste (yard waste, garden waste, and woody debris waste) landfilling starting in the 1980s, so composting has been widely employed to deal with this waste stream. Municipalities have different approaches for gathering green waste such as compulsory resident bagging or brush and pan collection methods. Approximately 70% of yard waste is grass clippings, 25% is leaves, and 5% is brush and other materials (Haug, 1993). Green waste feedstocks typically have very little inert material, such as plastic contamination, especially if bagging is not compulsory for collection. Other sources of green waste include agricultural crop residues and tree materials, such as bark, ground/shredded trees, and remnants from clearing and grubbing activities.

Excreted wastes are another valuable feedstock in the composting process. Biosolids are a resultant solid material from the municipal waste water treatment process. The National Sewage Sludge Survey, which was carried out between 1989 and 1990, indicated that only 1/3 of sewage sludges were used for land application (U.S. EPA, 1990). Manures represent another viable feedstock in farmed areas. Manure management has been a long-standing issue in many communities. For example, a feedlot containing 10,000 beef cattle would produce the same amount of manure as 500,000 people (Haug, 1993). While these composts can have problems with metals or pathogens, they typically do not have as many problems with plastic waste.

Food waste can also be a noteworthy feedstock. However, an ongoing issue with this feedstock is contamination from inert materials. Three major types of food waste ranked from, typically, least contaminated to most contaminated are food processing residuals, large scale food waste, and residential/municipally collected. Food processing residuals are left over from industrial processing, and examples include leftover potatoes from French fry production, cranberry waste, apple processing residuals, and beer/wine processing waste. Examples of large-scale suppliers of food waste feedstocks are food wholesalers, grocery stores, restaurants, K-12 schools, universities, correctional facilities, large company campuses, and hotels or other venues. Food waste collected from residents, diverted from the municipal solid waste stream, has a more arduous road to finished compost due to the high rate of contamination.

A lot of food waste ends up in landfills. Of the 136 million tons of municipal solid waste landfilled in 2014, food waste comprised the largest portion, over 21%. Additionally, in 2014, only 5% of food waste was composted and the majority (76.3%) was landfilled (U.S. EPA, 2016).

Other feedstocks do exist. Papermill waste can be substantial feedstock in certain areas of the country. Mushroom growing facilities produce a large amount of organic waste after mushroom cultivation has occurred. This feedstock is known as spent mushroom compost. Although less common, animal carcasses from butchering facilities or vehicular mortality can also be composted if conditions are met to reduce the risk of pathogen contamination. Pet waste could also be composted, but given the logistical differences in collecting this feedstock, it should be considered separately.

The diversion of organic waste from landfills was first attempted at the landfill sites. Organic material removed from the general waste stream had high contamination rates as it was in contact with household chemicals, batteries, electronics, and other waste. As a result, there was an impetus to divert organic material at the waste generator rather than at a waste transfer station or landfill. If compostable waste is sorted from other waste and recyclables by the waste generator, it is commonly called source separated organic material (SSOM).

1.2 The composting process

Important characteristics of compost for erosion control are discussed in Chapter 2. However, a cursory examination of the carbon to nitrogen ratio (C:N) is an important parameter for optimizing the composting process. Nitrogen is required in higher concentrations by microbes than other inorganic nutrients. During aerobic metabolism, microbes use between 15 and 30 parts carbon for each part nitrogen (Haug, 1993). If there is too much carbon in the mixture, the decomposition process may slow. If there is too much nitrogen, the composting process may produce noxious odors (Rynk, 2008). Compost derived from green waste typically has high C:N while food waste- and manure-derived compost typically have low C:N ratios. A mixture of these feedstocks sources has shown to be effective to achieve a C:N ratio less than or equal to 25:1 for proper decomposition (California Compost Quality Council, 2001).

Composting falls low on the food recovery hierarchy (Figure 1.1) (US EPA, 2017), but is still an important component in today's food waste-intensive society as the transition is made to preferable options. Furthermore, composting is best carried out at the source of generation and re-used on site. However, many organic waste generators do not have the space or resources available to compost, and/or do not have a use for the finished product on site.

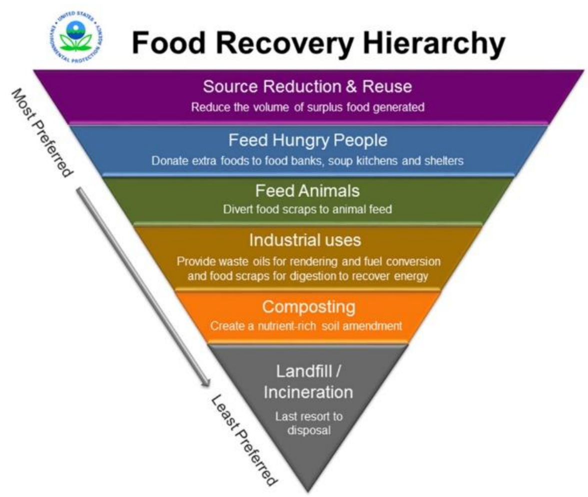

Figure 1.1: Food recovery hierarchy taken directly from the U.S. EPA Sustainable management of food website (2017)

These constraints can make municipal-scale composting facilities a sound option. Facilities can vary in set-up depending on quantity of material to be composted, land area, and financial restrictions. One simple method of composting is wind rows, where organic waste is placed in long rows where heat is contained, and the organic material can break down aerobically.

1.3 Compost for erosion control and vegetation establishment

The application of compost to exposed soil areas has many benefits and is outlined well in the literature. A surface compost layer limits the kinetic impact energy of raindrops, allows water to adsorb to particle surfaces, limits sediment detachment and surface crusting, and roughens the surface which hinders overland flow and sediment losses (Bresson et al., 2001; Faucette et al., 2004; Persyn et al., 2004; Reinsch et al., 2007). Compost also causes a faster infiltration rate (Logsdon and Malone, 2015).

Another important consideration is that compost provides a suitable growing substrate for vegetation, aiding in seed germination and vegetation establishment (Persyn et al., 2007; Singer et al., 2006). Vegetation further helps with runoff and soil loss reduction by intercepting rainfall, increasing surface roughness and stability, and transpiring subsurface water.

Throughout the United States, DOTs undergo massive projects to build, renovate, and redirect roadways; build bridges; and create rail transportation corridors. These large-scale earthwork projects have a high risk of deleterious effects on the environment due to the vast amount of exposed soil area, which can erode and pollute streams, wetlands, lakes, and oceans. Significant effort has gone into controlling erosion and sediment export from sites both during construction and after, but there is still room for improvement. Compost could increase in popularity for soil stabilization and vegetation establishment use on construction sites, especially DOT projects.

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Chapter 2

Literature and documentation review

This chapter outlines what testing parameters are required to obtain United States Composting Council (USCC) certification. The USCC is the authority on composting in the U.S. This organization conducts extensive research on compost, supplies training, and develops compost standards. Thus, the integration of their standards is a reasonable place to start with determining standards for compost use in construction. Then, requirements that have been published specifically for compost blankets will be reviewed. Finally, important previous scientific works that have been conducted on the use of compost in erosion control and vegetation establishment on construction sites will be examined. This information is compiled, and DOT specifications are assessed related to the findings in Chapter 3.

2.1 U.S. Composting Council Seal of Testing Assurance

The USCC lays out requirements for compost to be approved, called the Seal of Testing Assurance (STA). For compost to meet the USCC's guidelines, the compost must first comply with local and state laws. Other requirements are outlined below.

The engineer should be presented with a record of compost sampling and the test results of required parameters. Sampling frequency at the compost generation site depends on the quantity of compost produced annually, shown in Table 2.1 (U.S. Composting Council, 2018).

Table 2.1: Compost sampling frequency requirements

Tons of compost produced annually	Sampling frequency
1-2500	1 per quarter (or less)
2501-6200	1 per quarter
6201-17500	1 per 2 months
17501 and above	1 per month

The USCC has developed and approved methods for verifying compost properties, called the Test Methods for the Examination of Composting and Compost (TMECC). All lab testing should adhere to the procedures outlined in TMECC. The following parameters must be tested: pH, soluble salts (conductivity), nutrient content (N-P-K, Ca, Mg), organic matter [%], moisture content [%], particle size, maturity (bioassay), stability (respirometry), inerts, trace metals, weed seed and pathogens.

The pH should be near neutral and salt concentration should be low to ensure vegetation is not harmed. The nutrient content (N-P-K) is one of many measures for nutrient characterization. The USCC indicates there is no ideal organic matter content, but it generally ranges from 30% to 70%. Overly wet compost are difficult to transport and apply while overly dry compost can create too much dust. The particle size in Table 2.2 is a guideline for top dressing and should not be used in erosion control compost.

Table 2.2: US Composting Council Seal of Testing Assurance Parameters with general guidelines for ranges listed

Parameter	General acceptable range
pH [pH units]	6-8
Soluble salts (conductivity) [dS/m]	1-10
Nutrient content [%TN + %P_2O_5 + %K_2O]	2-5
Organic matter [%]	30-70
Moisture content [%]	40-50
Particle size* [in]	all particles screened through 3/8 or ½
Maturity (bioassay – seedling emergence) [% of control]	"Very mature" > 90% "Mature" 80% to 90% emergence†
Maturity (bioassay – seedling vigor) [% of control]	"Very mature" > 95% "Mature" 85% to 95%
Stability (respirometry – CO2 evolution) [mg CO_2-C per g OM per d]	"Very Stable" <2 "Stable" 2-8
Inerts	Not given
Trace metals	See Table 2.3
Pathogens: Fecal coliform	Less than 1,000 most probable number (MPN) per gram
Pathogens: Salmonella	Less than 3 MPN/4g

*Indicates for top dressing

Maturity indicates the composting process is finished, and the compost can support vegetation. The maturity test involves the planting of cucumber seeds in a 1:1 mixture of vermiculite and compost. Then the percent of seedlings that emerge and vigor of the seedlings are compared to seedlings grown in a 100% vermiculite growing substrate. Cucumbers are sensitive to ammonia and organic acid, but not to salt, so they are indicative of phytotoxic effects that are not induced by soluble salt concentration (Haug, 1993). Other tests are available to test for maturity of compost, such as ammonium concentration, ammonium:nitrate ratio, in-vitro germination and root elongation, earthworm bioassay, and others (California Compost Quality Council, 2001).

Stability is the stage of decomposition the compost is in. It measures the remaining biological activity in the compost. If a compost is stable, it will not use nutrients or deplete oxygen in soil once it is applied. The stability test in Table 2.2 is a measurement of the amount of CO_2 released from sampled compost under moisture and temperatures that are optimal for respiration. Other stability tests include oxygen demand and the Dewar self-heating test (California Compost Quality Council, 2001).

The USCC recommends following a document published by the California Compost Quality Council, Compost Maturity Index (2001) that outlines procedures for determining maturity of compost. “Maturity is in part, affected by the relative stability of the material but also describes the impact of other compost chemical properties on plant development.” In order for compost to be mature and ready for use, it must first have a carbon to nitrogen (C:N) ratio that is less than or equal to 25. Then, it must comply with one test from group A, which includes Carbon Dioxide Evolution or Respiration, Oxygen Demand, or Dewar Self Heating Test. However, the compost must also satisfy one of four other tests: ammonium:nitrate ratio, ammonia concentration, volatile organic acids concentration, or the plant test.

Trace metals can impair receiving water bodies, so the concentration in compost should be considered. A logical starting place for compost requirements is the US EPA Class A Standard.

The standard was created to test biosolids compost routinely to verify it was safe for land application, limiting pollution risk. However, the requirements can be transferred to other composts. Table 3 of 40 CFR § 503.13 (U.S. EPA, 1990) outlines the following maximum concentrations for metals (Table 2.3).

Table 2.3 Maximum allowable metals concentrations in biosolids compost that can be used for other composts following the US EPA Class A standard, 40 CFR § 503.13 (U.S. EPA, 1990)

Pollutant	EPA Limit (mg/kg)
Arsenic	41
Cadmium	39
Copper	1500
Lead	300
Mercury	17
Nickel	420
Selenium	100
Zinc	2800

Pathogens should also be below a threshold to minimize risk to handlers and fauna. The limits in Table 2.2 are derived from US EPA Class A standard, 40 CFR § 503.32(a). It is assumed that if heating throughout the composting process was sufficient to kill bacteria, it was sufficient to kill weed seeds.

2.2 Compost for use in erosion/sediment control

The USCC website links to two different documents that outline the specifications for how to use compost in erosion control:

1. The first document is Standard Specifications for Compost for Erosion/Sediment Control, published by Ron Alexander in 2003. The document states that the report summarizes technical specifications outlined by the Association of State Highway and Transportation Officials (AASHTO).
2. Another document, which is a U.S. EPA achieve document called Landscape architecture/design specifications for compost use by the U.S. Composting Council (n.d.).

The recommendations for compost blankets are identical except for a slight variation in the pH range. However, these documents appear to be outdated as the AASHTO has created a third iteration of this document, *Standard practice for compost for erosion/sediment control (compost blankets), AASHTO designation: R 52-10* (American Association of State Highway and Transportation Officials, 2010). In this document, AASHTO notes, “Stability/Maturity rating is an area of compost science that is still evolving, and as such, other various test methods could be considered. Also, never base compost quality conclusions on the result of a single stability/maturity test.”

The recommendations of this document are outlined in Table 2.4. There are limits on pH, soluble salt concentration, moisture content, organic matter content, particle size, stability, and physical contamination. However, for compost used in erosion control, there are no requirements for nutrient content, maturity, trace metals, or pathogens. This is likely because AASHTO may not have deemed this necessary.

N-P-K can be important for vegetation establishment. This may have been left out because compost is typically used as a soil amendment, not a fertilizer. However, an engineer knowing the N-P-K can make informed decisions about whether to add a fertilizer to the compost.

Table 2.4: AASHTO Erosion Control Compost Blanket product parameters (American Association of State Highway and Transportation Officials, 2010)

Parameter	Vegetated compost blanket	Unvegetated compost blanket
pH [pH units]	6-8.5	N/A
soluble salts (conductivity) [dS/m]	0-5	0-5
organic matter [%]	25-65	25-100
moisture content [%]	30-60	30-60
particle size [screen size (in), % passing mesh]	3”: 100% 1”: 90% to 100% ¾”: 65% to 100% ¼”: 0% to 75% Max particle length: 6”	3”: 100% 1”: 90% to 100% ¾”: 65% to 100% ¼”: 0% to 75% Max particle length: 6”
stability (respirometry – CO_2 evolution) [mg CO_2-C per g OM per d]	<8	N/A
Inerts [%]	<1	<1

Table 2.4 outlines what AASHTO deems important. The pH of the compost should be near neutral for aid in facilitation of vegetation growth. The lack of a range of acceptable pH values on un-vegetated compost blankets raises concern as highly acidic or basic composts could

affect downstream or underground ecosystems. Low pH composts have more phosphorus loading (Faucette et al., 2005) as well. The soluble salt concentration, moisture content, and organic matter content should fall within the ranges specified. Only one stability test is indicated with no maturity requirement. Compost has recently been implicated as a potential source of microplastics in the environment (Weithmann et al., 2018). Although the contribution of microplastics from compost is less than other sources, physical contaminants, such as plastics, metals, and glass should be kept to a minimum.

The particle size distribution of compost also warrants further examination, discussed below. The particle size distribution recommendations are designed to limit kinetic energy of raindrops and facilitate adsorption. Many studies have shown the deleterious effects of using compost with particle size distributions that contain too many fine materials; smaller particles are more likely to runoff. Compost that is not finished can be hydrophobic, increasing runoff. Particle size and the completion of the composting process seem to be the major drivers of erosion from compost blankets.

2.3 Blanket thickness based on precipitation conditions of the site

A variable depth of compost blanket scheme has been proposed by AASHTO and is based on the erosivity index and total precipitation, Table 2.5 (American Association of State Highway and Transportation Officials, 2010). The document states, “In regions subject to lower rates of precipitation or rainfall intensity, or both, lower compost application rates may be used.” Thus, the lower value is assumed to be used. This could be clearer on the table in the document which states, "Total precipitation and rainfall erosivity index".

Annual precipitation averages for the lower 48 states are shown in Figure 2.1 (PRISM Climate Group, Oregon State U, 2015). The rainfall erosivity index is an input to the universal soil loss equation (USLE) and is shown for the lower 48 states in Figure 2.2 and Figure 2.3 (U.S. EPA, 2012). Given this information, we assessed the annual rainfall and erosivity values for each state and determined what range of compost blanket thicknesses are needed, shown in Table 2.6. A simplified map of rainfall erosivity can be found in Appendix A.

Table 2.5: Variable compost application rate, based on precipitation from the American Association of State Highway and Transportation Officials (2010)

Potential runoff and erosion category	Total precipitation or rainfall erosivity index (whichever is lower)	Application rate for vegetated* compost blanket	Application rate for unvegetated compost blanket
Low	1-25 in., 20-90	½ - ¾ in.	1 – 1 ½ in.
Average	26-50 in., 91-200	¾ - 1 in.	1 ½ - 2 in
High	≥ 51 in., ≥201	1 – 2 in.	2 – 4 in.

*Use vegetated compost blanket during planting season in region

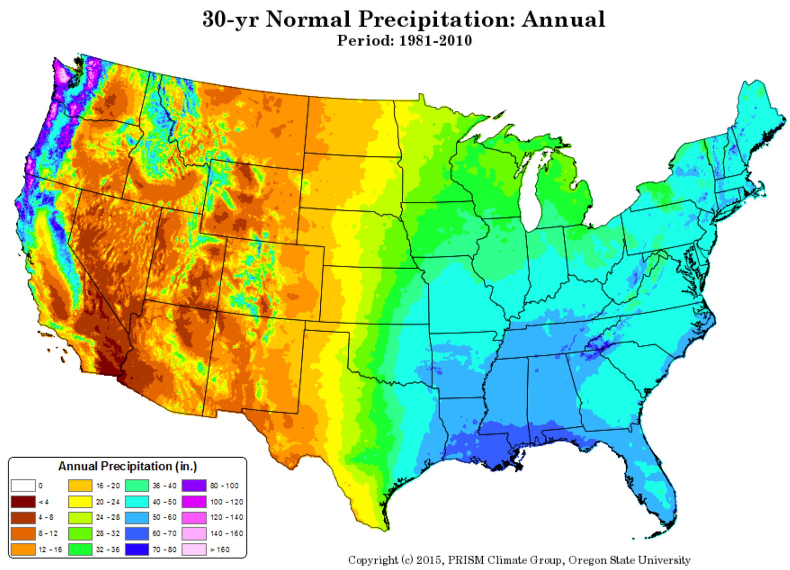

Figure 2.1 Annual precipitation for the lower 48 states. States with wide ranges in annual rainfall, such as those on the West Coast and from Texas to North Dakota to Minnesota may have a problem with using a constant value for a statewide specification. Note: This figure is taken directly from the PRISM research group's website, http://www.prism.oregonstate.edu/normals/.

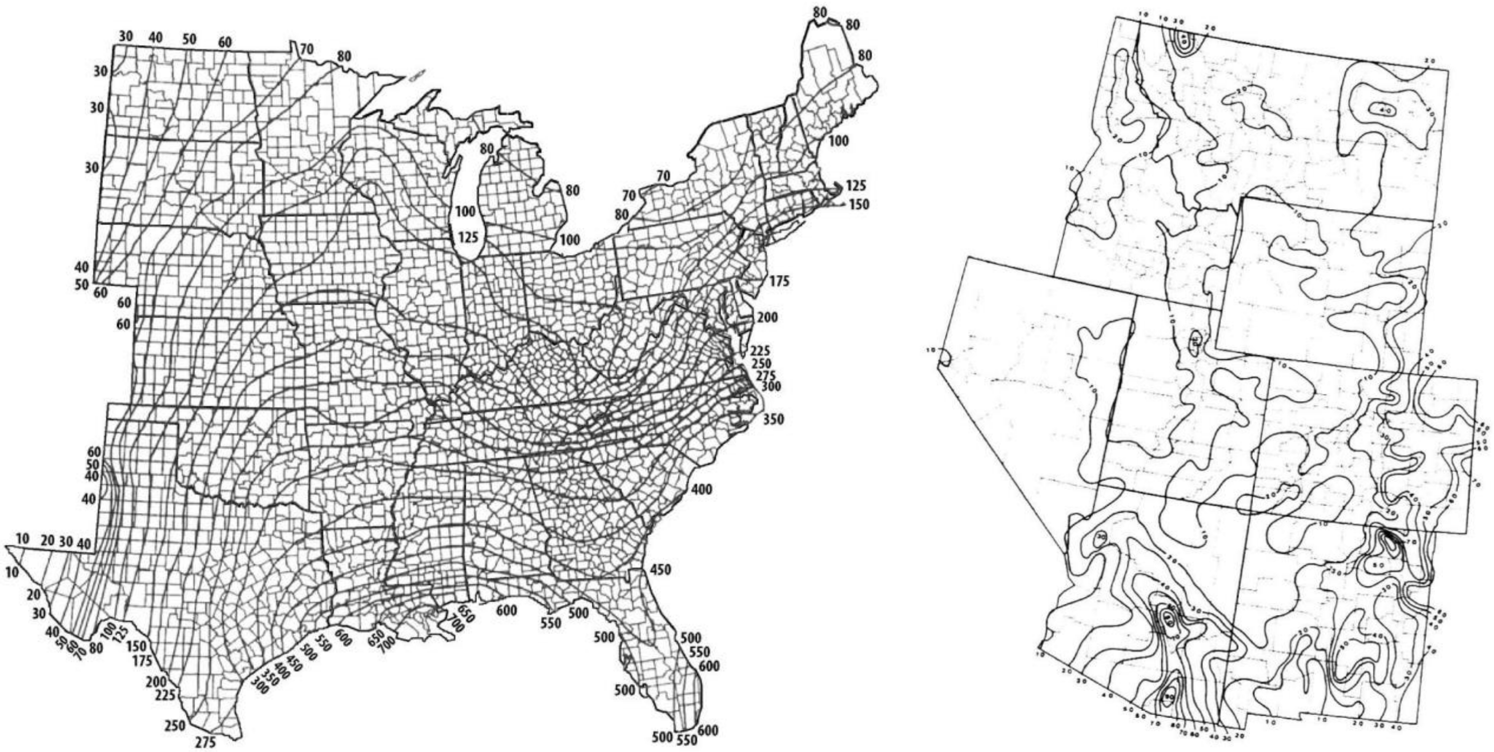

Figure 2.2 Rainfall erosivity indices for the Eastern and Western United States. Note: This figure is taken directly from the document Stormwater phase II final rule: construction rainfall erosivity waiver by the U.S. EPA (2012).

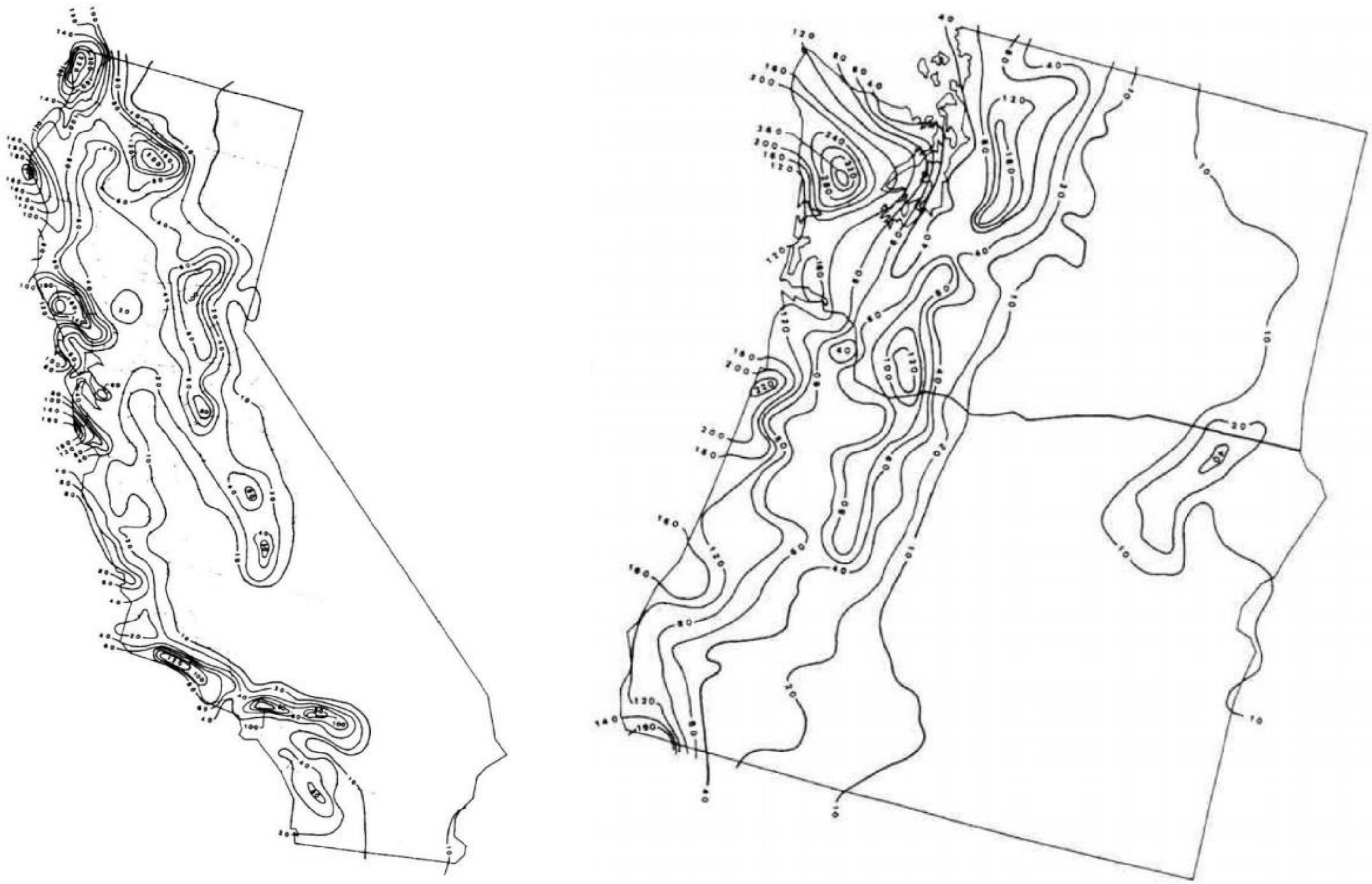

Figure 2.3 Rainfall erosivity indices for California and for Oregon and Washington. Note: This figure is taken directly from the document Stormwater phase II final rule: construction rainfall erosivity waiver by the U.S. EPA (2012).

Table 2.6: Minimum and maximum thicknesses for vegetated and unvegetated compost blankets

State	PRISM annual P		Erosivity index		Final category		Vegetated CB depth		Unvegetated CB depth	
	min	max	min	max	Min of mins	Min of maxs	min [in]	max [in]	min [in]	max [in]
Alabama	High	High	High	High	High	High	2	2	4	4
Alaska	Low	High	Low	High	Low	High	0.75	2	1.5	4
Arizona	Low	Average	Low	Low	Low	Low	0.75	0.75	1.5	1.5
Arkansas	Average	High	High	High	Average	High	1	2	2	4
California	Low	High	Low	High	Low	High	0.75	2	1.5	4
Colorado	Low	Average	Low	Low	Low	Low	0.75	0.75	1.5	1.5
Connecticut	Average	High	Average	Average	Average	Average	1	1	2	2
Delaware	Average	Average	Average	Average	Average	Average	1	1	2	2
Florida	Average	High	High	High	Average	High	1	2	2	4
Georgia	Average	High	High	High	Average	High	1	2	2	4
Hawaii	Low	High	Low	High	Low	High	0.75	2	1.5	4
Idaho	Low	Average	Low	Low	Low	Low	0.75	0.75	1.5	1.5
Illinois	Average	Average	Average	High	Average	Average	1	1	2	2
Indiana	Average	Average	Average	Average	Average	Average	1	1	2	2
Iowa	Average	Average	Average	Average	Average	Average	1	1	2	2
Kansas	Low	Average	Low	High	Low	Average	0.75	1	1.5	2
Kentucky	Average	High	Average	High	Average	High	1	2	2	4
Louisiana	High	High	High	High	High	High	2	2	4	4
Maine	Average	Average	Low	Average	Low	Average	0.75	1	1.5	2
Maryland	Average	Average	Average	Average	Average	Average	1	1	2	2
Massachusetts	Average	High	Average	Average	Average	Average	1	1	2	2
Michigan	Average	Average	Low	Average	Low	Average	0.75	1	1.5	2
Minnesota	Low	Average	Low	Average	Low	Average	0.75	1	1.5	2
Mississippi	High	High	High	High	High	High	2	2	4	4
Missouri	Average	Average	Average	High	Average	Average	1	1	2	2
Montana	Low	Average	Low	Low	Low	Low	0.75	0.75	1.5	1.5
Nebraska	Low	Average	Low	Average	Low	Average	0.75	1	1.5	2
Nevada	Low	Low	Low	Low	Low	Low	0.75	0.75	1.5	1.5
New Hampshire	Average	High	Low	Average	Low	Average	0.75	1	1.5	2
New Jersey	Average	High	Average	Average	Average	Average	1	1	2	2
New Mexico	Low	Low	Low	Low	Low	Low	0.75	0.75	1.5	1.5
New York	Average	High	Low	Average	Low	Average	0.75	1	1.5	2
North Carolina	Average	High	Average	High	Average	High	1	2	2	4
North Dakota	Low	Low	Low	Low	Low	Low	0.75	0.75	1.5	1.5
Ohio	Average	Average	Average	Average	Average	Average	1	1	2	2
Oklahoma	Low	Average	Low	High	Low	Average	0.75	1	1.5	2
Oregon	Low	High	Low	High	Low	High	0.75	2	1.5	4
Pennsylvania	Average	High	Average	Average	Average	Average	1	1	2	2
Rhode Island	Average	High	Average	Average	Average	Average	1	1	2	2
South Carolina	Average	High	High	High	Average	High	1	2	2	4
South Dakota	Low	Low	Low	Average	Low	Low	0.75	0.75	1.5	1.5
Tennessee	Average	High	Average	High	Average	High	1	2	2	4
Texas	Low	High	Low	High	Low	High	0.75	2	1.5	4
Utah	Low	Average	Low	Low	Low	Low	0.75	0.75	1.5	1.5
Vermont	Average	High	Low	Average	Low	Average	0.75	1	1.5	2
Virginia	Average	Average	Average	High	Average	Average	1	1	2	2
Washington	Low	High	Low	High	Low	High	0.75	2	1.5	4
West Virginia	Average	High	Average	Average	Average	Average	1	1	2	2
Wisconsin	Average	Average	Average	Average	Average	Average	1	1	2	2
Wyoming	Low	Average	Low	Low	Low	Low	0.75	0.75	1.5	1.5

It should be noted that a 4-inch depth of compost has been found to be significantly better at reducing erosion and runoff in some studies (Persyn et al., 2004), but supplies no additional benefit from a 2-inch depth in others (Bakr et al., 2012). There is not specific mention in the AASTO guideline about thicknesses for higher slopes. Instead, for highly sloped areas or long slopes, compost filter berms are recommended to mitigate erosion potential. The maximum slope allowed by AASHTO is 2:1 (H:V) without additional BMPs. From this analysis, those states with wide ranges of annual precipitation and/or erosivity indices should require engineers to adjust compost depth (and other erosion BMPS) based on location within the state.

2.4 Scientific journal articles

2.4.1 Foundational works

Compost has been evaluated as a means for erosion control on construction sites since the early 2000s. Much of the early research focused on comparing different types of compost to bare soil and/or to other erosion and sediment control best management practices (BMPs). Between 2003 and 2006, two research groups published the seminal works on assessing compost for use on construction sites. One group published papers with T. D. Glanville and R. A. Persyn as the principal authors, from Iowa State University and Texas A&M University, respectively. The other group was led by L. B. Faucette, research director at Filtrexx.

Persyn and Glanville, conducting experiments in Iowa, assessed compost from three different feedstocks:

1. Biosolids (BSC),
2. Two types of yard waste (YWC), and
3. A compost sourced from a mixture of paper mill and grain processing sludge and yard waste, called bio-industrial (BIC).

These composts were compared against topsoil and compacted roadway embankment soil. The experiment was a 2-year study in 120 cm *180 cm test plots with 3:1 (H:V) sloped highway embankment under simulated average rainfall of 9.5 $cm \cdot hr^{-1}$. Sampling occurred 1 hr after runoff initiated. Composts were applied at 5- and 10-cm depths to determine the effect of application depth on runoff and vegetation growth.

While conventional soils produced runoff in the first 8 minutes, all compost media did not produce runoff in the first 30 minutes. Steady state runoff rates were higher on soil and topsoil than all compost treatments. The 5-cm depth had a greater runoff rate than the 10-cm depth. YWC, the coarsest compost, had a rate of interrill erosion (erosion in between main erosion channels) that was 17% of the BSC and 33% of the BIC on unvegetated plots (Persyn et al., 2004). Metals and nutrient concentrations were higher in biosolids compost. However, due to runoff being 120x greater in the untreated plots, total mass loading of metals and nutrients in runoff were higher in untreated plots (Glanville et al., 2004). Rill erosion was greater on the BSC and BIC treated of soils but was much lower than control soils (Persyn et al., 2005).

Examining the field sites after 3 years, all of the composts were at least as effective as the control soils for establishing crop biomass, while weed species total biomass was significantly reduced. Additionally, increasing compost depth from 5 cm to 10 cm did not affect plant biomass (Persyn et al., 2007).

Faucette et al. (2004) examined the following erosion control measures against a bare soil with a rainfall simulator at 16 $cm \cdot hr^{-1}$ and 2:1 (H:V) sloped sediment chambers:

1. Two types of poultry litter compost,
2. Aged poultry litter,
3. Municipal solid waste compost and biosolids compost mixture,
4. BSC and peanut hulls compost mixture,
5. Food residuals and ground wood waste compost,
6. Yard waste, ground wood waste, and manure compost mixture,
7. Finely ground and medium ground wood mulch, and
8. Coarse ground yard waste and waste wood mulch.

Under this higher rainfall rate, which is higher than the 1-hr 100-yr storm event for Georgia, and steeper slope, compost treatment decreased total runoff volume in all but one of the poultry litter compost treatments. The mulches had the lowest runoff volumes, although not statistically significantly different from composts. The mulches typically had less solid loss, and the municipal solid waste and poultry litter composts were the less effective at reducing solids loss. The aged poultry litter treatment created more solids loss than bare soil, probably due to the hydrophobic nature of the material. Interestingly, poultry litter compost behaved like other composts, indicating that the complete composting procedure is vital for reducing runoff and pollutant export from compost-amended slopes. In contrast to the works of T. D. Glanville and R. A. Persyn, the TP and TN loads from some composts, especially biosolids compost and poultry litter compost, had significantly higher nutrient loads than bare soils.

Many other studies have demonstrated that compost is better than bare soil, topsoil, straw layers, and hydroseed at reducing runoff, erosion, and pollutant export, while establishing vegetation with less weeds (Eck et al., 2010; Faucette et al., 2007; Reinsch et al., 2007; Tyner et al., 2011). While some composts can contain greater concentrations of nutrients and metals than soils, the total mass loading of composts are generally lower than exposed soils or hydroseed due to lesser overall runoff volume (Chaganti and Crohn, 2014; Ho et al., 2008; Xiao and Gomez, 2009).

2.4.2 Particle size distribution and wood chip/wood mulch studies

The particle size distribution and addition of chipped wood mulch to compost is a topic of more recent research. Particle size distribution of compost and mulch blankets are the leading variable that reduces soil loss and runoff (Faucette et al., 2007). However, a critical review of many studies ranked best management practices (BMPs) for erosion control ranked compost behind mulches. From best to worse, the BMPs were ranked: erosion control mats, mulches, composts, hydromulches, bonded fiber matrices, polyacrylamides, and lastly compaction methods (Tyner et al., 2011).

Bhattarai et al. (2011) determined that under an average slope of 3.5%, a 1:1 mixture of wood mulch:compost under natural rainfall conditions provided better erosion control than either compost or mulch blanket alone. However, under laboratory experiments with simulated rainfall, the mulch and 1:1 mixture performed better than compost. The compost in this experiment was "screened garden compost," which would not meet requirements for erosion control compost. Faucette et al. (2007) examined yard waste compost/mulch mixtures on a 10% slope and simulated rainfall, concluding that higher percentages of compost reduce runoff while higher percentages of mulch lower sediment and suspended sediment. The paper also suggests that compost with particle size distributions containing a higher portion of fines were more erodible than compost that meets requirements. The addition of wood mulch into dairy manure compost (1:1 mixture) allows for vegetation growth (Eck et al., 2010).

Large particles can limit the impact energy of raindrops while small particles can adsorb water to their surfaces. Finer particle size distribution compost (biosolids, paper mill/grain processing sludge, poultry litter, and "general use compost") without amendments such as green waste compost or shredded wood mulch have more sediment loss than yard waste compost (Birt et al., 2007; Hansen et al., 2009; Persyn et al., 2004). Care should also be taken to ensure these composts are stable and mature, as the hydrophobic nature of these materials can compound runoff and erosion issues resulting from noncompliant particle size distributions. Based on the studies examining particle size distribution, the AASHTO guideline for erosion control compost is suitable to meet runoff and sediment reduction goals. However, adding woodchips to erosion control compost would be beneficial in most cases.

2.4.3 Prescribing compost blanket thicknesses

Faucette et al. (2009) conducted soil loss tests on a green waste compost blankets in tandem with different BMPs; the universal soil loss equation crop management factor (C) for green waste compost with different BMPs was determined. Rather than examining annual precipitation averages, the 24-hour precipitation depths and slope were used to prescribe a compost depth, Table 2.7. If engineers seek a storm-based approach to determining compost blanket thickness, rather than yearly precipitation and erosivity rates, this approach could be followed with a daily precipitation depth based on the 1-year recurrence interval or whatever design requirements exist for the project.

Table 2.7 Recommended compost erosion control blanket thickness (cm) based on slope angle (H:V) and rainfall accumulation (cm in 24 h period) ***taken directly*** *from Faucette et al. (2009)*

Faucette et al. (2009) compost thickness conclusions [cm]			
Slope (H:V)	Rainfall = 1.65 cm·day^{-1}	Rainfall = 5.0 cm·day^{-1}	Rainfall = 10.0 cm·day^{-1}
≤4:1	1.25 to 5.0	2.5 to 5.0*	5
4:1 to 3:1	1.25 to 5.0	2.5 to 5.0	5
3:1 to 2:1	2.5 to 5.0	2.5 to 5.0	2.5 to 5.0

2.5 Additional notes

It should also be noted that tilling compost into the soil significantly reduces the efficacy of the compost to reduce runoff and erosion (Bakr et al., 2012; Curtis et al., 2009). Another potential issue is adding compost to clay soils. Clay can be stable before any compost is added, but compost can decrease the stability (Xiao and Gomez, 2009). Netting applied under compost has been though to limit loss of sediment, but it only decreased the USLE C factor for 2.5 cm compost depth by 0.02 and increased it by 0.03 and 0.13 for the 5 cm and 1.25 cm depth, respectively (Faucette et al., 2009).

2.6 Conclusion

In conclusion, there should be updates to the erosion control compost requirements that are published by AASHTO. For compost used in erosion control, a pH should be limited to near neutral, even for unvegetated compost blankets. A specific limit on nutrient contents, such as N-P-K, C:N, or other measure would be helpful. Also, the specification table should explicitly state that compost used erosion control blankets should have limited trace metals and pathogens, outlined by the US EPA Class A Standard. Both stability and maturity tests need to be better outlined by the AASHTO. Currently, only one test is required. There should also be information provided in the text about other tests and acceptable results. Information about compost/wood chip mixtures could also be added to the AASHTO document.

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Chapter 3

Analysis of 50 states specifications

3.1 Introduction

Although AASHTO, the United States Environmental Protection Agency (EPA), the Federal Highway Administration, the Department of Agriculture (USDA), and a host of other organizations set guidelines about how to use compost for erosion control and vegetation establishment, how state DOTs prescribe the use of compost varies considerably. Based on the guidelines derived from the literature review in the previous chapter, each state is assessed.

This assessment assumes that compost of all sorts can be legally generated in each state. This may not be the case, as some states have restrictions on biosolids production. Additionally, we assume that compost is being generated in each state. Some states or areas of states may not have adequate feedstocks, space, monetary resources, or required permits. However, as composting systems will become more and more prevalent, compost application guidelines should be prescribed in each DOT's specification book.

Interestingly, a survey was conducted in 2009 by the Wisconsin DOT (WiscDOT) to determine how different state DOTs use compost in construction (CTC & Associates LLC and WisDOT Research and Library Unit, 2009). However, only 20 of the 50 states responded to this survey. The survey did not examine design specifications of the states that responded; only responses from willing participants were reported.

3.2 Methods

Each of the DOTs create their own specifications for design, which are publicly available. However, publishing frequency and comprehensiveness vary by state. The latest available specifications for each state were downloaded from each DOT and are current as of July 2018. Electronic copies were searched for “compost,” and relevant specifications were summarized in an analysis table. A testing parameter-by-parameter breakdown of differences between states is first presented.

Then, for each specification related to compost, the summarized results were tabulated in a Boolean data type (1 it has the relevant specification and 0 it does not). The parameters were based on the US Composting Council’s requirements for compost, AASHTO’s erosion control compost requirements, and peer-reviewed literature on how compost performs in erosion control and cover crop establishment. The variables of interest were the following:

1. Is compost mentioned (1 point)?
2. Does compost need to be source separated? Mentioning that the compost needs to be source separated in an easy way to mitigate risks from contamination (1 point).
3. Is compost mentioned as a way to control erosion on sites (1 point)?
4. Are the following types of compost included (1 point each):
   5.1 Green material (yard/garden waste, agricultural crop residues, and/or forest residues),
   5.2 Biosolids,
   5.3 Manure, and
   5.4 Food waste (food scraps or food processing residuals)?
6. Is there a depth of compost blanket given (1 point)? Also, is there a difference for vegetated compost blankets and unvegetated compost blankets (1 point)? If the depth of a compost blanket is given, is the depth consistent with recommendations from Table 2.5 (1 point)? Requirements are used from AASHTO's recommendation for unvegetated compost blankets.
7. Are slopes that compost can be used on restricted (1 point)?
8. Are sieve sizes for compost given (1 point)? Does the sieve size require larger particles, not precluding particles larger than 1 inch (1 point)?
9. Is there a range on pH values given, at least a minimum to reduce P loading (1 point)?
10. Is there a limit on salt or cation exchange (1 point)?
11. Is there a stability (1 point) and/or maturity (1 point) index listed?
12. Is there a limit on fecal coliform and/or salmonella (1 point)?
13. Is there a limit on inert materials or plastics (1 point)?

3.3 Results

3.3.1 How is compost prescribed, if it is?

Thirteen of the 50 states did not mention compost at all in their specifications. Those states are Alabama, Alaska, Arkansas, Hawaii, Kentucky, Louisiana, Mississippi, Nebraska, North Carolina, South Dakota, Tennessee, Utah, and West Virginia. Nineteen of the remaining 37 states have compost listed as a way to control erosion on site.

3.3.2 Feedstocks

The feedstocks for approved composts vary widely by state. Eight of the 37 states that mention that feedstocks should be source separated. It is unlikely that organic materials are removed from the municipal waste stream, but it is important that this be specified. Some states do not list explicit feedstocks but instead have more general requirements. Arizona's specifications lists "organic vegetative materials," Michigan lists "or other organic materials," Nevada lists "vegetative materials," South Carolina lists "composted organic material, Wisconsin says, "manure or other organic material," and Wyoming says "manure… mixed with a carbon source." A few states (Idaho, Kansas, North Dakota, Oklahoma, and Vermont) do not list a type of approved material.

For the states that listed approved feedstocks, at least one green waste source was unanimously considered, and include yard/garden waste, leaves, agricultural crop residues, and wood-based materials, such as forest residues, bark, ground/shredded trees, and clearing and grubbing mulch. Seventeen states allowed biosolids, which generally explicitly had to comply 40 CFR Part 503. Twenty-two states allowed manure-based compost. Food waste (scraps and processing residuals) were approved feedstocks by 17 states. Spent mushroom growing substrate was specifically approved only by Oregon and Pennsylvania. Paper industry wastes, such as paper mill and paper fiber, were allowed by 9 states. Animal carcasses were allowed by Montana but prohibited by New Mexico. Florida allows "municipal solid waste compost" while California and Texas specifically disallow it.

Most states have only one type of compost listed. States that have multiple types of compost in their specifications are described and differences are summarized in Appendix B. Arizona and Virginia have specifications for planting compost and erosion control compost. California, Oregon, and Washington specifications outline fine, medium, and coarse compost listed. California does not indicate how to use each of the composts, Oregon only uses coarse compost in erosion control, and Washington only uses fine compost. Georgia and Texas have general use compost, and erosion control compost, which is a 1:1 mixture of compost and woodchips. Iowa has two types of compost listed; one is for use in urban areas and one is for use in rural areas. Maryland has three types of compost listed; only wood/bark feedstocks can be used for erosion control. Minnesota has two grades of compost; manure-based compost cannot be used for erosion control, but other feedstocks can be used if compost complies with the specification. New Jersey and New Mexico both have separate specifications for compost based on biosolids. New York has five different types of compost listed; three can be from a variety of feedstocks and differentiated by particle size distribution. The other two composts must be derived from deciduous leaf material only and manure only. Pennsylvania has seven different compost specifications that vary by the source such as sewage sludge compost (1) mulch and (2) soil amendment, spent mushroom compost (3) mulch and (4) soil amendment, (5) paper mill compost soil amendment, and two other compost specifications including one for erosion control.

3.3.3 Compost blanket application requirements

Fourteen states have a specification listed for a depth of compost needed. Ten of the 14 states have 2 inches listed as a depth to use. The Idaho specification indicates that more than 2 inches shall be used, and it at the discretion of the engineer on site. Kansas requires 1.25 inches and New Mexico requires 1 inch. Ohio only requires 0.25 inches of compost. The state of Washington requires 3 inches, which is suitable for vegetated compost blankets through the entire state and unvegetated compost blankets in the eastern side of the state. Additionally, Pennsylvania requires 2 inches of compost on areas to be seeded and 4 inches of compost on areas that are to remain unseeded. This in the only state that has disparate requirements for vegetated and unvegetated compost blankets. A few states, in addition to or instead of compost thicknesses, list application rates. Idaho specifies 2 inches or more of compost, and 110 to 140 cy·acre^{-1} for less than 3:1 (H:V) and 140 to 300 cy·acre^{-1} for steeper slopes. Missouri requires 2.5 tons·acre^{-1}.

In terms of what slopes compost is suitable for, only six states offered limitations. Ohio and Texas require slopes to be less than 3:1 (H:V). In Minnesota, Pennsylvania, and Virginia, compost can be used on slopes up to 2:1 (H:V). Compost can be used in Minnesota on steeper slopes, but netting must be placed on top of the compost layer.

3.3.4 Particle size distribution

The particle size distribution of approved compost varied widely from state-to-state, shown in Table 3.1. For states that had multiple types of compost, compost used for erosion control was examined. Eight states (Delaware, Illinois, North Dakota, Ohio, Oklahoma, South Carolina, Wisconsin, and Wyoming) do not have any restrictions on compost particle size. Only New York and Virginia had particle size distribution requirements that matched the USCC requirement for erosion control blanket. New Hampshire, Oregon, and Washington have similar requirements, but not a perfect match. Again, Georgia and Texas require woodchip mixtures, to minimize impact of raindrops (Faucette et al., 2007). Arizona only specifies "fine to medium" particle size for compost.

Table 3.1: Particle size distribution of composts

State	Compost Type	Erosion control?	when given sieve is used [in], % of particles passing										retained % 3/8in	Max particle dimension [in]	Mix 1:1 w/ woodchips?
			1/8	1/4	3/8	1/2	5/8	3/4	1	2.5	3	6			
California	Coarse	X			70					99					
Colorado	General Use					95			100						
Connecticut	General Use	X							100						
Florida	General Use	X				50						100			
Georgia	General use	X					100						70		X
Idaho	General Use	X							100						
Indiana	Compost mulch													3*0.5*0.5	
Iowa	Urban	X				100									
	Rural	X				70-80		90	100						
Kansas	General Use					100									
Maine	Humus								100						
Maryland	Wood/bark	X						75				100			
Massachusetts	General use								100						
Michigan	General Use														
Minnesota	Grade 2	X						100							
Missouri	clearing & grubbing											100			
Montana	General use								90						
Nevada	General use		85			100									
New Hampshire	Erosion Control	X		30-75				70-100	90-100		100				
New Jersey	General use								100						
New Mexico	Composted mulch							40-70						4*2*2	
New York	Type C	X		0-75				65-100	90-100		100			6	
Oregon	Coarse	X		30-60		60-100	70-100	70-100	90-100		100			6	
Pennsylvania	"Compost"	X			30-50										
Rhode Island	General use								100						
Texas	Base product	X			70		95								X
Vermont	General use								100						
Virginia	Erosion Control	X		0-75				65-100	90-100		100				
Washington	Medium	X		70-85			85-100		100					4	

3.3.5 Compost specifications: chemical characteristics

States have different requirements for chemical assessment for compost. In general, the pH of compost is around neutral, 7. On the acidic end, Maine allows compost with a pH down to 4.5 while most states only allow pH values greater than 5 or 6. Maximum pH values range from 7.5 to 8.5. Some states outline a minimum pH, but no maximum. Twenty-five states had some sort of limit on the pH of compost.

Twenty-five states have limits on soluble salts, which is measured in terms of electrical conductivity of compost leachate. Acceptable maximum values range from 4 to 11 dS/m (equivalent to mmhos/cm). However, Pennsylvania allows its spent mushroom growing substrate compost to have a maximum electrical conductivity of 20 dS/m. Florida also has requirements on electrical conductivity, but only for soil amendment compost, not compost used as mulch.

Moisture contents range either from 30 or 35 to, generally, 55 or 60%. A notable exception is Idaho having a minimum of 0% and maximum of 35%. Some states had qualitative requirements such as no dust and no free water.

Twenty-four states had minimum acceptable organic matter percentages by dry weight, which ranged from 25 to around 40%. There were three states that had minimums OM of 50%. Arizona's minimum OM was 85% and Pennsylvania's minimum for paper mill compost was

70%. Only seven states had maximums for organic matter percentages, which were listed as 60, 65, 70, or 100%.

Twenty-one states had some sort of requirement for maturity or stability. Specifically testing for maturity, both Arizona and Nevada required a maturity index of greater than 50% on a 10:1 ratio. These two states also are the only two that required a stability test requiring a maximum of 100 mg O_2/kg of compost. California required maturity to be measured using the plant test with germination 80% relative to a control. Nine states outlined maximum CO_2 generation ranging from 5 to 10 mg CO_2-C/g OM/day compost. Ten states required Solvita tests for stability and four states require using the Dewar heating test to measure stability. Nine states required in-vitro germination and root elongation testing. New Mexico measured maturity with a unique test requiring 50% germination of marigold seeds in a compost/sand mixture. It also measures stability by ensuring the core temperature of the compost pile being less than 110°F after composting.

Bacteria/pathogens restrictions were in place for 7 states. For salmonella, a most probable number (MPN) of 3 per 4g dry weight and/or for fecal coliform, an MPN of 1000 per 1 g dry weight were listed, following the federal standard for biosolids.

Inert materials limitations were in place in 20 of the specifications. Generally, the maximum inert materials allowed was 1% of the dry weight. Florida's specification said 0%, while

Georgia and Massachusetts had qualitative measures, “no visible,” and “free of,” respectively. Minnesota allowed up to 3% and Washington required inert materials to be less than 0.5%.

Fifteen states had some sort of requirement on nutrient ratios and/or concentrations such as C:N, C:P, total nitrogen, total phosphorus, or N:P:K. Ten states listed a maximum C:N ratio, which ranged from 20 to 35C:1. Indiana’s maximum was 100:1, however. Of those states, half had minimum C:N ratios, which ranged from 6:1 to 25:1. Only Connecticut had a limitation on the C:P ratio, which must be between 120:1 and 240:1. For total nitrogen, Arizona’s and Nevada’s minimum were 1%, Kansas’ was 0.8%, and Ohio’s was 1.4%. Idaho only specified a maximum, 1.8%, and Vermont allowed between 0.5% and 2% total nitrogen. Minnesota allowed a maximum N:P:K ratio of 1:1:1. Vermont specified a total Kjeldahl nitrogen range between 0.5% and 2%. Arizona and Nevada also require 5% minimum of humic acid.

Biosolids compost is required to meet trace metals requirements before land application. However, not all states have requirements for metals in compost. Fourteen states indicate maximum concentrations of trace metals in compost, or state that compost must comply with the biosolids metals requirement, 40 CFR 503.

A few states also give requirements on the bulk density of compost [$kg \cdot m^{-3}$]. Units listed in $lb. \cdot yd^{-3}$ and $lb. \cdot ft^{-3}$ were converted to $kg \cdot m^{-3}$. Kansas allows 450 to 560 $kg \cdot m^{-3}$, Minnesota allows 415 to 949 $kg \cdot m^{-3}$, and New York only has a requirement on leaf compost (no other types), 636 to 812 $kg \cdot m^{-3}$. Maryland requires the bulk density to be less than 831 $kg \cdot m^{-3}$.

3.3.6 State rankings

Overall, there was significant difference from state to state on compost requirements, shown in Table 3.2. Given the scoring system, the maximum score was 15 out of 18 for Georgia, Oregon, and Texas. There was a 13-way tie for last place with no mention of compost in the latest document.

To evaluate the particle size distribution, we looked for specifications that did not preclude larger particles. Giving the benefit of the doubt for states with simpler specifications, we looked for distributions that had some resemblance to Table 2.4's requirement. If the specifications had 100% passing a smaller particle size than 1 inch, they were not granted a point as the particles would be too small and would be susceptible to erosion.

In general, if one the items are not addressed in Table 3.2, it should be corrected. Unique specifications and other specific issues to be addressed by each state are outlined in the next section.

Table 3.2A: State-by-state scoring of parameters

	Wording			Feedstocks				Compost blanket				Particle size		Compost testing					Results	
State	Compost included ?	"source separated"	For erosion control?	Green waste	Bio-solids	Manure	Food waste	Depth given ?	Different: veg vs unveg?	Thickness correct?	Max slope given?	Specif-ied?	Sieve sizes ok	pH limits?	Salts/ electrical conductivity	Stability and/or maturity	Pathogens: F. coliform or salmonella	Inerts	Score out of 18	Rank
Alabama	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Alaska	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Arizona	1	0	1	1	0	1	0	0	0	0	0	1	0	1	0	2	0	0	8	22
Arkansas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
California	1	0	1	1	1	1	1	0	0	0	0	1	1	1	1	2	1	1	14	5
Colorado	1	0	0	1	1	1	1	0	0	0	0	1	1	1	1	2	1	1	13	10
Connecticut	1	1	1	1	0	1	1	0	0	0	0	1	1	1	1	2	0	1	13	10
Delaware	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	33
Florida	1	0	1	1	1	1	0	0	0	0	0	1	1	0	0	0	0	1	8	22
Georgia	1	0	1	1	1	1	1	1	0	0	0	1	1	1	1	2	1	1	15	1
Hawaii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Idaho	1	0	1	0	0	0	0	1	0	1	1	1	1	1	1	2	0	1	12	15
Illinois	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	4	29
Indiana	1	0	1	1	1	1	1	0	0	0	0	1	1	1	0	0	0	1	10	20
Iowa	1	1	1	1	1	1	1	1	0	0	0	1	0.5	1	1	2	1	0	14.5	4
Kansas	1	0	0	0	0	0	0	1	0	0	0	1	0	1	1	1	0	0	6	24
Kentucky	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Louisiana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Maine	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	11	17
Maryland	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	0	13	10
Massachusetts	1	0	0	1	1	1	1	0	0	0	0	1	1	1	1	2	0	1	12	15
Michigan	1	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	5	28
Minnesota	1	0	1	1	0	1	0	1	0	1	1	1	0	1	1	2	0	1	13	10
Mississippi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Missouri	1	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	4	29

Table 3.1B: State-by-state scoring of parameters (continued)

	Wording			Feedstocks				Compost blanket				Particle size		Compost testing					Results	
State	Compost included ?	"source separated"	For erosion control?	Green waste	Bio-solids	Manure	Food waste	Depth given ?	Different: veg vs unveg?	Thickness correct?	Max slope given?	Specif-ied?	Sieve sizes ok	pH limits?	Salts/ electrical conductivity	Stability and/or maturity	Pathogens: F. coliform or salmonella	Inerts	Score out of 18	Rank
Montana	1	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	1	11	17
Nebraska	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Nevada	1	0	0	1	0	0	0	0	0	0	0	1	0	1	0	2	0	0	6	24
New Hampshire	1	0	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	6	24
New Jersey	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	11	17
New Mexico	1	0	0	1	1	1	1	1	0	0	0	1	1	1	1	2	1	1	14	5
New York	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	1	14	5
North Carolina	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
North Dakota	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	37
Ohio	1	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	4	29
Oklahoma	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	33
Oregon	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	2	0	1	15	1
Pennsylvania	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	1	14	5
Rhode Island	1	0	0	1	0	0	1	0	0	0	0	1	1	1	1	1	0	1	9	21
South Carolina	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	33
South Dakota	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Tennessee	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Texas	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	2	1	0	15	1
Utah	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Vermont	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	1	6	24
Virginia	1	0	1	1	0	0	0	1	0	1	1	1	1	1	1	2	1	1	14	5
Washington	1	0	1	1	0	1	1	1	0	0	0	1	1	1	1	2	0	1	13	10
West Virginia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
Wisconsin	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	32
Wyoming	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	33

3.4 Discussion

3.4.1 State-by-state guidance

Some states have specific corrections or unique specifications that require further discussion. Those states are Arizona, California, Delaware, Florida, Idaho, Iowa, Kansas, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New Mexico, New York, Ohio, Pennsylvania, South Carolina, Washington.

The Arizona DOT requires erosion control compost to be derived from "organic vegetative materials"; and be stabilized with a tacking agent, which is unique to this state’s requirements. Manure-based compost can be used as a soil amendment, but not in erosion control. The stability test involves oxygen, but says mb O_2 per kg of compost; this should be mg.

California lists that there should be no detection of sharps. This is reasonable if the state has had problems in the past. The specification about erosion control should state which compost, fine, medium, or coarse, can be used in compost blankets.

In Delaware, most of the information about compost use is in the compost filter log area of the document. It would be ideal to include a compost blanket detail in the specification.

For Florida, we assume that "municipal solid waste compost" includes food waste. The specification requires "no foreign matter," which should be replaced with a 1% restriction or similar.

Idaho's last specification was from 2007, which was also reviewed. There was information about feedstocks in the 2007 version of their specifications, but not in the 2017 version. Instead of being the compost section, the feedstocks were moved to the fertilizer section.

The differentiation of urban vs rural compost is unique Iowa. Since both of these composts have the same purpose, they could be merged.

Kansas requires soil to be rototilled. Then after compost is applied, it must be rototilled again. Tilling compost into soil induces a 67% increase in total suspended studies (Bakr et al., 2015). Also, most of the information about how compost should be used in DOT projects was written in an auxiliary document. This may be difficult for contractors to follow.

Maryland's Type B compost "shall be tree leaf compost or non-tree leaf compost." This wording is ambiguous and should be updated.

Massachusetts feedstocks include "food and agricultural residues, animal manure, or other biosolids." The other biosolids leads us to believe non-class A biosolids are accepted. There may be some confusion about what biosolids are.

Michigan's specifications also state the compost should be "free of… plastic, glass, metal, or other physical contaminants." This is too strict and should be replaced with a 1% threshold.

Minnesota is the only state that calls for netting to be applied to the top of compost if the slope is greater than 2:1 (H:V). Additionally, every state that has a limit on inert material has the maximum at 1% while Minnesota has a limit of 3%. Minnesota also allows compost tea.

The state of Missouri only allows one type of compost, leftovers from clearing and grubbing operations. There could be more feedstocks allowed.

New Hampshire only allows composted bark as a feedstock. Additional green waste feedstock or other feedstocks could be included.

New Jersey's specification calls for compost to "contain no heavy metals," which is unrealistic from an analytical chemistry point of view. Limits from 40 CFR Part 503 enforced by analytical testing would be more appropriate.

New Mexico calls for compost to be tilled into the top of the soil, which produces more sediment discharge than with a top treatment. They also have unique testing protocols for stability and maturity.

New York's five different types of composts may be redundant and confusing for contractors to follow. These could be consolidated into one or two types of compost, allowing different feedstocks. Additionally, Type B compost requires a “minimum organic matter content 25% - 65%.” This is a range, not minimum.

Ohio has information for how to apply compost in an additional document, not in the primary specification document. This may be difficult for contractors to find.

Pennsylvania has a comprehensive compost outline, but has compost listed in three separate sections. In the Section 805 – Mulching, the following are listed: “shredded bark,” “sewage sludge compost,” and “wood chips” are listed. In Section 808 – Plants, planting, and transplanting, the following are listed: “peat,” “paper mill compost,” “sewage sludge compost,” “compost,” and “spent mushroom compost.” In Section 868 – Compost blanket and compost filter berm, only “compost” is listed, allowing for the following feedstocks: “Organic compost derived from agriculture, food, stump grindings, and yard or wood/bark organic matter sources.” Each of these composts have disparate requirements with some overlap. This could be better organized.

South Carolina requires the addition of fertilizer with compost. This depends on the circumstance and could be more specific about when it is needed.

The state of Washington outlines course compost but does not have a use for it the latest version of their specifications. Also mentioned is that a tackifier is needed in windy or dry conditions.

3.4.2 General discussion

The wide range detailed specifications was unexpected. It would be advantageous to follow up with those states that have unique requirements to see if why they were put in place and if they are helpful. Of the states that do not have any compost listed, it would be beneficial to know if compost is not available, if they are not using it, or if they just do not have requirements about compost in the document. More states ought to adhere to the guidelines from AASHTO and the USCC.

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Chapter 4

Modeling the hydrologic response of vegetated compost blankets

4.1 Introduction

While research has been conducted on the erosion control properties of compost, a model to explicitly detail how vegetated compost blankets function, hydrologically, is an area that can be further developed. In this chapter, we first examine **un**vegetated compost blankets, compost applied as a surface layer compared to bare soil. We then compare unvegetated compost blankets to two different vegetation scenarios: vegetation that is fully established and vegetation that grows from seed. Under the vegetation growth scenario, the canopy of the vegetation and the root zone develop throughout the simulation. Next the compost blanket thickness was varied under the growing vegetation scenario. Finally, we use different composts' hydraulic properties to model how changing the compost type affects water balance under the vegetation growth scenario. The entire water balance is considered, but runoff is the component that is most closely examined.

A conceptual diagram of an unvegetated and vegetated compost blanket with water balance fluxes and change in soil water storage are shown in Figure 4.1.

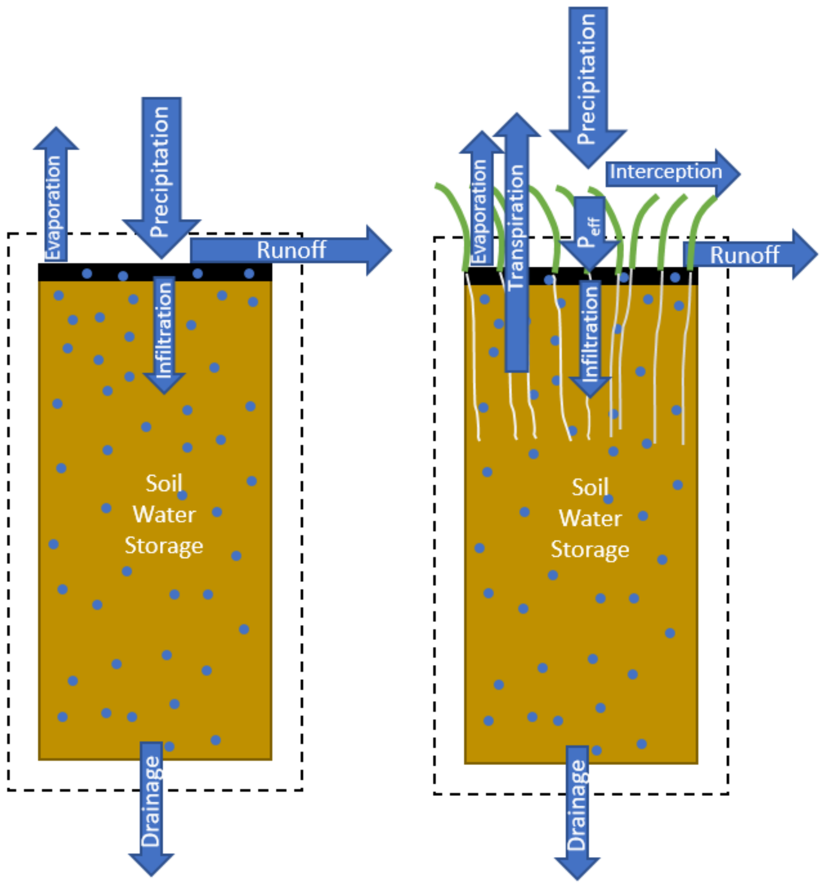

Figure 4.1: Conceptual diagram of an unvegetated compost blanket (left) and vegetated compost blanket (right) indicating different fluxes entering and exiting the control boundary

Water balance equations for each flux were set up and evaluated on the surface (Eqn. 4.1) and within control boundary (Eqn. 4.2) to verify no missing mass.

$$P - int = infil + RO \quad (4.1)$$

$$\frac{\Delta s}{\Delta t} = inputs - outputs = (P - int) - (E + T + RO + D) \quad (4.2)$$

where P is precipitation [$L \cdot T^{-1}$], int is interception from vegetation [$L \cdot T^{-1}$], $infil$ is infiltration [$L \cdot T^{-1}$], RO is runoff [$L \cdot T^{-1}$], $\frac{\Delta s}{\Delta t}$ is the change in soil water storage storage during the timestep [$L \cdot T^{-1}$], E is evaporation [$L \cdot T^{-1}$], T is tranpsiration [$L \cdot T^{-1}$], and D is the drainage from the bottom of the control boudary [$L \cdot T^{-1}$].

The purpose of the HYDRUS-1D model is to evaluate the effects unvegetated and vegetated compost blankets with a vadose zone hydrology model in the one-dimensional (1D) domain. HYDRUS-1D is a freely available program online from PC-Progress. This model is not for evaluating erosion control properties of compost. It would not be valid on highly sloped soils, but it is useful for analyzing horizontal soil surfaces and helps to give a general idea about the functionality of compost blankets. The research question addressed in the chapter is:

> *To what extent do design specifications control runoff and root water uptake from vegetated compost blankets during a modeled timeframe, which was a 34-day period in summer in Madison, WI, USA?*

4.2 Methods

4.2.1 Modeled climate

This model was run based on climate data from Madison, WI, USA during the summer of 2017 (Figure 4.2). This model could easily be run in different climates or ahead of compost application under any forecasted local conditions. Precipitation data were taken from USGS gaging site 05427718 at the Yahara River at Windsor, WI, near Madison, WI. This site was selected since precipitation data were available in up to five-minute data increments. Minimum, maximum, and average temperature data were taken from the Madison, WI Long Term Ecological Research website. The modeled period was June 18 to July 21, 2017. This timeframe was selected because within this amount of time, the compost was likely to retain most of its characteristics measured before application. It was the rainiest 34-day period of the summer of 2017.

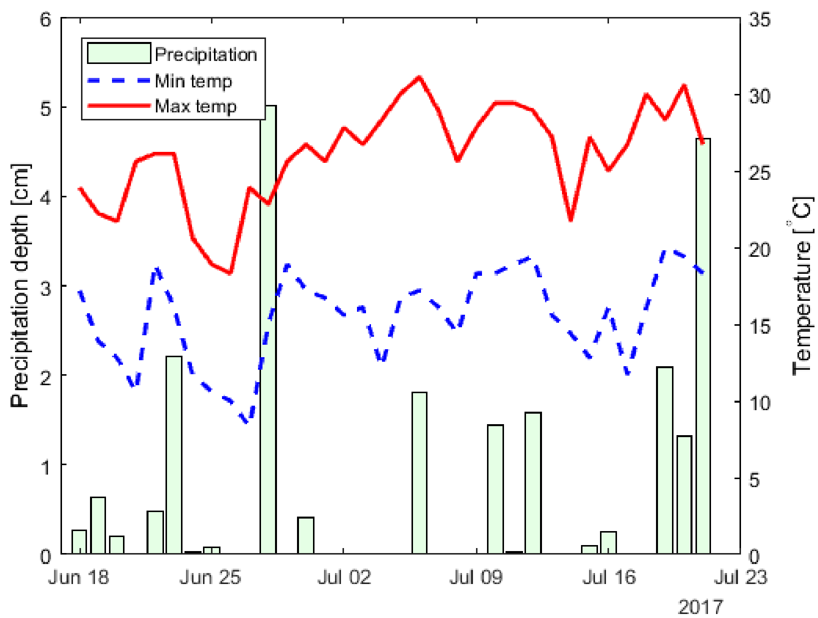

Figure 4.2: Precipitation and temperature records for Madison, WI June 18 to July 21, 2017 indicate this was a relatively wet period of the summer, but also relatively mild as the maximum temperature was 31°C.

4.2.2 Water flow

HYDRUS-1D is a numerical model of water flow in variably saturated porous media. It iteratively solves the Richards' Equation for transient unsaturated flow in the 1D domain. The development of the Richards' Equation is outlined in Unsaturated Soil Mechanics (Lu and Likos, 2004) and in the HYDRUS-1D manual (Šimůnek et al., 2013), and is summarized below.

Two relationships describing the hydraulic properties of the soil are needed to solve Richards' Equation: The soil water characteristic curve (SWCC) and the hydraulic conductivity function.

The SWCC quantifies the relationship between soil suction/pressure head or tension and water content. We focus on the matric suction head which we designate as h [L], and not osmotic and van der Waals force heads. The variable *h* should not be confused with total head, the sum of matric suction head and elevation head, which is often termed H. In this model, the volumetric water content (θ) [$L^3 \cdot L^{-3}$] the water content term of interest. Conceptually, if there is a more negative head in the soil, less water is retained within the pore space. This relationship is highly non-linear, but Van Genuchten (1980) parameterized one way of approximating the general form of a SWCC with the following equation:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + (|\alpha \cdot h|^n)]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{4.3}$$

where θ_r is the residual volumetric water content [$L^3 \cdot L^{-3}$], and θ_s is the saturated volumetric water content [$L^3 \cdot L^{-3}$], α is an empirical constant related to inverse of air entry suction [L^{-1}], $\alpha > 0$, n is a measure of pore-size distribution [-], and *m* is a fitting parameter (usually taken to be 1-1/*n*). In the equation, $n>1$. Figure 4.6 shows example of characteristic curves.

The hydraulic conductivity function quantifies the relationship between suction, (or effective saturation or volumetric water content) and the unsaturated hydraulic conductivity.

Conceptually, if the soil matrix is fully saturated, water moves faster through the pores, all else equal. The effective saturation (S_e) of the soil media is used to approximate the hydraulic conductivity for different values of h or θ, which is defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{4.4}$$

The hydraulic conductivity function can be written as:

$$K(h) = K_{sat} \cdot {S_e}^l \cdot \left[1 - \left(1 - {S_e}^{1/m}\right)^m\right]^2 \tag{4.5}$$

where K_{sat} is the saturated hydraulic conductivity, *m* is from the van Genuchten equation, and *l* is a fitting parameter. The parameter *l* is taken to be 0.5 for a wide range of soils (Mualem, 1976).

Darcy's Law can be applied to unsaturated fluid flow in the 1D domain (z-direction), knowing that the hydraulic conductivity is a function of the soil suction head [K(h)].

$$q_z = -K(h) \cdot \frac{\partial h}{\partial z} \tag{4.6}$$

where q_z is the flux in the z direction.

Richards (1931) derived the transient unsaturated fluid flow based on the conservation of mass in the vertical domain of the subsurface with a partial differential equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\cdot\left(\frac{\partial h}{\partial z}+1\right)\right] - S \tag{4.7}$$

where S is a sink term [$L^3 \cdot L^{-3} \cdot T^{-1}$] from the domain.

The left-hand side of this equation can be rewritten using the chain rule:

$$\frac{\partial\theta}{\partial t} = \frac{\partial\theta}{\partial h}\cdot\frac{\partial h}{\partial t} \tag{4.8}$$

where $\frac{\partial\theta}{\partial h_m}$ is referred to as the specific moisture capacity (*C*), the first derivative of the SWCC. This relationship can be rewritten as:

$$C(h_m) = \frac{\partial\theta}{\partial h} \tag{4.9}$$

Finally, the Richards' Equation can be rewritten as:

$$C(h)\,\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S \tag{4.10}$$

which can be solved iteratively with suitable boundary and initial conditions, resulting in suction field in time and space. Changes in head or fluxes of water can be modeled with respect to time.

4.2.3 Determination of vegetation type and growth

The three different modeled scenarios of vegetation were (1) no vegetation, (2) established vegetation, and (3) vegetation growth. Many DOT specifications prescribe different seed mixtures, depending on climate, time of year, area to be replanted, portion of state, etc. For example, in the WisDOT design specifications, highway seed mixtures include mixtures of cool season grasses (Kentucky bluegrass; red, hard, and tall fescue; perennial ryegrass), clover (red, white, Alsike), Japanese millet, and annual oats. Native seed mixtures contain mixtures of forbs, such as Canada Anemone, blackeyed Susan, and purple prairie clover, as well as grasses such as sideoats grama, Canada wildrye, and slender wheatgrass (Wisconsin DOT, 2013).

Although the USDA has determined that some variations of tall fescue are detrimental to wildlife due to its endophytic fungus (Henson, 2001), it is still prescribed in design specifications. With some variety of fescue being prescribed in four of the five WisDOT highway seed mixtures at an average of 46% of the seed composition, we chose it to represent vegetation in the model. Because experimental data and fescue is somewhat limited, the model incorporates growth of ryegrasses, which comprise 27% of the highway seed mixtures of the WisDOT (Figure 4.3).

Fescue, a cool season grass, grows best under milder temperatures. One reason for this simulation is to understand how compost functions in relation to runoff, which is why a rainy timeframe was chosen. However, another reason the model was built is to better understand how vegetation could function, optimally, in a vegetated compost blanket. During the simulation, the maximum temperature was 31°C (88°F). The timeframe was milder than spring and fall, as this temperature was exceeded both in May and September for sustained periods.

To model how the vegetation's height, canopy, and root zone developed, a total time to reach maturity was needed. For growing grass, we assumed the number of days to reach maturity (DTM) as 120 days. This timeframe was chosen, first, because Borg and Grimes (1986) showed that other grasses (wheat and oats) take around 120 days to reach that maturity. Similarly, R. A. D. Pegler (1976) showed that fescue takes around 96 days, on average, to achieve maximum germinable seed yields in the first harvest year. This likely coincides to when 75% of the seed heads have matured (Government of Alberta, 2002). The Alberta, Canada government (2002) also reports that fescue is usually harvested for seed in early August. Assuming a planting date in May, 120 days to full maturity is a reasonable assumption.

4.2.4 Daily potential evapotranspiration

The daily potential evapotranspiration was estimated using the Hargreaves equation with the approach described below. Each day of the modeled timeframe (J) was determined as the number of days after January 1. The solar declination angle was calculated as:

$$\delta = 0.409 \cdot sin\left(\frac{2\pi}{365}J - 1.39\right) \quad (4.11)$$

The relative distance between the sun and earth (d_r) was calculated as:

$$d_r = 1 + 0.033 \cdot cos\left(\frac{2\pi}{365}J\right) \quad (4.12)$$

The sunset hour angle (ω_s) [rad] was calculated as:

$$\omega_s = arccos(-tan\varphi \cdot tan\delta) \quad (4.13)$$

where φ is the site latitude [rad].

Then the extraterrestrial radiation (R_a) [J·m^{-2}·s^{-1}] was determined as:

$$R_a = \frac{G_{sc}}{\pi} \cdot d_r \cdot (\omega_s \cdot sin\varphi \cdot sin\delta + cos\varphi \cdot cos\delta \cdot sin\omega_s) \quad (4.14)$$

where G_{sc} is the solar constant, 1360 W·m^{-2}. Finally, the daily potential evapotranspiration (ET_p) was found with the Hargreaves equation:

$$ET_p = 0.0023 \cdot R_a(T_m + 17.8)\sqrt{TR} \quad (4.15)$$

where T_m is the daily mean air temperature [°C] and *TR* is the temperature range [°C]. During the modeled period, ET_p ranged from 0.61 cm·d^{-1} to 1.05 cm·d^{-1} during the simulation.

4.2.5 Disaggregating daily potential evapotranspiration

The Hargreaves equation determines ET_p on a daily timestep. However, with the precipitation timescale in finer resolution, it was necessary to break down the ET_p into a by-the-minute scale. To do this, ET_p between midnight and 6 a.m., and 6pm to midnight each day was set to be 1% of the daily total, and between 6 a.m. and 6 p.m., the ET_p followed a sinusoidal shape (times approximate; see equation 4.16 (Fayer 2002):

$$ET_p(t) = \begin{cases} 0.24 \cdot ET_p & t < 0.264d \ or \ t > 0.736d \\ 2.75 \cdot ET_p \cdot sin\left(\frac{2\pi \cdot t}{1day} - \frac{\pi}{2}\right) & 0.264d \leq t \geq 0.736d \end{cases} \quad (4.16)$$

4.2.6 Crop coefficients

A crop coefficient (K_c) is a multiplier for ET_p to determine the ET of a crop (ET_c). The Food and Agricultural Organization outlines the use of single and dual crop coefficients (Allen et al., 1988). The effects of both crop transpiration and soil evaporation are included in the coefficient. Although a dual crop coefficient model that partitions soil evaporation and crop transpiration depending on the available water in the soil would be most accurate, HYDRUS-1D does not yet have the availability to use this function within each timestep. Thus, for the scenarios with vegetation, we used the single crop coefficient model, and partitioned the potential evaporation and transpiration based on the leaf area index (Section 4.2.8). A K_c curve outlines a period of a constant K_c during stage 1 (initial stage), then a linear increase during stage 2 (crop development), a constant K_c during stage 3 (mid-season), and a linear decrease during stage 4 (late season). Values of $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ are given for each constant K_c.

Fescue does not have a specific K_c curve parameterized by Allen et al. (1988), but Bermuda hay grown from seed does. We believe that this curve would be representative of the K_c for grass in a vegetated compost blanket. The curve is similar to the curve for cereals (barley, oats, and wheat), so it could also be used for other commonly used vegetation. The days spent in stages 1, 2, 3, and 4 are 10, 25, 35, and 35, respectively. The total number of days to harvest was 105 in California, so 120 days is assumed for a grass in Wisconsin. The same fraction of time spent in each stage was followed, but the season was expanded to 120 days. The initial, mid, and end K_c are 0.35, 0.9, and 0.65, respectively. Note that during the simulation, the vegetation would not reach maturity. Based on the beginning of the 120-day growing season, for the growing vegetation case, the K_c was 0.35 for the first 11 days, and increased linearly to 0.79 on between day 11 and day 34. For model runs with established vegetation, $K_{c\ mid}$ was used, 0.9.

To determine the ET_c for the no vegetation model runs, an inference was made from the single and dual K_c models. The dual K_c model partitions soil evaporation from plant transpiration:

$$ET_c = (K_{cb} + K_e) \cdot ET_0 \tag{4.17}$$

where K_{cb} is the basal crop coefficient and K_e is the soil evaporation coefficient. The values of K_{cb} are 0.15. 0.85, and 0.6 for the initial, mid, and late season. We assume that the initial season partitioning before vegetation was established would be most accurate for an unvegetated compost blanket. For the no vegetation case, the K_c was assumed to be the difference between $K_{c\ initial}$ and $K_{cb\ initial}$, 0.2. Due to naming convention in HYDRUS-1D, ET_c hereafter will continue to be referred to as ET_p.

4.2.7 Leaf area index and soil cover fraction

Studies have been conducted to determine the leaf area index (LAI) of fescue. Simon and Lemaire (1987) found that fescue LAI ranged from 1 to 5 in France during the winter. Duru et al. (1995) measured fescue LAI after it re-established each year. For years 1, 2, and 3 of the study, the LAI started at 0 and ranged to 2, 4, and 6, respectively based on the daily average accumulated temperature. Gower et al. (1999) indicated that fescue LAI ranged from 1 to 4. Scheneiter and Assuero (2010) found that the LAI of fescue cut five times per year ranged from 2 to 7.4, and nine cuts per year ranged from 1.6 to 5.9. Given these studies, the LAI for the established vegetation case was approximated as a maximum for one season of growth from seed, 5.

For the growing vegetation model runs, the increasing LAI function was estimated based on how LAI increases after seed germination. Most studies examining fescue LAI development were conducted after cutting or yearly regrowth (Duru et al., 1995). However, J. C. Simon

(1985) showed how accumulated degree days (ADD) affect Italian rye-grass LAI from seed, varying nitrogen and densities of seeds (Figure 4.3). P. Hayes (1976) measured the height of fescue grown in a lab setting based on the number of days since a germinated seed was planted.

The HYDRUS-1D manual also suggests estimating the LAI based on crop height (h_c) with two approaches: based on clipped grass or based on other field crops. The equations are valid for clipped grass h_c between 0.05 m and 0.15 m and for other field crops with h_c between 0.10 m and 0.50 m. For both equations, LAI = 3.6 when h_c = 0.15 m, so the LAI was governed by the former before h_c = 0.15 m, and the later after h_c reached 0.15 m.

$$LAI = \begin{cases} 24 \cdot h_c & h_c < 0.15\,m \\ 5.5 + 1.5 \cdot \ln(h_c) & h_c \geq 0.15\,m \end{cases} \qquad (4.18)$$

Hayes' (1976) experimental values were recorded to day 18 where h_c = 0.087 m. Although this study was only carried out for 18 days, we fit two h_c lines of best fit, separated at day 10 and extrapolated to day 34 (Eqn. 4.19). Note that Equation 4.18 would not be valid until day 8 of the simulation since the h_c of fescue does not reach 0.05 m until this time, but during this time, LAI is ~0.

$$LAI = \begin{cases} 0 & 0 < Day < 3 \\ 0.2574 \cdot Day - 0.8903 & 3 \geq Day < 10 \\ 0.05552 \cdot Day - 1.1632 & 10 \geq Day \leq 34 \end{cases} \qquad (4.19)$$

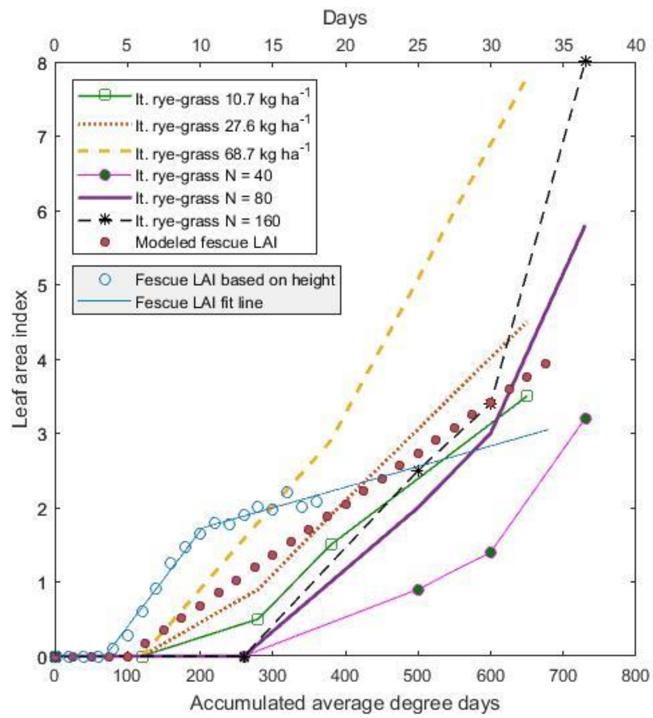

Figure 4.3: The LAI of Italian rye-grass as it grows from seed based on accumulated degree day is variable depending on planting density and fertilization rate (J.C. Simon 1995). The rye-grass densities indicate the mass of seeds applied per hectare. All had 160 units of N applied. The N treatments of rye-grass were all seeded at 10 kg seeds ha^{-1}. Compost amendment provides some nitrogen, but not as much as a nitrogen fertilizer and the density would probably be mid-range. Also shown are an estimation of LAI of fescue based on days of growth in a lab experiment (P. Hayes 1976) and the LAI used in the vegetation growth modeling scenarios.

The ADD at the end of the HYDRUS-1D simulation was 685.1 ADD. The two studies have different shapes of how LAI would increase with respect to time after planting. This may be due to differences in how the seeds germinate/plants grow, the lab setting vs. the field site, the LAI measurement techniques and the formula, or the nutrients in the soil. Because these shapes differ, the approach employed for the growing vegetation model runs was to assume 0 LAI until 100 ADD, and a linear increase based on ADD from 0 to 4 until the end of the simulation, also shown in Figure 4.3:

$$LAI = \begin{cases} 0 & 0 \leq ADD \leq 100 \\ 0.00684 \cdot ADD - 0.6836 & 100 < ADD \leq 685.1 \end{cases} \quad (4.20)$$

The soil cover fraction (SCF) is the area of the soil that is covered by plants, which can be determined as follows:

$$SCF = 1 - e^{-k \cdot LAI} \quad (4.21)$$

where k is a constant governing radiation extinction by the canopy [-]. It is a function of the sun angle and plant characteristics, and ranges from 0.5 to 0.75. Because the sun angle varied throughout each day, and the distribution of plants and arrangement of leaves were modeled, an average value of k was used, 0.625. Thus, for the established vegetation case, the soil cover fraction was 0.96, and for the growing roots case, it increased from 0 to 0.92.

4.2.8 Partitioning of potential evapotranspiration

Evapotranspiration and can be partitioned into evaporation and transpiration. The technique is outlined in the HYRDUS-1D manual (Šimůnek et al., 2013). Evaporation occurs in the upper layer of soil and transpiration takes place as plants uptake water from the root zone. The partitioning can be done, based on the following two equations:

$$T_p = ET_p \cdot (1 - e^{-k \cdot LAI}) = ET_p \cdot SCF \quad (4.22)$$

$$E_p = ET_p \cdot e^{-k \cdot LAI} = ET_p \cdot (1 - SCF) \quad (4.23)$$

where T_p is the potential transpiration [L·T^{-1}], E_p is the potential evaporation [L·T^{-1}].

4.2.9 Effective precipitation

Interception (*I*) [cm] of precipitation [cm] by the vegetation canopy can be calculated as:

$$I = a \cdot LAI \cdot \left(1 - \frac{1}{1 + \frac{b \cdot P}{a \cdot LAI}}\right) \quad (4.24)$$

where a and b are empirical constants, which can be approximated as a ≈ 0.025 cm and b ≈ SCF. Since the rain events were not always falling on a daily timestep, we allowed for interception on an event-by-event basis. We assumed that an inter-storm duration of 12 hours would be adequate for the interception to reset.

For each storm, the total precipitation that fell was determined, and the interception was calculated based on equation 4.24. This value was set at the first timestep of the storm, the initial remaining interception capacity. For each timestep in a rain event, if the remaining interception capacity was lower than the precipitation, effective precipitation was the timestep's precipitation minus the remaining interception, and remaining interception was set to zero. Any precipitation in remaining timesteps of the storms became effective precipitation.

If the remaining interception capacity was greater than the precipitation, there was no effective precipitation and the interception capacity of the next step decreased by the precipitation amount. To avoid errors in the interception calculation, if LAI = 0, we set it to 10^{-6}. For the growing vegetation case, the LAI remained the value of the initial LAI throughout the storm if a storm occurred. The effect of LAI on effective precipitation is shown in Figure 4.4.

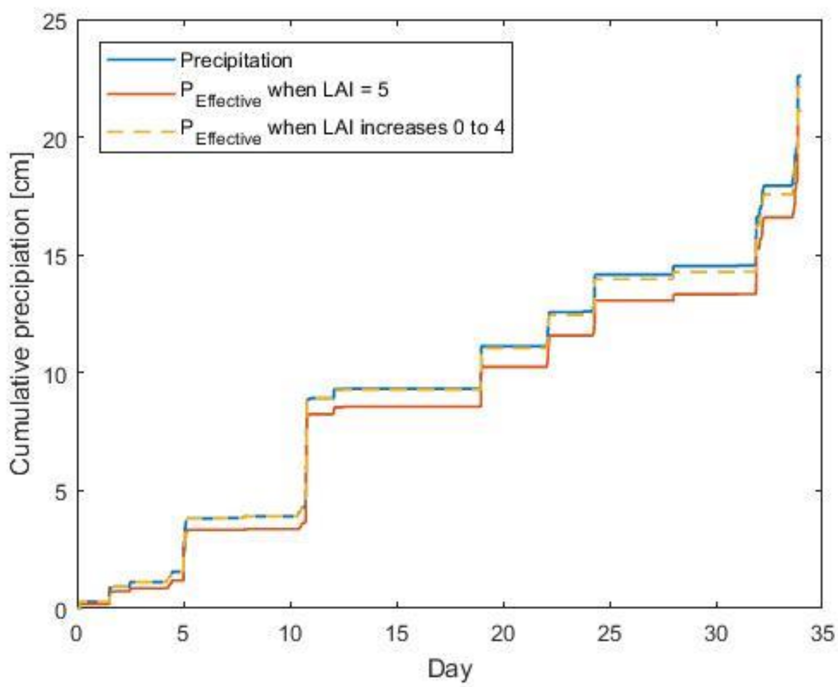

Figure 4.4: A higher LAI decreases the effective precipitation. In the vegetation growth model, LAI increases from 0 to 4 starting on day 5 of the simulation, but is goverened by accumulated degree days. In the vegetation growth scenario, the effective precipitation is equal to the precipitation at the beginning of the run, and similar to the LAI of 5 run near the end of the model run as LAI develops.

4.2.10 Root zone length and root growth

Fescue has been classified as an annual root grass that regrows roots each year (Stuckey, 1941), so some data from root re-growth experiments can be considered. This model uses a simplified root model with a cover crop under ideal growing conditions. The estimated average maximum rooting depth was found to be 78.4 cm for fescue, 176.8 cm for alfalfa, and 128.1 for cereal grains, such as wheat, oats, and barley (Fan et al., 2016). Other research points rooting depths being 180 to 240 cm for alfalfa (first year), 160 to 260 cm for oats, 140 to 180 cm for red clover (first year), and 150 to 300 cm for rye (H. Borg and D. W. Grimes, 1986).

HYDRUS-1D has a root growth simulation, following a logistic model:

$$L_R(t) = L_m \cdot f_r(t) \tag{4.25}$$

$$f_r(t) = \frac{L_o}{L_0 + (L_m - L_0) \cdot e^{-r \cdot t}} \tag{4.26}$$

where, L_R is the root depth at a given time, L_m is the maximum rooting depth, $f_r(t)$ is a root growth coefficient, L_0 is the initial rooting depth length, and r is the growth rate. The growth rate can be assumed to be 50% of their full extent half way to the DTM, which HYDRUS-1D calls ‘harvest time.’ However, given the 50% growth restriction, the growth function in HYDRUS-1D may underestimate the rooting depth at the beginning and end of the simulation while overestimating it at the middle (Figure 4.5).

Instead, the sinusoidal root growth modeling method of Borg and Grimes (1986) can be used to estimate L_R with respect to time, also shown in Figure 4.5:

$$L_R = L_m \cdot \left[0.5 + 0.5 \cdot sin\left(3.03\frac{t}{DTM} - 1.47\right)\right] \tag{4.27}$$

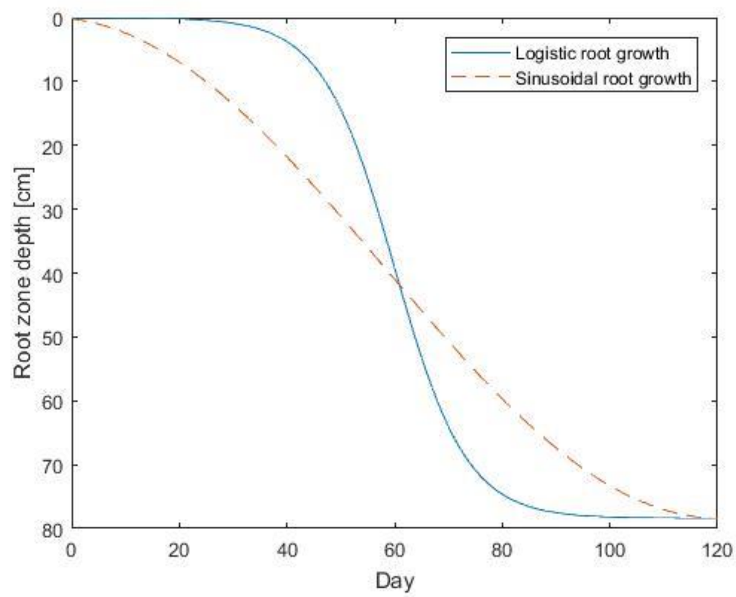

Figure 4.5: The logistic root growth model that is recommended in the HYDRUS-1D manual offers a suggestion to have the length of the roots be half way to the maximum depth half way through the growing season. The logistic function underestimates growth rate at the beginning and end of the season, and overestimates growth mid-season. With the logistic root growth model, the roots would only extend to 2 cm by the end of day 34 of the simulation. In contrast, the sinusoidal root growth model proposed by Borg and Grimes (1986) indicates more root growth would be occurring at the beginning of the simulation.

For established vegetation model runs, the length of the roots was assumed to be 78.4 cm, the average maximum rooting depth of fescue determined by Fan et al. (2016). This choice was made to determine what the effect of fully established fescue would be on the hydrology of a vegetated compost blanket. For the vegetation growth model runs, root zone depth lengthened based on the Borg and Grimes curve starting from day 0 to the end of the modeled timeframe, 34 days. After 34 days, the rooting depth was 36.2 cm.

4.2.11 Root characteristics and root water uptake

The vertical distribution of the roots that uptake soil water within the root zone can be described with the linear root water uptake distribution b(z):

$$b(z) = \begin{cases} \dfrac{1.667}{L_r} & z > L - 0.2L_r \\ \dfrac{2.0833}{L_r} \cdot \left(1 - \dfrac{L - z}{L_r}\right) & L - L_r \geq z \geq L - 0.2L_r \\ 0 & z < L - L_r \end{cases} \tag{4.28}$$

This function must integrate to unity. Although other versions of the root water uptake distribution exist, HYDRUS-1D requires this linear distribution of *b(z)* when root growth is parameterized. For this reason, it is also used in the established roots scenarios.

The potential root water uptake sink term (S_p) can be found as the product of the modeled T_p and *b(z)*. However, the roots only uptake water from soil at a maximum rate when it is neither too dry (water stress) nor too wet (oxygen stress). The Feddes function (α) describes the linear decrease in the amount of water removed due to water and oxygen stress. In HYDRUS-1D, the Feddes function for grass indicates that water uptake due to oxygen stress halts at -25 cm, the function was maximized between -300 cm and -1000 cm, and the cessation of water uptake due to water stress occurs at -8,000 cm.

The actual root water uptake sink term [$S(h,z)$], or transpiration, can be found as the integral of T_p, α, and $b(z)$ over the rootzone.

$$S(h,z) = T_p \cdot \int_{Lr} \alpha(h,z) \cdot b(z)dz = \int_{Lr} \alpha(h,z) \cdot S_p(z)dz \qquad (4.29)$$

4.2.12 Literature review of soil and compost hydraulic properties

The measurement of the SWCC and saturated hydraulic conductivity are essential for solving Richards' Equation and modeling flow in the subsurface. The hydraulic properties of the compost were modeled as a surface layer and the underlying soil's properties were constant. This is valid because Bakr et al. (2015) showed that over the course of one year, compost applied to a soil in a construction project did not decay. Additionally, Logsdon and Malone (2015) showed that when compost was applied to a soil column, the infiltration rate for the column as a whole was higher, but the saturated hydraulic conductivity and other hydraulic properties of the underlying soil was not largely affected by the compost amendment.

The underlying soil used in the model, silt loam, is characteristic of Dane County where Madison, WI is located as well as much of the upper midwestern United States. The silt loam follows the van Genuchten parameters and K_{sat} based on the literature review conducted by Carsel and Parish (1988). The Hydraulic properties of many different composts were found from relevant literature, shown tabularly in Table 4.1 and graphically in Figure 4.6. Methods for data acquisition are discussed below.

Whelan et al. (2013) conducted a study examining “green compost,” which was derived from green waste. The other compost assessed was a 1:1 mixture of green waste and catering meat waste. Composts were packed into 6 cm diameter and 5.4 cm deep cores for analysis. The SWCC was found with a sand table apparatus for pressure heads 0 to 100 cm, and with a pressure cell apparatus for pressure head of 200 to 15,000 cm. K_{sat} was found using a falling head permeameter. The van Genuchten properties were given and m = 1-1/n. The green compost from this study was used as the control or archetype compost as the depth of compost and vegetation parameters varied.

Al Naddaf et al. (2011) measured the hydraulic properties of composted pig manure. Samples were placed in 100 cm^3 rings and a sandbox apparatus was used to determine the water content at different suctions up to 100 cm. The van Genuchten parameter m = 1-1/n. K_{sat} was not determined in this study and we were unable to locate a value in the literature, so we estimated it to be the mean of other compost K_{sat} values, 100 $cm \cdot hr^{-1}$.

Table 4.1: Van Genuchten fitting parameters for silt loam and composts show a variety of fitted parameters. In this table, all curves are fit with the stipulation that m = 1-1/n. The saturated hydraulic conductivity from each paper is also presented. Shaded cells indicate an estimate found by averaging other compost types.

Source	Soil/compost type	Θ_s [vol-frac]	Θ_r [vol-frac]	α [cm^{-1}]	n [-]	K_{sat} [cm·hr^{-1}]
Carsel and Parish 1988	Silt loam (underlying)	0.450	0.067	0.02	1.41	0.45
Whalen et al. 2013	Green waste compost	0.563	0.264	0.117	1.748	93.25
Whalen et al. 2013	50% green waste, 50% catering meat waste	0.550	0.297	0.089	1.993	55.5
Al Naddaf et al. 2011	Composted pig manure	0.702	0.287	0.21	1.83	100
Raviv and Medina 1997	Composted cattle manure	0.90	0.084	0.48	1.16	100
Wallach et al. 1992	Composted grape marc	0.811	0.3	0.691	1.34	60.52
Naasz et al. 2005	Decomposed sphagnum peat	0.886	0.344	0.052	3.550	138.6
Naasz et al. 2005	Composted pine bark	0.805	0.495	0.068	3.258	159.6
Glab et al. 2014	Municipal compost	0.727	0.00659	0.0027	1.25	100

Raviv and Medina (1997) found the SWCC of compost prepared from separated cattle manure. The manure was run through methanogenic fermentation in an anaerobic reactor prior to the composting process. Samples with a volume of 250 cm^3 were placed in a funnel with a porous plate. A 400 g plummet was placed on samples for 1 hour. Suction was induced by raising the funnel by a few cm every 24 hours. Van Genuchten parameters were not given, so suction head and volumetric water contents were read off the curve given in the paper. We fit van Genuchten parameters to sample number 3 in the paper using least squares regression. This sample was chosen from the paper since the water content was in between the content of the other two samples for much of SWCCs. The maximum suction applied was 100 cm of water and there was no hydraulic conductivity value given, so 100 cm·hr^{-1} was used in the model. The curves from this study indicate that more water is retained in the soil matrix under a given suction head than the pig manure samples and most other compost samples. This may be due to the anaerobic decomposition process the manure was put through prior to the composting process or the 24 hours in between suction steps was not an adequate amount of time given for compost samples to equilibrate with suction heads. The ASTM (2016) standard requires after suction is set, the movement at the air-water interface shall cease for at least 24 hr.

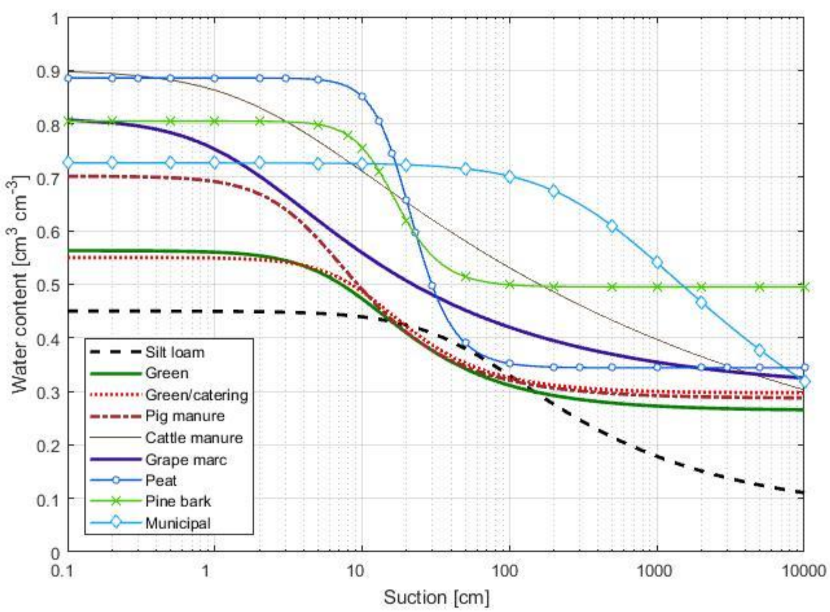

Figure 4.6: Graphical representation of the van Genuchten fitted soil water characteristic curves for the underlying silt loam soil and the assessed composts. While there was a wide range of saturated and residual water contents, most composts began losing water between 5 cm and 10 cm of suction head.

Wallach et al. (1992) found properties of composted grape marc, or the residuals after pressing for grape juice or wine. A hanging-water-column was used to a maximum suction head of 120 cm. Unsaturated hydraulic conductivity was measured with a long column version of the steady-state flux control method. K_{sat} was calculated with linear regression over the linear range of Darcy's Law. The van Genuchten Θ_r was reported to be 0, which is not possible and would not solve in HYDRUS-1D. We re-fit the curve to the data points with a Θ_r of 0.3 using least squares regression. The SWCC with the updated Θ_r had an r^2 of 0.993 with the given data points from their experiment.

Naasz et al. (2005) found the hydraulic properties of decomposed sphagnum peat and composted pine bark. Two PVC (polyvinylchloride) cylinders with a 14-cm diameter and 14-cm height were manually filled without packing. K_{sat} was determined by measuring the unsaturated hydraulic conductivity and extrapolating to saturation. The volumetric water content was found with tensiometers, and water potential (or suction head) was determined with time domain reflectometry probes. Both drying and wetting curves, hysteresis, are presented in this paper. The van Genuchten α value unit was reported as m^{-1}. However, we believe the van Genuchten equation was mistakenly fitted to the kPa curve given in the figure, and the actual unit of α provided in the table is kPa^{-1}. We converted units, and re-determined all van Genuchten parameters with least squares regression. The curve fit now fit the data well. Additionally, m was given as a free parameter, rather than m = 1-1/n. Updated van Genuchten parameters were determined with this constraint using least squares regression. These two transformations had a coefficient of determination (R^2) of at least 0.9989 with the given experimentally derived SWCCs.

Głąb et al. (2014) examined the hydraulic properties of municipal compost, which was derived from "plant and other biodegradable waste" from Krakow, Poland. The compost samples were placed in 100 cm^3 steel cylinders and placed in pressure chambers, ranging from 40 cm to 15,859 cm of water. The van Genuchten parameters were not given, so we interpolated the SWCC values were to the best of our abilities and fit van Genuchten parameters. A value of K_{sat} was not given in this paper either, so an average value of 100 $cm \cdot hr^{-1}$ was assumed.

In this municipal compost, there was very little water lost from the soil matrix until 100 cm of water suction, and the reason for this is perplexing. This was an order of magnitude higher than the other composts, which generally started losing water around 10 cm of suction or less. These results indicate anomalously high water holding capability of this compost. SWCCs of sand were also measured in this paper and were similar to those derived by Carsel and Parish (1988). This indicates that there were not experimental or unit errors. One note, however, is that the initial suction step of 40 cm may have been too high.

There was significant variation on the methods used for determining the SWCC. One major consideration is a few of the papers did not get the higher suction portion of the characteristic curve. This would be important in drier climates where the suction head may be more negative than the wet, temperate Madison, WI summer of 2017. While the compaction techniques varied, the weights applied to the composts were not large. Some DOTs required compost to be tracked over with a bulldozer, so the compaction could represent differences in functionality after slight compaction in the field.

4.2.13 Initial conditions

To determine the initial conditions, we first modeled average rainfall conditions in the 78 days leading up to the model for April, May, and part of June conditions for Madison, based on statistical values outlined in Eagleson (2002). Both the 5 cm green compost and no compost conditions were run from near saturation (h = 0.1 m) with average evaporation conditions form the model (Eqn. 4.16). At the end of the simulation with compost, *h* for the soil column ranged from -80 cm to -94 cm and the column was generally wetter near the surface. The bare soil run, *h* ranged from -103 to -125 cm and was wetter in the deeper parts of the column.

The other method we examined to determine initial conditions was using the effective saturation at field capacity (S_{fc}) equation from HYDRUS-1D:

$$S_{fc} = \frac{\theta_{fc} - \theta_r}{\theta_s - \theta_r} = n^{-0.60 \cdot [2 + log_{10}(k_{sat})]} \tag{4.30}$$

where θ_{fc} is the θ at field capacity, and *n* is the parameter from the van Genuchten equation. Solving equation 4.30 for θ_{fc} and using the SWCC to convert to *h*, the *h* of the compost layer would be -49.3 cm and the soil layer would be -88.3 cm.

Given results of the two methods, we decided the most representative initial conditions would be a constant head throughout the soil and all composts as -90 cm. The soil at construction site would probably be recently worked. For compost, a head of -90 cm represents a value that is in the center of the range of the wetting and drying cycles during the initial conditions run. For the soil, it represents a value that is slightly drier than the field capacity calculated in equation 4.30, and a little wetter than the runup period.

4.2.14 Model runs

The model was run with no vegetation, established vegetation, and growing vegetation for both bare soil and for 5 cm of green compost. Compost blanket thicknesses were then varied under the vegetation growth model, since the weeks directly after application are in a crucial time to assess vegetated compost blankets. The thicknesses of compost blankets reflected common depths of compost application: 2.5 cm, 3.75 cm, and 7.5 cm. Finally, the different composts were run under the vegetation growth model with a 5 cm compost blanket thickness. A summary of the different model runs is shown in Table 4.2.

Table 4.2: Modeled scenarios in HYDRUS-1D where one parameter was changed for each run. 5 cm of green waste compost from Whelan et al. (2013) was used to compare results. The domain depth was a constant 200 cm.

Grouping	Established Vegetation?	Vegetation growth?	Compost thickness [cm]	Silt loam thickness [cm]	Compost type
Bare soil			0	200	None
Vary vegetation			5	195	Green waste
	X				
		X			
Vary compost blanket thickness		X	0	200	Green waste
			2.5	197.5	
			3.75	196.25	
			7.5	192.5	
Vary composts		X	5	195	Green/catering meat waste
					Composted pig manure
					Composted cattle manure
					Composted grape marc
					Decomposed sphagnum peat
					Composted pine bark
					Municipal

4.2.15 Lab Experiment

We also collected two commercially available composts in Wisconsin from Purple Cow Organics (PCO) and Blue Ribbon Organics (BRO). PCO was purchased from a store and is plant based, mainly yard residuals. The BRO compost was collected from the generation facility near Milwaukee, WI, and was derived from green waste and SSOC.

Compost samples were placed in a Buchner funnel and saturated with de-aired water in vacuum supplying a negative pressure at the top of the funnel. After saturation, samples were placed in a hanging column apparatus, outlined in the ASTM standard (2016). Suction heads were applied and reported from a minimum ~4 cm. The maximum heads the apparatus allowed for were 209.8 cm for the BRO and 184.4 cm for the PCO sample. At the end of the test, the samples were weighed, dried in a soil oven for 24 hours, and weighed again to determine the final gravimetric water content. The volumetric water content was found by multiplying the gravimetric water content by the dry bulk density (oven dried mass/pre-dried volume). Water removed from the sample was added incremental to determine the SWCC. Van Genuchten parameters were found by least squared regression of the given water contents.

4.3 Results

Comparisons are first made between bare soil and the archetype compost. The parameters of interest were the volumetric water content at different depths and the cumulative fluxes. For the established vegetation and growing vegetation runs, the root water uptake, or transpiration, was also compared. Modeled results of the different types of compost are also presented.

4.3.1 Compost vs bare soil without vegetation

The volumetric water content using observation points at 5 cm, 20 cm, 50 cm, and 75 cm depths below the surface were examined for both bare soil (Figure 4.7 upper left) and 5 cm of green compost (Figure 4.7 upper right). The θ at 5 cm (the bottom of the compost zone if present) was subject to larger variation of θ when compost was applied. At the 5 cm depth, θ decreases during dry periods were linear for bare soil and had a decreasing derivative for compost. This indicates that when compost was applied, soil water at that depth was being retained despite potential sinks of drainage or evaporation. At z = 75 cm, θ increased with time in the compost-amended soil, while it was more constant with the unamended soil.

Cumulative fluxes throughout the simulation were also examined for the bare soil (Figure 4.7 lower right) and compost-treatment (Figure 4.7 lower right) scenarios. The runoff curves throughout the time series indicate that runoff was produced more often and in greater depths (9.9 cm) with the bare soil compared to the compost-treated soil (4.1 cm). The initial water storage in the 200 cm domain of the no compost and compost treatments were similar, 67.6 and 67.5 cm, respectively. By the end of the simulation, the no compost scenario increased by 3.7 cm, and the compost treated scenario increased by 8.9 cm. The addition of green waste compost only reduced the evaporation from the soil surface by 3%, from 5.6 cm to 5.5 cm.

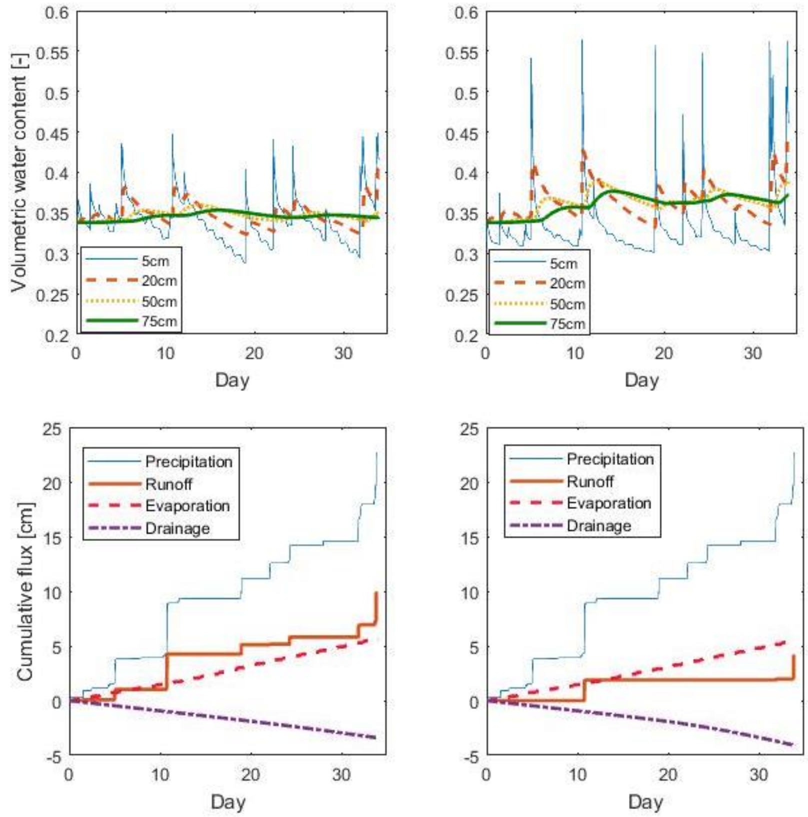

Figure 4.7: Volumetric water content at observation nodes from different depths for ***No*** *compost (upper left) and compost* ***treatment*** *(upper right); Cumulative fluxes for* ***No*** *compost (lower left) and compost* ***treatment*** *(lower right). All figures have no vegetation. With the compost treatment, more water is infiltrated into the soil column and there is less runoff. Most of the reduced runoff is filling the soil water storage. By the end of the simulated period, the compost treatment has higher drainage as the increased infiltrated water drains from the bottom of the domain.*

4.3.2 Varied vegetation scenarios and varied compost thicknesses

Transpiration of water from the root zone was an important component of the water balance in cases with vegetation. Example of cumulative fluxes with 5 cm of green compost under the established vegetation scenario (left) and growing vegetation scenario (right) are shown in Figure 4.8. In the established vegetation model run, the transpiration does not appear to be limited by oxygen or water stress. Also, evaporation is not an important component of the water balance with a high LAI throughout the modeled timeframe. For the growing vegetation scenario, evaporation from the soil surface is a noteworthy sink term until the canopy is developed half way thought the model when transpiration becomes more significant. The cumulative effective precipitation is affected at the end of the season as the LAI increases. Other figures portraying the cumulative fluxes over time are shown in Appendix C.

Varying the vegetation scenario while controlling the depth and type of compost had a impact on the water balance, especially the change in storage (Figure 4.9). Without any vegetation, but with compost, the soil column had a significant increase in storage, 8.9 cm. With no transpiration component, the evaporation was higher than other scenarios. Contrary to the unvegetated scenario, the established vegetation scenario had a significant decrease in soil water storage, 9.5 cm due to high amounts of transpiration. While the evaporation component was 0.9 cm, 3.7 cm less than the growing vegetation scenario, the cumulative transpiration of 23.7 cm was 3.3 times larger than the equivalent growing vegetation case.

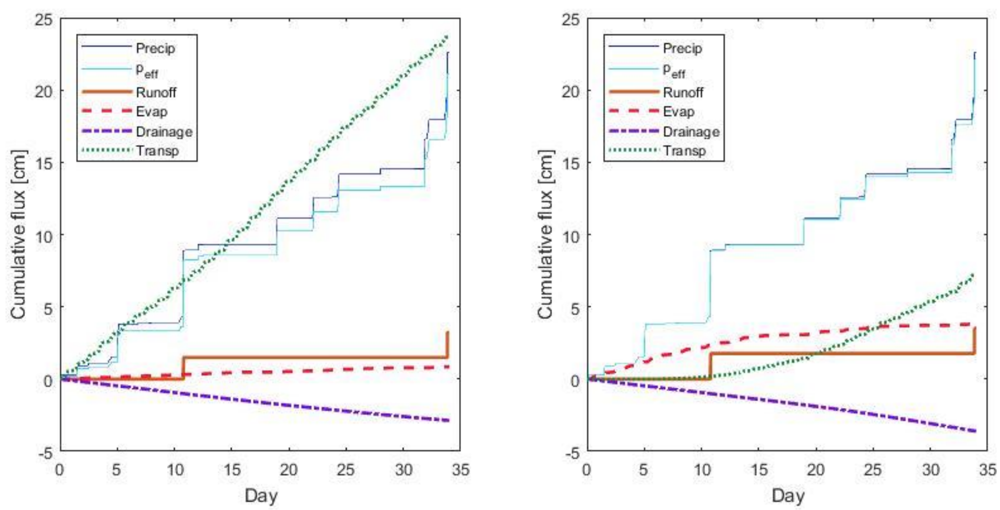

Figure 4.8: Five cm of archetype green waste compost under the established vegetation (left) and vegetation growth (right) scenarios cumulative fluxes over time. In the established vegetation scenario, the transpiration does not appear to be limited throughout the simulation. The cumulative transpiration is near zero cm until around day 10 in the growing vegetation model.

The depth of compost was also varied under the growing vegetation scenario (Figure 4.9). The model results indicate that thicker layers of compost increase the soil water storage and reduce runoff, as what would be expected. However, as more compost is applied, both evaporation and transpiration decreased because the negative potentials induced by these sinks were less able to access soil water.

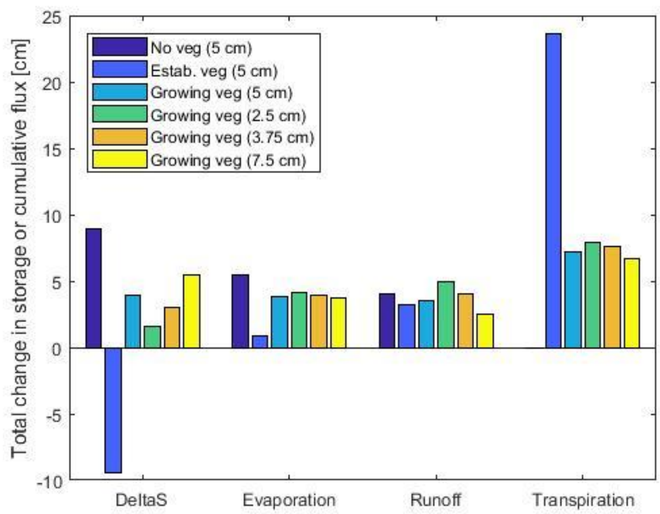

Figure 4.9: Four important water balance parameters from scenarios were vegetation stage was varied and scenarios where compost depth was varied (in parenthesis).

4.3.3 Different composts

Changing the compost type based on the characteristic curves parameterization from the literature search induced significant differences in water balance parameters. Observation nodes at different depths for each run are shown in Figure 4.10. Setting the head throughout the domain as a constant -90 cm influenced the results of the model runs. Reviewing Figure 4.6, for h of -90 cm, θ ranged 0.3 to 0.55 for the compost other than the anomalous municipal compost, which θ would be 0.7. All the curves, except the municipal compost, were on the drier side of the SWCCs. These differences in initial conditions could be a major driver of runoff and infiltration, especially at the beginning of the timeframe. However, examining θ at z = 5 cm, the bottom of the compost layer, throughout the simulation shows that conditions differ. One anomaly is the pine bark compost, which stayed near a minimum θ = 0.5 for most of the simulation. We tried starting this with initial heads ranging from -0.2 cm to -1000 cm, but the compost layer went back to this state. Overall, the chosen initial conditions for each of the runs allow for the layer to become wetter and drier throughout the time series, so this looks to be a reasonable starting place.

The total change in storage and cumulative fluxes are shown in Figure 4.11 and these time series are shown in Appendix C. Under the growing vegetation scenario, soil without a compost layer had a negative change in storage. Assuming an across-the-board similarity in vegetation for the untreated soil, and all composts may not be realistic as some composts may help or hinder vegetation growth. However, controlling vegetation scenario does illustrate what effect the compost has on the water balance.

The other composts are compared to the green waste compost used in the previous simulations. The green waste/catering meat waste combination's SWCC and K_{sat} were measured by the same author and contained 50% of the same material as the archetype compost. Still, the evaporation and transpiration decreased by 17% and 6%, respectively, while the runoff increased by 8% throughout the growing season. This indicates that using the addition of catering meat waste compost to green waste compost can increase runoff.

The manure composts induced opposite changes when compared to the archetype compost for the change in storage, evaporation and transpiration. Compared to the archetype compost, the change in storage was 74% higher with the pig manure compost and 41% lower with the cow manure. Other than the municipal compost, the cow manure had the lowest change in storage. Interestingly, this change in storage was not principally controlled by increased runoff, which the cow manure was only 9% higher. Instead, the cow manure-based compost had 94% higher evaporation and 29% higher transpiration.

A vegetated compost blanket with the grape marc feedstock would, compared to the green waste compost, decrease evaporation, transpiration, and runoff by 17%, 12%, and 27%, respectively. Within the soil column, there was also as increase in soil water storage by 49%.

The sphagnum peat material and the pine-bark-based compost had characteristic curves that were measured by the same authors. The total change in storage was higher than other treatments and only varied by 4%; however, this was due to different reasons. The sphagnum peat was better at reducing runoff, but the additional evaporation and transpiration offset the differences. The pine bark compost had a similar runoff depth to the green waste compost, but evaporation and transpiration were decreased by 51% and 29%, respectively.

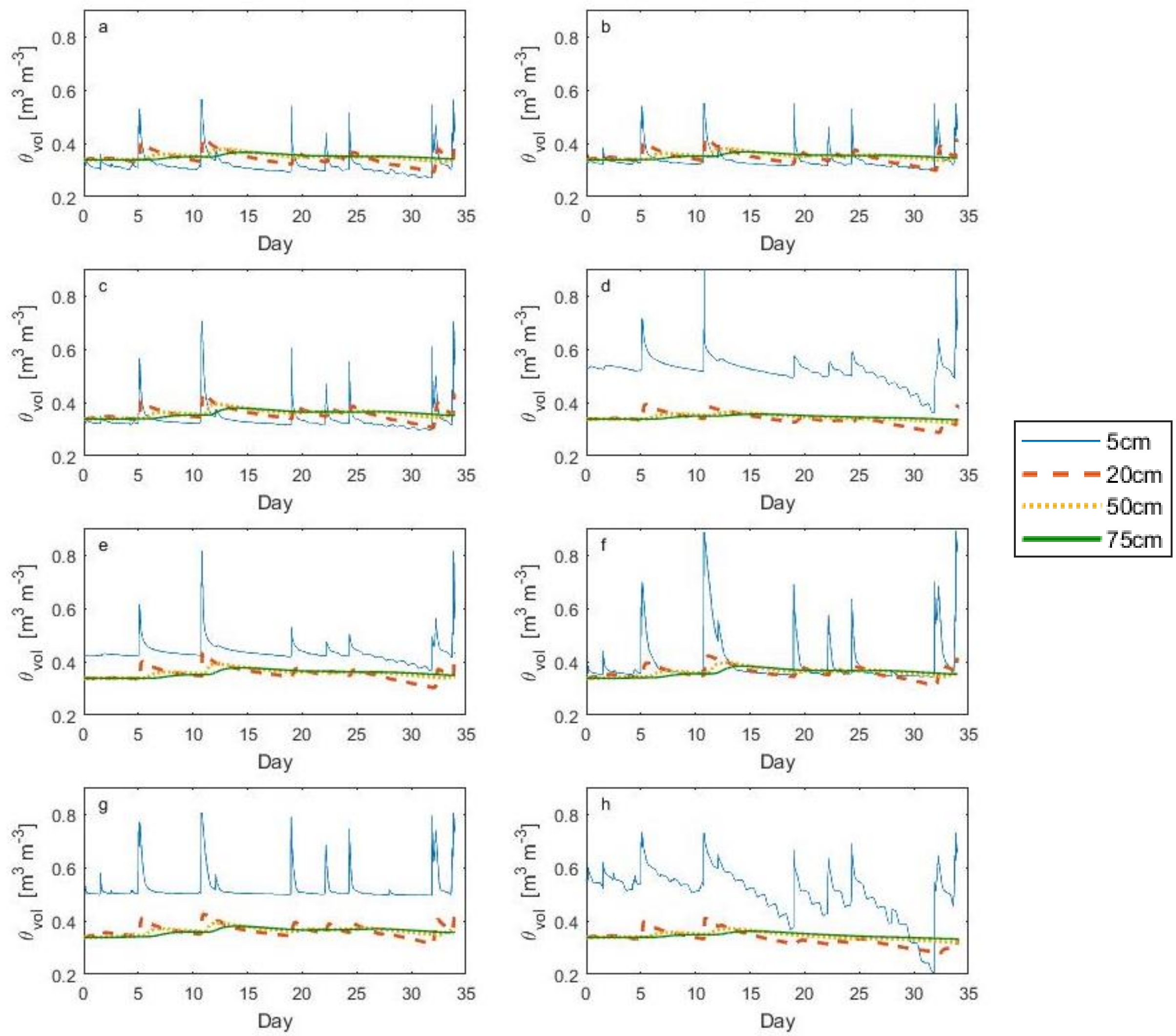

Figure 4.10: The volumetric water content of different compost at different depths throughout the simulation. a: green waste b: green/catering meat waste, c: pig manure, d: cattle manure, e: grape mark, f: sphagnum peat, g: pine bark, h: municipal

The municipal compost's anomalous characteristic curve did create different results in the components of the water balance. It was the only compost the result in a negative change in storage. Runoff was greater than all other compost treatments, only 32% lower than the no compost treatment. Other composts reduced runoff by 64%. Evaporation and transpiration from this vegetated compost blanket was also higher than the bare soil treatment.

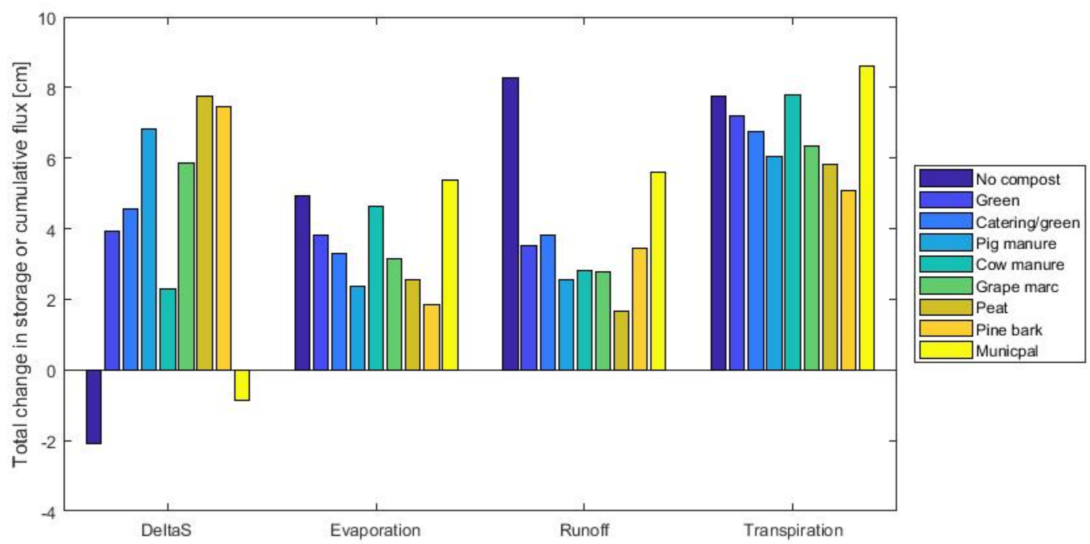

Figure 4.11: Different composts applied at 5 cm depths under the vegetation growth scenario had variable changes in storage, evaporation, runoff, and transpiration. The "No compost" run indicates no compost was on the surface, but vegetation was assumed to grow at the same rate as if compost were to be applied.

4.3.4 Drainage

The drainage from the bottom of the domain differed between the treatments, ranging from 2.9 cm in the established vegetation with green waste compost scenario to 4.3 cm in the pine bark compost under the vegetation growth scenario. Drainage is dependent on effective precipitation, runoff, evaporation, and transpiration. As more water enters the domain, and is not evaporated or transpired, the drainage will increase as water moves through the soil column. Cumulative drainages for each modeled scenario are shown in Figure 4.12.

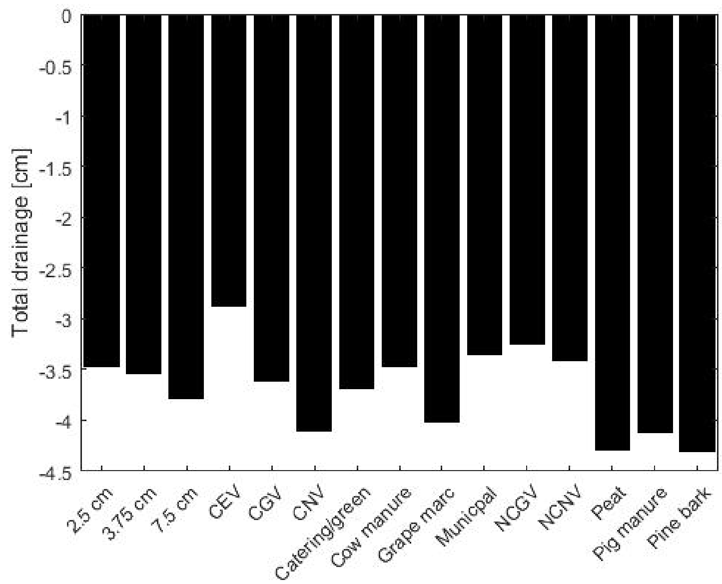

Figure 4.12: Drainage from the bottom of the control boundary for different treatments indicate there was variability in this flux. The drainage at the bottom of the soil column is an important part of the water balance. Compost treatment caused more drainage as more water entered the domain rather than ran off. Since roots transpired water that could have drained, the compost with established vegetation (CEV) had less drainage than the compost with growing vegetation (CGV), which had more drainage than compost with no vegetation (CNV). The no compost growing vegetation (NCGV) and no compost no vegetation (NCNV) had less drainage than the equivalent scenarios with compost, CGV and CNV, respectively. The grape marc, peat, pig manure, and pine bark treatments had more drainage than green, catering/green, cow manure, and municipal compost because more water entered the domain as infiltrated rainfall and less left the domain as evaporation and transpiration sinks.

4.3.5 Lab experiment results

The lab results of the characteristic curves of the two composts indicate very different water retention properties. The PCO compost SWCC looks the most like the pine bark or grape marc curves with high θ_s and θ_r, but with a sizeable range, and much of the water dropping out by 80 cm of suction. The BRO SWCC held less water under a given suction and did not have as wide of a range between θ_s and θ_r.

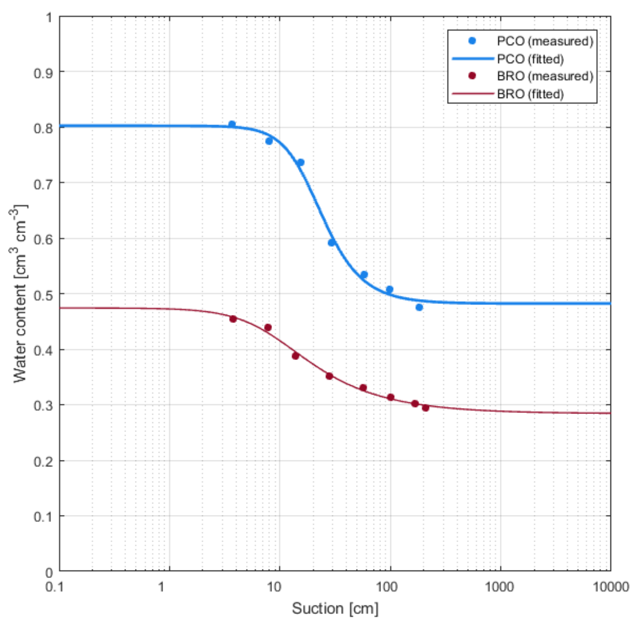

Figure 4.13: Characteristic curves of two composts collected in Wisconsin, Purple Cow Organics and Blue Ribbon Organics

Table 4.3: Van Genuchten fitting parameters for two composts collected in Wisconsin

Compost type	Θ_s [vol-frac]	Θ_r [vol-frac]	α [cm^{-1}]	n [-]
PCO	0.802	0.482	0.053	2.80
BRO	0.474	0.284	0.116	1.80

Overall, the lab procedures could be revised for collecting SWCCs for compost samples. First, the ASTM requires the sample to equilibrate at no suction. This took weeks and went up or down, depending on the atmospheric pressure in our lab. We also set suction measurements at 0.5 cm, 1 cm, and 2 cm, which took a many days to equilibrate. While we controlled for evaporation with the sample covered with a pin hole, as per the ASTM standard, some water likely evaporated during this initial calibration period. It would be best to test compost starting at 4 or 5 cm of suction. However, these results validate the wide range in SWCCs of different composts from the literature review.

4.4 Discussion and conclusion

Throughout the model runs, we first sought to assess the effects of adding compost to bare soil without including vegetation. Then we varied the vegetated compost blanket layer thickness, the vegetation stage, and the type of compost. The changing of these modeled parameters had significant effects on the components of the water balance in the 1D domain.

For unvegetated compost blankets, the model indicates that the application of compost is beneficial to reducing runoff, increasing soil water storage throughout the domain, and increasing drainage. The model does not, however, indicate a large change in evaporation based on the addition of 5 cm of green waste compost. Both cumulative evaporation curves exhibited linear a linear increase until the end of the simulation. These results are indicative that both unvegetated soil and unvegetated green-waste compost had ample water to evaporate, and evaporation was energy limited. This result was interesting enough that we also examined the evaporation from unvegetated compost blankets of 5 cm depths using other composts. The green waste/catering meat waste, pig manure, and grape marc had cumulative evaporations of 5 cm 3.75 cm and 4.2 cm, respectively. Our assessment of the green waste compost is that it had an equivalent amount of water infiltrated, there would be decreased evaporation. However, it happened to be that with this compost, more water infiltrated into the material which could evaporate. Cumulative evaporation is not the best indicator of a function compost blanket.

This model was run during a rainy timeframe, so given the normal initial conditions, most of the treatments experienced positive changes in storage, especially during and following the two large rain events.

To assess which parameter had the most influence on portions of the water balance, a standard deviation table was created using the following formula:

$$Standard\ deviation = \sqrt{\frac{\sum(x-\bar{x})^2}{n}} \tag{4.31}$$

where x is the variable of interest, $\bar{x}$ is the mean from different treatments, and n is the number of samples.

Table 4.4: *Standard deviations due to changing of modeling scenarios*

	ΔS [cm]	Evaporation [cm]	Runoff [cm]	Transpiration [cm]
Vegetation	7.8	1.9	0.4	9.9
compost depth	1.4	0.2	0.9	0.5
compost type	2.7	1.11	1.09	1.06

The three vegetation scenarios outlined that the stage of vegetation can be a major driver of differences in the water balance. The change in storage was greatly affected by the vegetation stage because the established vegetation was a major sink of soil water. The evaporation and transpiration also had the highest standard deviations due to the two different vegetation scenarios. Interestingly, the runoff was least affected by the vegetation scenarios.

It is likely that if the vegetation was fully established that there would be differences in the material properties of compost. The established vegetation case could be analogous to reality if established vegetation were planted into compost amended soil or if compost retained its hydraulic properties into vegetation establishment. The latter could happen with slow degradation or reapplication. Different vegetation types, root lengths, Feddes functions, and growth rates would give variable results from the model. More vegetation types can be explored in the future, but since grass seed is currently used in many DOT projects it was a good starting point.

Changing the depth of compost had the smallest effect on the change in storage, evaporation, and transpiration. However, for the blanket thicknesses examined, 2.5 cm, 3.75 cm, 5 cm, and 7.5 cm, there was a strong inverse relationship between the compost depth and cumulative runoff depth during the simulation (Figure 4.14).

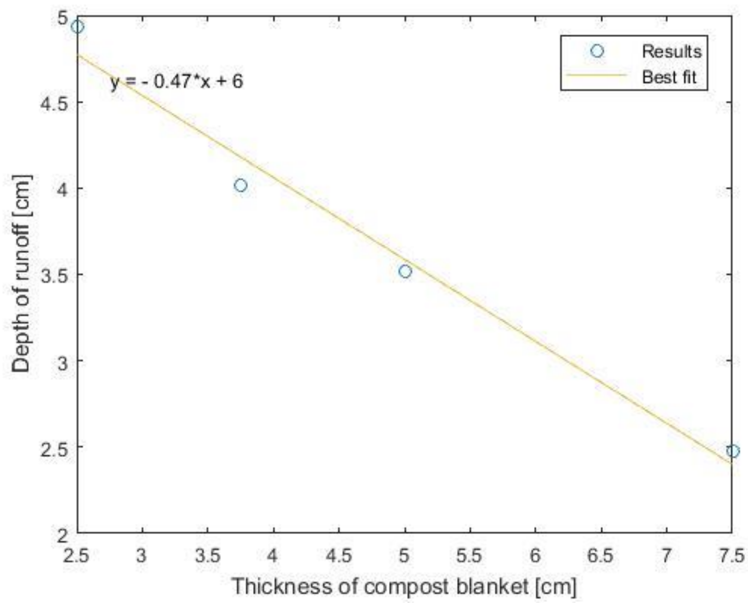

Figure 4.14: Thicker compost blanket thicknesses, on the growing vegetation scenario, decreased runoff. The inverse relationship is not necessarily linear within or outside of this range.

Varying the hydraulic properties of the upper 5 cm, corresponding to the different composts caused a greater standard deviation in runoff than changing the vegetation scenario or compost depth. The municipal waste compost produced the worse results in terms of runoff. Another item worthy of discussion is the difference in the results of the pig and cow manure. The pig manure while having similar runoff depths, had less evaporation and transpiration than the cow manure. During day 25 to 32, the less rainy portion of the modeled simulation, the cow manure dried out under the evaporation and transpiration (Figure C 2).

Ranking the different composts assessed in terms of their ability to reduce runoff from best to worse: peat, pig manure, grape marc, cow manure, pine bark, green waste, catering meat waste/green waste mixture, and municipal compost. However, all composts were better than untreated soil at reducing runoff.

In conclusion, the vadose zone model indicates the stage of the vegetation is the most important driver for the soil water storage, evaporation, and transpiration. A fully developed root system and canopy would add transpiration and limit evaporation fluxes in the domain. However, in terms of reducing runoff, the compost type is most important, and compost depth is to a slightly lower degree.

Overall, this model evaluated compost treatments during a relatively mild and wet portion of a summer in temperate climate. There are a host of actual and modeled conditions that could be inputted into this vegetated compost blanket model to aid in decision to reach goals of the engineer. There has been research conducted on the characteristic curves of different composts for various reasons. This is the first attempt, to our knowledge, to pull the various sources together and model them against one another. Methodologies from this paper outline a system for evaluating vegetated compost blankets.

Inputting daily precipitation data in HYDRUS-1D and allowing it to model variable precipitation rates throughout the day did not adequately represent the rainfall data in this region. The non-linearity in the precipitation rates throughout a day is not like the sinusoidal approximation that HYDRUS-1D uses. Thus, finer resolution precipitation data were necessary. However, using data of this resolution required a significant amount of manual pre-processing.

Looking to the future, this work could be continued in many ways. First, calibrating this model with field observations is a logical next step. Some of the papers have hysteretic effects of wetting and drying; this could be included in the model easily with HYDRUS-1D’s built in functionality. Saturated hydraulic conductivity measurements could be taken from the samples that were not given in the academic papers. It would also be interesting to find results of different vegetation types and modeled climates. Finishing a subsurface-surface flow coupled 2D model could help designers know how slope impacts the rate of overland and subsurface flow. Another area of interest is measuring the hydraulic properties of compost as it decays and implementing that into the model over a longer timeframe.

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Chapter 5

Conclusion

Overall, compost represents the cyclical fashion of natural processes. What was once thought of as waste material can be transformed into a valuable, suitable growing medium that can limit erosion from land surfaces. The literature indicates that there are differences among feedstocks and mixtures. With care taken to ensure compost is stable and mature, follows particle size distribution requirements, and meets chemical requirements, DOTs and other construction companies can use it. While the DOTs throughout the U.S. vary considerably as to how they outline the use of compost, it is encouraging to see it outlined in many specifications. USCC and AASHTO guidelines could more strictly adhered to, however.

We have also explored a possible way to model the hydrologic response of vegetated compost blankets, as well as unvegetated compost blankets. Modeled results indicate that compost type does matter for runoff, which is supported by the literature. The thickness of the compost layer matters in the ranges we assessed, but it appears to be slightly less important that the type of compost. Controlling other variables, the vegetation stage had the least effect on runoff.

Appendix A: Simplified erosivity index in the U.S.

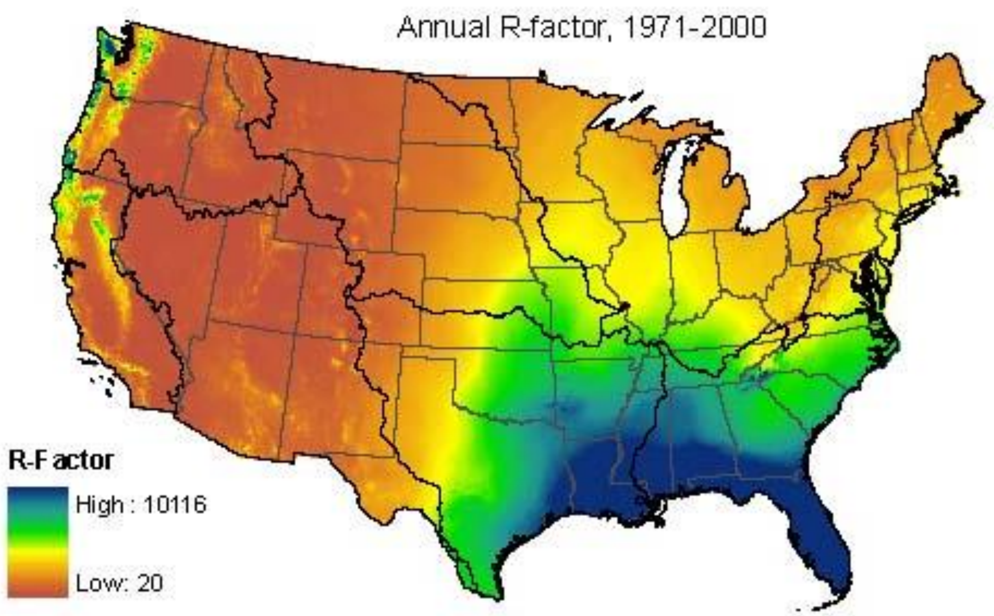

Figure A 1: Simplified erosivity index map of the lower 48 states, taken directly from the USGS (2006)

Appendix B: Results of DOT specifications

Table C 1: For states that have more than one compost prescribed, what differs from type-to-type

	Feedstocks	Particle size	pH	Salts	Moisture	OM	Stability	Nutrients	Other
Arizona	X	X	X			X	X	X	Maturity
California		X							
Iowa		X							
Maryland	X	X	X	X					
Minnesota	X		X						
New Jersey	X	X	X	X	X		X		
New Mexico	X								Metals and Pathogens
New York	X	X	X	X	X	X			Inerts
Oregon		X						X	
Pennsylvania	X	X	X	X	X	X			
Virginia		X							
Washington		X					X	X	

Appendix C: Cumulative Fluxes over time

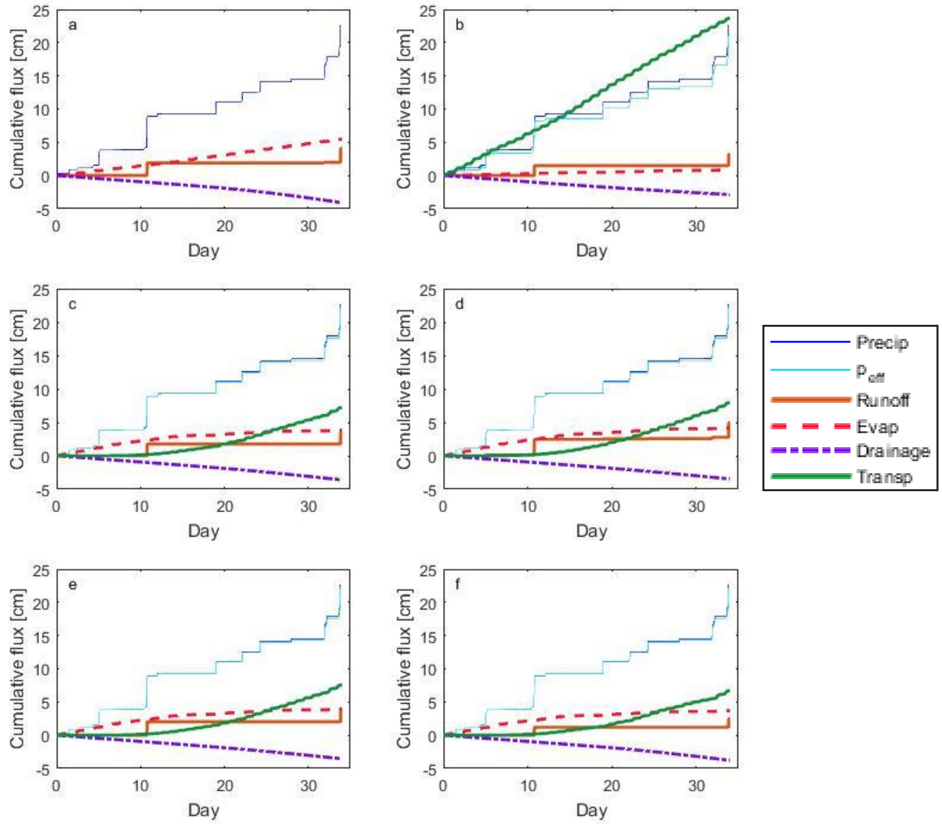

Figure C 1: Cumulative fluxes over time of the different vegetation and depth scenarios. a: No vegetation (5 cm); b: Established vegetation (5 cm); c: Growing vegetation (5 cm); d: Growing vegetation (2.5 cm); e: Growing vegetation (3.75 cm); f: Growing vegetation (7.5 cm)

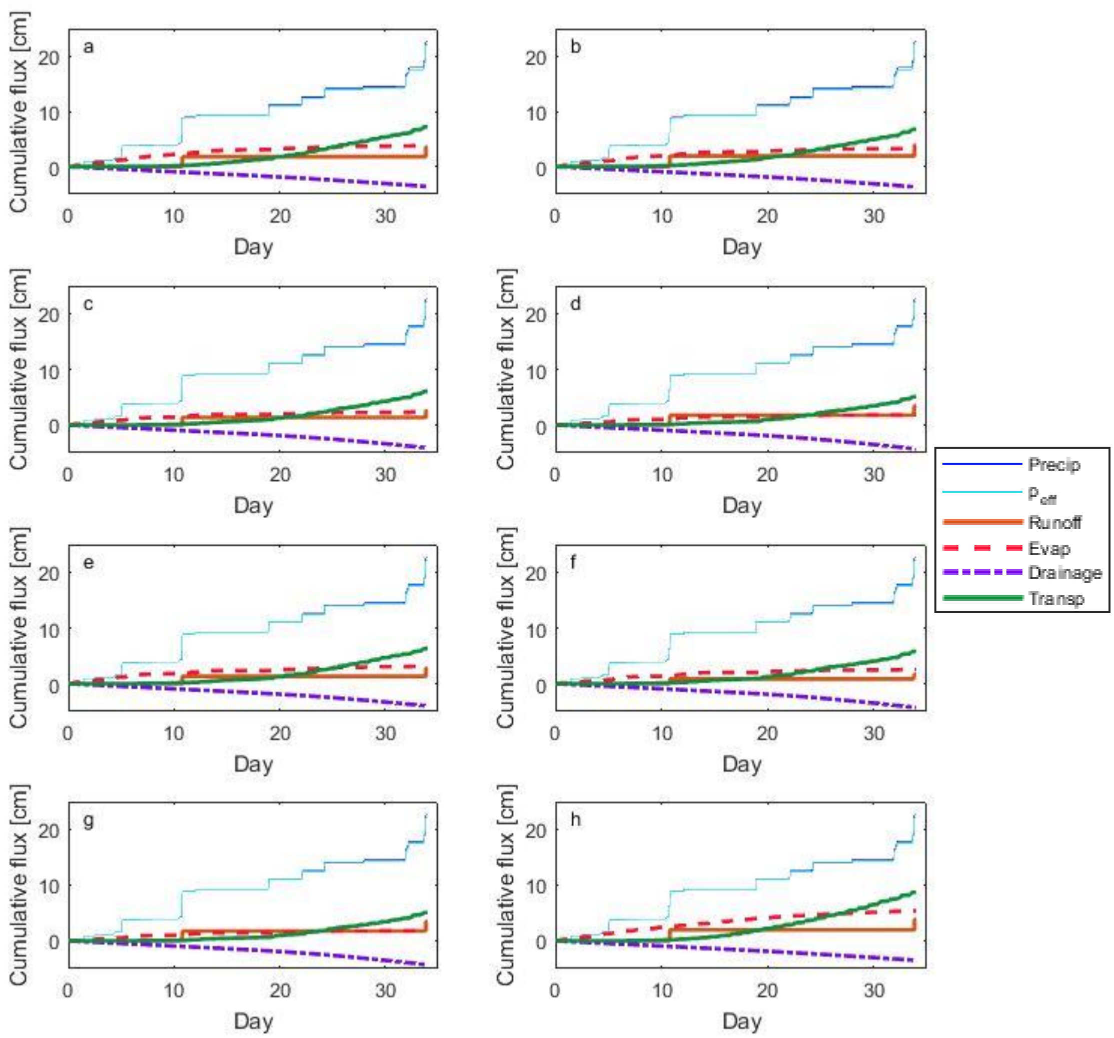

Figure C 2: Cumulative fluxes for different composts. a: green waste b: green/catering meat waste, c: pig manure, d: cattle manure, e: grape mark, f: sphagnum peat, g: pine bark, h: municipal

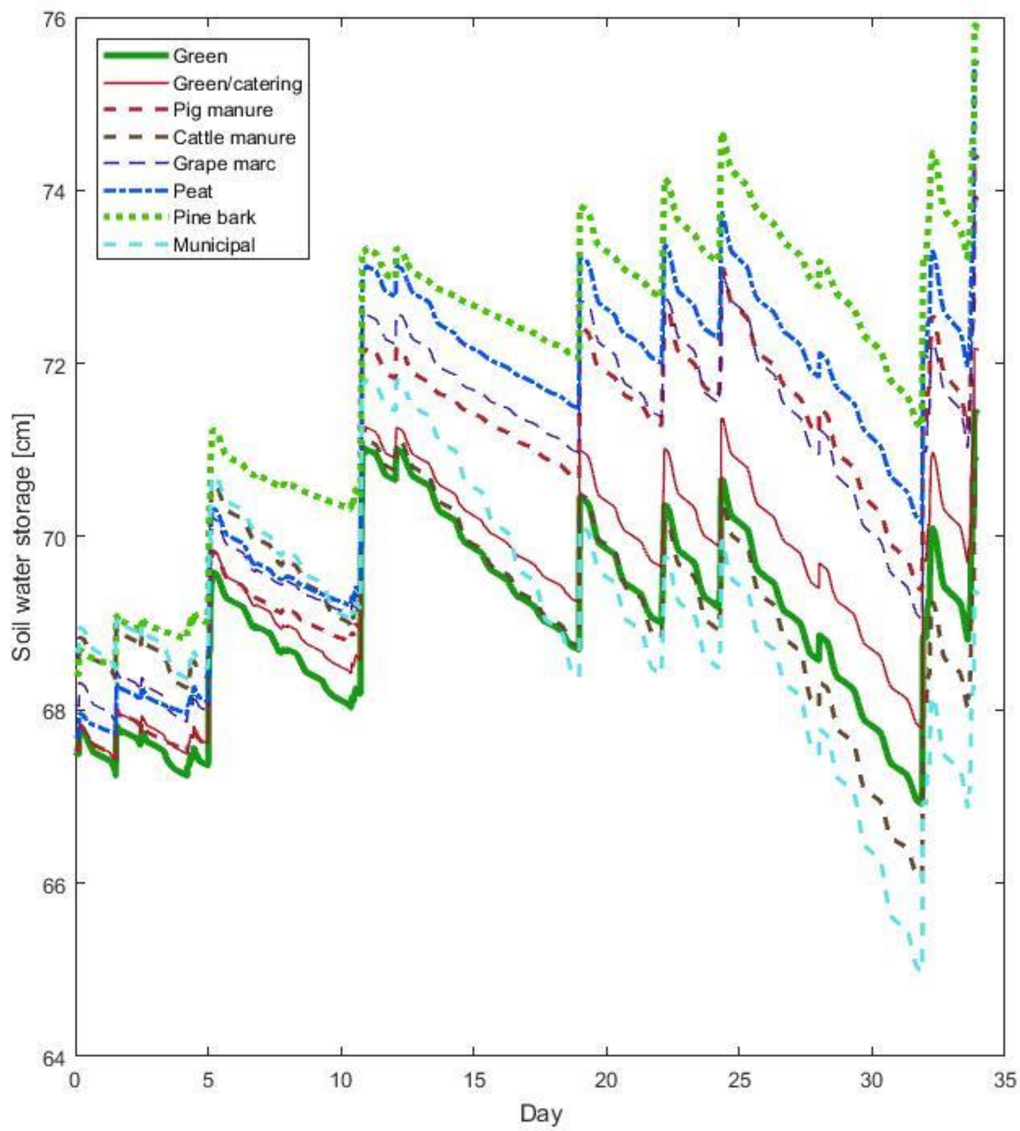

Figure C 3: Change in soil water volume [cm] for each of the runs where compost type was varied

Appendix D: Photos of compost

Figure D 1: Purple Cow Organics compost is less tightly held together

Figure D 2: Blue Ribbon Organics looks to have more fine particles

Appendix E: Mapped results

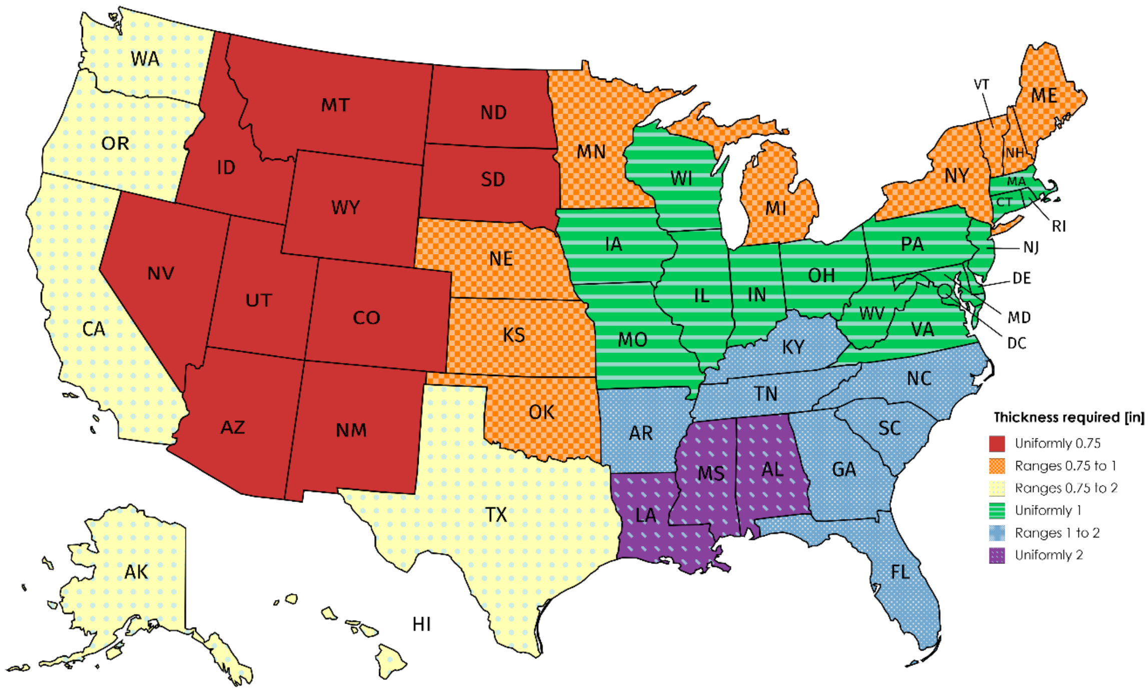

Figure E 1: Thickness requirements for a vegetated compost blanket for each of the 50 states

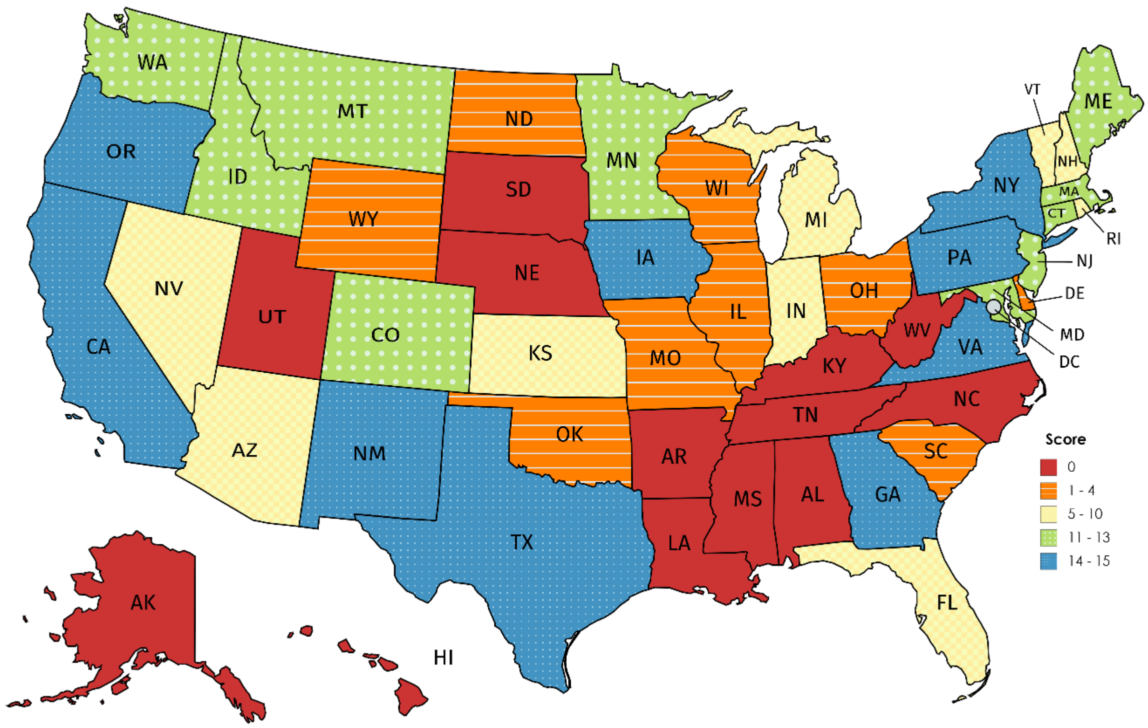

Figure E 2: Map representation of how each state included compost in their latest design specification document. The maximum score was 15 out of 18.